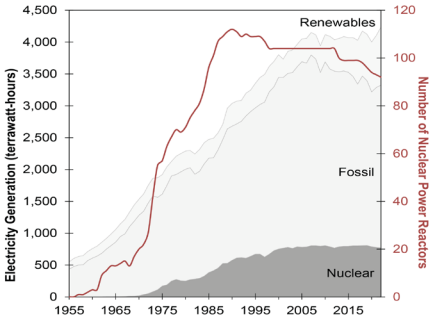
Nuclear Energy

Nuclear power plants generate electricity by using controlled nuclear fission chain reactions (i.e., splitting atoms) to heat water and produce steam to power turbines. Nuclear is often labeled a "clean" energy source because no greenhouse gases (GHGs) or other air emissions are released from the power plant. As the U.S. and other nations search for low-emission energy sources, the benefits of nuclear power must be weighed against the operational risks and the challenges of storing spent nuclear fuel and radioactive waste.

Nuclear Energy Use and Potential

- Nuclear energy provides about 19% of U.S. electricity, and this share has remained stable since around 1990. Nuclear power plants had a capacity factor of 92.6% in 2022.[1]
- The first U.S. nuclear power plant began commercial operations in 1958.[2] During the 1970s, more than 50 nuclear reactors went online.[1] Presently, 28 states have at least one nuclear plant and 32 plants have two or more reactors.[2]
- 667 reactors have been built worldwide since the first was built in 1954 in Obninsk, Russia, though currently, there are only 436 in operation, 93 of which are in the U.S.[3,4] As of May 2023, 59 reactors were under construction, including 1 in the U.S. and 23 in China.[4]
- In 2021, the U.S. generated nearly a third of the world's nuclear electricity. Countries generating the next largest amounts of electricity using nuclear were China, France, and Russia.[5]
- Levelized cost of energy (LCOE) includes the lifetime costs of building, operating, maintaining, and fueling a power plant. Estimated LCOE for plants built in the near future are: combined cycle natural gas: 4.27 ¢/kWh; advanced nuclear: 7.10 ¢/kWh; and biomass: 7.72 ¢/kWh.[6]
- Estimated LCOE for new nuclear plants built in the near future are about two times higher than estimates for wind and about three times higher than solar.[6]
- Final construction costs for U.S. nuclear plants have typically been 2 to 3 times higher than original estimates.[7]

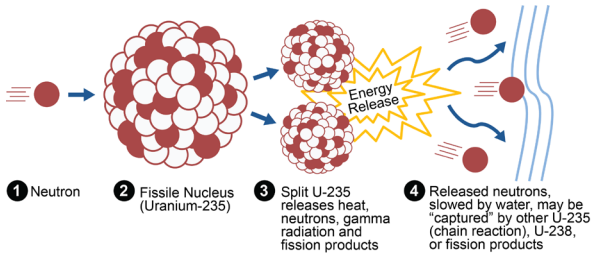
U.S. Electricity Generation by Source[1]



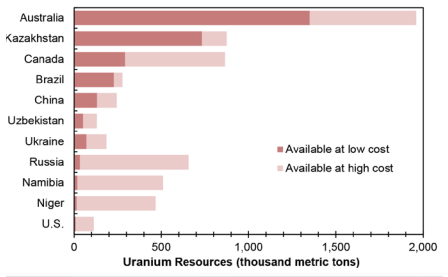
Nuclear Fuel

- Most nuclear reactors use "enriched" uranium, meaning the fuel has a higher concentration of uranium-235 (U-235) isotopes, which are easier to split to produce energy. When it is mined, uranium ore averages less than 1% U-235.[8]
- The highest grade ore in the U.S. average less than 1% uranium, some Canadian ore is more than 15% uranium.[9,10]
- 1% of uranium available at reasonable cost is found in the U.S. The largest deposits are in Australia (28%), Kazakhstan (13%), Canada (10%), Russia (8%), and Namibia (8%).[10] U.S. nuclear plants purchased 18,370 metric tons (t) of uranium in 2022. Fuel was imported mostly from Canada (27%), Kazakhstan (25%), Russia (12%) and Uzbekistan (11%).[11]
- Globally, nuclear power reactors required 62,496 t of uranium in 2021.[4]

Fission of Uranium-235 in a Nuclear Reactor



Largest Identified Uranium Resources[10]

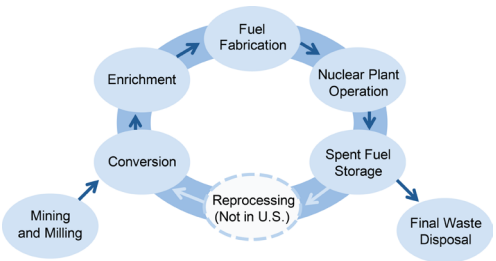


Energy and Environmental Impacts

The nuclear fuel cycle is the entire process of producing, using, and disposing of uranium fuel. Powering a one-gigawatt nuclear plant for a year can require mining 20,000-400,000 t of ore, processing it into 27.6 mt of uranium fuel, and disposing of 27.6 t of highly radioactive spent fuel, of which 90% (by volume) is low-level waste, 7% is intermediate-level waste, and 3% is high-level waste.[12,13] U.S. plants currently use "once-through" fuel cycles with no reprocessing.[14,15]

- Uranium is mostly extracted by in-situ leaching (ISL) (58.3%), open pit mining (18.7%), and underground mining (16.1%).[10]
- A uranium fuel pellet (~1/2 in. height and diameter) contains the energy equivalent of one ton of coal or 149 gallons of oil.[16] Typical reactors hold 18 million pellets.[17]
- Each kWh of nuclear electricity requires 0.1-0.3 kWh of life cycle energy inputs.[18]
- Although nuclear electricity generation itself produces no GHG emissions, other fuel cycle activities do release emissions.[19] The life cycle GHG intensity of nuclear power is estimated to be 34-60 gCO_2e/kWh—far below baseload sources such as coal (1,001 gCO_2e/kWh).[19,20]
- Nuclear power plants consume 270-670 gallons of water/MWh, depending on operating efficiency and site conditions.[21]
- For pressurized water reactors and boiling water reactors most environmental impacts are caused by the extraction and production of fuel elements.[23]

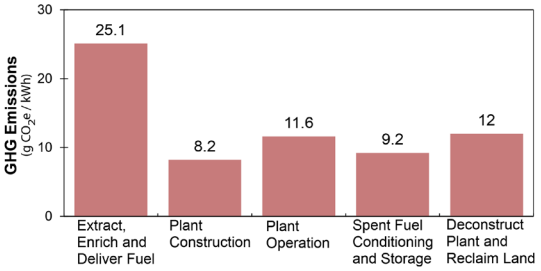
Uranium Fuel Cycle[12]



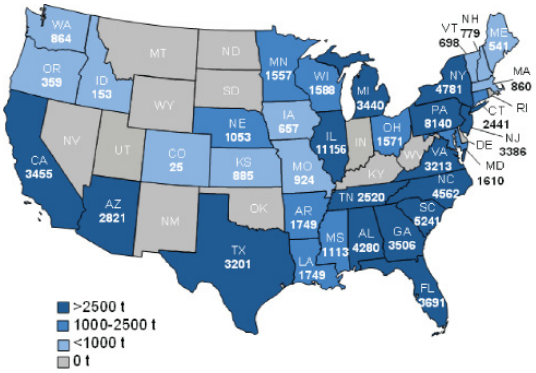
Nuclear Waste

- The U.S. annually accumulates about 2,000 mt of spent fuel.[24]
- During reactor operation, fission products and transuranics that absorb neutrons accumulate, requiring a third of the fuel to be replaced every 12-18 months. Spent fuel is 95% non-fissile U-238, 3% fission products, 1% fissile U-235, and 1% plutonium.[12]
- Spent fuel is placed in a storage pool of circulating cooled water to absorb heat and block the high radioactivity of fission products.[25]
- Many countries, though not the U.S., reprocess used nuclear fuel. The process reduces waste and extracts 25-30% more energy.[15]
- Many U.S. spent fuel pools are reaching capacity, necessitating the use of dry cask storage. Dry casks, large concrete and stainless steel containers, are designed to passively cool radioactive waste and withstand natural disasters or large impacts. In 2011, 27% of spent fuel was held in dry casks, after sufficient cooling in storage pools.[26]
- Ten years after use, the surface of a spent fuel assembly releases 10,000 rem/hr of radiation (in comparison, a dose of 500 rem is lethal to humans if received all at once).[14] Managing nuclear waste requires very long-term planning. U.S. EPA was required to set radiation exposure limits in permanent waste storage facilities over an unprecedented timeframe—one million years.[27]
- The U.S. has no permanent storage site. Nevada's Yucca Mountain was to hold 70,000 t waste, but is no longer under consideration, mostly due to political pressure and opposition by Nevadans.[28,29]
- The Nuclear Waste Policy Act required the U.S. federal government to begin taking control of spent nuclear fuel in 1998. When this did not occur, the government became liable for the costs associated with storage at reactor sites.[30]

Life Cycle GHG Emissions of Nuclear Power[22]



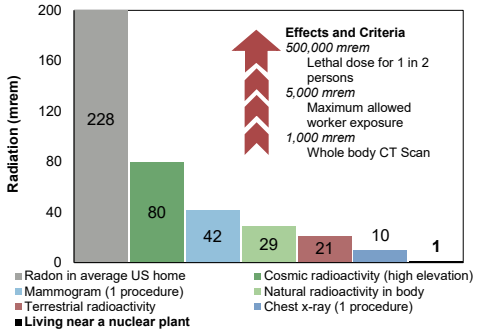
Spent Commercial Nuclear Fuel, Metric Tons[38]



Safety and Public Policy

- In 1986, a series of explosions occurred at the Chernobyl power plant in Ukraine. The loss of water in the reactor allowed the fuel to heat to the point of core meltdown. 134 workers and emergency responders were diagnosed with acute radiation syndrome and 28 died within weeks. Radiation releases were highest in Belarus, Ukraine, and Russia, lower in other parts of Europe. About 350,000 people were evacuated and/or permanently resettled, and a 1,000 square mile Chernobyl Exclusion Zone has been established to restrict public access. The number of long-term cancers and deaths are unknown, with most fatality estimates in the low thousands.[31]
- On March 11, 2011, a magnitude 9.0 earthquake occurred near Fukushima, Japan. The resulting tsunami damaged the reactor cooling system, leading to 3 meltdowns and hydrogen explosions. No deaths or radiation sickness have been directly linked to the accident. Radiation releases were lower than from Chernobyl, and mostly deposited in the Pacific Ocean. About 150,000 people were evacuated. The long-term cancers and deaths are unknown, with most fatality estimates in the hundreds to very low thousands.[32]
- The U.S. Price-Anderson Act limits the liability of nuclear plant owners if a radioactive release occurs to $450 million for individual plants and $13.5 billion across all plants.[33]
- Incentives for new nuclear plants include insurance against regulatory delays, a production tax credit of 1.8¢/kWh of electricity generated and $10.9 billion for federal loan guarantees.[34,35]
- In 2022, The Inflation Reduction Act (IRA) provided updated production tax credits for existing reactors and new nuclear deployment. Other incentives are also available to promote nuclear advancement and electricity generation including an investment tax credit.[36]
- The Bipartisan Infrastructure Deal allocated $6 billion for the Civilian Nuclear Credit program to prevent premature retirement of existing nuclear plants.[37]

Natural and Man-Made Exposures to Radiation[39]



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