

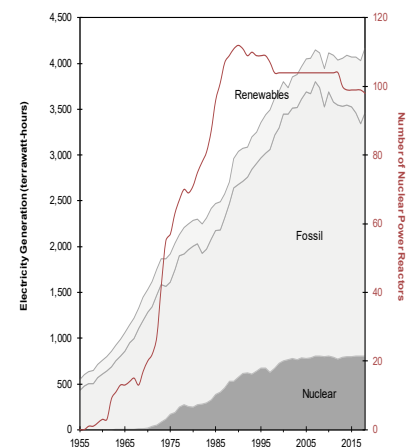
Nuclear Energy

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 20% of U.S. electricity, and this share has remained stable since around 1990. Nuclear power plants had a capacity factor of 93% in 2018.¹
- The first U.S. nuclear power plant was completed in 1957.² During the 1970s, more than 50 nuclear reactors went online.¹ Presently, 30 states have at least one nuclear plant and more than half have multiple reactors.^{2,3} Since 1995, U.S. nuclear electricity generation has grown despite no new reactors and 11 shutdowns, due to higher capacity and utilization of existing plants.^{1,2}
- 667 reactors have been built worldwide since the first was built in 1954 in Obninsk, Russia, though currently, there are less than 450 in operation, 98 of which are in the U.S.^{1,4,5} As of June 2019, 56 reactors are under construction, including 4 in the U.S. and 13 in China.⁵
- In 2016, the U.S. generated nearly a third of the world’s nuclear electricity. The next largest generators of nuclear electricity were France, China, and Russia.⁶
- Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) are the most common technologies in use.⁷ Two-thirds of U.S. reactors are PWRs.⁸
- Levelized cost of energy (LCOE) includes the expected costs of building, operating & maintaining, and fueling a power plant. Estimated LCOE for plants built in the near future are: combined cycle natural gas: 5.01 ¢/kWh; coal with 30% carbon capture and sequestration: 13.01 ¢/kWh; nuclear: 9.26 ¢/kWh; and biomass: 9.53 ¢/kWh.⁹

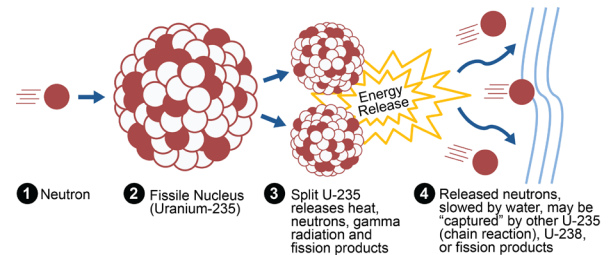
U.S. Electricity Generation by Source¹



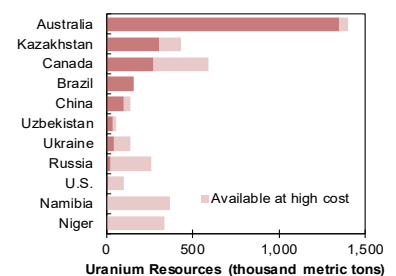
Nuclear Fuel

- 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-235.¹⁰
- Milling and enrichment processes crush the ore and use solvents to extract uranium oxide (U₃O₈, i.e., yellowcake), chemically convert this to uranium hexafluoride (UF₆), this is enriched to increase the U-235 concentration in the fuel, finally a fuel fabricator converts UF₆ into UO₂ powder which is pressed into pellets with 3%-5% U-235 concentrations.¹¹
- Uranium can be enriched by gaseous diffusion or gas centrifuge. Both concentrate the slightly lighter U-235 molecules from a gas containing mostly U-238, the former with membrane filters and the latter by spinning. Other technologies are currently in development, with laser enrichment processes closest to commercial viability.¹²
- In 2018, 721,000 pounds of U₃O₈ were extracted from 7 mines in the U.S.¹³ The highest grade ore in the U.S. average less than 1% uranium, some Canadian ore is more than 15% uranium.^{14,15}
- 1% of uranium available at reasonable cost is found in the U.S. The largest deposits are in Australia (30%), Kazakhstan (14%), Canada (8%), and Russia (8%).¹⁵ U.S. nuclear plants purchased 40 million pounds of uranium in 2018.¹⁶ 10% of the fuel originated in the U.S.; the remainder was imported mostly from Canada (24%), Kazakhstan (20%), Australia (18%), and Russia (13%).¹⁶
- Globally, nuclear power reactors required 65,014 metric tons of uranium in 2017.¹⁷

Fission of Uranium-235 in a Nuclear Reactor



Largest Identified Uranium Resources¹⁵

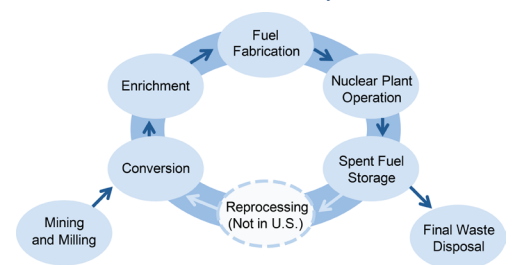


Energy and Environmental Impacts

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 metric tons (mt) of ore, processing it into 27.6 mt of uranium fuel, and disposing of 27.6 mt of highly radioactive spent fuel and 200-350 m³ of low- and intermediate-level radioactive waste.^{18,19} U.S. plants currently use “once-through” fuel cycles with no reprocessing.^{20,21}

- A uranium fuel pellet (1/2 in. height and diameter) contains the energy equivalent of one ton of coal or 3 barrels of oil.²² Typical reactors hold 18 million pellets.⁷
- Each kWh of nuclear electricity requires 0.1-0.3 kWh of life cycle energy inputs.²³
- Although nuclear electricity generation itself produces no GHG emissions, other fuel cycle activities do release emissions.²⁴

Uranium Fuel Cycle¹⁸



- The life cycle GHG intensity of nuclear power is estimated to be 34-60 g CO₂e/kWh—far below baseload sources such as coal (1,001 g CO₂e/kWh).^{24,25}
- Uranium is mostly extracted by open pit mining (13.7%), underground mining (31.9%) and in-situ leaching (ISL) (48.1%).¹⁵ ISL/ISR, the injection of acidic/alkaline solutions underground to dissolve and pump uranium to the surface, eliminates ore tailings associated with other mining but raises aquifer protection concerns.²⁶
- ISR standards were initially instituted in 1983, and have been multiple times since, most recently in 1995. Though recent attempts (2015/2017) by the EPA have been made to add more groundwater and monitoring standards, neither have been finalized.²⁷
- Nuclear power plants consume 270-670 gallons of water/MWh, depending on operating efficiency and site conditions.²⁸

Nuclear Waste

- The U.S. accumulates about 2,000-2,400 mt of spent fuel each year.³⁰
- 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.¹⁸
- Spent fuel is placed in a storage pool of pumped, cooled water to absorb heat and block the high radioactivity of fission products, where it typically remains for at least 5 years.³⁰
- Many countries, though not the US, reprocess used nuclear fuel. The process reduces waste, and gains 25% more energy than would have been used originally.³¹
- 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.³²
- Currently, 34 states have complexes designed for interim storage of spent nuclear fuel, or Independent Spent Fuel Storage Installations (ISFSI).³³
- 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).²⁰ 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.³⁴
- The U.S. has no permanent storage site. Nevada's Yucca Mountain was to hold 70,000 mt waste but is no longer under consideration, mostly due to political pressure and opposition by Nevadans.^{35,36}
- 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 continued on-site, at-reactor storage.³⁷

Safety and Public Policy

- In 1986, a series of explosions occurred at the Chernobyl power plant in Ukraine. Pieces of the reactor were ejected from the building and into the atmosphere. The lack of water in the reactor allowed the fuel to heat to the point of conflagration and core meltdown.³⁸
- On March 11, 2011, a magnitude 9.0 earthquake occurred off the east coast of Japan, the resulting tsunami damaged the cooling system, leading to 3 reactor meltdowns and hydrogen explosions. 167 workers received radiation doses over 10 rem, with one receiving 67.8 rem. The 28 workers who died following Chernobyl likely received up to 2000 rem.^{38,39}
- The U.S. Price-Anderson Act limits the liability of nuclear plant owners if a radioactive release occurs to \$375 million for individual plants and \$12.6 billion across all plants.⁴⁰
- Incentives for new nuclear plants include a production tax credit of 1.8¢/kWh of electricity generated, \$18.5 billion for federal loan guarantees, and insurance against regulatory delays.⁴⁰

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