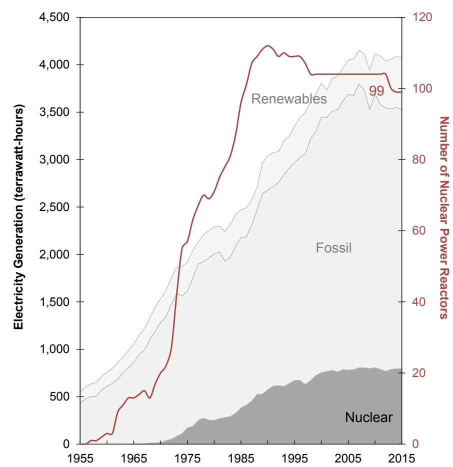
Nuclear Energy

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 radioactive waste.

Nuclear Energy Use and Potential

- Nuclear energy provides about 20% of U.S. electricity. Nuclear is a baseload resource, with an average capacity factor of approximately 92%.[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, 31 states have at least one nuclear plant and each plant may have multiple reactors.[2] Since 1995, U.S. nuclear electricity generation has grown despite no new reactors and 10 shutdowns, due to higher capacity factors from existing plants.[1,2]
- The U.S. has 99 of the world’s 440 commercial nuclear reactors. As of May 2016, 65 reactors are under construction, including 5 in the U.S. and 22 in China.[3]
- In 2013, the U.S. generated nearly a third of the world’s nuclear electricity. The next largest generators of nuclear electricity were France, Russia, and South Korea.[4]
- Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) are the most common technologies in use.[5] Two-thirds of U.S. reactors are PWRs.[6]
- 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: 6.63 ¢/kWh; coal: 9.56 ¢/kWh; nuclear: 9.61 ¢/kWh; and biomass: 10.3 ¢/kWh.[7]

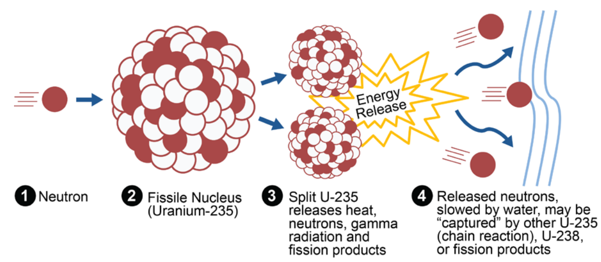
U.S. Electricity Generation by Source[1]



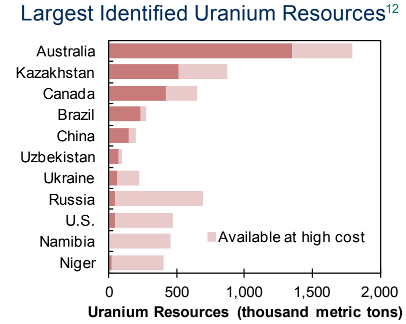
Nuclear Fuel

- 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]
- Milling and enrichment processes crush the ore to extract uranium oxide (U_3O_8, i.e., yellowcake), chemically convert this to uranium hexafluoride gas (UF_6), then concentrate the U-235 into ceramic uranium dioxide (UO_2) pellets with 3%-5% U-235 concentrations.[9]
- 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.[10]
- In 2015, 3.7 million pounds of U_3O_8 were extracted from 9 uranium mines in the U.S.[11] Although even the highest grade ore deposits in the U.S. average less than 1% uranium, some Canadian ore is more than 15% uranium.[12]
- Less than 4% of uranium available at reasonable cost is found in the U.S. The largest deposits are in Australia, Kazakhstan, and Russia.[12] U.S. nuclear plants purchased 56.5 million pounds of uranium in 2015.[13] 6% of the fuel originated in the U.S.; the remainder was imported mostly from Kazakhstan (19%), Australia (17%), Canada (30%), Russia (16%), and Namibia (6%).[13]
- Globally, nuclear power reactors required 65,220 metric tons of uranium in 2016.[3]

Fission of Uranium-235 in a Nuclear Reactor



Largest Identified Uranium Resources[12]

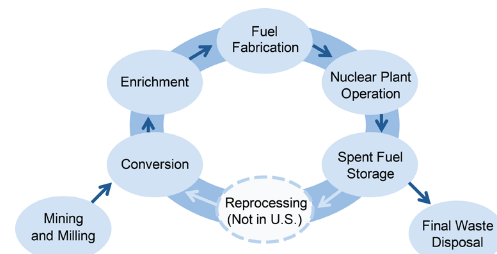


Energy and Environmental Impacts

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 25.5 mt of uranium fuel, and disposing of 25.5 mt of highly radioactive spent fuel and 200-350 m^3 of low- and intermediate-level radioactive waste.[14,15] U.S. plants currently use “once-through” fuel cycles with no reprocessing.[16]

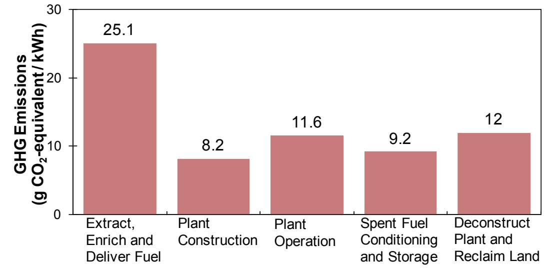
- A uranium fuel pellet (1/2 in. height and diameter) contains the energy equivalent of one ton of coal or 17,000 ft^3 of natural gas.[17] Typical reactors hold 18 million pellets.[18]
- Each kWh of nuclear electricity requires 0.1-0.3 kWh of life cycle energy inputs.[19]
- Although nuclear electricity generation itself produces no GHG emissions, other fuel cycle activities do release emissions.[20]

Uranium Fuel Cycle[14]



- The life cycle GHG intensity of nuclear power can be 13 to 66 gCO_2e/kWh—far below baseload sources such as coal (1,001 gCO_2e/kWh).[20,21,22]
- Globally, uranium is mostly extracted by open pit mining (18.5%), underground mining (25.6%) and in-situ leaching (ISL) (47.5%).[12] ISL, 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.[23]
- U.S. EPA is updating the current standards for uranium mining facilities and their effects on groundwater in response to a broader domestic use of ISL. The standards are expected to go into effect in April of 2016.[24]
- Nuclear power plants consume 270-670 gallons of water/MWh, depending on operating efficiency and site conditions.[25]

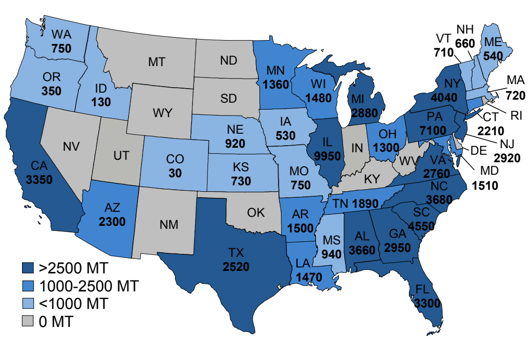
Life Cycle GHG Emissions of Nuclear Power[21]



Nuclear Waste

- The U.S. accumulates about 2,000-2,400 mt of spent fuel each year.[26]
- 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.[14]
- 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.[26]
- Some countries (excluding U.S.) reprocess spent fuel for reuse as mixed oxide fuel, which reduces the volume of radioactive waste but raises proliferation concerns.[27]
- 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.[28]

Spent Commercial Nuclear Fuel, Metric Tons[36]

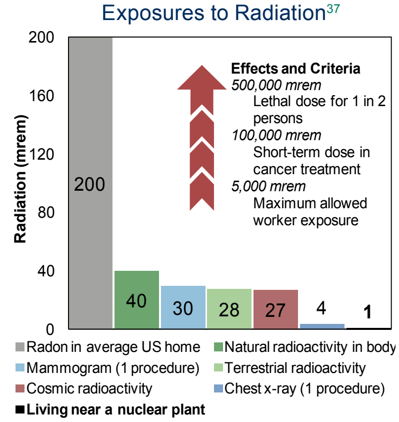


- Currently, 34 states have complexes designed for interim storage of spent nuclear fuel, or Independent Spent Fuel Storage Installations (ISFSI).[29]
- Ten years after use, the surface of a spent fuel assembly releases 10,000 rem/hr of radiation (in comparison, a dose of 500 rem is lethal to humans if received all at once).[16] 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.[30]
- 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.[31]
- 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.[32]

Safety and Public Policy

- After an earthquake and tsunami in March 2011, Japan's Fukushima Daiichi nuclear plant lost the ability to cool reactors and spent fuel, resulting in large releases of radiation.[33]
- Nuclear radiation at the plant was around 13 rem/hr with some localized dose rates greater than 1,000 rem/hr. By April 2011, 17 million curies of radiation had been released—4.5% the amount emitted during the 1986 Chernobyl accident.[33] A recent report by the World Health Organization estimates that residents of the most affected areas were exposed to radiation doses of 1.2 to 2.5 rem in the first year after the incident.[34]
- The U.S. Price-Anderson Act limits the financial liability of nuclear plant owners if a severe radioactive release occurs to $375 million for individual plants and $12.6 billion across all plants.[35]
- 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.[35]

Natural and Man-Made Exposures to Radiation[37]



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