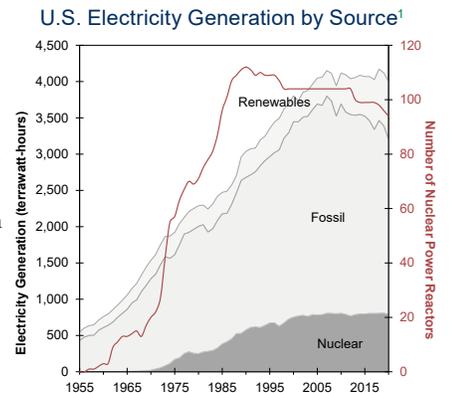


# Nuclear Energy

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

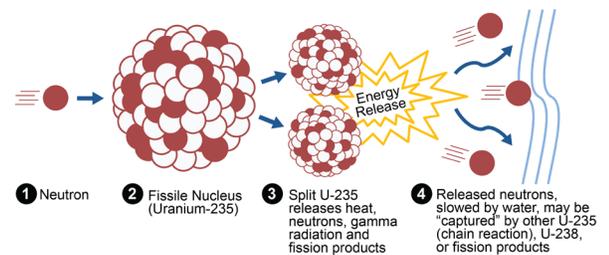
- Nuclear energy provides about 20% of U.S. electricity, and this share has remained stable since around 1990. Nuclear power plants had a capacity factor of 92.5% in 2020.<sup>1</sup>
- The first U.S. nuclear power plant began commercial operations in 1958.<sup>2</sup> During the 1970s, more than 50 nuclear reactors went online.<sup>1</sup> Presently, 28 states have at least one nuclear plant and 32 plants have two or more reactors.<sup>2</sup> Since 1995, U.S. nuclear electricity generation has grown despite no new reactors and 15 shutdowns, due to higher utilization and uprating of existing plants.<sup>1,2</sup>
- 667 reactors have been built worldwide since the first was built in 1954 in Obninsk, Russia, though currently, there are only 443 in operation, 93 of which are in the U.S.<sup>3,4</sup> As of May 2021, 55 reactors were under construction, including 4 in the U.S. and 18 in China.<sup>4</sup>
- In 2018, the U.S. generated nearly a third of the world’s nuclear electricity. Countries generating the next largest amounts of electricity using nuclear were France, China, and Russia.<sup>5</sup>
- Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) are the most common technologies in use.<sup>6</sup> Two-thirds of U.S. reactors are PWRs.<sup>7</sup>
- 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: 3.71 ¢/kWh; advanced nuclear: 6.31 ¢/kWh; and biomass: 8.92 ¢/kWh.<sup>8</sup>



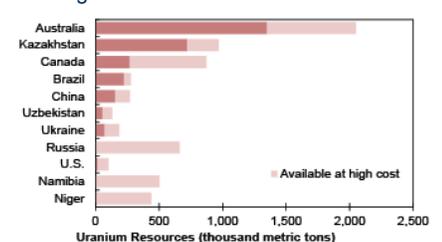
## Nuclear Fuel

- 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.<sup>9</sup>
- Milling and enrichment processes crush the ore, use solvents to extract uranium oxide (U<sub>3</sub>O<sub>8</sub>, i.e., yellowcake), and chemically convert it to uranium hexafluoride (UF<sub>6</sub>), which is enriched to increase the U-235 concentration in the fuel. Finally, a fuel fabricator converts UF<sub>6</sub> into UO<sub>2</sub> powder that is pressed into pellets with 3%-5% U-235 concentrations.<sup>10</sup>
- 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.<sup>11</sup>
- In 2019, 79 metric tons (mt) of U<sub>3</sub>O<sub>8</sub> were extracted from 6 mines in the U.S.<sup>12</sup> The highest grade ore in the U.S. average less than 1% uranium, some Canadian ore is more than 15% uranium.<sup>13,14</sup>
- 1% of uranium available at reasonable cost is found in the U.S. The largest deposits are in Australia (28%), Kazakhstan (15%), Canada (9%), and Russia (8%).<sup>14</sup> U.S. nuclear plants purchased 22,135 mt of uranium in 2020. Fuel was imported mostly from Canada (22%), Kazakhstan (22%), Russia (15%) and Australia (11%).<sup>15</sup>
- Globally, nuclear power reactors are forecast to require 68,269 mt of uranium in 2021.<sup>4</sup>

Fission of Uranium-235 in a Nuclear Reactor



Largest Identified Uranium Resources<sup>14</sup>

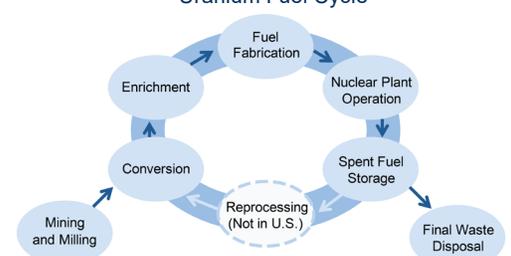


## Energy and Environmental Impacts

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 mt of ore, processing it into 27.6 mt of uranium fuel, and disposing of 27.6 mt 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.<sup>16,17</sup> U.S. plants currently use “once-through” fuel cycles with no reprocessing.<sup>18,19</sup>

- A uranium fuel pellet (~1/2 in. height and diameter) contains the energy equivalent of one ton of coal or 149 gallons of oil.<sup>10</sup> Typical reactors hold 18 million pellets.<sup>6</sup>
- Each kWh of nuclear electricity requires 0.1-0.3 kWh of life cycle energy inputs.<sup>20</sup>
- Although nuclear electricity generation itself produces no GHG emissions, other fuel cycle activities do release emissions.<sup>21</sup>

Uranium Fuel Cycle<sup>16</sup>



- The life cycle GHG intensity of nuclear power is estimated to be 34-60 gCO<sub>2</sub>e/kWh—far below baseload sources such as coal (1,001 gCO<sub>2</sub>e/kWh).<sup>21,22</sup>
- Nuclear power plants consume 270-670 gallons of water/MWh, depending on operating efficiency and site conditions.<sup>23</sup>
- Uranium is mostly extracted by open pit mining (16.1%), underground mining (20%) and in-situ leaching (ISL) (57.4%).<sup>14</sup> 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.<sup>24</sup>
- ISL standards were initially instituted in 1983, and have been amended multiple times since, most recently in 1995.<sup>25</sup>

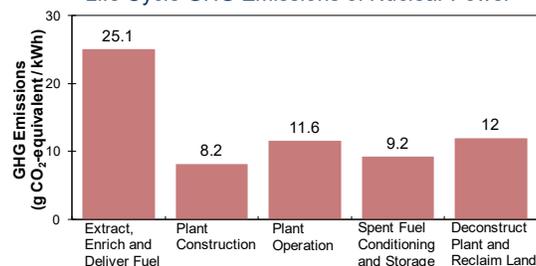
## Nuclear Waste

- The U.S. annually accumulates about 2,000 mt of spent fuel.<sup>27</sup>
- 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.<sup>16</sup>
- Spent fuel is placed in a storage pool of circulating cooled water to absorb heat and block the high radioactivity of fission products.<sup>28</sup>
- Many countries, though not the U.S., reprocess used nuclear fuel. The process reduces waste and extracts 25-30% more energy than non-reprocessed fuel.<sup>19</sup>
- 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.<sup>29</sup>
- Currently, 34 states have complexes designed for interim storage of spent nuclear fuel, or Independent Spent Fuel Storage Installations (ISFSI).<sup>30</sup>
- 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).<sup>18</sup> 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.<sup>31</sup>
- 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.<sup>32,33</sup>
- 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.<sup>34</sup>

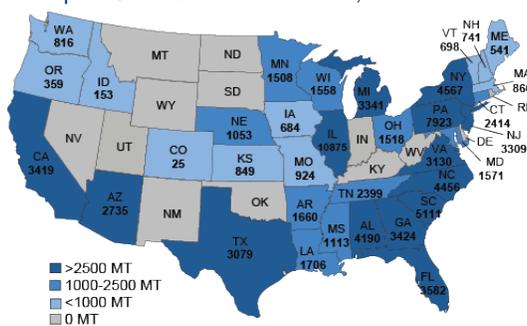
## Safety and Public Policy

- In 1986, a series of explosions occurred at the Chernobyl power plant in Ukraine. Pieces of the reactor were ejected high into the atmosphere. 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.<sup>35</sup>
- 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.<sup>36</sup>
- 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.<sup>37</sup>
- 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.<sup>38,39</sup>

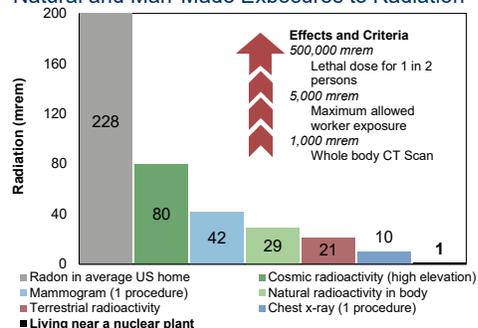
Life Cycle GHG Emissions of Nuclear Power<sup>26</sup>



Spent Commercial Nuclear Fuel, Metric Tons<sup>40</sup>



Natural and Man-Made Exposures to Radiation<sup>41</sup>



1. U.S. Energy Information Administration (EIA) (2021) Monthly Energy Review May 2021.

2. U.S. EIA (2021) "Nuclear Explained: U.S. Nuclear Industry."

3. Carbon Brief (2016) "Mapped: The world's nuclear power plants."

4. World Nuclear Association (WNA) (2021) World Nuclear Power Reactors & Uranium Requirements.

5. U.S. EIA (2021) International Energy Statistics.

6. WNA (2021) "Nuclear Power Reactors."

7. U.S. Nuclear Regulatory Commission (NRC) (2021) "List of Power Reactor Units."

8. U.S. EIA (2021) "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2021."

9. U.S. NRC (2020) "Uranium Enrichment."

10. Nuclear Energy Institute (NEI) (2020) "Nuclear Fuel."

11. WNA (2020) "Uranium Enrichment."

12. U.S. EIA (2021) Domestic Uranium Production Report 2020.

13. U.S. Nuclear Energy Agency (NEA) & International Atomic Energy Agency (IAEA) (2012) Uranium 2011: Resources, Production, and Demand.

14. U.S. NEA & IAEA (2020) Uranium 2020: Resources, Production, and Demand.

15. U.S. EIA (2021) 2020 Uranium Marketing Annual Report.

16. WNA (2021) "Nuclear Fuel Cycle Overview."

17. WNA (2021) "Radioactive Waste Management."

18. U.S. NRC (2019) "Background on Radioactive Waste."

19. WNA (2020) "Processing of Used Nuclear Fuel."

20. Lenzen, M. (2008) "Life cycle energy and greenhouse gas emissions of nuclear energy: A review." Energy Conversion and Management, 49: 2178-2199.

21. Norgate, T., et al. (2014) "The impact of uranium ore grade on the greenhouse gas footprint of nuclear power." Journal of Cleaner Production, 84:360-367.

22. Whitaker, M., et al. (2012) "Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity

Generation." Journal of Industrial Ecology, 16: S53-S72.

23. Macknick, J., et al. (2011) A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies. U.S. DOE, National Renewable Energy Laboratory.

24. WNA (2020) "In Situ Leach Mining of Uranium."

25. U.S. Environmental Protection Agency (EPA) (2019) Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings.

26. Sovacool, B. (2008) "Valuing the greenhouse gas emissions from nuclear power: A critical survey." Energy Policy, 36: 2940-2953.

27. U.S. Department of Energy (DOE) (2020) "5 Fast Facts about Spent Nuclear Fuel."

28. U.S. NRC (2020) "Spent Fuel Storage in Pools and Dry Casks: Key Points and Questions & Answers."

29. Werner, J. (2012) U.S. Spent Nuclear Fuel Storage. Congressional Research Service.

30. U.S. NRC (2021) U.S. Independent Spent Fuel Storage Installations.

31. U.S. EPA (2020) "Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada (40 CFR Part 197)"

32. U.S. DOE (2008) Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007.

33. Los Angeles Times (2019) "Americans are paying more than ever to store deadly nuclear waste."

34. U.S. DOE (2013) Strategy for the Management and Disposal of Used Nuclear Fuel and High Level Radioactive Waste.

35. WNA (2021) Chernobyl Accident 1986.

36. WNA (2021) Fukushima Daiichi Accident.

37. U.S. NRC (2019) Nuclear Insurance and Disaster Relief.

38. Holt, M. (2014) Nuclear Energy Policy. Congressional Research Service.

39. U.S. DOE (2021) "Advanced Nuclear Energy Projects Loan Guarantees."

40. NEI (2021) "Used Fuel Storage and Nuclear Waste Fund Payments by State."

41. U.S. EPA (2018) "Radiation Sources and Doses."