# Energy 101: Introduction to Nuclear

From the CSIS Energy & National Security Program

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Nuclear energy, or the energy released during nuclear fission, generates nearly one-fifth of U.S. electricity and about 11 percent of the world's electricity. In nuclear fission, atoms are split apart when they come into contact with neutrons, releasing energy in the form of heat and radiation (as well as further neutrons). The released neutrons split apart other atoms, creating a chain reaction. This process, which is self-sustaining, takes place in the reactor core of a nuclear power plant. Uranium is the primary fuel used in nuclear reactors. While uranium itself is relatively common in nature, the types of uranium used in nuclear reactors, U-238 and U-235, are scarcer. All nuclear power plants use the process of nuclear fission; the ability to obtain energy from nuclear fusion is still in the research phase.

In 2013, 30 countries operated 443 nuclear reactors, with an additional 69 reactors (76 gigawatts) under construction. Nuclear energy is closely connected with foreign trade, defense, and climate change policies. Nuclear energy's role in a variety of important policy areas, combined with international concerns about nuclear safety and proliferation, translates into significant government involvement in regulating and setting policy for all parts of the commercial nuclear industry.

## The Nuclear Fuel Cycle

The activities associated with the production of electricity from nuclear reactors—from so-called "front end" (upstream) activities, including extraction and preparation of the fuel (uranium) to the "back end" (downstream) waste management—are known as the nuclear fuel cycle. Every step in the fuel cycle produces radioactive waste that must be responsibly managed to minimize damage to the environment and

**Quick Facts about Nuclear**

- Nuclear energy is measured in kilowatts (KW), megawatts (MW), and gigawatts (GW).
- Australia, Canada, and Kazakhstan are the world's largest uranium producers.
- The United States, France, Japan, and Russia are the countries with the most installed nuclear capacity.
- Globally, there are 392 gigawatts of installed nuclear capacity.
- Nuclear energy provided 19 percent of U.S. electricity in 2014.
- 80 percent of global nuclear generation capacity is in OECD countries, but 80 percent of nuclear energy projects currently under construction are in non-OECD countries, with the largest projected additions in China, Russia, Korea, and India.
- The most recent reactor to come online for operation in the United States was in 1996; all other capacity additions have been upgrades to existing nuclear power plants.
- The U.S. Nuclear Regulatory Commission approved the first new U.S. nuclear facility in decades in early 2012. There are currently five nuclear reactors under construction in the United States.

human health. The first stages include commercial uranium mining, milling and refining, conversion, enrichment, and fuel fabrication, as uranium must be chemically processed before it can be used as fuel.

Fuel is then used in nuclear reactors to generate electricity. The two main forms of nuclear electricity generation in the United States are boiling-water reactors and pressurized-water reactors. Both of these methods convert water into steam to turn a turbine. Once all the fuel is spent, the resultant nuclear waste is either reprocessed (recycled) or it is stored until it no longer poses a threat to humans (which can be thousands of years). There is significant debate about the relative merits of a once-through cycle (also referred to as an open fuel cycle in which fuel is used once and then stored as waste) versus recycling nuclear waste to use again for power generation (also referred to as a closed cycle). Whether to recycle fuel influences waste storage, overall costs of nuclear power generation, and the potential for proliferation.

## Nuclear Power

In 2013, electricity generated from nuclear power accounted for nearly one-fifth of U.S. electricity, compared with 11 percent globally. The United States has the largest global nuclear capacity, with 100 reactors—about a quarter of the global total—generating over 790 thousand gigawatt-hours of power. France has the second-largest nuclear capacity, but generates a much larger share of its electricity from nuclear power (approximately 75 percent, although France has committed to cutting its share to 50 percent by 2025). Other countries with large nuclear fleets include Japan, Russia, South Korea, and Germany.

Going forward, the largest capacity additions are expected in non-Organization for Economic and Cooperation Development (OECD) countries (China and Russia in particular) with nuclear capacity declining in OECD countries (with the exception of South Korea). In fact, two-thirds of the 69 reactors under construction are in Asia. Recent safety concerns have led some OECD countries—notably Japan and Germany—to move away from nuclear energy, bringing into question the future of an energy source that was expected to be an important part of any low-carbon future due to its zero-carbon emissions profile. While nuclear is projected to account for about 7 percent of total primary energy demand in 2040, up from less than 5 percent in 2012, it is not expecting to return to its 2001 peak.

## Nuclear and the Environment

Nuclear energy is the largest low-carbon source of electricity in the United States and is a reliable source of baseload power. While nuclear power plants do not emit greenhouse gases when generating electricity, other steps in the nuclear fuel cycle, especially on the front end, do result in potentially significant carbon emissions; the processes for mining and refining uranium, the creation of the reactor core, and the building of the nuclear power plant itself (involving large cement facilities) are all very energy intensive.

The other significant environmental impact of nuclear power is radioactive waste. Radioactive waste poses a threat to the environment and to human health until it decays—a process that ranges from tens to hundreds of thousands of years, depending on the radioactive isotopes.

While studies have found that radioactive waste can be safely disposed of in permanent repositories such as geological caverns, to date, no such repositories have been commissioned; in the United States, radioactive waste is currently being contained at temporary disposal sites. The U.S. situation is reflective of the situation globally: most nuclear repository sites aren't expected to be operational before 2025, with many countries still involved in site selection.

There are different options for utilizing spent fuel, including reprocessing it for further use. In addition to the once-through nuclear fuel cycle utilized in the United States, in the single-pass recycle process,


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primarily used in France, the spent fuel is reprocessed and small amounts of uranium and plutonium are extracted for reuse in new reactor cores. While the latter process lessens the total nuclear waste, the relative economic merits of each fuel cycle are disputed. Scientists are also currently working on a fully closed fuel cycle through which even more elements of the spent nuclear fuel would be preserved. How much reprocessing should be done remains a matter of significant debate. Nonetheless, such processes contain other risks and would still result in certain wastes that would require permanent disposal.

Finally, the nuclear energy industry's water use is an issue of concern for some environmentalists. In all steam-cycle power plants (including coal and natural gas plants), water is used to cool steam produced for electricity generation and is then discharged back to the source from which it was drawn (lake, river, or ocean). The warm water discharged, which can also contain other pollutants, has an adverse impact on aquatic ecosystems.

## Nuclear Proliferation

Nuclear technology was originally developed for military uses during World War II. As civilian usage expanded thereafter, there were concerns that the number of countries with nuclear weapons would expand as well. The Nuclear Non-Proliferation Treaty (NPT) and the International Atomic Energy Agency, however, have been the primary international tools to limit the proliferation of weapons and encourage the use of nuclear fuel for solely civilian purposes. Nonetheless, concerns about the potential for nuclear weapons proliferation remain.

Two steps in the nuclear fuel cycle are particularly vulnerable to nuclear weapons proliferation. The first is enrichment; if a country has the technical capability to enrich uranium for a power plant, it can enrich uranium for a nuclear weapon. The second, specific to closed fuel cycles, is reprocessing, where the potential exists for the misuse of fuel cycle facilities and the diversion of material for military purposes. In addition to the concerns about physical capabilities, there is also a broader concern about the spread of scientific and engineering knowledge.

Over the decades, domestic and international treaties and institutions have been established to address proliferation concerns; these include the Nuclear Proliferation Treaty, the International Atomic Energy Agency, and the Nuclear Suppliers Group, as well as a host of export control regimes and laws (in the United States, the most important is Section 123 of the U.S. Atomic Energy Act). These treaties and institutions seek to control and monitor the flow of nuclear materials, technology, and expertise to prevent proliferation. While these institutions and laws have been relatively successful (with notable exceptions), there is considerable opportunity to make them more effective.

## Nuclear Safety

Nuclear safety is a key challenge for the nuclear power industry. Safety concerns and regulations are focused on two related issues: radiation exposure in the air and groundwater, which can have adverse impacts on public health, and reactor safety. Nuclear safety is regulated at the national level. The U.S. Nuclear Regulatory Commission, along with other national bodies, regulate the use and storage of nuclear materials and waste to prevent unnecessary exposure to local populations and workers. Safety precautions at nuclear power plants are extensive and include physical barriers and redundant systems to accommodate natural and human error. The International Atomic Energy Agency (IAEA) also has an important safety coordination role and can perform safety inspections, but its authority in member countries is circumscribed.

Despite these safeguards, the Fukushima-Daiichi nuclear accident in Japan in 2011 led to a renewed focus on safety globally and resulted in calls to strengthen national and international oversight. The


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radiation released by the accident has sparked environmental and public health concerns, although the full impacts are as of yet unknown. The accident rekindled fears initially sparked by the 1979 Three Mile Island accident in the United States and the 1986 Chernobyl incident in Ukraine and resulted in a widespread reexamination of existing regulations and, in some countries, a reassessment of nuclear power itself.

In many instances, Fukushima reignited debates about the place of nuclear power in a country's energy mix. For example, Germany had decided to phase out nuclear, which was reversed. However, in the wake of the accident, the German government decided again to phase out all nuclear power by 2022. Several other European countries, including Italy, Switzerland, and Belgium, took similar actions to phase down nuclear, while almost all European countries have enforced stricter regulations. In Japan, there is a strenuous debate over the role that nuclear reactors will play in that country's energy future. In the United States, the Nuclear Regulatory Commission's Near-Term Task Force released a report that included 12 recommendations for safety improvements based on lessons learned from the Fukushima-Daiichi accident. China temporarily suspended its new nuclear plant project approvals, conducted extensive safety inspections of its existing plants, and created a new nuclear safety plan, but the country has nonetheless reaffirmed that nuclear will be an important part of its energy mix going forward.

Finally, safety is not simply a technical matter but has a human component as well. Realizing nuclear safety also requires that the nuclear workforce have the proper qualifications, training, and skills. While nuclear power can be safely operated, there is always the potential for human or technical error and it thus requires a culture of vigilance even after the shock of an accident wears off.

## The Economics of Nuclear Energy

Nuclear power plants are expensive to build due to the complex engineering required to ensure their safe operation. Building a nuclear plant requires large upfront capital costs (billions of dollars) that must be financed. Thus, while the operation of nuclear power plants and the fuel itself is relatively inexpensive, construction requires a major initial investment and a slower netback recovery. In the United States, costs of the current plants under construction have also been driven up by project delays.

These costs must be recovered over the asset life of the plant and thus it only makes commercial sense to build the reactor if the asset can remain in use for several decades; in liberalized electricity markets, where a return on investment is not guaranteed, obtaining financing for nuclear plants is challenging, despite the presence of federal tax incentives and loan guarantees. This is less of a challenge in markets where the government is involved in making decisions about the electricity generation mix.

## The Future of Nuclear Power

While the United States experienced rapid expansion of nuclear capacity during the 1970s and 1980s, this growth slowed with an increasingly complex regulatory process after the Three-Mile Island accident, project cost overruns, and construction delays. While there are a host of federal and state level policies to support nuclear development, there are only five new units under construction in the United States. Further, the current U.S. nuclear fleet is aging, with 74 of the 100 operating reactors in the United States operating on 20-year extensions following the initial 40-year license to operate. Whether these licenses will be renewed beyond their current 60-year operating lifetime remains to be seen.

The future of new nuclear plants in the United States and in the OECD more generally will depend in part on whether building nuclear plants looks like an attractive


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investment decision. This, in turn, will hinge upon access to low-cost financing, which will depend on the ability of firms and utilities to build nuclear plants on schedule and control project costs. A cap or price on carbon also has the potential to favorably change the economics of nuclear power.

While nuclear power appears to be on the decline in the OECD due to concerns about costs, safety, and environmental sustainability, nuclear power outside the OECD is growing, due mostly to growth in China. Nuclear energy has a prominent role in China's strategy to meet its growing energy demand and to diversify its fuel mix. China's Energy Development Strategy Action Plan (November 2014) confirmed the 2012 State Council target of 58 gigawatts of installed capacity by 2020, enabling a robust national push for the expansion of the sector in the form of both policy and financial support. The Chinese commitment to nuclear power, plans for expansion of the domestic supply chain, and the government willingness to advance nuclear science and innovation have created an environment that make the economic hurdles much easier to overcome. The United Arab Emirates is also likely to use nuclear power, and other non-OECD economies may also choose to include nuclear in their energy mix, although the cost and safety issues in place are likely to deter many countries.

To a significant extent, the future of nuclear power depends upon government policies at the national and subnational level, including but not limited to a carbon policy. Whether nuclear power expands in the coming decades depends on reducing costs (including financing costs), building public and industry confidence in ensuring the safe design and operation of nuclear facilities, finding a solution to long-term waste management, and ensuring and updating proliferation safeguards.

## About the CSIS Energy and National Security Program

The CSIS Energy and National Security Program is a leader in understanding the shifting global and domestic energy landscape. Through its collaboration with leaders in industry, government, academia, and nonprofits, the CSIS Energy and National Security Program identifies new energy trends and helps to illuminate the opportunities and challenges that we expect to confront policymakers and industry players in the coming years.

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