STANFORD UNIVERSITY

# THE STANFORD EMERGING TECHNOLOGY REVIEW 2023

## A Report on Ten Key Technologies and Their Policy Implications

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# NUCLEAR TECHNOLOGIES

## KEY TAKEAWAYS

- Nuclear fission offers a promising carbon-free power source that is already in use but faces safety and proliferation concerns, economic obstacles, and significant policy challenges to address long-term radioactive waste disposal.
- Nuclear fusion recently achieved an important milestone by demonstrating energy gain in the laboratory for the first time. However, further research breakthroughs must be achieved in the coming decades before fusion can be technically viable as an energy alternative.
- Many believe that small modular reactors (SMRs) are the most promising way to proceed with nuclear power, but some nuclear experts have noted that SMRs do not solve the radioactive waste disposal problem.

Nuclear technologies include those for nuclear energy production, nuclear medicine, and nuclear weapons. This chapter focuses on nuclear energy, which exploits the energy present in the nuclei of atoms. Fission and fusion are the two ways to tap that energy. Both fission and fusion reactions produce large amounts of heat, which can then be used to generate steam. Steam in large amounts can be used to drive turbines that produce electricity.

## Overview: Nuclear Fission Technology

Nuclear fission is the process of striking the nucleus of a fissile isotope such as Uranium-235 with a neutron, causing it to split into smaller nuclei of lighter elements—and release energy. The split also releases neutrons that can go on to split other fissionable nuclei, resulting in a chain reaction. If the chain reaction is uncontrolled, what happens is a nuclear explosion. But a tightly controlled nuclear chain reaction can produce a continuous release of energy at low levels that can generate electricity.

Fission-driven power generation was first demonstrated in 1951.[1] Nuclear (fission) reactors can produce electric power in vast amounts without carbon emissions, but the reaction also produces radioactive by-products that must be safely managed for tens of thousands of years.

The spread of fission reactors can also raise concerns about the spread of nuclear weapons, since knowledge and infrastructure to design, build, and operate a nuclear power plant overlap substantially with what is needed to build nuclear weapons. In this view, research on new nuclear reactors whitewashes the nuclear power–nuclear weapons connection. Others believe that the proliferation risks can be minimized to the extent that fission reactors are a viable option for emissions-free energy.

Overall, in the last couple of years, the global capacity for nuclear reactors to generate electric power has declined slightly. The new nuclear reactors coming online, mostly in Asia, are unable to replace the capacity loss due to aging nuclear reactors being decommissioned in the West.

In addition, the United States does not offer competitive exports of nuclear power plants. Although there are some exports from the United Arab Emirates and South Korea, Russia dominates the global market for nuclear reactor exports. South Korea has a single design and more expertise in industrial manufacturing, allowing it to maintain low costs. Russia's state-owned Rosatom nuclear energy corporation has better financing and offers a more complete fuel provision and waste disposal.

Commercial reactors offer other potential applications as well, since two-thirds of the energy converted from nuclear reactors are released as heat to the environment. This energy could be harnessed to use for heat demands in other industrial processes, notably in desalination plants, metal refining, and hydrogen generation. These use cases are still in the process of development, with the Department of Energy (DOE) supporting US nuclear energy companies.

Commercial nuclear energy is used exclusively for electricity generation. In 2020, nuclear energy provided 10 percent of global electricity generation, making it the second-largest source of low-carbon electricity, behind hydroelectricity.[2] In the United States, nuclear power contributes 18.2 percent of electricity generation, the largest source of carbon-free electricity.[3]

Research and development in nuclear energy focuses on new reactor designs that may reduce nuclear fuel requirements, provide improved safety, and be less expensive to build and operate. R&D is also exploring approaches to disposal and long-term management of radioactive waste resulting from reactor operation.

## Key Developments: Fission

### *New Reactor Designs*

Advanced reactors could potentially offer a variety of benefits for:[4]

- **Safety** Advanced reactors could offer passive safety features that do not require direct human intervention to be activated or reactor operation at lower pressure that can reduce the risk of explosion.
- **Industrial decarbonization** Some advanced nuclear reactors can generate enough heat for

industrial processes that would otherwise be generated by fossil fuels.

- **Radioactive waste reduction** Some designs seek to reduce the amount of long-term radioactive waste produced in the power generation process; however, no reactor produces no radioactive waste at all.

One new reactor design gaining traction is the small modular reactor (SMR). These reactors generate less than 300 megawatts of electricity, about 25 to 30 percent the capacity of a conventional reactor. Smaller than conventional reactors, SMRs have the benefit that they can be mass produced in factories and transported to installation sites. Timelines for approval could be significantly reduced because the design of any given SMR would have to be reviewed only once. Multiple SMRs could support large power plants, while single SMRs could power smaller ones.[5]

On the other hand, SMRs are currently at the demonstration and licensing phase and hence remain an unproven technology. Moreover, while SMRs are designed to reduce capital costs, a large fraction of an SMR's cost goes toward preparing the site, which means that the use of an SMR saves 30 to 40 percent in cost—but produces 70 percent less power. SMRs also generate a greater volume of waste per unit of energy produced as compared to larger reactors.[6]

## Fuel for New Reactors

Uranium ore consists of about 99.3 percent Uranium-238 and 0.7 percent Uranium-235. For use in today's commercial light-water reactors, uranium must be "enriched" to increase the concentration of U-235 from 0.7 percent to about 3 to 5 percent, making it "low-enriched" uranium. Most new reactor designs, however, call for the use of uranium fuel enriched with U-235 at a level between 5 percent and 20 percent, fuel known as high-assay low-enriched uranium (HALEU).[7] However, HALEU is unavailable at a commercial scale, and projections suggest that more than 40 metric tons of HALEU will be needed before the end of the decade in these advanced reactors should they actually be deployed.[8] US government–supported research is underway to develop processes to produce commercially viable HALEU. These processes use spent nuclear fuel from government-owned research reactors to produce small amounts of HALEU—the first steps in the creation of a domestic HALEU supply for advanced nuclear reactors.

More than 90 percent of the uranium used in US nuclear reactors is imported; Kazakhstan and Russia account for nearly half of all US uranium consumption, while Canada and Australia account for about 30 percent.[9] One approach to eliminate the need for uranium imports is to extract uranium from seawater. In total, seawater contains hundreds of times more uranium than is on land, but extracting it for use in nuclear power generation is challenging due to its low concentration and the high-salinity background.[10] As noted by Stanford professor Steven Chu, former US secretary of energy under President Barack Obama: "Seawater extraction gives countries that don't have land-based uranium the security that comes from knowing they'll have the raw material to meet their energy needs."[11]

## Nuclear Waste Disposal

Radioactive nuclear waste can be differentiated between high-level and low-level waste based on how long it takes before the waste decays and is no longer hazardous. High-level waste includes "spent," or used, nuclear fuel and waste generated from the reprocessing of spent fuel. Low-level waste includes items that have come in contact with radioactive materials; such items include paper, rags, plastic bags, or clothing. In terms of overall volume, less than 1 percent of existing radioactive waste is high level; about 4 percent is intermediate level; and around 95 percent is low level. This low-level waste can take a few years or decades to decay, while high-level waste can take upward of tens of thousands of years.

Managing nuclear waste requires answering two primary questions: how to store it and where to store it. Low-level nuclear waste is most often stored in metal drums; high-level waste is by law turned into glass, or vitrified, to immobilize it and then stored in containers. But by far the most controversial issue in waste management is where to store it.

After cooling for years in water, low-level waste is moved to dry storage aboveground. High-level waste requires deep underground repositories to isolate it for thousands of years. However, identifying suitable sites is highly contested, despite a broad consensus that such waste should be stored underground (as opposed to burying it at sea, for example). Because it must be stored for so long, a geologically stable environment is needed to ensure that earth movements do not disturb the waste repositories, and a dry environment is needed to ensure that running water does not leach away waste and transport it from the disposal site. This is a possibility because long-lived fission products and some activation products have geochemical properties that prevent them from binding onto the surfaces of minerals that would otherwise immobilize them in place.

Finally, the idea of transmuting the radioactive elements in nuclear waste into less dangerous elements is occasionally floated. Natural transmutation for nuclear waste materials occurs over time but takes hundreds of thousands or millions of years. Speeding up this process entails subjecting the nuclear waste elements to some other nuclear process to effect a transformation and has been demonstrated on the atomic scale in the laboratory—but never on a scale necessary to deal with the 86,000 tons of high-level radioactive waste now being stored temporarily in aboveground sites.

## Over the Horizon: Fission

### *Impact of New Reactor Designs*

Generation IV nuclear reactors are proposed reactors that are more advanced than the Generation III and III+ reactors in use today. Generation IV reactors seek to improve sustainability, economics, safety and reliability, proliferation resistance, and physical protection. Some of the technical goals of such reactors include increased efficiency of electricity generation; generation and capture of process heat to be used in other thermal applications, such as the production of hydrogen; increased safety; and reduced production of waste materials.

Generation IV reactors are characterized by their coolants, which can be water, helium, liquid metal, or molten salt, and by whether they operate with moderated (slower) or unmoderated (faster) neutrons. Reactors using moderated (or thermal) neutrons can operate with low-enriched uranium fuel, which presents a lower risk of nuclear weapons proliferation. Reactors using unmoderated (or fast) neutrons must use HALEU but are able to generate more power per unit of fuel.

According to the US National Academies of Sciences, Engineering, and Medicine, “advanced nuclear technologies likely will not be able to markedly contribute to electricity generation until the 2030s at the earliest.”[12] Nevertheless, they may compete with other energy technologies in the long term.

### *Challenges of Innovation and Implementation*

Bridging the gap between innovation and implementation remains a challenge for advanced Generation IV reactors. The design for such reactors has been on the books for many years, and the scientific theory of nuclear power generation and the engineering know-how to build nuclear plants have also been available for many years. Nevertheless, concerns over matters such as cost and safety have largely prevented any action being taken toward deployment. China connected the first Generation IV reactor—a demonstration project—to its power grid on December 20, 2021,[13] but no other Generation IV plants are known to be under construction anywhere else in the world.

## *Policy, Legal, and Regulatory issues*

**Waste management** There is no enduring US plan for a long-term "permanent" solution to disposing of nuclear waste, with essentially all civilian nuclear waste being "temporarily" stored on-site at nuclear power plants. The one site that was seriously proposed for permanent storage at Yucca Mountain was shut down in 2010. The Obama administration cited opposition from the State of Nevada in suspending the Yucca Mountain Project. There are no new fuel disposal or storage facilities for long-term US use currently in development by the DOE, although at this writing, Finland is expected to open its Onkalo site for permanent storage of spent fuel in 2024.[14] Two private-sector facilities for interim storage (Consolidated Interim Storage Facilities) have been proposed in Texas and New Mexico, but host states have opposed the Nuclear Regulatory Commission's licensing of these facilities.[15] Both states have received NRC licensing, but the approval of the Texas site was vacated by the US Court of Appeals for the Fifth Circuit.[16] The amount of US high-level nuclear waste to be managed is today around 86,000 tons and grows at the rate of an additional 2,000 tons per year—which makes management of such waste an important public policy concern.

**Economics** Nuclear energy and economics are intrinsically linked, with both capital costs and the operating costs of energy production directly influencing the economy's health and competitiveness. At the construction phase, conventional nuclear power plants have experienced significant construction cost overruns. The construction of new fission power plants faces delays due to Nuclear Regulatory Commission intervention during construction, state rules that delay permitting, and a lack of advocates for new nuclear plants. At the operational phase, nuclear-generated electricity is not cost-competitive due to high operating costs. In the United States, the cost of upgrades for older nuclear reactors and the relative marginal cost of nuclear compared to wind and solar (nuclear has higher marginal cost) have made nuclear power plants less economically feasible than other sources of renewable energy.

**Timescale** Recognizing the urgency of reducing greenhouse gas emissions and the time it takes to approve and build new reactor designs safely, it is unclear whether a sufficient number of nuclear reactors can become operational in time. According to the International Energy Agency, 439 nuclear power reactors were in operation in 2021, with a combined capacity of 413 gigawatts, which avoids 1.5 gigatons of global emissions per year.[17] Considering that global emissions in 2022 reached 36.8 gigatons,[18] doubling the number of reactors would only reduce global emissions by 4 percent (assuming efficiency remains the same). The median construction time of nuclear reactors connected to the grid in 2021 was eighty-eight months.[19] In the United States, the various approval processes take about sixty months.[20]

> There is no enduring US plan for a long-term "permanent" solution to disposing of nuclear waste.

All in all, a twelve-year period from initiation of the approval process to grid connection does not seem excessive.

**Fuel supply** For fission in new nuclear reactors, the only commercial source of HALEU today is Russia, and the security and reliability of Russia as a source is not assured. Although the US government is undertaking research that might result in the availability of a domestic supply, environmental and other land-use issues might inhibit the development and deployment of facilities to produce HALEU.

## Overview: Nuclear Fusion Technology

Fusion is another physical process that produces massive amounts of energy from atoms. Instead of splitting atoms like fission, fusion occurs when two atomic nuclei collide together to form a heavier nucleus. Substantial amounts of energy, several times greater than fission, are released without any long-lived radioactive waste. Fusion is the source of energy in a thermonuclear bomb—and the sun. As with nuclear fission, the hope is that fusion can be controlled to drive electrical generators.

Fusion energy comes from the fusion of deuterium (D) and tritium (T), both isotopes of hydrogen. Deuterium is common in seawater, but tritium is radioactive and, because of its short half-life of twelve years, is not found in nature and thus must be manufactured. The D-T reaction produces a helium-4 nucleus and a fast neutron.

Fusion energy is still in the R&D stage. There are two approaches in serious fusion research today, and both attempt to solve what is known as the confinement problem.[21]

The confinement problem refers to the challenge of keeping a fusion fuel—typically a mix of hydrogen isotopes like deuterium and tritium—at the necessary high temperatures and pressures long enough for a significant number of nuclear fusion reactions to occur. Because fusion involves "fusing" two nuclei together, the fusion reaction must overcome the repulsive forces between two charged nuclei—and the only known way to do that is to have the nuclei moving at very high speeds, corresponding to being at a very high temperature.

One way to confine the fuel is to use powerful magnets to trap a high-temperature plasma of deuterium and tritium, a process known as magnetic confinement fusion (MCF). These magnets keep the hot plasma away from the containment vessel walls, aiming to maintain the necessary high temperatures and densities for the fusion reactions to occur in sufficient frequency. The engineering challenge is to ensure stability of the plasma and maintain confinement conditions sufficiently long enough (several seconds) for a net positive energy output, as plasma instabilities can disrupt this process.

A second way—inertial confinement fusion (ICF)—calls for the very rapid compression of a fuel pellet using lasers or ion beams, causing the fuel pellet to implode. The beams hit the pellet's surface simultaneously, causing the pellet's outer layer to explode, thus driving the rest of the pellet toward its center. The beams are very powerful but illuminate the pellet for a short time, around 20 nanoseconds, during which the pellet is compressed. When an adequate degree of compression has been achieved, ignition of the fuel begins, and for an even shorter time of about 100 picoseconds, the compressed fuel—now a very hot plasma—does not have a chance to move very much because of its own inertia—hence the name inertial confinement. Here, the engineering challenge is ensuring that the beams hit the pellet simultaneously in a symmetrical manner, and the rate at which pellets can be dropped and imploded determines the rate at which energy is released.

In a typical conceptual design for a fusion reactor, a pellet might be dropped ten to twenty times per second, requiring the illuminating lasers to fire that often. The laser energy incident on the pellet would be a couple of megajoules, and the fusion reaction would produce around 100 to 150 megajoules, for an energy gain of fifty to one hundred times. (Energy gain is the ratio of the energy produced to the energy used to initiate the fusion reaction. It is important because only if the gain is greater than one is the reaction producing net energy.) Important engineering challenges include building facilities for mass production of fusion pellets, as a single reactor might use a million pellets per day. Other challenges include reducing the cost of pellets (a target goal might be 10 to 50 cents per pellet), developing lasers that can fire ten to twenty times per second, and finding structural materials for building the reactor that can acceptably withstand the fast neutrons that are emitted in the fusion reaction.

For fusion to be a viable energy source, the confinement strategy must allow more energy to be produced from the fusion reactions than the energy invested in initiating those reactions (i.e., the energy gain must be greater than one). Achieving a net positive energy output while managing the confinement challenges is a central problem in fusion research.

Research on nuclear fusion is performed in a number of government, commercial, and academic institutions. Government involvement occurs in a number of national laboratories. A few dozen private-sector companies are active in fusion and a dozen or so universities are also involved. Funding for fusion research comes from private capital and US government coffers: research for fusion for energy production received $763 million from the US government for fiscal year 2023 and fusion research related to nuclear weapons received an additional $630 million.[22] Private companies declared funding of $4.7 billion in the 2022 calendar year.[23]

## Key Developments: Fusion

A milestone was reached in December 2022, when the National Ignition Facility (NIF) at Lawrence Livermore National Lab reached better than "breakeven" in an ICF experiment—in other words, the point at which more energy was released by a nuclear fusion reaction than the proximate energy used to initiate the reaction;[24] in this experiment, the energy released was 1.53 times the proximate energy (i.e., the energy gain was 1.53). A second demonstration of "better-than-breakeven" was repeated in July 2023.[25]

In both cases, the proximate energy was the energy used by the lasers involved in initiation. However, these experiments did not come anywhere near to breakeven if the energy inputs to the lasers are considered. Nevertheless, these experiments have spurred interest in the field of nuclear fusion, especially among the large number of start-ups in this arena. While most of the investment in such companies comes from venture capital firms, the Department of Energy has outlined plans for public-private partnerships to develop on-grid fusion energy within the next few decades.

## Over the Horizon: Fusion

### *Impact of New Technology*

The fusion energy future faces many technical research challenges, including:

- **Reactor configuration** The feasibility of fusion as a power source depends on solving the confinement problem, and we don't know if magnetic confinement or inertial confinement will prove to be feasible methods in the long run.

- **Availability of tritium** Because tritium is not found in appreciable amounts in nature, it must be manufactured. Tritium can be produced in fission nuclear reactors by subjecting lithium to neutron irradiation in the reactor's core. The United States has not needed to produce tritium for several decades, but if fusion power becomes commercially viable, it will have to obtain sufficient supplies.

- **Fabrication of fuel** Fusion reactors require the preparation of the D-T mixture into geometric forms that easily absorb the energy needed to push the nuclei together.

- **Materials** The physical structures housing fusion reactions are subject to damaging bombardment, since most proposed fusion reactions, including deuterium-tritium, release high-energy neutrons. New materials are needed that are more neutron resistant.

## *Challenges of Innovation and Implementation*

Some press accounts of the genuine breakthrough in achieving scientific breakeven gave the impression that the experiment suggested that practical fusion energy was "just around the corner." Even the most optimistic private investors in fusion do not believe it is any closer than ten to fifteen years away.

## *Policy, Legal, and Regulatory Issues*

**Nuclear proliferation** Fusion power plants will generate fast neutrons in addition to producing useful heat. These neutrons can be used in principle to transmute certain elements into material that can be used to make fission weapons. One study on this topic acknowledges some proliferation risk but concludes that "proliferation risk from fusion systems can be much lower than the equivalent risk from fission systems, provided commercial fusion systems are designed to accommodate appropriate safeguards."[26]

**Waste management** The primary waste products from nuclear fusion are the materials irradiated by the intense neutron radiation produced in the fusion reaction. The neutrons serve to transmute the elements in the original materials into other elements, and often these "activation products" are radioactive. However, they generally do not remain dangerous for nearly as long as the waste products from fission reactors.

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