United States Government Accountability Office
Report to Congressional Addressees

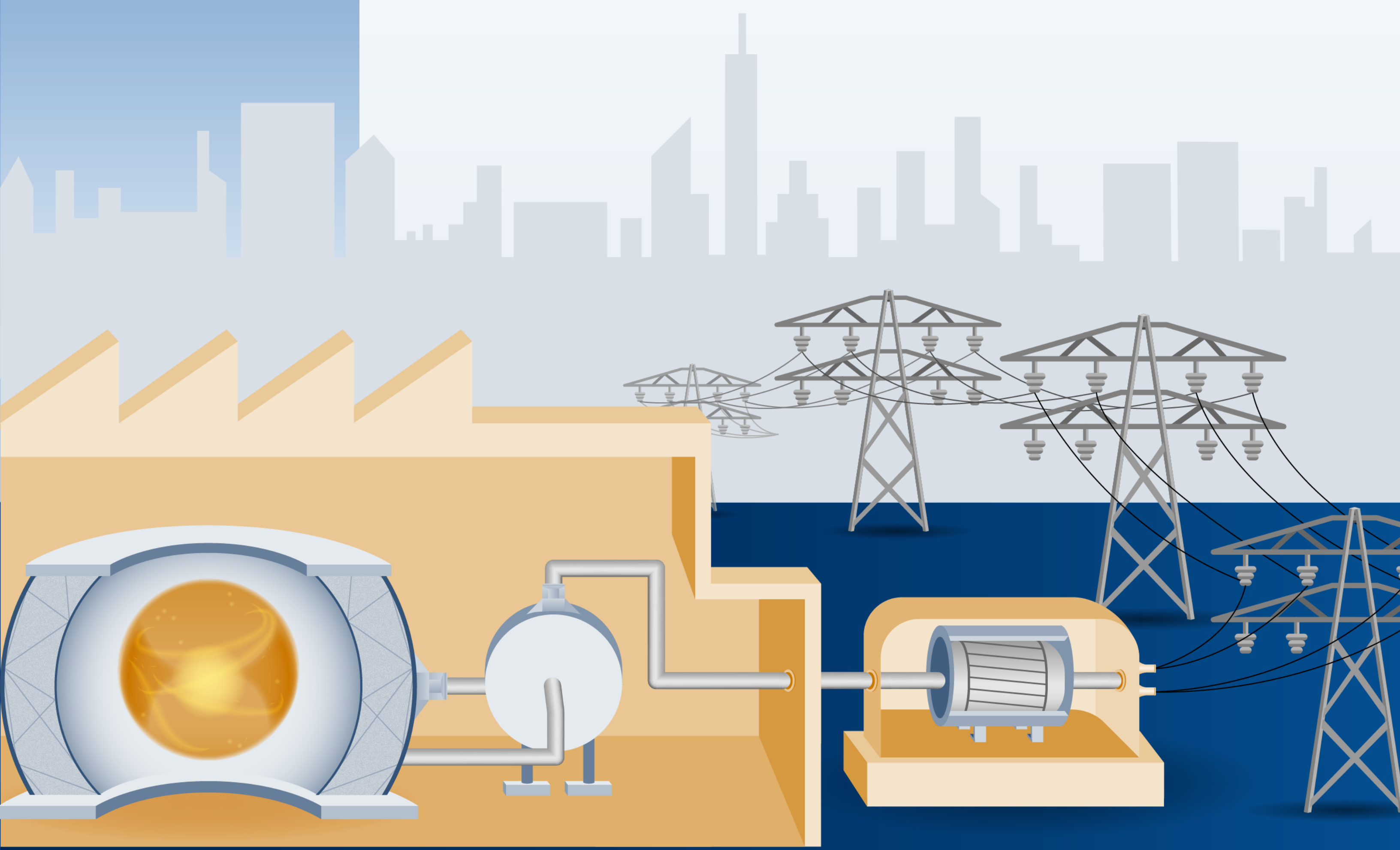
March 2023

TECHNOLOGY ASSESSMENT

Fusion Energy

Potentially Transformative Technology Still Faces Fundamental Challenges

Accessible Version



GAO-23-105813

The cover image displays a notional rendering of a fusion energy system connected to the electrical grid.
Cover sources: GAO. | GAO-23-105813

TECHNOLOGY ASSESSMENT

Highlights of GAO-23-105813, a report to congressional addressees

March 2023

Fusion Energy

Potentially Transformative Technology Still Faces Fundamental Challenges

Why GAO did this study

Fusion could address many energy challenges by providing abundant, safe, low-carbon energy. Researchers have achieved scientific and technological advancements in recent years. Fusion energy companies have received billions of dollars of private investment in addition to federal grants.

GAO conducted a technology assessment on (1) the status, potential benefits, and limitations of fusion energy, (2) challenges that might affect the development or use of fusion energy, (3) policy options that might help enhance the benefits or mitigate challenges associated with fusion energy.

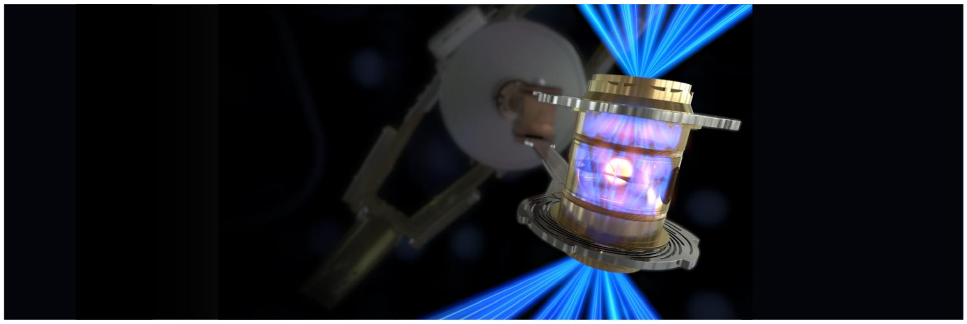
GAO reviewed key reports and scientific literature; interviewed stakeholders from government, industry, and academia; held focus groups with members of the public; attended a conference on issues related to fusion energy; and convened a meeting of experts in collaboration with the National Academies of Sciences, Engineering, and Medicine. GAO is identifying policy options in this report.

View GAO-23-105813. For more information, contact Brian Bothwell at (202) 512-6888, bothwellb@gao.gov.

What GAO found

Nuclear fusion, the process that powers the sun and other stars, could produce electric power without carbon emissions, long-lived nuclear waste, or risk of meltdowns. Researchers and companies are pursuing many different concepts for fusion energy and have reported recent progress, such as the development of high-temperature superconducting magnets that could make fusion devices much more compact. Also, in 2022, an experiment at the National Ignition Facility achieved a key scientific milestone, generating more energy from a fusion reaction than the amount of direct energy spent to start the reaction.

National Ignition Facility



Source: Lawrence Livermore National Laboratory. | GAO-23-105813

However, several challenges must be overcome to achieve commercial fusion, and stakeholders' projections of this timeline range from 10 years to several decades. One key scientific challenge is in the physics of plasmas, the state of matter needed for fusion. Researchers do not fully understand the behavior of burning plasmas, those whose main source of heat is from the fusion reaction itself rather than an external source. Researchers have made advancements in this area but lack sufficient experimental data to validate their simulations. One key engineering challenge is the development of materials that can withstand fusion conditions for decades, such as extreme heat and neutron damage, and no facility exists where materials can be fully tested. More generally, the task of extracting energy from fusion to provide an economical source of electric power presents several complex systems engineering problems that have yet to be solved.

Public and private sector misalignments, regulatory uncertainty, and other factors also present challenges to fusion energy development. One area of misalignment is research priorities. Public sector efforts prioritize basic science, but fusion energy development requires an additional emphasis on technology and engineering research. Another factor is regulatory uncertainty, which could slow development of fusion energy, although developing appropriate regulations to ensure safety without constraining development is difficult. Doing so may require significant public engagement, but little is known about public perception of fusion energy in the U.S.

GAO developed four policy options that could help address these challenges or enhance the benefits of fusion energy. These policy options are provided to inform potential actions to address the public policy challenges identified in this technology assessment. They identify possible actions by policymakers, which include legislative bodies, government agencies, academia, industry, and other groups. See below for a summary of the policy options and relevant opportunities and considerations.

Policy Options to Help Address Challenges or Enhance Benefits of Fusion Energy

	Opportunities	**Considerations**
Sustain current efforts (report p. 32)	• Some challenges described in this report may be addressed by current efforts. • Could allow policymakers to observe and evaluate the impact of existing efforts, which could limit risk and save money.	• Current efforts may not address all challenges described in this report. • Current efforts alone may delay or inhibit the development of fusion energy, which could result in forgone benefits or negative impacts, such as to the environment.
Align public and private efforts (report p. 33) <u>Implementation approaches:</u> *Align programs, missions, and organizational structures with fusion energy development goals* *Expand use of public private partnerships* *Reduce barriers to collaboration* *Leverage international coordination*	• Could accelerate the demonstration and commercialization of fusion energy by enhancing research on materials, technology, and engineering needs. • Could leverage strengths across sectors and expand programs that, according to experts and interviewees, are underused and have been effective in advancing fusion energy development. • Standardized research and development agreements could accelerate research, encourage knowledge sharing between organizations and countries, and reduce time-intensive negotiation.	• Aligning public and private efforts can be time intensive and may require additional resources or legislative action, according to experts. • To achieve fusion energy development timeline goals, policymakers may need to pursue parallel efforts and take more risks, which could incur greater costs. • Could require additional resources or reallocation of existing resources from other programs.
Build shared assets for fusion energy (report p. 34) <u>Implementation approaches:</u> *Support facilities that address scientific and engineering challenges* *Support workforce development* *Assess sources of critical supplies and manufacturing capabilities*	• Could help fill critical research gaps on the path to fusion energy commercialization. • Could help ensure fusion energy development is not limited by critical workforce or supply shortages.	• Test facilities require significant investment and years to build and commission. • Workforce development takes significant time and resources. National lab representatives said that long-term funding is needed for education and training. • Stakeholders may disagree on the best options to support community assets that are usable for a range of fusion energy technologies.
Engage the public in decision-making (report p. 35) <u>Implementation approaches:</u> *Study public opinion through surveys and focus groups* *Educate through cross-sectoral forums* *Include affected communities in decision-making related to fusion facilities*	• Could help inform policy decisions, such as those related to regulation of and investment in fusion energy. • Could ensure community stakeholders' views are represented so that decisions do not negatively impact issues of public concern, such as traffic or the environment. • Could ensure that benefits, such as economic development, are shared broadly and inclusively with affected communities. • Alignment between communities and fusion developers could reduce barriers to their success.	• Engagement should be proactive, transparent, and should set realistic expectations for benefits, risks, and timelines. • It may be difficult to ensure broad participation and representation. • Engagement should be used to learn about the public's perspectives about fusion energy rather than to persuade the public to support fusion.

Source: GAO. | GAO-23-105813

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Abbreviations

Acronym	Acronym text
AEA	Atomic Energy Act of 1954, as amended
ARIES	Advanced Reactor Innovation and Evaluation Studies
CRADA	Cooperative Research and Development Agreement
DEMO	Demonstration Power Plant
DOE	Department of Energy
FPNS	Fusion-Prototypic Neutron Source
IFMIF	International Fusion Materials Irradiation Facility
INFUSE	Innovation Network for Fusion Energy
JET	Joint European Torus
National Academies	National Academies of Science, Engineering, and Medicine
NEIMA	Nuclear Energy Innovation and Modernization Act
NIF	National Ignition Facility
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
NSTX-U	National Spherical Torus Experiment – Upgrade

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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March 30, 2023

Congressional Addressees

Nuclear fusion, the process that powers stars, could produce electric power without direct carbon emissions, long-lived nuclear waste, or risk of meltdowns. However, no fusion energy device has yet produced more energy than it consumes. Fusion occurs when one or more lighter elements combine to form a heavier element—hydrogen fusing to form helium, for example—releasing energy in the process. By comparison, current nuclear reactors use fission, where heavier elements split into lighter elements. Producing the conditions necessary for fusion on Earth is incredibly challenging because it requires control of a complex system at temperatures hotter than the sun. In addition, materials need to be developed that can withstand the conditions—high heat, ion damage, and bombardment by highly energetic neutrons—that will be present in a fusion energy system. These technological challenges have prevented the generation of usable fusion energy. Furthermore, if fusion can be harnessed for electricity in the future, it may not be commercially viable or cost-competitive with other energy sources depending on the future electricity market.

However, recent fusion experiments have reported significant progress toward the goal of usable fusion energy. In December 2022, a U.S. facility became the first to get more energy out of a fusion experiment than the energy directly injected into the experiment.[1] The development of high-temperature superconducting magnets in recent years was another key step, which may enable the construction of more compact fusion devices. Meanwhile, advances in computer modeling are helping scientists better predict the behavior of plasma, the state of matter needed for fusion.

Such advancements have prompted renewed interest in and funding for fusion energy. Private investors have committed several billion dollars of new investment to fusion startups. In fiscal year (FY) 2022, the Department of Energy (DOE) Office of Science received appropriations of $713 million for its Fusion Energy Sciences program, continuing a steady increase since its 2017 appropriation of $380 million. In FY 2022, the National Nuclear Security Administration received $580 million in appropriated funds for its Inertial Confinement Fusion program. In March 2022, DOE announced a department-wide initiative to accelerate the development and commercialization of fusion energy in partnership with the private sector.

We prepared this report under the authority of the Comptroller General to assist Congress with its oversight responsibilities, in light of broad congressional interest and the potential high value of fusion energy. We examined (1) the status of fusion energy technology, and the potential benefits and limitations of fusion energy; (2) challenges to the development or use of fusion

[1]Operating the lasers to run the experiment required about 100 times the energy released by the fusion event, so the experiment did not produce more energy than it consumed.

energy; and (3) policy options that may help enhance the benefits or mitigate challenges associated with fusion energy development and adoption.

We interviewed agency officials and other stakeholders, visited fusion energy experiments, held an expert meeting, conducted focus groups with the general public, attended the 2022 American Nuclear Society annual meeting, and reviewed agency documents and other literature. See appendix I for a full discussion of the objectives, scope, and methodology and appendix II for a list of experts who participated in our meeting.

We conducted our work from February 2022 to March 2023 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

1.1 Fusion could provide abundant, safe, low-carbon energy

If commercial fusion energy works, it could address many energy challenges, including the following:

- Emissions: It would reduce greenhouse gas emissions compared to fossil fuel energy because it does not involve combustion.
- Energy needs: It might more easily meet growing energy use, which the U.S. Energy Information Administration predicts will increase globally by nearly 50 percent by 2050. Fusion uses relatively abundant materials for fuel, such as deuterium, a common isotope of hydrogen. It uses these fuels in relatively small amounts: 1 ton of fusion fuels could produce as much energy as about 7 million tons of oil.
- Safety and waste: It does not create high-level or long-lived radioactive waste and does not pose the risk of a meltdown.
- Increased energy access: It may be possible to site fusion power plants in more locations than renewable energy sources because they are not limited by natural events like wind and sunshine. This capability would increase access to energy that can be produced without direct greenhouse gas emissions.

While fusion energy could provide these benefits, key limitations (see 1.3) and challenges (ch.3-4) may affect its development and potential use. GAO has reported on fusion energy and these issues over the past 50 years.[2]

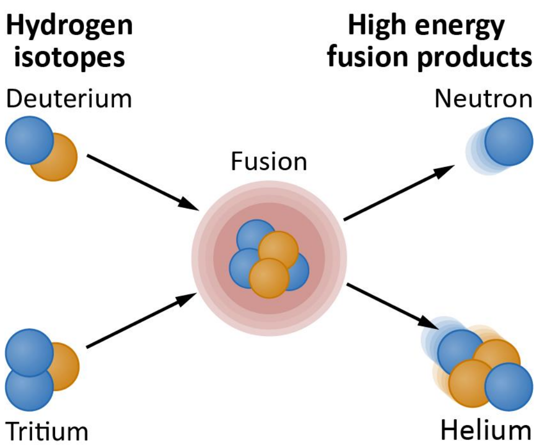
1.2 Fusion is the reaction that powers the sun

Fusion occurs when two atoms fuse to create a heavier atom, releasing energy in the process (see fig. 1). This process has been underway for billions of years on the sun, but it is extremely challenging to achieve on Earth because of the temperature and pressure required. Every atom contains a central mass known as a nucleus, which is positively charged and therefore repels other nuclei. In order to fuse, nuclei must be moving fast enough and have many chances for a collision. To achieve this, they must be extremely hot and either highly pressurized or confined in a small space for long enough, often at least a few seconds. Fusion in the sun

[2]Selected GAO reports on fusion energy include: GAO *Management of the Atomic Energy Commission's Controlled Thermonuclear Research Program* B-159687 (Washington, D.C.: Dec., 1972); *Fusion – a Possible Option for Solving Long-Term Energy Problems* EMD-79-27 (Washington, D.C.: Sept. 28, 1979); *Performance of Participants in DOE's Inertial Confinement Fusion Program*, T-RCED-90-58 (Washington, D.C.: Apr. 5, 1990); *Fusion Energy: Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor,* GAO-14-499 (Washington, D.C.: June 5, 2014).

occurs at 15 million Kelvin (about 27 million degrees Fahrenheit) and a pressure that is about 100 billion times the pressure of the Earth's atmosphere at sea level. That pressure is extremely challenging to achieve on earth, so fusion experiments use much higher temperatures, often greater than 100 million Kelvin (about 180 million degrees Fahrenheit), to create the conditions for fusion.

Figure 1: Fusion energy combines elements into heavier elements



Source: GAO analysis. | GAO-23-105813

Accessible text for Figure 1: Fusion energy combines elements into heavier elements

Hydrogen isotopes

- Deuterium and Tritium goes into Fusion

High energy fusion products

- Neutron and Helium

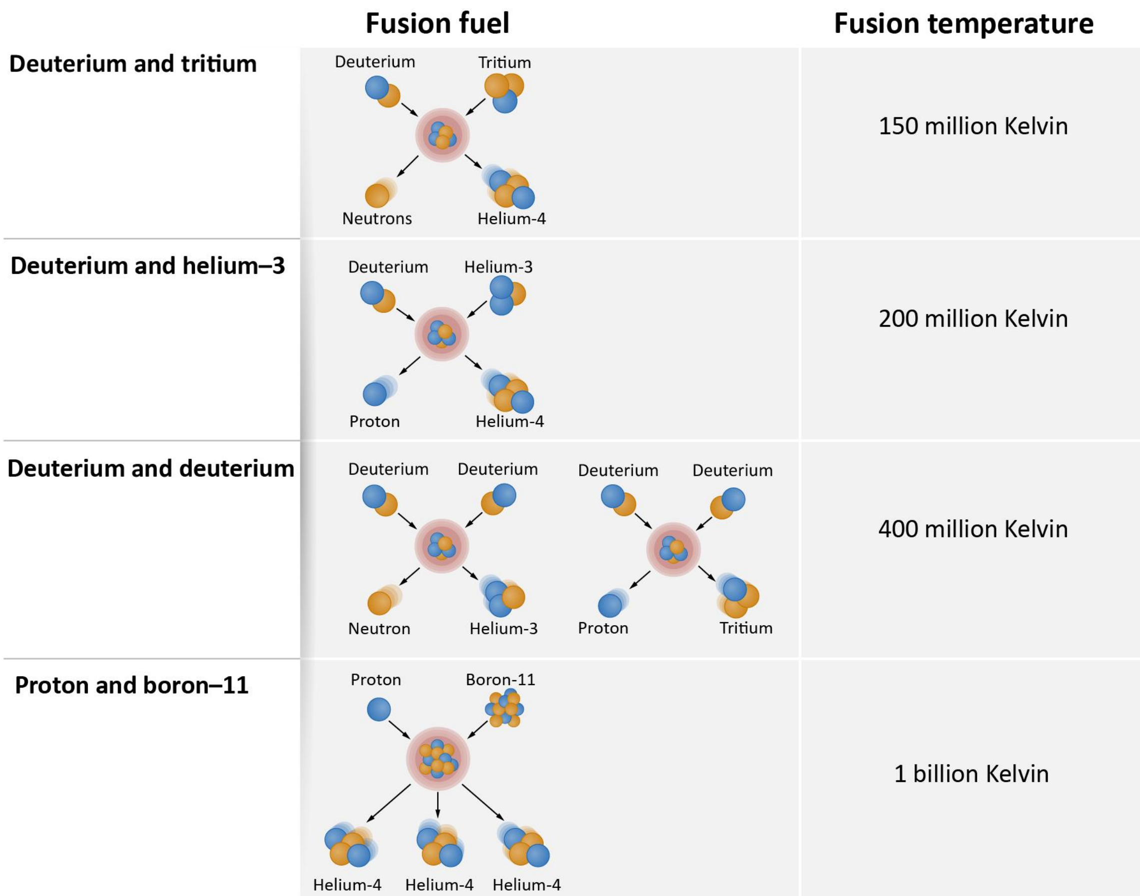
Source: GAO analysis. | GAO-23-105813

However, at the high temperatures needed for fusion the electrons and nuclei in atoms separate, creating plasma, which is difficult to control and which researchers are still working to fully understand. There are two pathways to create and control plasmas so that fusion can occur: magnetic confinement and inertial confinement. Magnetic confinement uses magnetic fields to control the charged particles in the plasma and contain them for long periods of time at moderate pressures. Inertial confinement compresses the fuel very quickly to very high pressures and temperatures, but for a comparatively short time. It is also possible to combine properties of magnetic and inertial confinement fusion, sometimes called magneto-inertial fusion.

Fusion fuels include isotopes of hydrogen, such as deuterium and tritium, or heavier elements, such as boron.[3] The deuterium-tritium reaction is the easiest to achieve, so it is highly studied and the likely basis for the first fusion energy systems. Because the first generation of fusion energy systems will likely use deuterium and tritium as fuel, this report refers to deuterium-tritium fusion unless otherwise stated. Other fuels may mitigate some challenges associated with deuterium-tritium fuel, but they require significantly higher temperatures. Figure 2 shows examples of fusion fuel combinations, resulting products, and required temperatures to produce sufficient fusion results.

[3] A deuterium nucleus has one proton and one neutron. A tritium nucleus has one proton and two neutrons. Most naturally occurring hydrogen is protium, which has one proton and no neutrons. Protons and neutrons are particles found in the nuclei of an atom. Protons are positively charged and neutrons do not have an electrical charge.

Figure 2: Different fuels can produce fusion energy but require different temperatures



Source: GAO analysis. | GAO-23-105813

Accessible text for Figure 2: Different fuels can produce fusion energy but require different temperatures

Source: GAO analysis. | GAO-23-105813

Note: The temperatures required for fusion are for attainable pressures.

1.3 Harnessing fusion energy requires engineering complex systems

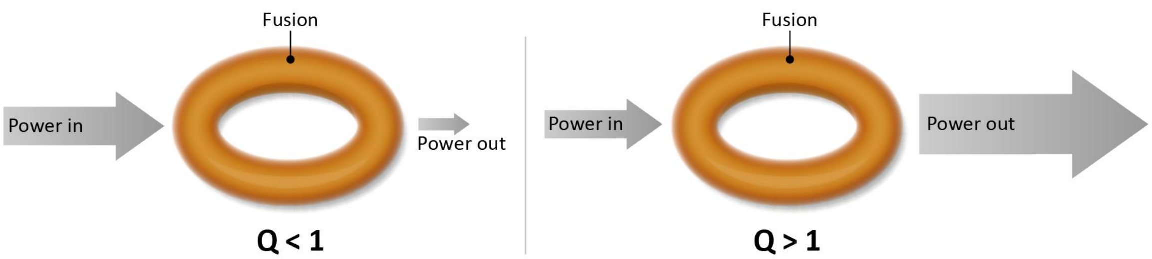
For a fusion energy system to be viable, it must produce more energy through fusion reactions than the energy needed to produce and maintain those reactions in a plasma. While there are fusion devices that produce fusion events, such as existing fusion research facilities, fusion energy systems will need to incorporate fusion reactors as well as supporting structures, systems and components. Furthermore, fusion energy systems will need to be integrated into power plants, which will require solving many complicated engineering problems.

1.3.1 Fusion energy requires controlled plasmas that take significant energy to create

Although fusion can generate large amounts of energy from a small fuel supply, it takes significant energy to create a plasma that can sustain fusion. Fusion researchers denote the gain of energy from a plasma undergoing fusion using the letter Q. A Q greater than one means that more fusion energy is released than is put into creating and maintaining the plasma, as seen in Figure 3. More specifically, $Q_{Scientific}$ considers only the energy that goes into the plasma. On December 5, 2022, a National Ignition Facility (NIF) experiment reached a $Q_{Scientific}$ of 1.5, the first time a fusion experiment achieved a $Q_{Scientific}$ greater than one.

$Q_{Engineering}$, on the other hand, also considers the energy needed to operate the fusion energy system and generate electricity for transmission and use. Economically viable commercial fusion energy will need a $Q_{Engineering}$ significantly greater than one over power plant operation timescales. To achieve this, a fusion energy plant needs to maintain a burning plasma, whose main source of heat is from the fusion reaction inside the plasma, as opposed to an external energy source.

Figure 3: Q is a metric that compares power to operate a fusion plasma versus the power out of the fusion plasma



Source: GAO analysis. | GAO-23-105813

Accessible text for Figure 3: Q is a metric that compares power to operate a fusion plasma versus the power out of the fusion plasma

Q<1

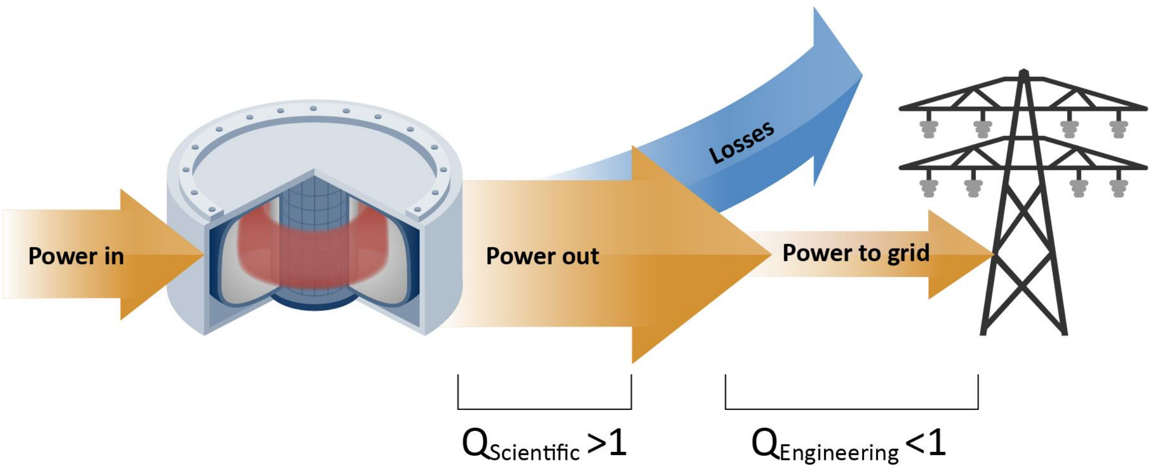
- Medium arrow representing power into Fusion, tiny arrow representing power out of Fusion

Q>1

- Small arrow representing power into Fusion, Large arrow representing power out of Fusion

Source: GAO analysis. | GAO-23-105813

Figure 4: $Q_{engineering}$ compares the power to the electrical grid compared to the power into the system



Source: GAO analysis. | GAO-23-105813

Accessible text for Figure 4: $Q_{engineering}$ compares the power to the electrical grid compared to the power into the system

Illustration of $Q_{engineering}$

1. Power in goes into the fusion plasma
2. Power comes out of the fusion plasma
3. $Q_{Scientific}$ is the power out of the fusion plasma compared to the power into the fusion device. It is greater than 1 if the power out is more than the power in.
4. $Q_{Engineering}$ is the energy delivered to the grid compared to the energy to operate the fusion plasma. $Q_{Engineering}$ is less than one if the power on to the grid is less than the power into the fusion plant.

Source: GAO analysis of scientific literature. | GAO-23-105813

Note: $Q_{Scientific}$ compares the energy into a plasma to the energy out, while $Q_{engineering}$ considers the energy in and out of the whole fusion energy plant.

There are many sources of energy loss and inefficiencies in a fusion energy system. Building a fusion power plant will introduce more sources of energy loss and inefficiencies in supporting equipment built around the fusion energy system. Some inefficiencies are unique to fusion, and some are common to all energy sources. For example, some fusion techniques require cooling large magnets to cryogenic temperatures, which is very energy intensive.[4] Others use lasers, which are very energy inefficient, requiring significantly more energy to operate than the energy that the laser emits. Similar to other energy sources, fusion energy systems will need to convert heat energy to electricity, a process that inevitably results in energy loss.

[4]Cryogenic temperatures are often below 120 K (-240 degrees F).

1.3.2 Neutrons from fusion reactions damage materials and produce low-level radioactive waste

Fusion reactions that use deuterium and tritium release high-energy neutrons.[5] These subatomic particles damage the materials containing the fusion reaction and can make them radioactive. New materials will need to be developed and tested to withstand the fusion environment, and fusion plants will need to safely contain radioactive materials and dispose of low-level radioactive waste. Chapter 3 discusses engineering, design, and safety challenges associated with these issues.

1.4 The U.S. has pursued fusion energy since the 1950s

1.4.1 History of fusion energy

Federally funded fusion research in the U.S.

For decades, researchers in the U.S. have been studying fusion, with funding primarily from DOE and its predecessors. The U.S. began federally funded magnetic confinement fusion research at national laboratories in 1951, and in FY2022 Congress appropriated nearly $1.6 billion for fusion energy sciences and the National Nuclear Security Administration's (NNSA) inertial fusion program, including $280 million from the Inflation Reduction Act.[6] Some major DOE activities included:

- In 1963, the Atomic Energy Commission, a DOE predecessor agency, began funding laser fusion research.
- In response to energy shortages during the 1970s, Congress approved funding for the Tokamak Fusion Test Reactor, a magnetic confinement project operating from 1982 to 1997 at the Princeton Plasma Physics Laboratory.
- From 1983 to 2014, the national Advanced Reactor Innovation and Evaluation Studies (ARIES) project assessed the economic, safety, and environmental features of various power plant design choices and the degree of extrapolation from existing capabilities needed to accomplish those designs.
- In 1996, DOE significantly restructured its fusion energy program at the request of Congress. Congress reduced the budget by 40 percent and DOE shifted emphasis to fusion and plasma science research.
- Since 2008, U.S. researchers at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory have been supporting national security by conducting experiments with powerful lasers, using inertial confinement approaches, to enhance nuclear weapon stockpile stewardship and some basic fusion science.[7]

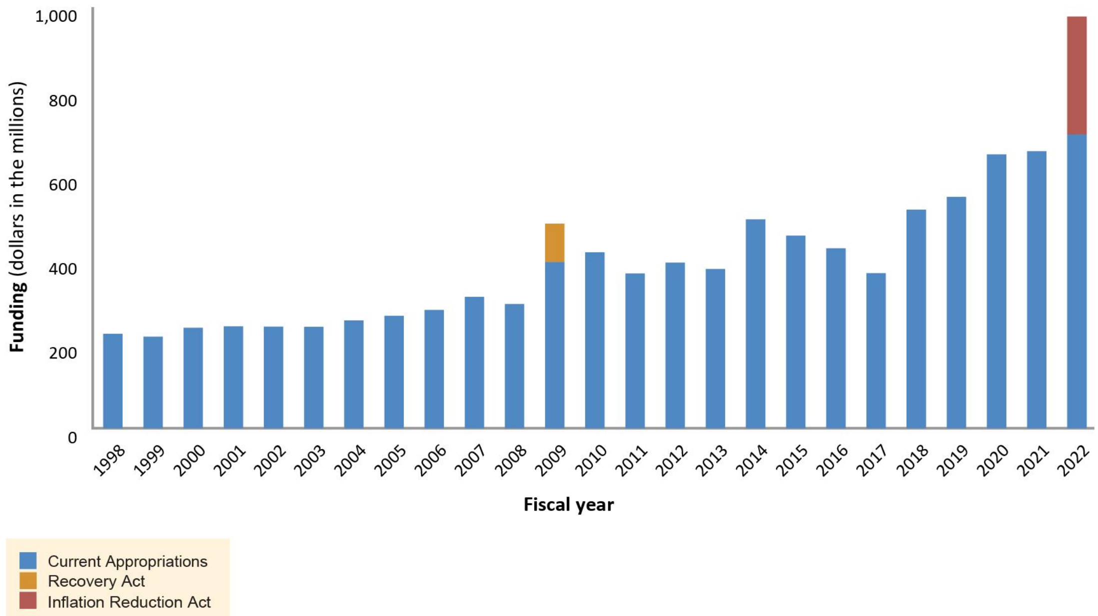
[5] Because the first generation of fusion reactors will likely use deuterium and tritium as fuel, the report is referring to deuterium-tritium fusion unless otherwise stated.

[6] The inertial fusion program supports NNSA's stockpile stewardship mission, and only part of that program supports research applicable to fusion energy. The Inflation Reduction Act provided a one-time budget increase for fusion energy science.

[7] Stockpile stewardship includes science-based assessment of the reliability of nuclear weapons to assess and certify the stockpile without nuclear explosive testing.

DOE also supports efforts to study plasmas for fusion energy at government labs, universities, and private industry. For example, in FY 2021, the Fusion Energy Sciences program awarded $174 million in cooperative agreements, grants, and interagency agreements. Figures 5 and 6 provide a summary of DOE funding for fusion research through the Office of Science and NNSA.

Figure 5: DOE Office of Science historic funding on fusion energy



Source: GAO (presentation), Department of Energy (data). | GAO-23-105813

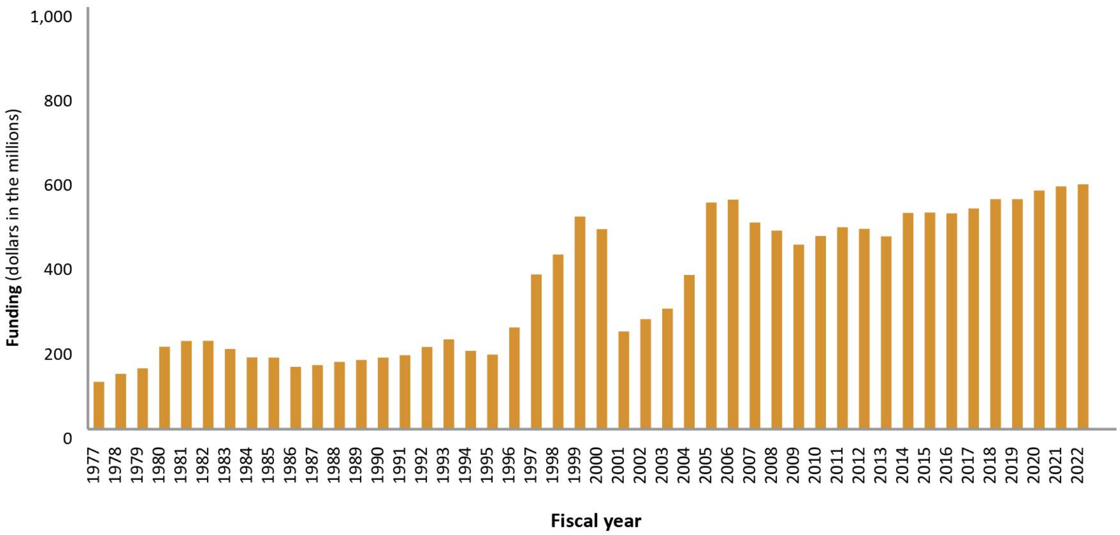
Accessible data for Figure 5: DOE Office of Science historic funding on fusion energy

Fiscal Year	Funding (dollars in the millions)
FY 1998	$224,190
FY 1999	$217,248
FY 2000	$238,593
FY 2001	$241,957
FY 2002	$241,100
FY 2003	$240,695
FY 2004	$255,859
FY 2005	$266,947
FY 2006	$280,683
FY 2007	$311,664
FY 2008	$294,933
FY 2009	$394,518
FY 2009 Recovery Act	$91,023
FY 2010	$417,650
FY 2011	$367,257
FY 2012	$392,957
FY 2013	$377,776
FY 2014	$495,855
FY 2015	$457,366
FY 2016	$427,267
FY 2017	$368,119
FY 2018	$518,824
FY 2019	$549,181
FY 2020	$650,311
FY 2021	$657,908
FY 2022	$697,556
FY 2022 Inflation Reduction Act	$280,000

Source: GAO (presentation), Department of Energy (data). | GAO-23-105813

Note: Current appropriations is a term DOE uses to reflect the enacted appropriation, as well as funding transfers from other accounts. All values are nominal dollars.

Figure 6: Historic DOE funding for inertial confinement fusion



Source: GAO (presentation), National Nuclear Security Administration (data). | GAO-23-105813

Accessible data for Figure 6: Historic DOE funding for inertial confinement fusion

Fiscal Year	Funding (dollars in the millions)
FY 1977	111,888
FY 1978	130,552
FY 1979	144,133
FY 1980	194,890
FY 1981	208,780
FY 1982	209,062
FY 1983	189,750
FY 1984	169,700
FY 1985	169,250
FY 1986	147,405
FY 1987	151,571
FY 1988	159,000
FY 1989	163,462
FY 1990	169,226
FY 1991	175,000
FY 1992	194,800
FY 1993	212,310
FY 1994	185,065
FY 1995	176,473
FY 1996	240,911
FY 1997	366,460
FY 1998	413,454

Fiscal Year	Funding (dollars in the millions)
FY 1999	503,382
FY 2000	473,481
FY 2001	231,225
FY 2002	260,373
FY 2003	285,185
FY 2004	365,136
FY 2005	536,756
FY 2006	543,582
FY 2007	489,706
FY 2008	470,206
FY 2009	436,915
FY 2010	457,486
FY 2011	478,106
FY 2012	474,484
FY 2013	456,676
FY 2014	512,395
FY 2015	512,895
FY 2016	511,050
FY 2017	522,959
FY 2018	544,934
FY 2019	544,934
FY 2020	565,000
FY 2021	575,000
FY 2022	580,000

Source: GAO (presentation), National Nuclear Security Administration (data). | GAO-23-105813

Note: All values are nominal dollars. Inertial confinement fusion funding is to support stockpile research, technology, and engineering.

International collaboration

Researchers have pursued fusion energy through international collaboration for decades. Beginning in 1973, European countries and researchers from around the world collaborated to build the Joint European Torus (JET) magnetic confinement fusion device in the United Kingdom. In 1997, JET set the then world record for fusion output at 16 megawatts and for $Q_{Scientific}$ of 0.67. Researchers continue to test plasma physics, systems, and materials using JET.

Meanwhile, the U.S. fusion research and development program has collaborated with other countries throughout the history of ITER, an experimental fusion project in southern France. Design of ITER started in 1988 and construction started in 2008, with construction still in progress today.[8] Researchers from around the world have collaborated to design, build, and eventually operate this large magnetic confinement fusion device to study long-duration burning plasma reactions.[9] The ITER Agreement of 2006 provided for sharing among the project collaborators the cost of project construction, operation, and decommissioning, as well as intellectual property. Today, 35 participating countries continue to build ITER with plans to address many of the technical challenges of commercial fusion energy after the device has been completed. If ITER demonstrates the technical feasibility of fusion through plasma energy gain, there are preliminary designs for a project or set of projects, known as demonstration power plants (DEMOs), to show the economic and environmental feasibility of fusion energy by integrating and demonstrating all relevant technology in a prototype fusion power plant.[10]

Private industry

In addition to some federal support in the form of grants and agreements, the fusion industry has received significant private funding in recent years. In a 2022 survey by the Fusion Industry Association, fusion companies declared $117 million in funding from government sources and over $4.7 billion of private funding commitments to date, an increase in private funding of $2.8 billion since the association's first report in 2021.[11] In addition, eight fusion energy companies were founded, or became known to the public, and at least seven companies received investments of $200 million or more since the 2021 survey.

1.4.2 Laws and regulations

Several laws established or clarified the roles of federally sponsored research programs for fusion energy and appropriated funds for those programs. In particular, the Nuclear Energy Innovation and Capabilities Act of 2017 directed DOE to identify "engineering designs for innovative fusion energy systems that have the potential to demonstrate net energy production not later than 15 years after the start of construction."[12] The Department of Energy Research and Innovation Act, as amended by the Research and Development, Competition, and Innovation Act, directs DOE to support research and development efforts for inertial fusion and magnetic confinement fusion for energy applications, as well as alternative fusion energy concepts.[13] It also directs DOE

[8]ITER (pronounced "eater") originally stood for International Thermonuclear Experimental Reactor but the project is now known simply as ITER.

[9]Scientists and engineers from the United States, Soviet Union, European Union, and Japan worked on the design for ITER from 1988-2001. The U.S. temporarily withdrew from ITER from 1998 to 2003. The People's Republic of China, the Republic of Korea, and India joined the effort in the 2000s.

[10]Future development programs are different in various ITER member states, but in general DEMO consists of a phase where each ITER member uses the knowledge gained by ITER participation to design and build their own unique devices with the goal of demonstrating industrial-scale fusion electricity by 2050. According to DOE, the U.S. plans to address these goals with a fusion pilot plant.

[11]Fusion Industry Association, "The Global Fusion Industry in 2022: Fusion Companies Survey by the Fusion Industry Association".

[12]Nuclear Energy Innovation and Capabilities Act of 2017, Pub. L. No. 115-248, § 2(j), 132 Stat. 3154, 3160 (2018).

[13]Department of Energy Research and Innovation Act, Pub. L. No. 115-246, § 307(c), 132 Stat. 3130 (2018) (codified at 42 U.S.C. § 18645(d) as amended by the Research and Development, Competition, and Innovation Act, Pub. L. No. 117-167, div. B, tit. I, § 10105, 136 Stat. 1366, 1441-42 (2022). One concept of magnetic confinement fusion is referred to in

to support research into materials, activities, and enabling technologies that could be used in fusion power systems and to assess the need for research and test facilities for those purposes.[14] The Inflation Reduction Act of 2022 appropriated $280 million for construction and major items of equipment projects related to fusion energy science.[15]

The Nuclear Regulatory Commission (NRC) has authority over all licensing and related regulatory functions relating to civilian nuclear facilities and materials under the Atomic Energy Act of 1954, as amended (AEA).[16] In a 2009 memorandum, NRC asserted that this jurisdiction includes fusion energy devices whenever they are of significance to the common defense or security or could affect the health and safety of the public. In 2019, the Nuclear Energy Innovation and Modernization Act (NEIMA) directed NRC to develop a regulatory framework for fusion reactors by the end of 2027.[17]

NRC is determining the framework with which it will regulate fusion energy. NEIMA requires that a technology-inclusive regulatory framework include the use of risk informed, performance-based licensing techniques for "advanced nuclear reactors," which includes both nuclear fission and fusion reactors. In September 2022, NRC released a white paper on options for licensing and regulating fusion energy systems. In January 2023, NRC staff submitted a paper to NRC commissioners, putting forth three options for regulating fusion energy systems:

- Under a byproduct material framework augmenting NRC regulations in 10 C.F.R. Part 30, which is similar to how NRC regulates radioactive materials used at hospitals and certain other materials facilities.
- As a utilization facility under the provisions of the AEA. Under this option, NRC would determine by rule that fusion energy systems are "peculiarly adapted for making use of atomic energy in such quantity as to be of significance to the common defense and security, or in such manner as to affect the health and safety of the public." Following such a determination, NRC would assess how to implement certain AEA requirements for utilization facilities, and rulemaking would commence for a new utilization facility framework addressing the specific hazards and safety considerations of fusion energy systems.
- Under a hybrid approach using either a byproduct material or utilization facility approach to license and regulate based on potential hazards. This would apply byproduct material or utilization facility approaches based on the risk profiles of

the law as tokamak research and development, (42 U.S.C. § 18645(c)), and the statute addresses other fusion energy concepts which include other magnetic confinement fusion concepts and other alternative confinement concepts. 42 U.S.C. § 18645(e).

[14]42 U.S.C. § 18645(e)(2)(B), and § 18645(b)(1)(B).

[15]This law, to Provide for Reconciliation Pursuant to Title II of S. Con. Res. 14, is commonly known as the Inflation Reduction Act of 2022, Pub. L. No. 117-169, tit. V, § 50172(a)(3), 136 Stat. 1819, 2050.

[16]Atomic Energy Act of 1954, Pub. L. No. 83-703, 68 Stat. 919, as amended by the Energy Reorganization Act of 1974, Pub. L. No. 93-438, 88 Stat. 1233, 1244, tit. II, §§ 202-04, codified at 42 U.S.C. §§ 5842-44.

[17]Nuclear Energy Innovation and Modernization Act, Pub. L. No. 115-439, §3(1), 132 Stat. 5565 (2019), codified at 42 U.S.C. § 2215 note.

particular fusion energy systems, allowing it to encompass still-unknown future fusion energy system concepts with differing risk profiles, but would require added NRC resources to develop criteria and could result in less regulatory clarity for applicants.[18]

NRC's Advisory Committee on Reactor Safeguards and NRC staff recommended a hybrid approach for fusion energy using both byproduct material and utilization facility approaches. The Fusion Industry Association, in contrast, has called to regulate fusion energy facilities under Part 30 – a byproduct material approach. According to NRC, there are four states participating in NRC's Agreement State Program that regulate some fusion facilities, such as fusion test facilities, as byproduct materials facilities.

[18]Policy Issue (Notation Vote), Options for Licensing and Regulating Fusion Energy Systems, SECY-23-0001 (Jan. 3, 2023).

2 Despite Recent Advancements, Fusion Has Not Achieved Net Energy Gain

2.1 Projections of the time to putting fusion energy on the grid vary widely

Fusion energy stakeholders disagree on when fusion energy will become technically feasible as an energy source for the electrical grid, as well as when it will become commercially viable. [19] Projections range from 10 years to several decades in the future. Some companies are claiming that they will achieve commercial fusion energy in about 10 years, while other stakeholders and experts said fusion might put electricity on the grid in 10 to 20 years but would require significant resources to do so. Still other stakeholders and experts said fusion energy will take more than 20 years.[20] We identified several technical challenges to fusion energy, described in chapter 3, some of which could take at least a decade to solve.

Specific projections for fusion energy on the grid include the following:

- The Fusion Energy Sciences Advisory Committee, which advises DOE, in 2020 described a timeline to make fusion economically viable by the mid-2040s.[21]
- The National Academies of Sciences, Engineering, and Medicine (National Academies) in 2021 described a timeline for a fusion pilot plant in the 2035 to 2040 time frame, which could demonstrate solutions to technical challenges of fusion energy.[22]
- In 2022, at a White House Summit DOE and the Office of Science and Technology Policy announced a "decadal vision" for fusion energy, with the goal of having fusion energy on the grid by the early 2030s.[23]
- Several countries are proposing demonstration power plants to generate electricity in the 2050 time frame.
- The Fusion Industry Association reported that many commercial companies predict fusion industry will be commercially viable in the 2031 to 2035 time frame.

[19]Stakeholders refers to entities that GAO interviewed, as described in Appendix I Objective, Scope and Methodology.

[20]Experts refers to attendees of the GAO meeting of experts, as described in Appendix I Objective, Scope and Methodology.

[21]Fusion Energy Sciences Advisory Committee, *Powering the Future, Fusion & Plasmas: A Long-Range Plan to Deliver Fusion Energy and to Advance Plasma Science* (2020).

[22]National Academies of Sciences, Engineering, and Medicine, *Bringing Fusion to the U.S. Grid* (Washington, D.C.: The National Academies Press, 2021).

[23]White House, *Fact Sheet: Developing a Bold Vision for Commercial Fusion Energy*, Press Release (Washington, D.C.: Mar. 15, 2022). DOE described this goal as a pilot-scale fusion energy power plant on the grid.

2.2 Fusion researchers have reported significant accomplishments in the past decade

Fusion science has made many significant advancements in the past decade, the culmination of decades of work. The following describes three of them.

In December 2022, the NIF reported the first fusion experiment with a $Q_{Scientific}$ greater than one. Using inertial confinement fusion, the experiment delivered 2.05 megajoules of energy to the container holding the fusion fuel, known as a hohlraum, and produced 3.15 megajoules of fusion energy output, resulting in a $Q_{Scientific}$ of about 1.5.[24] Inertial confinement fusion will need to produce significantly more energy before it is a viable energy source. The energy to power the lasers was about 300 megajoules, so if this were used in a fusion power plant the $Q_{Engineering}$ would be no higher than 0.01 – meaning that at least 100 times more energy would need to be produced by the experiment just to account for the energy required to run it. According to a laboratory representative, NIF was not designed to be energy efficient, and significantly more efficient lasers are envisioned to help improve the Q of the experiment, although these will have to be demonstrated.

Another important advancement was a record sustained energy output for a fusion device, set by JET. The project reported an output of 59 megajoules over 5 seconds from a fusion experiment on December 21, 2021. While the $Q_{Scientific}$ of this experiment was only 0.33, the experiment allows scientists to better understand fusion over longer durations.

A third advancement is the development of high-field magnets using high-temperature superconducting materials, which could help reduce the cost of fusion energy systems. In September 2021, Massachusetts Institute of Technology Plasma Science and Fusion Center researchers and Commonwealth Fusion Systems reported operating a 20 tesla magnet for about 5 hours using a material known as rare earth barium copper oxide.[25] This magnetic field is significantly stronger than other magnets designed for fusion energy. For example, the magnets used for ITER are designed to have a maximum field of 11.8 tesla. The strength of the magnetic field drives the size of many magnetic confinement fusion devices, so creating high-field magnets could allow for smaller devices, potentially reducing cost.

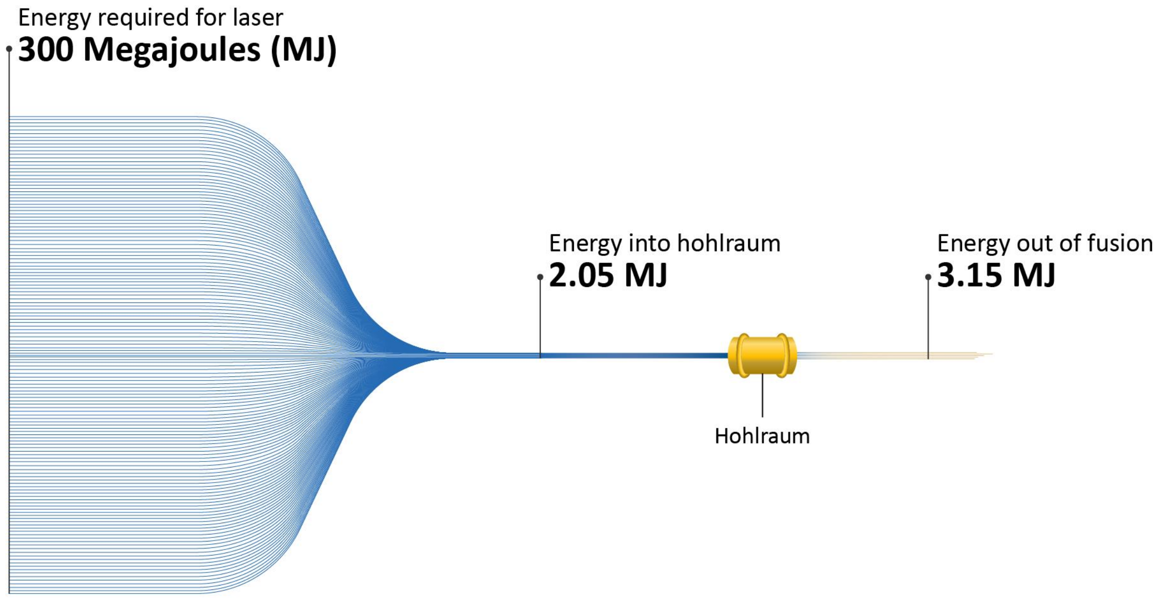
2.3 Commercial fusion energy requires major advancements

Even with recent accomplishments in fusion technologies, significant advancements are needed before fusion can become an economically viable energy source. Fusion energy will need to show that it can create more power than the whole power plant

[24] A megajoule is 1 million joules. The average U.S. home in 2021 consumes about 38,000 megajoules of energy in a year according to the U.S. Energy Information Administration.

[25] Household refrigerator magnets are about 0.01 tesla. Magnetic resonance imaging devices in hospitals often range from 1.5 to 3 tesla.

Figure 7: Inertial confinement fusion will need to release significantly more energy to be a viable energy source



Source: GAO (presentation) Lawrence Livermore National Laboratory (information). | GAO-23-105813

Accessible text for Figure 7: Inertial confinement fusion will need to release significantly more energy to be a viable energy source

Energy required for lasers is about 300 MJ
Energy into hohlraum is 2.05 MJ
Energy out of fusion was 3.15 MJ

Source: GAO (presentation) Lawrence Livermore National Laboratory (information). | GAO-23-105813

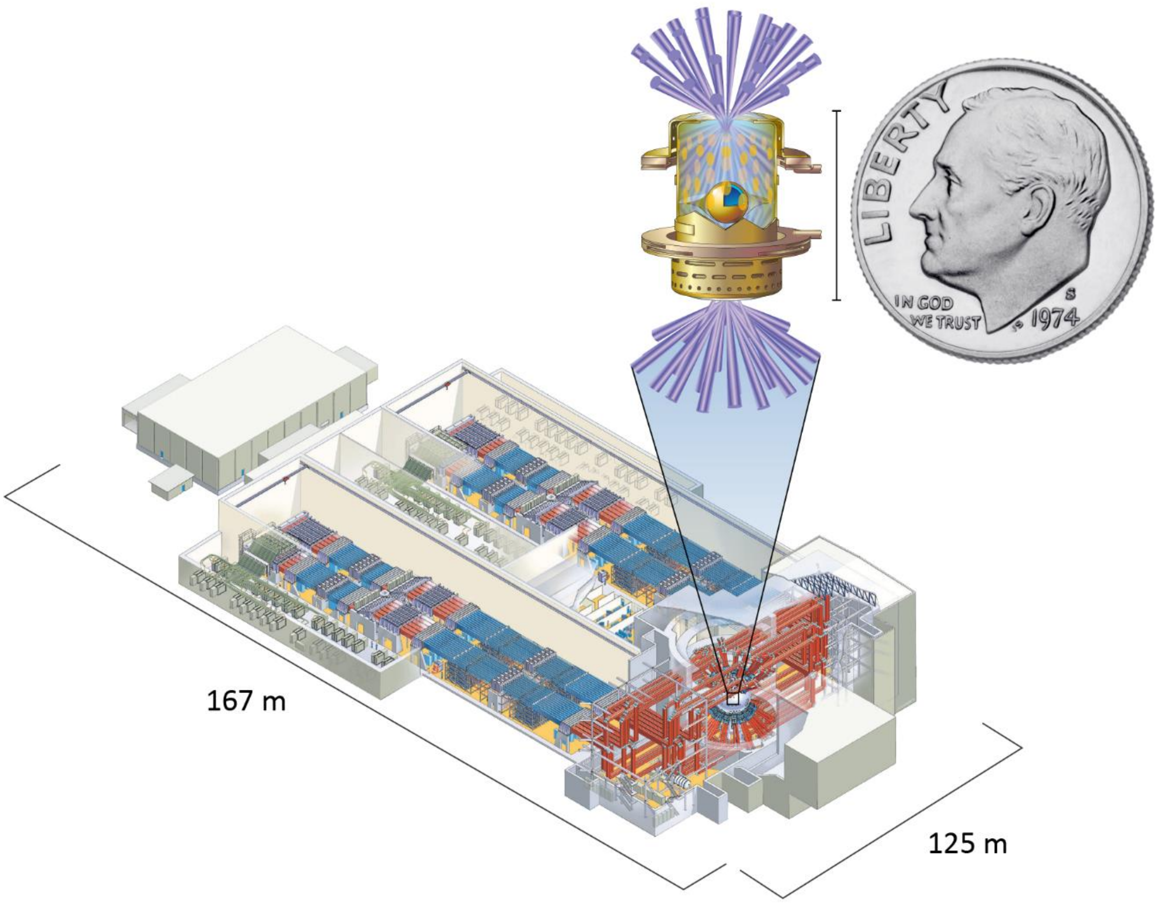
consumes, demonstrating a $Q_{Engineering}$ greater than 1. This means that fusion energy machines will require $Q_{Scientific}$ to be much greater than 1. For example, ITER is planning for a $Q_{Scientific}$ greater than 10. Figure 7 shows how $Q_{Engnieering}$ needs to improve significantly for inertial confinement fusion. Chapters 3 and 4 detail the challenges that need to be overcome to make fusion a competitive energy source.

2.4 Researchers and companies are pursuing many different concepts for fusion energy

There are many different proposed concepts to achieve fusion energy. Most either use magnetic fields to control the plasma– magnetic confinement– or use lasers or electrical discharges to compress the plasma – inertial confinement. Some approaches combine techniques. The two concepts that have set significant records for fusion energy are inertial confinement and tokamaks, a magnetic confinement approach. Other concepts are less advanced but are improving and have unique advantages. Below, we highlight a selection of concepts researchers and companies are pursuing.

Inertial confinement fusion

Figure 8: Inertial confinement fusion concept



Sources: Lawrence Livermore National Laboratory (facility and hohlraum), BillionPhotos.com/stock.adobe.com (dime). | GAO-23-105813

Accessible text for Figure 8: Inertial confinement fusion concept

Sources: Lawrence Livermore National Laboratory (facility and hohlraum), BillionPhotos.com/stock.adobe.com (dime). | GAO-23-105813

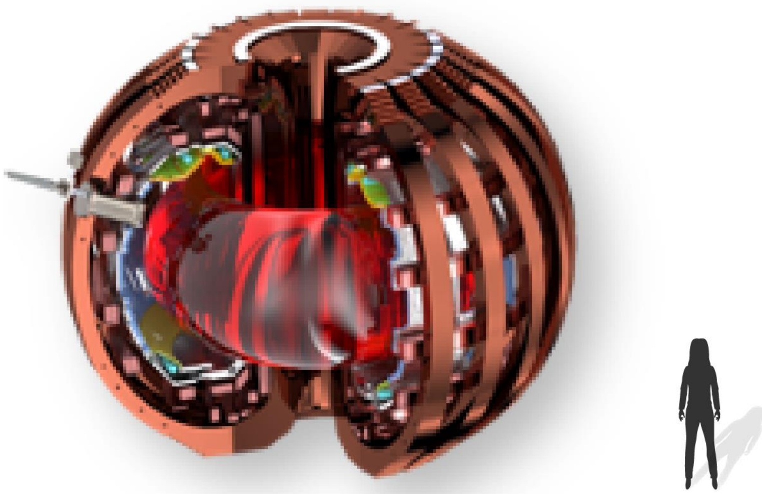
Inertial confinement fusion uses high-power lasers or electrical discharges to compress a small capsule of fusion fuel to extreme temperatures and pressures for a short time. Using high-power lasers NIF has reported a $Q_{Scientific}$ of 1.5, but inertial confinement needs to advance significantly before it could be an energy source. For example, it will need to dramatically increase how often it compresses fuel targets. A 2013 National Academies report said that an inertial confinement power plant would need to compress about 10 targets every second.[26] According to laboratory representatives, NIF was designed to conduct single experiments for the Stockpile Stewardship Program, and it compresses about 20 deuterium-tritium targets for inertial confinement fusion and thermonuclear burn research in a year. In addition to NIF, inertial confinement research is underway at Los Alamos National Laboratory, the Naval Research Laboratory, Sandia National Laboratories, and the Laboratory for Laser Energetics at the University of Rochester. Several private companies are also pursuing inertial fusion energy.

Tokamaks

A *tokamak* is a magnetic confinement concept, which confines the plasma in a donut shape, called a torus, for several seconds at a time using magnetic fields. While the $Q_{Scientific}$ record is only 0.67 for tokamaks, the supporting technologies are some of the most advanced for fusion. It is the design basis for many fusion energy projects; ITER and JET both use tokamaks, and a large fraction of U.S. fusion funding goes towards supporting tokamak-based fusion. A benefit of a tokamak is that it is simpler than other designs to simulate and build because it is geometrically symmetric. Several other facilities in the U.S. and internationally are working to understand how tokamaks behave, including General Atomics' DIII-D National Fusion Facility in San Diego, National Spherical Torus Experiment – Upgrade (NSTX-U) at the Princeton Plasma Physics Laboratory, JT-60SA in Japan, KSTAR in the Republic of Korea, EAST in China, and MAST Upgrade in the United Kingdom. Several private companies are also using this concept in their pursuit of fusion energy.

[26]National Academies of Sciences, Engineering, and Medicine, An Assessment of the *Prospects for Inertial Fusion Energy* (Washington, D.C.: The National Academies Press, 2013).

Figure 9: Tokamak fusion concept



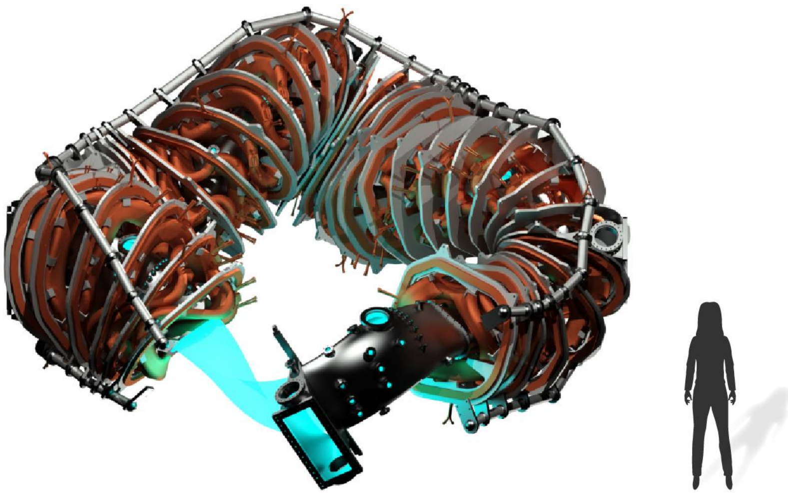
Sources: General Atomics (tokamak), GAO (silhouette). | GAO-23-105813

Accessible text for Figure 9: Tokamak fusion concept

Sources: General Atomics (tokamak), GAO (silhouette). | GAO-23-105813

Stellarators

Figure 10: Stellarator fusion concept



Sources: Helically Symmetric eXperiment, University of Wisconsin at Madison (stellarator), GAO (silhouette). | GAO-23-105813

Accessible text for Figure 10: Stellarator fusion concept

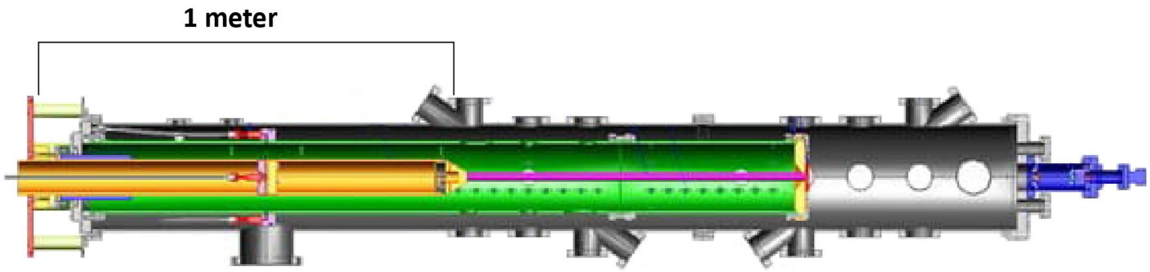
Sources: Helically Symmetric eXperiment, University of Wisconsin at Madison (stellarator), GAO (silhouette). | GAO-23-105813

Stellarators are another type of magnetic confinement fusion energy concept. While the plasma performance of stellarators to achieve fusion energy conditions is not as advanced as tokamaks,[27] they could avoid disruptions described in chapter 3. A stellarator contains the plasma using twisted magnets that are challenging to simulate and build. Major stellarator projects include the Wendelstein 7-X at the Max Planck Institute for Plasma Physics in Germany, the Large Helical Device in Japan, and the Helically Symmetric eXperiment at University of Wisconsin-Madison. Several companies are pursuing stellarator designs to achieve fusion energy.

[27]The plasma performance with respect to fusion energy conditions are often compared using the Lawson criterion, which incorporates a plasma's temperature, confinement time, and fuel density. The Lawson criterion for stellarator devices is about 1/10th of the value for tokamaks and about 1/100th of the value for inertial confinement fusion.

Z-pinch

Figure 11: Z-pinch fusion concept



Source: U. Shumlak, University of Washington. | GAO-23-105813

Accessible text for Figure 11: Z-pinch fusion concept

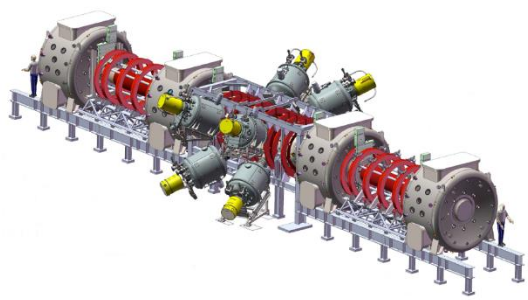
Source: U. Shumlak, University of Washington. | GAO-23-105813

The Z-pinch is a hybrid approach that uses an electrical current to magnetically confine and compress the plasma. It was an early design for fusion energy, with research starting in the 1950s; however, the performance of Z-pinch machines is significantly lower than tokamaks and inertial confinement fusion.[28] Z-pinch devices will need to improve significantly before they are commercially viable. The experimental design does not require external magnetic fields, resulting in a simpler design and potentially lower cost compared to other concepts. Early designs for Z-Pinch devices were susceptible to plasma instabilities that prevented the devices from achieving fusion energy. More recently, research has demonstrated ways to stabilize Z-pinch machines, renewing interest among academic, national laboratory, and industry researchers. Researchers at Lawrence Livermore National Laboratory, Sandia National Laboratories, and private companies are studying Z-pinch designs.

[28]Z-pinch Lawson criterion values are about a ten thousandth of the value for tokamaks.

Field reversed configuration

Figure 12: Field reversed configuration concept



Source: TAE Technologies. | GAO-23-105813

Accessible text for Figure 12: Field reversed configuration concept

Source: TAE Technologies. | GAO-23-105813

The field reversed configuration design is another magnetic confinement approach that uses a much simpler magnetic field compared to tokamaks to create a compact plasma torus whereby the plasma can contain itself using its own magnetic field rather than external magnets. The simpler design could make it easier to engineer and less expensive than tokamaks and could offer a potential solution that does not require deuterium-tritium. However, field reversed configuration devices are susceptible to many plasma instabilities, and the performance of such machines is lower than tokamaks and inertial confinement fusion.[29] Researchers have studied field reversed configuration devices since the 1950s. Several companies are pursuing this concept for fusion energy.

[29] Field reversed configuration Lawson criterion values are about 1/10,000th of the value for tokamaks.

3 Significant Scientific and Engineering Challenges Impede Fusion Energy Development

3.1 The behavior of burning plasmas needs to be better understood

Some aspects of plasma behavior are poorly understood, making it difficult to optimize plasma confinement and reliably drive fusion energy production. For example, turbulence is a highly complex behavior in which regions of a burning plasma move in ways that current methods cannot fully predict. Plasma turbulence is a multi-dimensional problem involving both the positions and velocities of large numbers of particles. In the last decade, more powerful computers have improved the accuracy of simulations, allowing scientists to adjust plasma confinement to compensate for turbulence. However, these models lack some experimental data needed to fully validate their performance, so they cannot yet predict how turbulence will affect the behavior and performance of plasmas with sufficient accuracy.

In addition, self-heating or “burning” plasmas could exhibit as-yet-unknown behaviors. So far, nearly all plasma research has been done on plasmas heated by an external source. As of March 2023 only one facility, NIF, has created a burning plasma.[30] Therefore, most scientific understanding of burning plasmas on earth is derived from simulations, and it is possible that burning plasmas in fusion energy devices will behave differently. For example, they may generate greater electromagnetic instabilities, which in turn may trigger equipment failure because of sudden, very high heat loads and other stresses on system components. Scientists need experimental data to study the behavior of burning plasmas further and enable the design of fusion energy systems.

3.2 Available materials cannot withstand fusion conditions for sustained operations

A key challenge for the development of fusion energy is that fusion energy systems, particularly components that are exposed directly to the plasma, will need to withstand extreme physical conditions for extended periods in order to generate commercial electricity. In a commercial fusion energy power plant, materials will need to last for months or longer to avoid frequent repair or replacement of components. However, when subjected to the stresses that fusion plasmas generate, materials currently available degrade or fail too quickly for commercial use. Without advances in materials, it will not be possible to build fusion energy systems that can reliably produce commercial electricity.

In order for fusion to occur, the plasma must reach a temperature of about 150 million Kelvin, about 10 times as hot as the sun. The plasma then transfers heat to the parts of the

[30] Prior to NIF’s demonstration of a burning plasma, JET and the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory studied the heating of plasmas by energetic particles released by fusion reactions.

fusion device that face the plasma. A key component is the *blanket*, which surrounds the plasma and must simultaneously harness heat energy, enable the creation of more tritium to fuel the device, and shield other device components from radiation.

In magnetic confinement devices, including tokamaks and stellarators, another critical component is the divertor, which removes heat and impurities from the plasma. In tokamaks like ITER, the divertor can experience extremely high bursts of heat that create significant thermal stress, causing even heat-tolerant materials to fail.[31] Using simulations and experimental data, researchers have developed methods to avoid such bursts, but these methods remain to be fully tested.

Another factor that will degrade fusion device materials is bombardment by the helium ions created by fusion. These particles can embed themselves within the material, changing its mechanical properties. For example, helium ion damage causes brittleness in tungsten, a candidate for plasma-facing components in fusion devices.

A third source of stress is high-energy neutrons, which can cause multiple types of damage to components. Neutrons can degrade the mechanical and thermal properties of materials, and change their physical properties. They can also transmute elements in components into new elements, which would reduce their structural soundness and even make them radioactive. Furthermore, damaging helium ions can more easily accumulate in components that have been irradiated with neutrons. The effect of neutrons cannot be entirely overcome, but they could be reduced through the use of specialized materials that are resistant to neutron damage and could transmute into short-lived or nonradioactive isotopes.

Some materials can withstand high heat, high neutron flux, or ion damage, but no existing material can simultaneously tolerate all three of these stresses at the levels and durations that would be needed for a commercially viable fusion energy system. Due largely to a lack of durable materials, experimental fusion devices are not designed to run for long periods, usually operating for a matter of seconds or minutes at a time. The National Academies has estimated that for a demonstration fusion energy plant to be considered successful, its materials, including those used in the plasma-facing components that will experience the greatest stresses, will need to last for around 1 year under fusion conditions. Scientists will therefore need to develop more advanced materials if fusion energy is to improve the economics of fusion energy.

However, developing new materials will be difficult because, as of March 2023, no facility exists where materials can be fully tested under fusion-relevant conditions. The Materials Research Facility at the United Kingdom's Culham Science Centre has equipment to test materials against stresses like those induced by fusion, including mechanical and ion damage, but no facility has a source of high-energy neutrons like

[31]The continuous heat flux experienced by the divertor is as high as 20 MW/m^2, with bursts up to 1 GW/m^2.

those produced by fusion. Efforts are in the planning stage to build such facilities in some countries. For example, the International Fusion Materials Irradiation Facility (IFMIF) is currently under development through a collaboration between the European Union and Japan. IFMIF will allow the study of fusion neutron damage when it is completed. However, stakeholders have said that the need for a Fusion-Prototypic Neutron Source (FPNS) that produces neutrons similar to those from a fusion energy system is urgent. Stakeholders have also called for facilities that would allow the evaluation of materials under the full range of stresses that fusion energy will impose. Stakeholders and experts said that materials testing facilities would benefit a wide range of fusion energy stakeholders; but they are expensive and time-consuming to build. Stakeholders said that such facilities are unlikely to provide a high enough return on investment for the private sector to fund their construction. In addition, personnel at one national laboratory said that it would take at least 6 years to build an FPNS and another 6 years to get useful data from it, and that the wait would be too long to make it an attractive investment for the private sector.

3.3 Harnessing fusion energy poses complex systems engineering challenges

Fusion energy will require complex systems engineering to efficiently extract energy from the fusion reaction and provide an economical source of electric power. The complexity of fusion systems means that solving one challenge may reveal another. Examples of the complex challenges of engineering a fusion energy system include:

- **Extracting fusion byproducts from the plasma.** These byproducts can reduce the efficiency of fusion, but so can removing them because it would also mean removing some of the heat energy that promotes the reaction.
- **Creating plasma-facing systems that are easily maintained and replaced.** Plasma-facing systems will be very complex because they will need to perform multiple functions at the same time, including harnessing heat to generate electricity, shielding the outer parts of the plant from heat and radiation, and enabling the creation of more tritium. They will also need remote maintenance systems, because radioactivity will make it unsafe for human technicians to work with them directly. These systems will need to be robust enough to allow maintenance of complex components without damaging them. They will also need ports to access the components, but these must be placed so they do not weaken the device or interfere with operation.
- **Managing extremes of both heat and cold.** Fusion energy systems have components that need to operate at both temperature extremes. ITER, for example, requires insulating its superconducting magnets with both thermal insulating material and a vacuum, and cooling them to cryogenic temperatures, while simultaneously making the plasma hotter than the sun. Experimental fusion devices have successfully operated superconducting magnets at cryogenic temperatures, but engineering cryogenic systems for a largescale fusion energy device introduces challenges.

3.4 Using tritium fuel raises supply, safety, and security concerns

The use of tritium, a radioactive isotope of hydrogen, as fuel raises many concerns for fusion energy.[32] One is that the global supply of tritium is far too limited to meet the needs of commercial fusion energy plants. The only appreciable source is from fission in certain nuclear power plants, many of which are expected to retire in the coming decades. Meanwhile, tritium cannot be effectively stored because it decays quickly, with a half-life of around 12 years. The global available inventory is predicted to peak in 2027 at about 27 kilograms (about 60 pounds), of which ITER experiments could consume the majority. Further, a fusion energy system that produces 1GW of power could consume about 56 kg of tritium per year.

Fusion energy systems may be able to produce—or *breed* —their own tritium by bombarding lithium with high-energy neutrons. While this ability to breed its own tritium fuel is key to many fusion energy system concepts, some estimates suggest that fusion energy systems may not be able to breed enough tritium to fully provide for their ongoing fuel needs. Many fusion energy system designs include a component called the *breeding blanket*, which incorporates lithium to create tritium. However, as of March 2023, there has been no large-scale demonstration of a tritium breeding blanket. Though researchers have demonstrated that lithium can release tritium and have tested materials against neutron damage, demonstrating tritium breeding at a scale relevant to commercial fusion energy would require testing in ITER or a pilot fusion energy plant.

Tritium can also pose health risks and raise proliferation concerns. For example, ingesting water that contains tritium may lead to health effects, such as an increase in cancer risk. The U.S. Environmental Protection Agency has a maximum allowable level of exposure of radiation in drinking water from tritium. In addition, tritium is used in nuclear weapons, so deliberate production could be considered sensitive from a nuclear weapon proliferation standpoint in certain circumstances. To address these concerns, fusion energy plants will need systems to account for their tritium inventories. However, containing and accounting for tritium is challenging because, as a light element, tritium can permeate many materials, becoming embedded in the plasma-facing components of a fusion energy system or escaping into the environment. Therefore, fusion energy systems will also require complex equipment for handling tritium, as well as procedures for managing the radioactive waste from materials embedded with tritium.

[32]These concerns will not apply to fusion energy systems that do not use tritium. See section 1.2 for information on potential alternative fuel types.

4 Public and Private Alignment of Efforts, Regulatory Uncertainty, and Other Factors Affect Fusion Energy Development

4.1 Public and private efforts are not fully aligned

The fusion energy programs, missions, and organizational structures of the public and private sectors are not fully aligned. Coordination between the public and private sectors is key to accelerating the development of fusion energy. However, stakeholders and experts identified a number of areas, including research priorities, risk tolerance, and time frames, where each sector could align efforts to complement the other.

Public sector efforts prioritize basic science, but fusion energy development requires an additional emphasis on technology and engineering research. In the 1990s, DOE restructured the U.S. fusion program, shifting its mission to focus on plasma science research and away from technology and engineering. Stakeholders told us that this shift has caused the U.S. to fall behind in areas such as heat-resistant materials and breeding blanket development research. DOE has established relatively small public-private partnership programs in recent years to support this research. For example, in 2019, DOE put forth the Innovation Network for Fusion Energy (INFUSE) initiative to support research in enabling technologies, such as materials science and modeling and simulation.[33] Stakeholders said these programs are highly effective and recommended that they be expanded, as they account for a small portion of the nearly $1.6 billion in DOE funding for fusion research in FY 2022 (see ch.1.4).

Because of this historical focus on enabling science rather than technology and engineering, experts said that the U.S. fusion program is not well organized to support the commercialization of fusion energy, including the transfer of newly developed technology to commercial use. One expert contrasted the science-focused mission of DOE's Fusion Energy Sciences program to that of DOE's Office of Nuclear Energy, which has an energy-focused mission and is organized to support the research, development, and transfer of new technologies to industry. For example, the Office of Nuclear Energy is planning to develop an advanced nuclear fission test reactor to address research and development gaps, such as testing materials, fuels, and instrumentation, that stand on the path to commercialization. In addition, according to experts, the public sector's focus on basic science limits federal funding for fusion energy development because research programs with science missions generally have lower funding than energy programs.

[33] Typical INFUSE awards are for up to $250,000 for 1 year, but INFUSE may grant 2 year awards of up to $500,000. In September 2022, DOE announced up to $50 million to launch another public private partnership program to help recipients meet major technical and commercialization milestones toward the successful design of a fusion pilot plant.

Another difference in alignment between the public and private sectors is their different attitudes toward risk. Industry representatives said that government should commit resources to support multiple technological approaches. However, some private companies' concepts for fusion energy systems may have a high risk of failing. Public sector stakeholders said that supporting high-risk efforts may not be a good use of public funds and could divert resources from more productive lines of research and development. Some national lab personnel said that they would like to see more transparency and accountability from private companies seeking access to national lab facilities and expertise. These personnel noted that some private companies seeking help from national labs have not produced peer-reviewed publications or credible design documentation.

The public and private sectors also work on different timelines. Private sector investors expect returns on their investments, typically within about 20 years, according to fusion industry stakeholders. Therefore, private companies must demonstrate progress toward intermediate goals or milestones quickly to satisfy investors. However, industry stakeholders said that processes required to work with the public sector make it challenging for them to work as quickly as they want to. For example, one industry stakeholder said that it can take a long time for them to gain access to government funding when they receive awards. Furthermore, negotiating cooperative research and development agreements (CRADAs) between private companies and national labs is time intensive, with some companies reporting it taking over a year. According to stakeholders and experts, this process should be much quicker because these agreements are usually similar to one another.

4.2 Regulatory uncertainty could slow development, but developing regulations for fusion energy is complex

Lack of regulatory clarity could add time and cost to fusion energy development and commercialization, according to stakeholders, but developing regulations tailored to fusion energy poses complex challenges. A regulatory process that minimizes unnecessary regulatory burden is critical to the timely development of a cost-effective fusion pilot plant.[34] At the same time, regulations must be sufficient to protect the public and reassure them it that it is safe to accept the development of fusion energy projects in their communities.

NRC is still in the process of developing the regulatory framework for fusion energy plants. States participating in NRC's Agreement State Program regulate some fusion facilities, such as fusion test facilities, as materials facilities. NRC is also considering regulating fusion energy plants under a utilization facility approach (see ch.1), which could impose requirements that are considered appropriate for fission reactors but may not be needed for fusion, such as

[34] National Academies of Sciences, Engineering, and Medicine, *Bringing Fusion to the U.S. Grid,* National Academies Press (Washington, D.C.: 2021), p.43.

those related to financial protection or mandatory hearings.

Imposing legislative and regulatory burdens on fusion that are similar to those for fission might slow or prevent the development of fusion energy plants. For example, experts said that similar excessive requirements from the French nuclear regulatory body were responsible for most of the delays and cost increases that ITER has experienced. Experts also said that the risks of fusion and fission are very different, and that fusion would not be cost competitive if subjected to the same regulations as fission.

However, while fusion is likely safer than fission, some stakeholders have argued that commercial fusion energy plants will pose greater risks than the technologies for which 10 C.F.R Part 30 was developed, and that fusion energy plants should therefore be regulated under a stricter framework. One nuclear safety stakeholder told us that the amount of tritium that may be kept on site at certain fusion energy facilities could cause serious harm to workers and surrounding communities if released. Another nuclear safety stakeholder told us that fusion regulations should include siting criteria, emergency planning, financial assurance, and environmental impact assessment, similar to requirements for fission energy.

NRC officials recognized these issues, stating that the most critical regulatory challenge for fusion energy is ensuring regulations are adequate to protect human safety without constraining technology development. These officials added that their goal is to right size the regulations as much as possible and to provide flexibility for different technological approaches and levels of risk. In addition to the materials facility and utilization facility approaches, NRC is also considering a hybrid approach to regulate different fusion energy systems based on their potential hazards.

The length of time required for NRC to develop a regulatory framework for fusion may pose a challenge for fusion energy development by creating uncertainty for private investors. One expert said that clear regulation appropriate for the benefits and risks of fusion could be significant for improving cost competitiveness, speed to market, and the cost of capital. Meanwhile, stakeholders said that the lack of regulatory certainty could be inhibiting investment and slowing the development of fusion energy, and could lead companies to choose sites in countries with greater regulatory certainty for their pilot plants. Another expert said that some private investors may not step up unless there is more certainty in the legal and regulatory processes.

However, achieving regulatory certainty without enough public engagement could impede fusion development in the long term. Experts said that if the public is not involved early in the regulatory process it will cause delays later on, and that public education and buy-in about fusion are critical to its success. NRC held public meetings with fusion stakeholders to inform NRC’s January 2023 paper on options for licensing and regulating fusion energy systems. However, experts stated that the stakeholders attending these forums may not be representative of the broader population.

4.3 Little is known about public perception of fusion energy

Public perception of fusion energy could affect its development and adoption. For example, if the public is enthusiastic about fusion energy, it may support devoting additional resources to research and development and welcome fusion facilities in communities. Conversely, if the public is skeptical, it may raise barriers to government investment in fusion research or the construction of fusion facilities. Understanding public perceptions of fusion is critical to its development, according to stakeholders.

However, few studies have assessed public opinion of fusion energy, particularly in the U.S. To begin to address this gap, we held three focus groups with members of the public regarding fusion energy. Participants across the three groups offered reactions and raised questions and concerns in the following areas:

Safety

Multiple participants said that safety was an important concern. Participants said that they would want sufficient regulatory oversight before they would be comfortable with fusion energy plants in their communities. One participant said they may not want to live near a fusion energy plant if it were radioactive, while others said that their safety concerns were not specific to fusion energy plants, adding that they would have concerns about living next to a coal-burning power plant as well. One participant said that the first fusion energy plants should be built in deserts or other areas away from where people live, to allow time for the full spectrum of risks to become known.

Environmental impact

Multiple participants said that the lack of direct carbon emissions was an appealing quality of fusion energy. One said that all decisions regarding energy in the U.S. should be guided by limiting environmental impact. Another noted, though, that fusion energy development may take decades, and that it might be more productive to invest in technologies that could solve climate issues in the nearer term.

Cost

Multiple participants asked about the cost of fusion energy, including how much money would be needed to develop it. Participants asked whether the government or the private sector would be primarily responsible for financing fusion energy. One said that tax dollars should not go to fusion energy until a net benefit is proven on a small scale.

Impact on daily life

Participants asked how a fusion energy plant might affect daily life in their communities. Some noted that fusion energy could benefit them by bringing jobs and other economic opportunities. One said that they would oppose the construction of any power plant that would affect the aesthetics of their community, noting, for example, that certain industrial features would be unattractive.[35] One participant raised other community effects, like traffic congestion, as a potential negative impact of fusion energy on daily life.

Public engagement

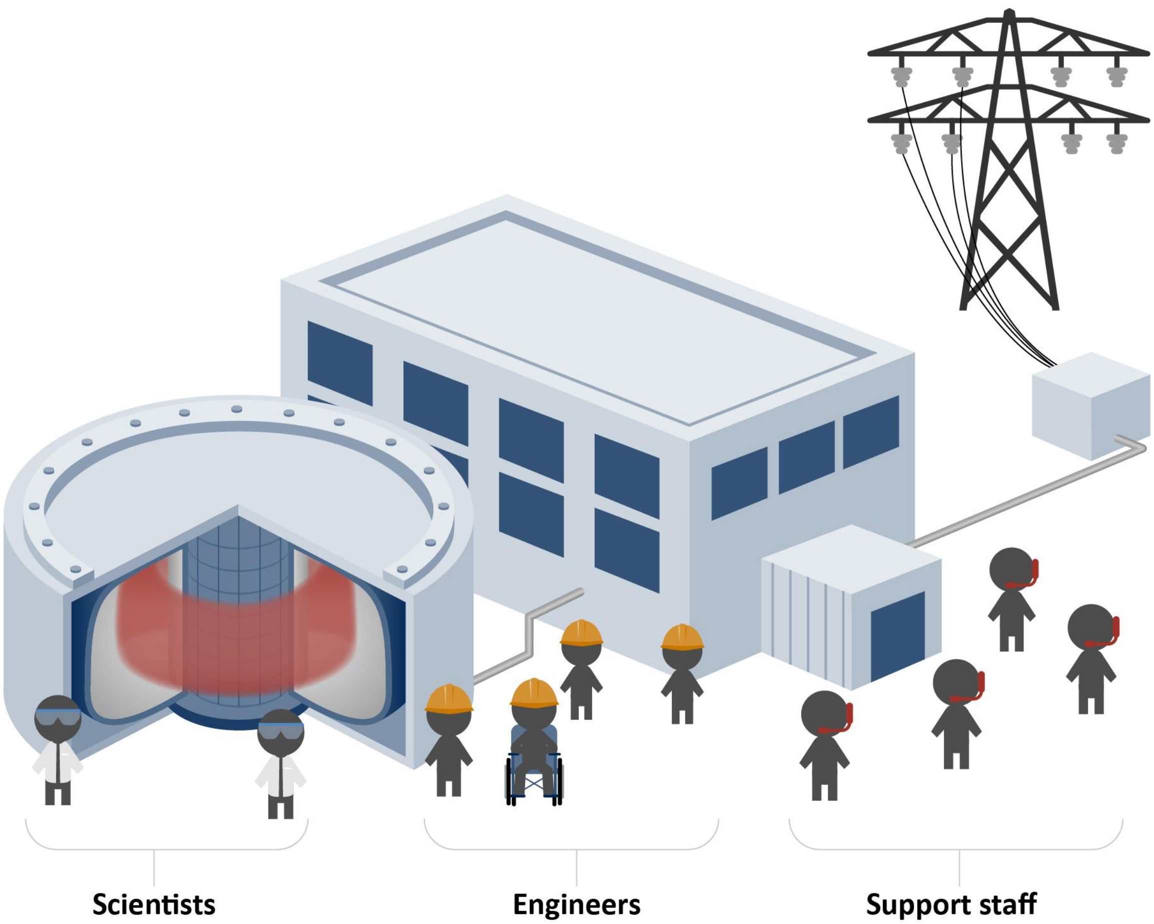
Multiple participants said that they would want government and industry to engage with communities where fusion energy facilities might be sited. They said they would want to receive information regarding the benefits and potential risks of fusion energy in an open and transparent manner, and that they would expect government and industry to listen to their concerns and take them seriously. Some participants expressed concern that fusion energy, like other energy technologies, might have disproportionate negative impacts on disadvantaged communities.

4.4 Fusion energy development relies on a limited workforce and limited suppliers

The lack of a sufficient fusion workforce, which would include professionals in many areas of expertise, may hinder the development of fusion energy. A shortage of fusion scientists, nuclear engineers, and electrical engineers has reportedly made it difficult to meet timelines and has resulted in fusion developers needing to recruit from other countries that are producing more qualified professionals in these fields. Experts said that the U.S. does not produce enough graduates in fusion-related physics and engineering disciplines and that many existing fusion researchers have or will soon retire. Training engineers, advanced technicians, and physicists takes many years, and funding and training opportunities are limited. Most research programs for masters and PhD candidates in magnetic confinement fusion are connected to federal funding, and a reduction in government funding to universities a decade ago resulted in significantly fewer positions available at universities for fusion energy research. Stakeholders said that emphasizing diversity, equity, and inclusion in education and hiring could help expand the pool of available talent and bring new ideas and perspectives into the field.

[35]Participants said that aspects like smokestacks are unattractive. Fusion power plants will not have smokestacks but will likely have cooling towers, which may be confused with smokestacks.

Figure 13: Fusion energy plant showing interdisciplinary workforce



Source: GAO analysis. | GAO-23-105813

Accessible text for Figure 13: Fusion energy plant showing interdisciplinary workforce
Illustration of Fusion Energy facility staff.
Source: GAO analysis. | GAO-23-105813

A related challenge to the development of fusion energy is that specialized components are produced by few suppliers and sometimes by a single vendor. For example, stakeholders stated that only one or two companies in the world make certain commercially available diagnostic systems needed for fusion energy systems. The producer of a critical component for ITER stated that they only created one spare, and that the suppliers for the necessary parts to produce another component are no longer in business. One stakeholder stated that it is not possible to obtain some components in the quantities needed for a fully developed device.

Limitations in the supply chain could prevent the ability to build fusion energy systems at scale. For example, stakeholders said accumulating the needed supply of power electronics, such as semiconductors, may be unattainable due to their use in other industries. Further, stakeholders said that raw materials such as rare earths and helium are also in limited supply.

4.5 The path to commercialization is uncertain

Various factors make the economic viability of commercial fusion power plants uncertain. The costs of commercial fusion energy power are unknown, making cost estimates likely unreliable. Fusion energy could have some cost advantages, such as potentially inexpensive fuel. However, other costs, such as capital costs and maintenance and operations, will be determined by many of the factors previously discussed in this report. For example, fusion energy will likely not be economically viable without significant advancements in materials for components susceptible to damage from plasma, as materials affect the amount of time a plant can produce energy and generate revenue. Maintenance costs and run time may also be impacted by complex engineering challenges, such as how the system is designed for ease of maintenance or reliability. National lab representatives told us that they do not trust the accuracy of estimated costs for fusion energy until there is more information on the materials and maintenance routines proposed for a fusion power plant. Regulations could also impact costs, such as by increasing timelines and costs of capital, but regulatory decisions may depend on how fusion energy develops and whether new risks emerge or existing risks, such as tritium handling, are mitigated.

Fusion energy, if it becomes viable, will face competition with other developing energy technologies. We have reported on many emerging technologies that could modernize and diversify the electrical grid while reducing carbon emissions. These technologies include carbon capture, renewable energy sources, energy storage, and advanced nuclear fission reactors.[36] Fusion, similar to fission, will likely operate as a steady supply to meet continuous energy demands, known as baseload. However, the future development and adoption of other energy technologies may alter the energy landscape, including the need for baseload energy sources. See the text box for more information on how different energy sources work together.

[36]Selected GAO reports on emerging energy technologies include GAO *Technology Assessment Decarbonization: Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage,* GAO-22-105274 (Washington, D.C.: Sept. 29, 2022); *Science and Tech Spotlight: Alternative Materials for Solar Cells,* GAO-22-105378 (Washington, D.C.: Nov. 4, 2021); *Technology Assessment: Nuclear Reactors: Status and Challenges in Development and Deployment of New Commercial Concepts,* GAO-15-652 (Washington, D.C.: July 28, 2015); *Science and Tech Spotlight: Advanced Batteries,* GAO-23-106332 (Washington, D.C.: Dec. 8, 2022); *Science & Technology; Tech Spotlight: Renewable Ocean Energy,* GAO-21-533SP (Washington, D.C.: June 9, 2021); *Science & Technology; Tech Spotlight: Nuclear Microreactors,* GAO-20-380SP (Washington, D.C.: Feb. 26, 2020)).

Electrical grid energy generation capacity needs

The electrical grid addresses various energy demands using different energy generating capacity types such as baseload, intermediate load, and peak load:

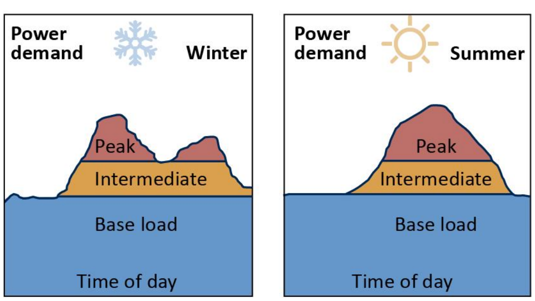
- Baseload generating units operate continuously at an essentially constant rate and are designed to maximize system mechanical and thermal efficiency while minimizing operating costs. Nuclear fission and some hydropower, gas, and coal power plants are examples of baseload units.
- Intermediate load generating units are responsive to changing energy needs and can adjust operation between base load and peak service as needed to support baseload generating units. Natural gas is often the fuel for intermediate energy, but solar and wind power can also function as intermediate energy sources.
- Peak load generating units are able to turn on quickly to meet electricity demands at their highest, and although peak energy generators are often more inefficient and costly to operate than baseload and intermediate generators, they are able to quickly provide energy in a high demand period. Natural gas and petroleum fueled generators are examples of peaking units.

Figure 14 shows how baseload, intermediate, and peak load generating units can address energy demands throughout the day.

It is important to have a diverse set of energy generation sources to meet both baseload and peak demand, and to ensure the electrical grid is resilient to disruptions. Fusion energy will need to work with many other energy sources and be economically competitive.

Source:. | GAO-22-105813.

Figure 14: Schematic showing how energy generating units address power demands



Source: M. Fedkin, The Pennsylvania State University. | GAO-23-105813

Accessible text for Figure 14: Schematic showing how energy generating units address power demands

Source: M. Fedkin, The Pennsylvania State University. | GAO-23-105813

Fusion energy may need to be cost-competitive on a life-cycle basis with these other energy technologies. The future costs of energy from these sources are difficult to predict and will be affected by economic conditions as well as state and federal policies. One stakeholder suggested that it could be more difficult to integrate fusion energy into a grid if renewable energy sources are meeting most of that grid's energy needs because fusion energy would be most profitable when it operates 100 percent of the time. However, at least one study noted that baseload nuclear may work well with grids using highly intermittent renewable sources, and another suggested fusion may not need to operate 100 percent of the time as baseload power to be economical. Time to market could also affect fusion's competitiveness, and a delayed timeline could diminish opportunities for fusion to enter the marketplace.[37] However, private investors have expressed confidence in fusion energy's potential to compete in the energy market, as evidenced by their recent increase in funding for fusion projects.

[37]National Academies of Sciences, Engineering, and Medicine, *Bringing Fusion to the U.S. Grid,* p.93.

5 Policy Options to Help Enhance Benefits or Address Challenges to the Development or Use of Fusion Energy

We developed policy options that policymakers—legislative bodies, government agencies, academia, industry, and other groups—could consider taking to help enhance the benefits of fusion energy or address challenges to the development or use of fusion energy. This is not an exhaustive list of policy options. We intend for these options to provide policymakers with a broader base of information for decision-making.

5.1 Policymakers could maintain status quo efforts

If policymakers do not find the prospects of fusion energy particularly compelling, or if they find other technologies more suitable to their energy goals, they could choose not to take any new actions to support the development of fusion technology. The following table provides further detail on this policy option.

Table 1: Policy Option: Status Quo

Implementation approach	Opportunities	Considerations
• Sustain current efforts until key near-term milestones for commercial fusion are achieved before taking additional action.	• Some challenges described in this report may be addressed by current efforts. For example, NIF's recent $Q_{Scientific}$ results are promising, suggesting some fundamental challenges might be overcome. • Could allow policymakers to observe and evaluate the impact of existing efforts, which could limit their risk and save money.	• Current efforts may not address all challenges described in this report. Current efforts alone may delay or inhibit the development of fusion energy, which could result in forgone benefits or negative impacts, such as to the environment. • Some challenges, such as materials research or workforce development, can take many years to address.

Source: GAO. | GAO-23-105813.

5.2 Policymakers could align public and private sector efforts to accelerate development of fusion energy

As section 4.1 describes, misalignments between the public and private sectors could result in missed opportunities to develop commercial fusion energy. In particular, federal efforts focus more on basic science and less on energy research than industry would need to bring fusion energy to the grid. Policymakers wishing to accelerate development of fusion energy could attempt to align public and private efforts. The following table provides illustrative approaches for implementing this option, along with opportunities the option may present and factors to consider.

Table 2: Policy Option: Align Public and Private Sector Efforts

Implementation approach	Opportunities	Considerations
• Align existing programs, missions, and organizational structures with fusion energy development goals. • Expand use of public private partnerships that focus on accelerating fusion energy development. For example, the INFUSE program is a public-private partnership for research focused on innovation in critical areas such as materials science and modeling and simulation. • Increase use of funding mechanisms that provide greater predictability for recipients and accountability for funders. For example, milestone-based programs reimburse funding upon reaching performance targets. • Reduce barriers to collaboration, for example by using standardized Cooperative Research and Development Agreements (CRADAs). • Leverage international coordination by, for example, increasing the use of facilities that are unavailable in the U.S.	• Could accelerate the demonstration and commercialization of fusion energy by enhancing research on the materials, technology, and engineering needs of fusion energy. • Leverage strengths across sectors and expand programs that, according to stakeholders, are underused and have been effective in advancing fusion energy development. • Could provide predictability and flexibility to funding recipients, while ensuring performance and accountability for the funder. • Standardized research and development agreements could accelerate research, encourage knowledge sharing between organizations, and reduce time intensive negotiation. • Improved knowledge sharing with other countries could help accelerate fusion energy research and workforce development. For example, a fusion developer recommended bringing staff from the U.S. to ITER to learn how to develop and operate a fusion plant on the ground so they could bring that knowledge back to the U.S. to support future fusion power plants.	• Aligning public and private sector efforts can be time intensive and may require additional resources or legislative action, according to experts. • To achieve fusion energy development timeline goals, policymakers may need to pursue parallel efforts and take more risks, which could incur greater costs. • Could require additional resources or reallocation of existing resources from other programs. • Reimbursement-based funding can be challenging for recipients, especially if reimbursement processes are slow. • Some research results may be proprietary, inhibiting knowledge sharing or coordination across organizations and countries.

Source: GAO. | GAO-23-105813.

5.3 Policymakers could build shared assets for fusion energy development

Given the many technical challenges to fusion energy (ch. 3) and the limited workforce and suppliers available to the industry (section 4.4), policymakers could choose to promote fusion energy development by enhancing shared assets for use by the research community, such as research facilities and training programs. The following table provides illustrative approaches to implementation, opportunities this policy option may present, and factors to consider.

Table 3: Policy Option: Build Shared Assets

Implementation approach	Opportunities	Considerations
• Support facilities to address shared needs of the fusion development community's scientific and engineering challenges, such as advanced materials and tritium management. • Support workforce development to address labor shortages specific to fusion energy. This approach could include supporting multidisciplinary education and training programs at universities and technical colleges. • Assess sources of critical supplies and manufacturing capabilities that will be needed to demonstrate and commercialize fusion energy, along with options to fill any gaps.	• Could help fill critical research gaps on the path to fusion energy commercialization. • Could help ensure fusion energy development is not limited by critical workforce or supply shortages.	• Test facilities require significant investment, and years to build and commission. For example, a study prepared for DOE in 2019 estimated that a fusion prototypic neutron source to test materials in a fusion environment could cost about \$470 million to \$1.18 billion and take 5-7 years to build and commission. • Workforce development takes significant time and resources. For example, one expert told us that it can take 8 years to train engineers and advanced technicians in the fields needed for fusion energy. National lab representatives also said that long-term funding is needed for education and training. • Stakeholders may disagree on the best options to support community assets that are technology inclusive. Some stakeholders recommended focusing efforts on the most promising approaches, while others warned that picking a winner too early could crowd out other approaches that may be better options in the long term.

Source: GAO. | GAO-23-105813.

5.4 Policymakers could engage the public in decision-making

Little is known about the U.S. public's perception of fusion energy (section 4.3), and it will be complex to craft a regulatory framework that allows the industry to develop while protecting the public (section 4.2). Policymakers could therefore choose to engage the public in decision-making about the appropriate level of government support and the appropriate regulations, among other things. The following table provides illustrative approaches to implementation, opportunities this policy option may present, and factors to consider.

Table 4: Policy Option: Engage the Public in Decision-Making

Implementation approach	Opportunities	Considerations
• Study public opinion, for example through surveys and focus groups, or host events to understand the public's questions and perspectives on the benefits and risks of fusion energy. • Engage and educate the public through cross-sectoral forums to ensure balance, transparency, and inclusivity. • Include affected communities in making decisions around siting, construction, design, and operations.	• Help inform policy decisions, such as those related to regulation of and investment in fusion energy. • Help ensure community stakeholders' views are represented so that decisions do not negatively impact issues of public concern, such as traffic or the environment. • Help ensure that benefits, such as economic development, are shared broadly and inclusively with affected communities. • Alignment between communities and fusion developers could reduce barriers to their success.	• Engagement should be proactive, transparent, and should set realistic expectations for benefits, risks, and timelines. • It may be difficult to ensure broad participation and representation. • Engagement should be used to learn about the public's perspectives about fusion energy rather than to persuade the public to support fusion.

Source: GAO. | GAO-23-105813.

6 Agency and expert comments

We provided a draft of this report to the Department of Energy and the Nuclear Regulatory Commission with a request for technical comments, and incorporated agency comments into this report as appropriate.

We provided our draft report to the experts for their technical review, consistent with previous technology assessment methodologies.

We are sending copies of this report to the appropriate congressional committees, relevant federal agencies, and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff have any questions about this report, please contact me at 202-512-6888 or BothwellB@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made contributions to this report are listed in Appendix III.

Brian Bothwell
Director
Science, Technology Assessment,
and Analytics

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The Honorable John Barrasso
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The Honorable Dianne Feinstein
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The Honorable Lori Trahan
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The Honorable David Trone
House of Representatives

Appendix I: Objectives, scope, and methodology

We prepared this report under the authority of the Comptroller General to assist Congress with its oversight responsibilities, in light of broad congressional interest and the potential high value of fusion energy. We examined (1) the status of fusion energy technology, and the potential benefits and limitations of fusion energy; (2) challenges that might affect the development or use of fusion energy; and (3) policy options that may help enhance the benefits or mitigate challenges associated with fusion energy development and adoption.

To conduct our work, for all objectives, we:

- Interviewed officials from the Department of Energy and the Nuclear Regulatory Commission. We also interviewed a nongeneralizable set of stakeholders from academia, industry, national laboratories, international fusion organizations, professional organizations, and nonprofits. We identified and selected interviewees with expertise in fusion energy or expertise in economic, social and legal factors for fusion energy, using a review of relevant documents and recommendations by those we interviewed over the course of our work.
- Visited three companies, two national laboratories, and an academic institution to observe their fusion energy experiments and learn about the status of their research.
- Attended the American Nuclear Society annual conference in Anaheim, CA, from June 13-16, 2022, on emerging topics in nuclear science, including fusion energy.
- Reviewed agency documents, peer-reviewed literature, and other literature, such as white papers and industry reports. We identified literature based on online searches and at the recommendation of agency officials, experts, and other stakeholders. We also conducted a literature search on public perception of fusion energy in the U.S. A GAO librarian searched databases using keywords such as fusion energy and public perception, awareness, or opinion to identify relevant articles that were published in the U.S. from 2019-2022.
- Conducted a virtual 3-day meeting of 21 experts, convened with the assistance of the National Academies of Sciences, Engineering, and Medicine. We selected experts based on their expertise on fusion energy, understanding of the electrical grid, and knowledge of social, legal, and economic challenges with fusion energy. Experts included representatives from government agencies, national laboratories, professional and international fusion organizations, industry, and academia. We also worked to ensure the experts represented a balanced perspective of the status, benefits, limitations, challenges, and policy options related to fusion energy. Experts provided documentation of any potential conflicts of interest, and, upon review, we found the group of experts, as a whole, did not have any inappropriate bias. This meeting of experts was planned and convened with assistance from the National Academies of Sciences, Engineering, and Medicine to better ensure that a breadth of expertise was brought to bear in its preparation. However, all final decisions regarding

meeting substance and expert participation are the responsibility of and were made by GAO. Consistent with our quality assurance framework, we offered our meeting experts the opportunity to review and provide technical comments on a draft of our report, which we incorporated as appropriate. We received comments from 15 of the 21 experts. We incorporated expert comments into the report, as appropriate.

- For objective two, in addition to the steps above, we conducted three virtual focus groups of four participants each to obtain nongeneralizable qualitative insight into how the U.S. public views fusion energy and questions the public may have about fusion energy. We conducted these focus groups because interviews and the literature indicated a lack of information about public perception of fusion energy, which may affect fusion energy development and adoption. Focus group participants were selected to reflect a diverse range of perspectives, identities, and backgrounds in the U.S. Characteristics we used to achieve a range of perspectives included gender, geography, race and ethnicity, education, and income level. We piloted the focus group protocol with a group of four current and former GAO employees and interns who were not part of the engagement team and did not have advance knowledge of the focus group topic before the pilot session. Based on the findings from this pilot, we made modifications to the protocol to improve the focus group sessions. For example, we simplified our description of fusion energy and provided more time for questions from participants. We reviewed focus group transcripts to identify themes and key findings.
- For objective three, we identified policy ideas or options that appeared in the literature, or that we heard about or discussed in interviews, our expert meeting, or focus groups. We synthesized and analyzed this information to develop policy options, including the status quo, that could address challenges or enhance the benefits of fusion energy. The policy options are not intended to be inclusive of all potential policy options.

We conducted our work from February 2022 to March 2023 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: Expert participation

We collaborated with the National Academies of Science, Engineering, and Medicine to convene a meeting of experts over 3 days to inform our work on this technology assessment. The meeting was held virtually from September 20-22, 2022. Experts who participated in this meeting are listed below. We corresponded with experts for additional assistance throughout our work, and provided our draft report to the experts for their technical review, consistent with previous technology assessment methodologies.

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