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ITER—An International Nuclear Fusion Research and Development Facility

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ITER—An International Nuclear Fusion Research and Development Facility

SUMMARY

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Todd Kuiken, Coordinator
Analyst in Science and Technology Policy

Mark Holt
Specialist in Energy Policy

Martin C. Offutt
Analyst in Energy Policy

ITER, previously referred to as the International Thermonuclear Experimental Reactor, is a multibillion-dollar collaboration of the European Union (host), China, India, Japan, Russia, South Korea, and the United States. The key goal of the consortium is to operate ITER at or near the ignition point of burning plasma, a critical step toward self-sustaining nuclear fusion. ITER's planned capabilities also include extensive instrumentation for advancing the scientific understanding of plasmas (the fourth state of matter), as well as opportunities for testing specialized materials for use in fusion applications. ITER is primarily an exploratory science initiative and is not designed or intended to produce electricity. However, ITER is designed to help develop the technology for a future fusion demonstration power plant.

ITER has experienced multiple schedule delays and cost increases. Initial projections suggested that ITER construction would be completed in 2016, with the first experiments beginning in 2020, at a total cost of $10 billion (adjusted for inflation). In 2016, the construction schedule was extended to 2025, with full operation expected by 2035, adding an additional $5.2 billion (adjusted for inflation) to the total cost. In July 2024, ITER announced that the facility would not be fully operational until 2039 and would cost an additional $5.2 billion.

Congress authorized U.S. participation in ITER in the Energy Policy Act of 2005 (P.L. 109-58) and reaffirmed this participation in the Energy Act of 2020 (enacted as Division Z of P.L. 116-260). From 2007 through 2023, the United States contributed more than $2.9 billion (adjusted for inflation) to ITER through research, hardware design, and manufacturing for 12 different ITER systems. This contribution represents about 9% of the total international cost. In FY2024, Congress appropriated $240 million to the Department of Energy (DOE) for the U.S. contribution to ITER, about 30% of the total appropriation for the Fusion Energy Sciences program in the DOE Office of Science. Given the current plan, the U.S. portion of ITER (US ITER) anticipates that hardware construction will be completed in December 2035, and U.S. cash contributions to ITER construction and operation will be completed in 2040.

Some researchers believe that private fusion companies may be moving faster than ITER toward achieving key fusion technical milestones. According to the Fusion Industry Association (FIA), at least 45 companies are developing commercial fusion energy across the globe, 25 of which are located within the United States. In its survey of the fusion industry, FIA reports that 89% of private fusion companies anticipate that fusion will provide electricity to the grid by the end of the 2030s, with 70% saying that milestone will happen by the end of 2035. However, the industry is split on whether a fusion energy plant will be commercially viable during that same time frame.

In 2022, using inertial confinement rather than ITER's magnetic confinement design, the U.S. National Ignition Facility in Livermore, CA, became the first to use a fusion device to achieve "scientific breakeven"—when the energy released by the reaction is greater than the energy added directly to the plasma. This accomplishment, together with industry projections and with the view that some of the componentry in ITER has been overtaken by technological advances, has led some observers to question ITER's future ability to achieve practical fusion energy. Others say that ITER remains an important component of building the scientific and technological understanding needed for a fusion energy industry.

Management of the ITER project has long been a subject of congressional interest. The most recent ITER schedule delays and cost increases raised concern at a Senate Committee on Energy and Natural Resources hearing in September 2024. A key question for Congress may be what options the United States could consider if there are additional ITER delays. Congress may also wish to examine the role of continued U.S. investment and participation in ITER and how it fits within DOE's Fusion Energy Strategy. This could include questions about the extent, if any, to which U.S. participation in ITER provides a strategic advantage to future economic competitiveness for the United States and for private U.S. companies.

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Introduction

U.S. nuclear fusion research and development (R&D) policy has been an ongoing congressional concern. A key focus of this concern has been ITER, previously referred to as the International Thermonuclear Experimental Reactor, a multibillion-dollar fusion energy project involving the European Union (host), China, India, Japan, Russia, South Korea, and the United States. This international collaboration intends to build a *tokamak*—"a magnetic fusion device that has been designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy."[1] The key goal of the consortium is to operate ITER at or near the ignition point of burning plasma (discussed below), a critical step toward self-sustaining nuclear fusion.[2] ITER's planned capabilities also include extensive instrumentation for advancing the scientific understanding of plasmas (the fourth state of matter), as well as opportunities for testing specialized materials for use in fusion applications. ITER is not intended to provide electricity commercially.

The fusion reaction in ITER is to be fueled by the hydrogen isotopes deuterium (D) and tritium (T).[3] Different isotopes of an element[4] have the same number of protons but differing numbers of neutrons (n) in their nuclei. Thus, while hydrogen isotopes each have one proton, deuterium additionally has one neutron and tritium has two neutrons. In the so-called D-T fusion process, as the particles of deuterium and tritium in the plasma collide, they can fuse to form helium (He) nuclei (two protons and two neutrons), plus one neutron and excess energy. The following equation illustrates this process:

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He}\ (3.56\ \mathrm{MeV}) + \mathrm{n}\ (14.03\ \mathrm{MeV})$$

MeV is a unit of energy representing a million electron volts and, as used in the equation, indicates the kinetic energy of the subatomic particles. The energy liberated from a fusion reaction is the result of the reorganization of the bonds that form the deuterium, tritium, and highly stable helium nuclei. At the conclusion of the reaction, a small amount of mass is converted to a relatively large amount of energy following Einstein's mass-energy equivalence relation, notated as $E = mc^2$, where E is energy, m is mass, and c is a constant for the speed of light.

The United States is a party to the multilateral *Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project* (ITER Agreement), which entered into force on October 24, 2007.[5] The agreement initiated a 35-year membership for the seven participating members and established the ITER Organization to lead the project.

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[1] ITER, "In a Few Lines," 2024, https://www.iter.org/few-lines.

[2] A *burning plasma* is defined as "a plasma in which the energy of the helium nuclei (alpha particles) produced by the fusion reaction is enough to maintain the temperature of the plasma; the external heating methods can then be strongly reduced or switched off altogether." ITER, "Fusion Glossary," https://www.iter.org/fusion-glossary.

[3] "Deuterium is a stable isotope of hydrogen, which, unlike 'normal' hydrogen atoms, or protium, also contains a neutron. The isotope deuterium has one proton, one neutron and one electron" (International Atomic Energy Agency [IAEA], "What Is Deuterium?" January 13, 2023, https://www.iaea.org/newscenter/news/what-is-deuterium). Tritium "is a hydrogen atom that has two neutrons in the nucleus and one proton" (Environmental Protection Agency, "Radionuclide Basics: Tritium," June 4, 2024, https://www.epa.gov/radiation/radionuclide-basics-tritium).

[4] IAEA, "What Are Isotopes?" August 19, 2022, https://www.iaea.org/newscenter/news/what-are-isotopes.

[5] U.S. Department of State, Office of Treaty Affairs, *Multilateral (07-1024) – Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project*, October 24, 2007, https://www.state.gov/07-1024.

The ITER members have divided the scope of the project and are mutually dependent, sharing the work and the benefits. Contracts for the development and construction of different components of the reactor were awarded across the ITER membership (see **Figure 1**). Construction began in southeastern France in 2010.

Initial projections suggested that ITER construction would be completed in 2016, with the first experiments beginning in 2020, at a total cost of $10 billion (adjusted for inflation).[6] In 2016, the construction schedule was extended to 2025, with full operation expected by 2035, adding an additional $5.2 billion (adjusted for inflation) to the total cost.

In July 2024, ITER announced that the facility would not be fully operational (with burning plasma) until 2039 and would cost an additional $5.2 billion (i.e., $10.4 billion more than the initial estimate).[7] One aspect of the delay and the increased costs involves switching materials for the first wall, the wall facing and confining the plasma in the tokamak, from beryllium to tungsten. The decision to switch materials included many factors, such as the susceptibility of beryllium to erosion by the plasma and its toxicity to workers, compared with the resistance of tungsten to vaporization and its comparatively low erosion.[8] This one change in material alone is estimated to cost about an additional $1 billion.[9]

ITER's governing body, the ITER Council, represents the seven member countries. The ITER Council is responsible "for the promotion and overall direction of the ITER Organization" and has the authority to appoint the Director-General, approve project management plans, and establish the total budget for the ITER project, including reestimating baseline funding (see "US ITER Re-baselining").[10] The United States is represented in the ITER Council by the Department of Energy's (DOE's) Office of Science.

Oak Ridge National Laboratory, in partnership with two other DOE laboratories—Savannah River National Laboratory and Princeton Plasma Physics Laboratory—manages the U.S. portion of ITER (US ITER)[11] for DOE. According to DOE, the United States contributes "in-kind hardware components and [makes] financial contributions for the ITER Organization . . . management and overhead (e.g., design integration, nuclear licensing, quality control, safety, overall project management, and installation and assembly of the components provided by the U.S. and other Members)."[12] This amounts to about 9% of the project's costs. After ITER construction is complete, the United States has agreed to pay a 13% cost share during the operation phase.[13]

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[6] ITER, "FAQs," 2024, https://www.iter.org/faqs. Dollar values were converted from euros.

[7] ITER, "New Baseline to Prioritize Robust Start to Exploitation," press release, July 3, 2024, https://www.iter.org/node/20687/new-baseline-prioritize-robust-start-exploitation.

[8] Forschungszentrum Jülich, "Plasma-Wall Interaction - A Key Issue in Progress Towards Fusion Power Plants," June 29, 2024, https://www.fz-juelich.de/en/ifn/ifn-1/forschung/plasma-wall-interaction-a-key-issue-in-progress-towards-fusion-power-plants; and Daniel Clery, "Giant Fusion Project in Big Trouble," *Science*, vol. 385, no. 7604 (July 5, 2024), pp. 10-11.

[9] Briefing provided to CRS by Department of Energy (DOE) Office of Science, December 6, 2024.

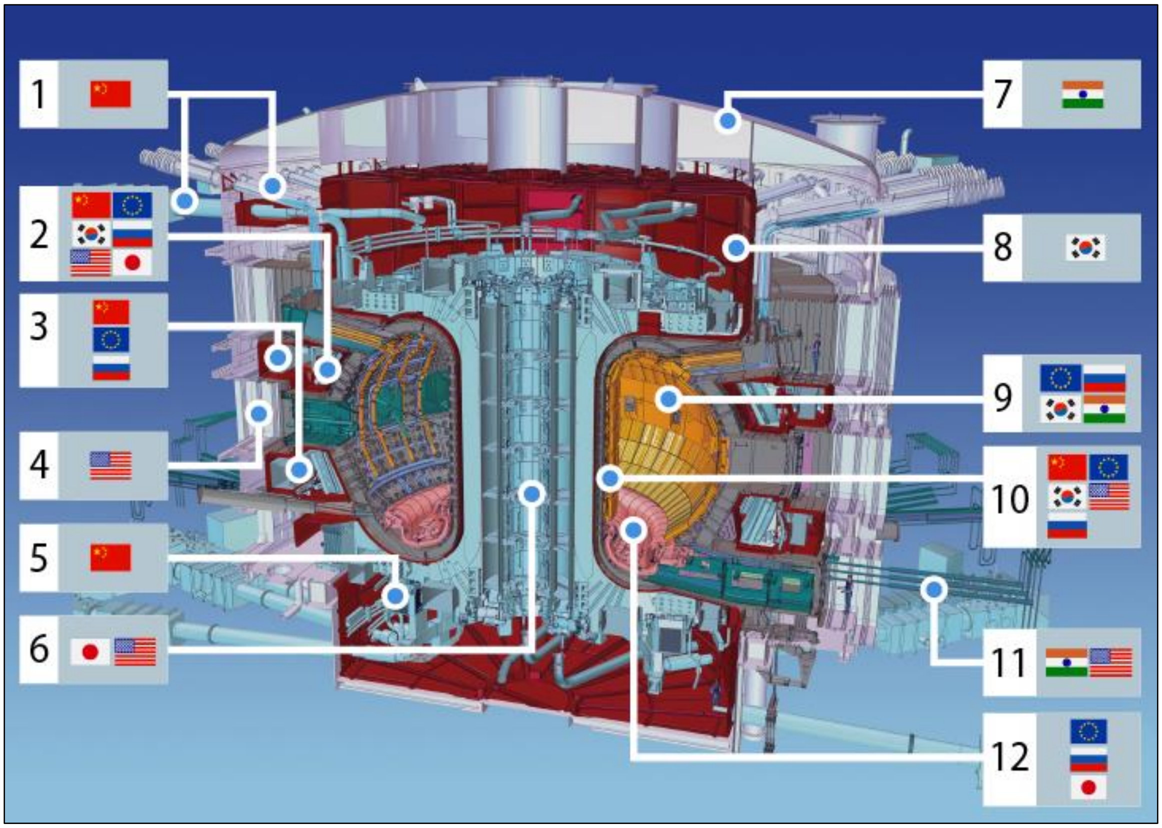
[10] ITER, "Governance," 2024, https://www.iter.org/about/governance. Re-baselining is a process of updating, or modifying, a project's schedule, deliverables, and costs. It typically occurs when a project has fallen behind schedule.

[11] For more information on US ITER, see https://usiter.ornl.gov/.

[12] DOE, *FY 2025 Congressional Justification, Volume 5: Science*, March 2024, p. 196, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-5-v2.pdf.

[13] Fusion Energy Sciences Advisory Committee (FESAC), "Report of the FESAC Facilities Construction Projects Subcommittee: In Response to the Charge Letter from Dr. Asmeret Asefaw Berhe to the Department of Energy Office of Science Federal Advisory Committees December 1, 2023," May 10, 2024, https://www.osti.gov/servlets/purl/2476326.

Figure 1. ITER's Tokamak Components and the Countries Involved in Their Development and Construction



Source: CRS, adapted from ITER Organization.

Notes: Not all systems or contributions are represented in this figure. Flags represent country's initial commitments for construction of specific components of the tokamak. 1 = ports; 2 = toroidal magnetic field coils; 3 = poloidal magnetic field coils; 4 = particle injection; 5 = correction coils; 6 = central solenoid; 7 = cryostat; 8 = thermal shield; 9 = vacuum chamber; 10 = blanket; 11 = cooling system; 12 = diverter. For a 3-D "fly-through" of the device, see ITER Organization, "ITER Fly-Through," YouTube video, January 15, 2015, https://youtu.be/IP7Vuqz-MAE.

Science and Technology Behind ITER

The science behind the ITER project is based on *nuclear fusion*. Nuclear fusion is a process in which the nuclei of two lightweight atoms (such as hydrogen) join, or fuse, to form a heavier nucleus, releasing energy. Fusion reactions take place in a hot, dense, ionized gas (i.e., one in which the electrons have separated) called *plasma*. Plasmas that generate a predefined ratio of energy from the ongoing nuclear fusion reaction relative to the added external energy from the experimental apparatus are deemed *burning plasmas*. Under the right conditions, burning plasmas can approach or exceed the point at which the reaction becomes self-sustaining (i.e., ignition). The Sun is an example of a burning plasma that has reached ignition.

ITER uses a tokamak reactor design (see **Figure 2**). The plasma fuel for the reaction must be confined to keep it hot and dense so the reaction can continue. At more than 150 million Kelvin, the plasma in ITER cannot be confined by a container of any physical material. The Sun's plasma is confined by the pull of the Sun's own gravity. A tokamak, which is doughnut shaped (toroidal), confines a plasma using magnetic fields. Developed by Soviet scientists, the first tokamak, T-1, began operation in Russia in 1958.

ITER is primarily an exploratory science initiative and is not designed or intended to produce electricity. However, ITER has designed the tokamak to help develop the technology for a future fusion demonstration power plant. According to the ITER Organization, there are five main scientific objectives behind the tokamak's design:[14]

- achieve a burning plasma sustained mostly by heat from the fusion reaction itself,
- "generate 500 MW [megawatts] of fusion power in its plasma,"[15]
- "contribute to the demonstration of the integrated operation of technologies for a fusion power plant,"
- test the feasibility of producing tritium (for fuel) within the vacuum vessel, and
- "demonstrate the safety characteristics of a fusion device."

Physics World summarized the goals of ITER as follows: The reactor's "main aim is to generate about 500 MW of fusion power over 400 seconds using a plasma heating of 50 MW, a power gain [i.e., Q value] of 10. The reactor would also test a 'steady state' operation under a power gain of five."[16]

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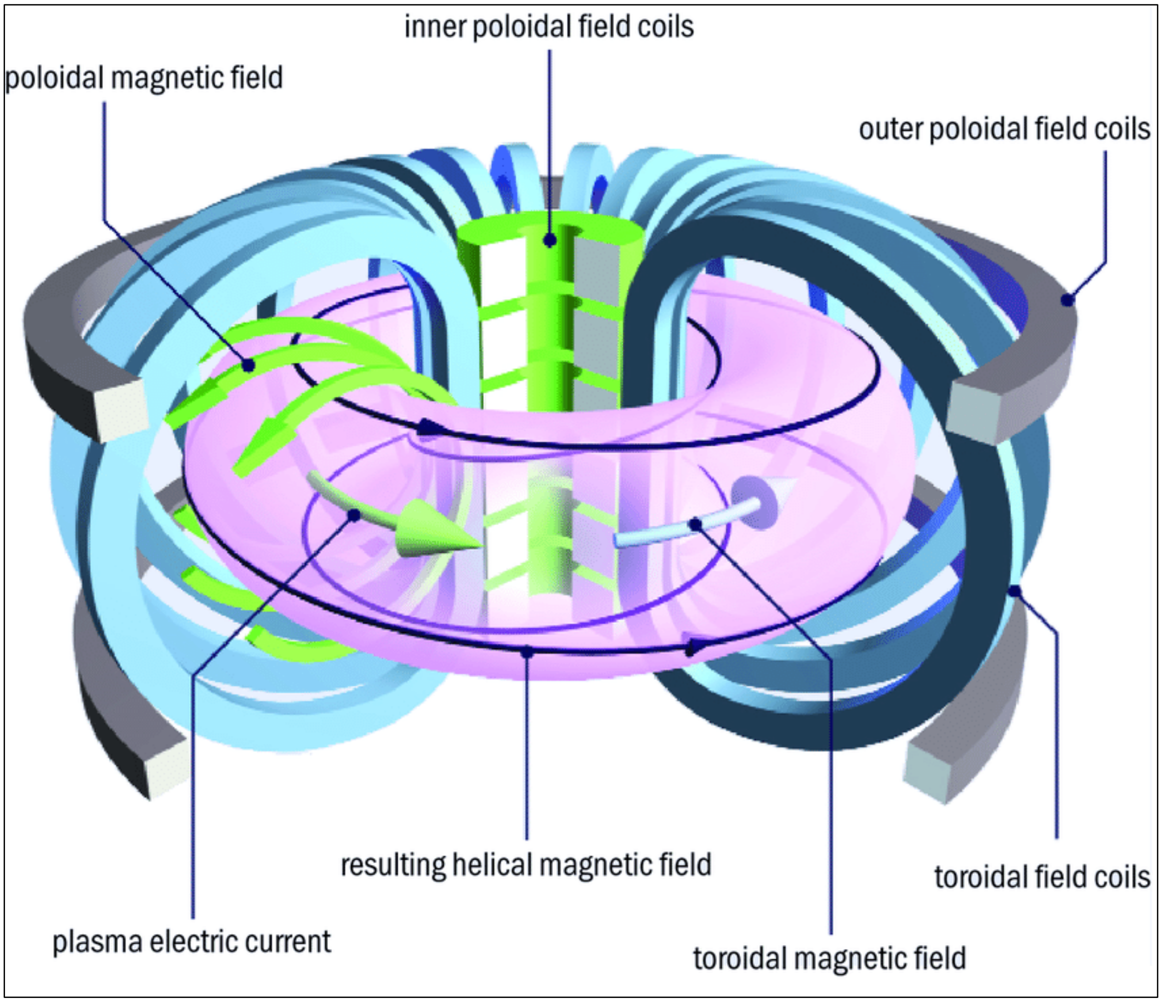
[14] ITER, "In a Few Lines," 2024, https://www.iter.org/few-lines.

[15] The output power is often compared to the power added directly to the plasma by the experimental apparatus, a ratio sometimes called the *power gain* or *Q factor*.

[16] Michael Banks, "ITER Fusion Reactor Hit by Massive Decade-Long Delay and €5Bn Price Hike," *Physics World*, July 3, 2024, https://physicsworld.com/a/iter-fusion-reactor-hit-by-massive-decade-long-delay-and-e5bn-price-hike.

Figure 2. Schematic of a Tokamak Reactor



Source: Francesco Romanelli, "Fusion Energy," *EPJ Web of Conferences*, vol. 246, no. 00013 (2020), https://doi.org/10.1051/epjconf/202024600013.

Notes: A tokamak reactor uses powerful magnets to confine the plasma within a toroidal (doughnut-shaped) reaction vessel, with the magnetic fields keeping the plasma away from the walls of the vessel to prevent damage to the walls and unintended cooling of the plasma.

U.S. Participation and Investment in ITER

Congress authorized U.S. participation in ITER in the Energy Policy Act of 2005 (P.L. 109-58) and reaffirmed this participation in the Energy Act of 2020 (enacted as Division Z of P.L. 116-260).[17] Specifically, Section 972(c)(3)(A) of the Energy Policy Act of 2005 (P.L. 109-58) says the Secretary of Energy may negotiate an agreement for U.S. participation in ITER. Section 972(c)(3)(B) specifies any agreement for U.S. participation shall

- "clearly define the [U.S.] financial contribution to construction and operating costs, as well as any other costs associated with a project;

[17] 42 U.S.C. §16312.

- "ensure that the share of high-technology ITER components manufactured in the United States is at least proportionate to the [U.S.] financial contribution to ITER;
- "ensure that the United States will not be financially responsible for cost overruns in components manufactured in other ITER participating countries;
- "guarantee the United States full access to all data generated by [ITER operations];
- "enable [U.S.] researchers to propose and carry out an equitable share of the experiments at the ITER;
- "provide the United States with a role in all collective decisionmaking related to the ITER; and
- "describe the process for discontinuing or decommissioning the ITER [facility] and any United States role in that process."

Enacted in 2020, P.L. 116-260 amended the 2005 authorization to include U.S. participation in the construction and operations of ITER, as required under the 2007 ITER Agreement.[18] The 2020 law additionally authorizes DOE's Director of the Office of Science to carry out U.S. responsibilities according to the terms of the ITER Agreement.[19]

The U.S. ITER project was initiated in FY2006. As part of its agreement with ITER, the United States committed to delivering multiple components (see **Figure 3**). While not specifically required to do so, DOE's Office of Science is executing ITER using the program and project management principles of DOE's Order 413.3B, which applies to capital assets with a total cost (acquisition) above $50 million.[20]

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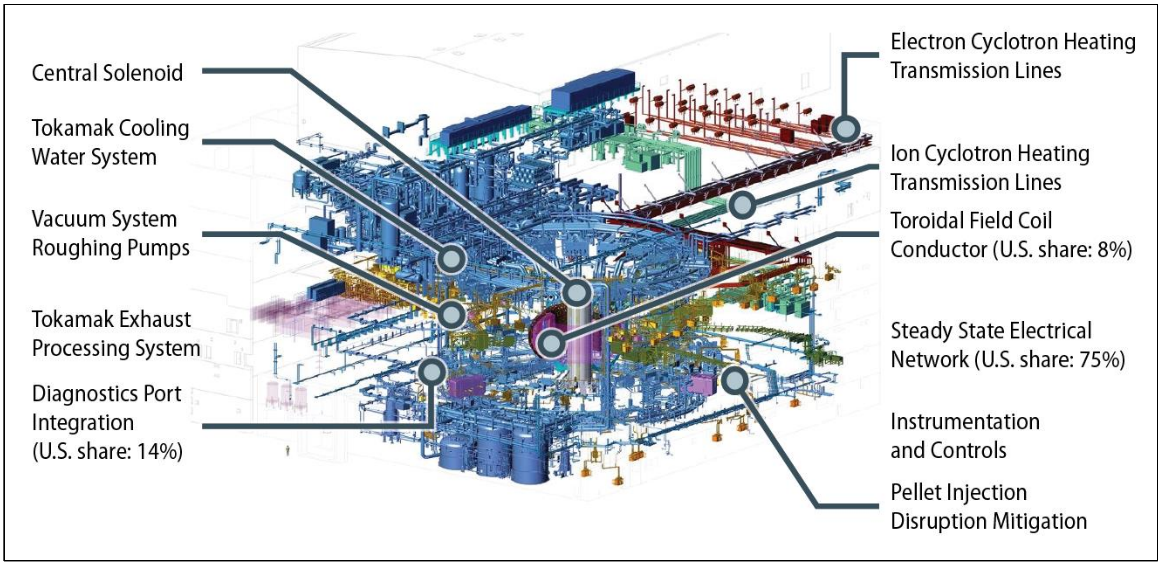
[18] U.S. Department of State, Office of Treaty Affairs, *Multilateral (07-1024) – Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project*, October 24, 2007, https://www.state.gov/07-1024.

[19] 42 U.S.C. §16312.

[20] DOE, Office of Project Management, *Program and Project Management for the Acquisition of Capital Assets*, DOE O 413.3B, Change 7, June 21, 2023, https://www.directives.doe.gov/directives-documents/400-series/0413.3-BOrder-B-chg7-ltdchg/@@images/file. In 2010, the Under Secretary for Science approved a request from the Office of Science that it be exempt from DOE O 413.3B. Steven E. Koonin, Under Secretary for Science, "Memorandum for the Deputy Secretary," EXEC-2010-017508, December 22, 2010, https://science.osti.gov/-/media/opa/pdf/processes-and-procedures/sc/SC-Order-Exemption-final.pdf.

Figure 3. U.S. Construction Contributions to ITER



Source: US ITER presentation to CRS on October 30, 2024.

Notes: The schematic shows the tokamak and its associated housing components. The tokamak exhaust processing system, including the input streams, extends through a large part of the overall tokamak and cannot be pinpointed to one location in the diagram. The steady-state electrical network is located outside the tokamak and thus does not appear in the diagram.

Figure 4 illustrates key terms and stages in the 413.3B process, which DOE frequently references in its project status updates with respect to the two subprojects DOE created in 2016 (see discussion in "US ITER Re-baselining"). On January 13, 2017, US ITER Subproject 1 (SP-1, "First Plasma [Hardware]") achieved both Critical Decision (CD)-2, "Approve Performance Baseline," and CD-3, "Approve Start of Construction [or Execution]"; CD-4, "Project Completion," for SP-1 is currently planned for December 2028.[21] According to a DOE July 2024 ITER project update, four of the six U.S.-delivered central solenoid modules that create magnetic fields are on site in France,[22] and the remaining two modules are scheduled for delivery in 2025.[23] The update also reports that "fabrication and delivery of other essential hardware systems continues."[24]

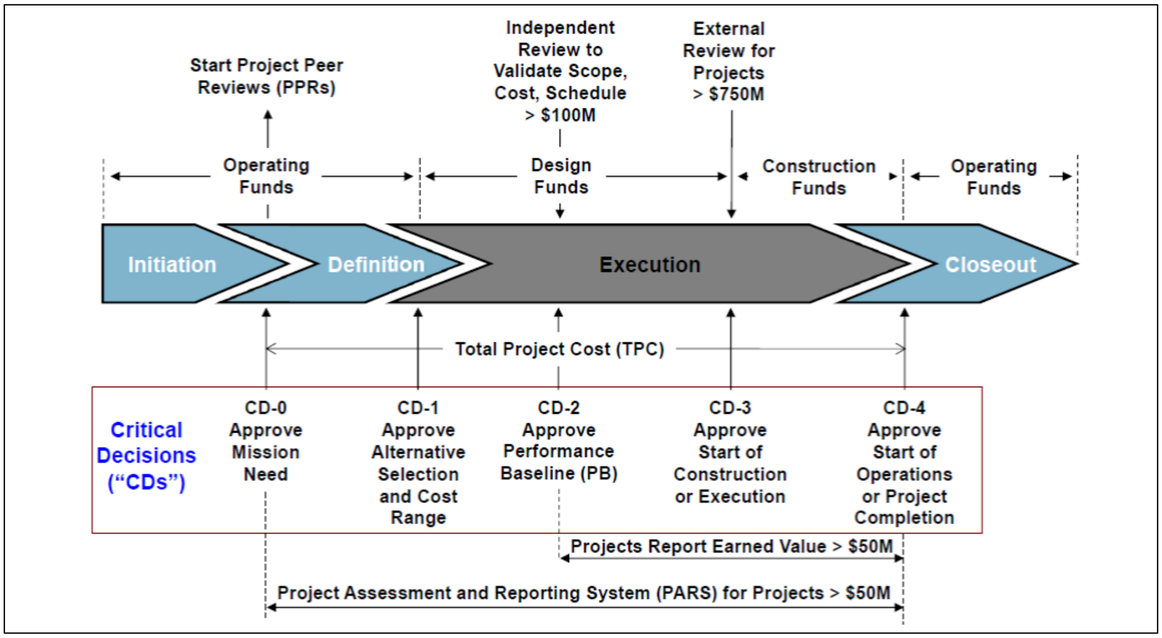
[21] DOE, *FY 2025 Congressional Request, Volume 5: Science*, March 2024, p. 209, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-5-v2.pdf.

[22] DOE, US ITER Project Office, "US ITER Project Update," July 2024, https://usiter.ornl.gov/wp-content/uploads/2024/07/US-ITER-Update-June-2024.pdf.

[23] Email from Lynne Degitz, Stakeholder Relations, US ITER, January 2025.

[24] DOE, US ITER Project Office, *US ITER Project Update,* July 2024, https://usiter.ornl.gov/wp-content/uploads/2024/07/US-ITER-Update-June-2024.pdf.

Figure 4. Department of Energy Project Management Process



Source: Paul Bosco, "Project Management (PM) Governance, Systems and Training," presentation to the National Academy of Sciences Committee on Review of Effectiveness and Efficiency of Defense Environmental Cleanup Activities of the Department of Energy's Office of Environmental Management, May 6, 2020, Washington, DC.

A 2024 Fusion Energy Sciences Advisory Committee (FESAC)[25] Facilities Construction Projects Subcommittee report said that the United States has delivered 60% of its planned in-kind contributions to the ITER project as of May 2024 (see **Figure 3**). Remaining deliverables include

- central solenoid modules and structures (expected FY2025);
- disruption mitigation components (expected FY2026);
- tokamak cooling system, vacuum auxiliary system, electron cyclotron heating transmission lines, and roughing pumps (expected FY2029);
- tokamak exhaust processing system (expected FY2030);
- pellet injection system (expected FY2032);
- ion cyclotron transmission lines (expected FY2033); and
- diagnostics systems (expected FY2031, and additional systems to be delivered after that).[26]

[25] FESAC has been chartered pursuant to Section 14(a)(2)(A) of the Federal Advisory Committee Act (P.L. 92-463) and 41 C.F.R. §101-6.1015. "The committee provides independent advice to the [DOE] Director of the Office of Science on complex scientific and technological issues that arise in the planning, implementation, and management of the fusion energy sciences program. The current charter is in effect until August 2025" (U.S. DOE, "Fusion Energy Sciences Advisory Committee (FESAC)," https://science.osti.gov/fes/fesac).

[26] FESAC, "Report of the FESAC Facilities Construction Projects Subcommittee: In Response to the Charge Letter from Dr. Asmeret Asefaw Berhe to the Department of Energy Office of Science Federal Advisory Committees December 1, 2023," May 10, 2024, https://www.osti.gov/servlets/purl/2476326.

Funding

In January 2008, DOE estimated the cost range for the U.S. contribution to ITER between $1.45 billion and $2.2 billion ($2.08 billion to $3.16 billion, respectively, in 2023 dollars).[27] The total U.S. share of ITER's projected overall cost is currently estimated at $6.5 billion (in 2023 dollars), which includes all projected U.S. in-kind hardware and financial contributions to ITER Organization construction operations. The increase in costs is related to the re-baselining of the ITER project (see "US ITER Re-baselining").[28]

From 2007 through 2023, the United States contributed more than $2.9 billion (see **Table 1**) to ITER through research, hardware design, and manufacturing for 12 different ITER systems. In FY2024, Congress appropriated $240 million to DOE for the U.S. contribution to ITER, about 30% of the total appropriation for Fusion Energy Sciences in the DOE Office of Science. This contribution represents about 9% of the total international cost.

DOE has awarded funding to support ITER activities to various U.S. companies and universities, along with DOE national laboratories, across 46 states and the District of Columbia (see **Figure 5**). The potential impact of ITER's delays and funding needs on resource availability for domestic U.S.-based fusion R&D has sometimes been a concern in both Congress and the scientific community, especially in tight fiscal environments.

US ITER Re-baselining

In 2016, DOE divided the ITER project hardware scope into two subprojects—"First Plasma [Hardware]," or SP-1, and "Post-First Plasma," or SP-2—"so that an initial portion of the project that was mature enough to baseline could be accomplished."[29] The baseline for SP-1 was estimated to be $2.5 billion in January 2017 ($3.1 billion in 2023 dollars).[30] In 2023, US ITER re-baselined the entire project. According to DOE Energy Systems Acquisition Advisory Board documents signed in December 2023, the total U.S. project cost for ITER contributions is estimated to be $6.5 billion, which includes all U.S. in-kind hardware and financial construction contributions through the completion of the ITER project, with a CD-4, "Approve Start of Operations or Project Completion" date of 2040.[31]

Given the current plan, US ITER anticipates that hardware construction will be completed in December 2035, and U.S. cash contributions to ITER will be completed in 2040. The ITER Organization provided an updated baseline to the ITER Council in 2024. U.S. contributions to ITER are estimated to remain within the total project cost of $6.5 billion. According to DOE, the

[27] U.S. Government Accountability Office, *Fusion Energy: Actions Needed to Finalize Cost and Schedule Estimates for U.S. Contributions to an International Experimental Reactor*, GAO-14-499, June 5, 2014, p. 15, https://www.gao.gov/products/gao-14-499. Amounts adjusted to 2023 dollars based on Bureau of Economic Analysis, "Table 3.10.4: Price Indexes for Government Consumption Expenditures and General Government Gross Output," August 29, 2024.

[28] Department of Energy, *FY 2025 Congressional Justification, Volume 5: Science*, March 2024, p. 196, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-5-v2.pdf.

[29] DOE, *FY 2025 Congressional Justification, Volume 5: Science*, March 2024, p. 214, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-5-v2.pdf. To *baseline* a project in this context refers to defining a point in time from which it is possible to measure the project's progress.

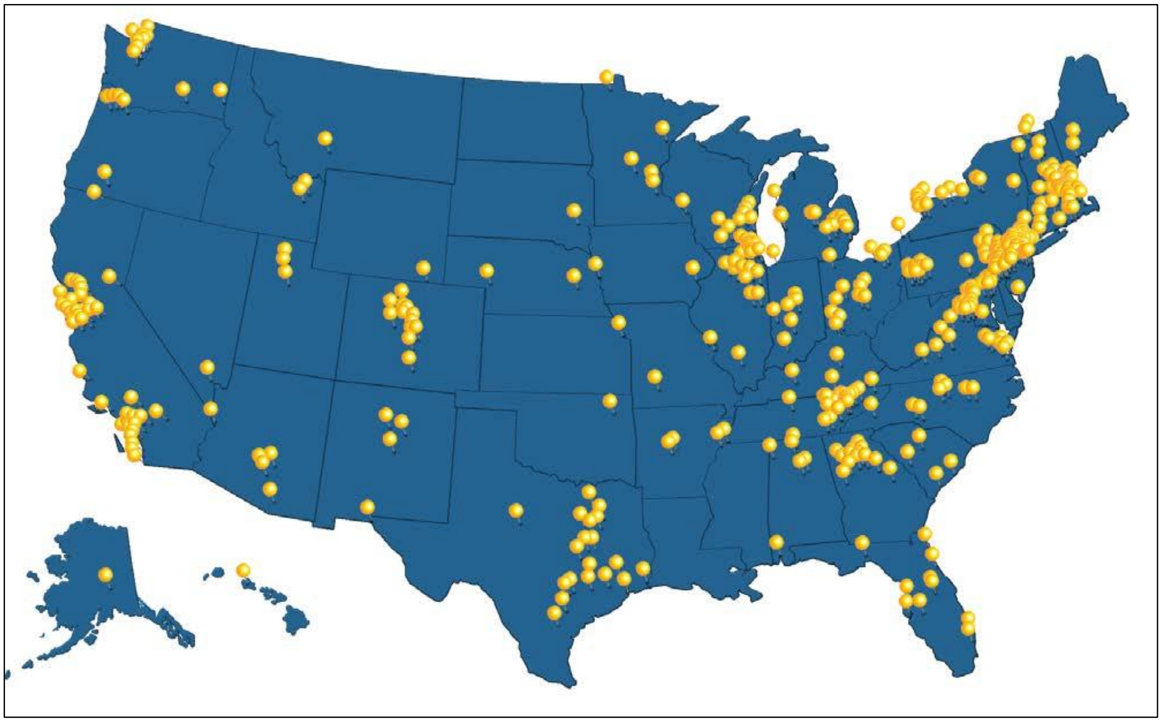
[30] Amounts adjusted to 2023 dollars based on Bureau of Economic Analysis, "Table 3.10.4: Price Indexes for Government Consumption Expenditures and General Government Gross Output," August 29, 2024.

[31] Briefing provided to CRS by Kathy McCarthy, Project Director US ITER, October 29, 2024.

total project cost has contingency funding built in to accommodate potential design, construction, and operational delays.[32]

Figure 5. Map of US ITER Contracts Awarded

As of December 2023



Source: US ITER, "US ITER Participants," March 2024, https://usiter.org/wp-content/uploads/2024/02/US-ITER-Participants-March-2024.pdf.

Notes: According to US ITER, as of December 2023, more than $900 million has gone to industry and over $500 million has gone to DOE national laboratories (briefing given to CRS on October 30, 2024).

[32] Briefing provided to CRS by DOE Office of Science, December 6, 2024.

Table 1. DOE Fusion Energy Sciences (FES) and ITER Program Budgets (FY2007-FY2024)

Fiscal Year	Total FES Budget (Includes ITER) (millions of 2023 dollars)	US ITER Budget (millions of 2023 dollars)	US ITER Percentage of FES Budget[a]
2007	468	90	19
2008	424	37[b]	9
2009	571	180	32
2010	586	189	32
2011	500	109	22
2012	526	140	27
2013	493	162	33
2014	645	255	40
2015	598	192	32
2016	559	147	26
2017	474	62	13
2018	639	146	23
2019	668	156	23
2020	775	280	36
2021	736	265	36
2022	729	248	34
2023	763	242	32
2024[c]	790	240	30

Source: Department of Energy (DOE), "Comparative Organization by Congressional Control," in *Congressional Budget Requests: Volume 5: Science* (FY2007-FY2025), https://www.energy.gov/cfo/listings/budget-justification-supporting-documents.

Notes: Budget amounts adjusted to 2023 dollars based on Bureau of Economic Analysis, "Table 3.10.4: Price Indexes for Government Consumption Expenditures and General Government Gross Output," August 29, 2024.

a. Values are rounded to the nearest whole number.

b. The planned FY2008 funding of $160 million was reduced in December 2007 by the FY2008 Energy and Water Development and Related Agencies Appropriations Act, P.L. 110-161.

c. FY2024 enacted budget as reflected in Department of Energy, "Comparative Organization by Congressional Control: FY 2025," in *Congressional Budget Requests: Volume 5: Science* (FY2025), https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-approps-org-v2.pdf.

Private R&D and Investment in Fusion Energy

According to one fusion researcher, "private fusion efforts are now likely to achieve many of the technical milestones ITER was intended to reach first, thanks to investment and advances in physics and materials science."[33]

[33] Elizabeth Gibney, "ITER Delay: What It Means for Nuclear Fusion," *Nature*, vol. 631, no. 8021 (2024), pp. 488-489.

According to a survey conducted by the Fusion Industry Association (FIA), at least 45 companies across the globe, aside from ITER, are developing commercial fusion energy, 25 of which are located within the United States (see **Figure 6**). According to FIA's analysis, private-sector fusion companies have raised over $7.1 billion. In 2024 alone, over $900 million was raised, $426 million of which came from public funding via direct grants or cost shares in public-private partnerships. These investments support R&D across a range of fusion technologies (e.g., magnetic confinement, inertial confinement) focused on various applications (e.g., electricity generation, space and marine propulsion, medical devices, and fuels).[34]

In its survey of the fusion industry, FIA reports that 89% of private fusion companies anticipate that fusion will provide electricity to the grid by the end of the 2030s, with 70% saying that milestone will happen by the end of 2035 (see **Figure 7**). However, the industry is split on whether a fusion energy plant will be commercially viable during that same time frame.[35] As noted above, ITER currently anticipates that its facility will begin full operations in 2039.

DOE anticipates releasing a fusion science and technology road map in 2025, which is to present metrics that inform decisionmaking on closing critical science and technology gaps, and which also aligns with the fusion industry's timeline.[36]

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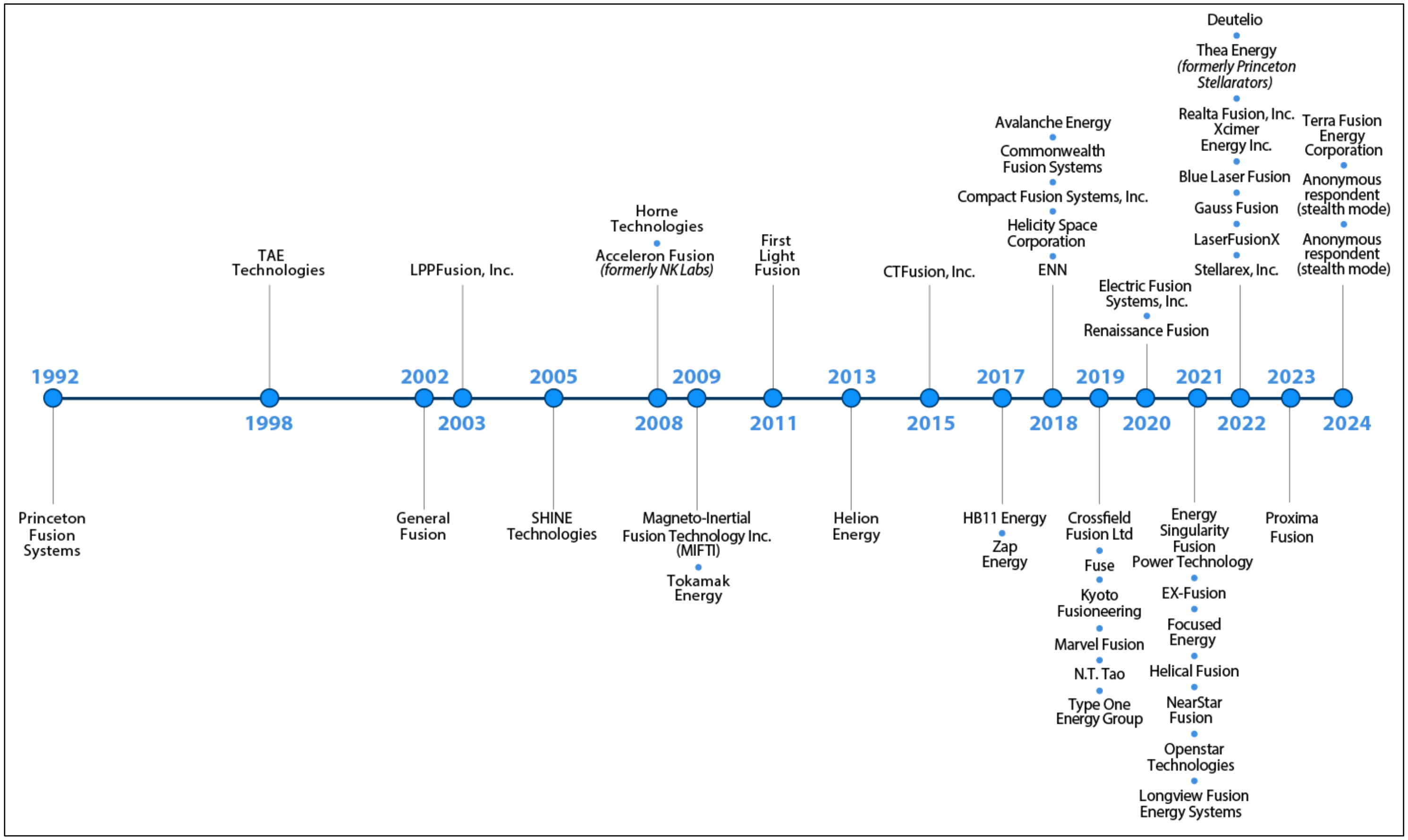
[34] Fusion Industry Association, *The Global Fusion Industry in 2024: Fusion Companies Survey by the Fusion Industry Association*, 2024, https://www.fusionindustryassociation.org/wp-content/uploads/2024/07/2024-annual-global-fusion-industry-report.pdf.

[35] Ibid.

[36] DOE, *Fusion Energy Strategy 2024*, 2024, p. 6, https://www.energy.gov/sites/default/files/2024-06/fusion-energy-strategy-2024.pdf.

Figure 6. Private-Sector Fusion Companies

Founding years for companies responding to the 2024 Fusion Industry Association survey

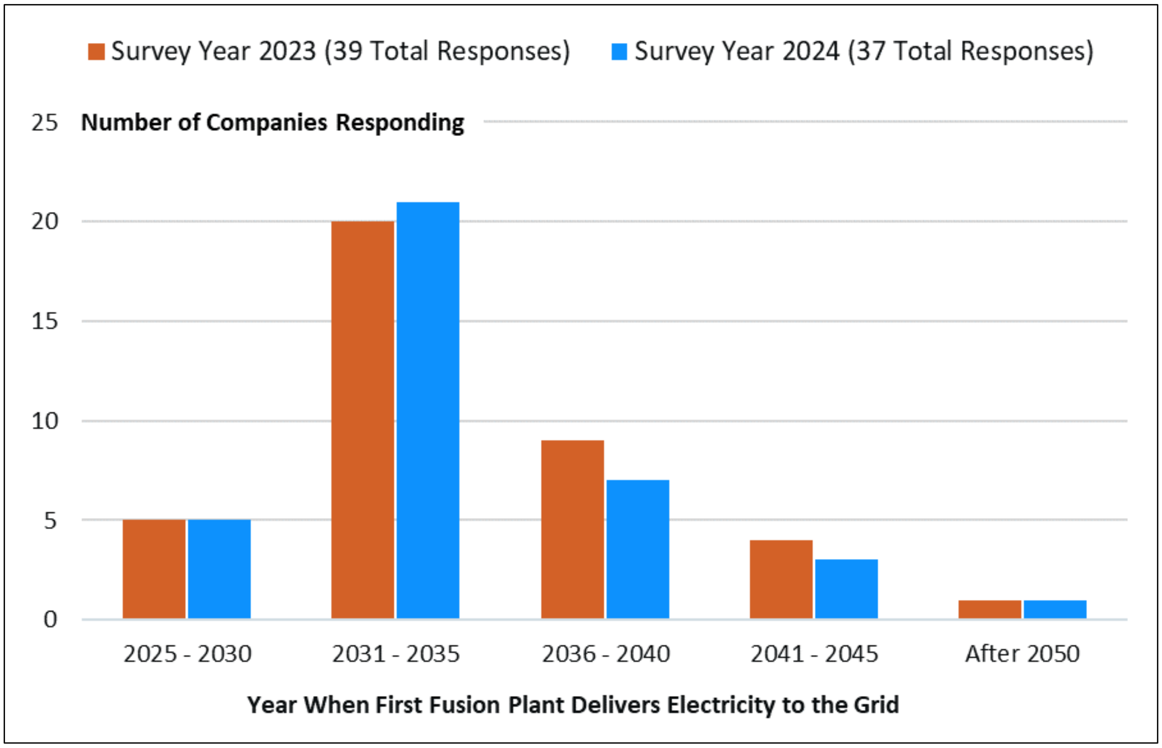


Source: Fusion Industry Association, *The Global Fusion Industry in 2024: Fusion Companies Survey by the Fusion Industry Association*, 2024, https://www.fusionindustryassociation.org/wp-content/uploads/2024/07/2024-annual-global-fusion-industry-report.pdf.

Notes: The figure shows only those private-sector companies that responded to the 2024 Fusion Industry Association survey.

Figure 7. Estimated Year When the First Fusion Plant Will Deliver Electricity to the Grid

According to companies surveyed by the Fusion Industry Association in 2023-2024



Source: Fusion Industry Association, *The Global Fusion Industry in 2024: Fusion Companies Survey by the Fusion Industry Association*, 2024, https://www.fusionindustryassociation.org/wp-content/uploads/2024/07/2024-annual-global-fusion-industry-report.pdf.

Notes: The survey asked private-sector fusion companies the question "When will the first fusion plant deliver electricity to the grid?"

Questions Facing Congress

ITER's progress has been delayed by the technical and engineering complexity of building such a device, as well as by multiple partners being responsible for different components (see **Figure 1**). Additionally, management issues, cost overruns, and the coronavirus disease 2019 (COVID-19) pandemic contributed to ITER's delays. Initial estimated costs for ITER were $12 billion in 2006 (about $18 billion in 2023 dollars) when the project began. In 2014, the estimate had increased to $21 billion (about $27 billion in 2023 dollars). The most recent estimate, with the new completion date of 2039, is that the total cost will rise an additional $5.4 billion (in 2023 dollars).

Given the delays in ITER's construction and projected operational readiness, some fusion science researchers have raised concerns about whether future investments are justified given the progress being made in other public and private research endeavors.[37]

Congress has had long-standing interest in federal policy on fusion R&D. For example, Senator Joe Manchin, former Chairman of the Senate Committee on Energy and Natural Resources, expressed concern at a September 2024 hearing that "ITER continues to face delays and its new

[37] Daniel Clery, "Giant Fusion Project in Big Trouble," *Science*, vol. 385, no. 6704 (2024), pp. 10-11.

startup date is in 2039, four years later than we hoped. So, we need to get a better understanding of why that is, and how we can get things back on track."[38]

In December 2023, the director of the DOE Office of Science charged the Chairs of the Office of Science Federal Advisory Committees to evaluate what new or upgraded facilities would best serve DOE needs and have the potential to contribute to world-leading science in the next decade (2024-2034). As part of this overall DOE science charge, the FESAC Facilities Construction Projects Subcommittee developed a report examining 10 fusion-related facilities, including ITER. ITER was rated "absolutely central" and identified as one of four facilities to be included in the "Best Serves Fusion" category to accelerate the "fusion energy timeline." The report asserted that ITER has and will continue to provide knowledge about the integrated engineering experience at industrial scale, including the importance of quality control in precision engineering and assembly.

In 2022, using inertial confinement rather than ITER's magnetic confinement design, the U.S. National Ignition Facility in Livermore, CA, became the first to use a fusion device to achieve "scientific breakeven"—when the energy released by the reaction is greater than the energy added directly to the plasma. This accomplishment, along with industry projections, has led some observers to question ITER's future ability to achieve practical fusion energy. Others say that ITER remains an important component of building the science, technology, and understanding for a future fusion energy industry.[39]

Congress may wish to examine the role of continued U.S. investment and participation in ITER and how it fits within DOE's Fusion Energy Strategy.[40] Possible questions for consideration include the following:

- What options should the United States consider if there are additional ITER project delays? How and by whom should potential options be determined?
- How should U.S. fusion R&D priorities adapt to both private industry and ITER progress?
  - What impacts could potential scientific and engineering advances from the academic and private fusion industry have on ITER's current R&D strategy?
    - To what extent, if at all, should potential advances be incorporated into the development of ITER (i.e., should the strategy and goals be modified)?
    - To what extent should these potential advances change U.S. participation in ITER?
- What is the state of fusion energy R&D and the fusion energy industry in other nations? To what extent, if any, does U.S. participation in ITER provide a strategic advantage to future economic competitiveness for the United States and for private U.S. companies?

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[38] Senate Committee on Energy and Natural Resources, *Full Committee Hearing to Examine Fusion Energy Technology Development*, September 19, 2024, https://www.energy.senate.gov/hearings/2024/9/full-committee-hearing-to.

[39] Elizabeth Gibney, "ITER Delay: What It Means for Nuclear Fusion," *Nature*, vol. 631, no. 8021 (2024), pp. 488-489.

[40] DOE, *Fusion Energy Strategy 2024*, 2024, https://www.energy.gov/sites/default/files/2024-06/fusion-energy-strategy-2024.pdf.

- To what extent should the FESAC findings and the 2024 DOE Fusion Energy Strategy inform congressional debate about future priorities for U.S. fusion R&D?

Author Information

Todd Kuiken, Coordinator
Analyst in Science and Technology Policy

Martin C. Offutt
Analyst in Energy Policy

Mark Holt
Specialist in Energy Policy

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