

Master Plan For Responsible Advanced Nuclear Development in New York:

Fusion Energy Study

NEW YORK STATE

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Notice

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Summary

Fusion technologies generate power by combining light atomic nuclei rather than, as in the case of nuclear fission, splitting heavy ones. The nuclear fusion industry is evolving from a long-standing scientific research effort to engineering development and early-stage commercialization, driven by recent advancements in plasma physics, materials science, and significant public and private investments.

Continued engagement with fusion technologies at this stage of development presents New York State with the opportunity to help shape an emerging global industry, position the State's research institutions and supply chain providers to contribute to its development, and capture early economic benefits as the sector matures.

Findings

Fusion has made progress and investment is accelerating. Recent advances in plasma physics, enabling technologies, federal funding programs, and private investment have contributed to this increased momentum for the growing fusion ecosystem. A key feature of the industry is public-private interactions with public research institutions and private developers advancing multiple technological pathways in parallel.

There remain significant hurdles to commercialization. Fusion remains in a pre-commercial phase, with significant technical, industrial, regulatory, and market challenges to be addressed before it can be deployed as a reliable source of electricity. As fusion technologies continue to advance, their role within future energy systems will depend on the pace at which these challenges are addressed. Given these dependencies, deployment timelines remain uncertain.

For New York State, near-term action can most meaningfully focus on readiness and option value, such as strengthening research and industrial capabilities and monitoring technology pathways; maximizing economic benefits from supply chain opportunities and ensuring the regulatory framework is ready to enable developments as the market progresses. **These issues are considered throughout the Advanced Nuclear Master Plan including in the Master Plan studies on Supply Chain, Regulatory Issues and Safety, and Research & Development.**

1. Introduction

This Fusion Energy Study is one of a collection of studies prepared by New York State Energy Research and Development Authority (NYSERDA) and Department of Public Service (DPS) as part of the "Master Plan for Responsible Advanced Nuclear Development in New York" (Master Plan). Collectively, these studies examine the technical, economic, workforce, supply chain, regulatory, environmental, community, and infrastructure considerations associated with the potential deployment of advanced nuclear technologies in the state. Each study addresses a distinct topic area and offers analysis, findings and conclusions to contribute to a comprehensive roadmap for advanced nuclear development in New York State.

NYSERDA and DPS acknowledge the contributions of The Brattle Group in preparing this study as well as supporting the discussion of fusion matters in other Master Plan studies. At the direction of NYSERDA and DPS, contractor Eastern Research Group (ERG) convened and facilitated a Fusion Technical Working Group (FUS–TWG) made up of relevant and expert stakeholders to inform and validate this study.[1]

Fusion could become a viable option for New York State's energy supply if and when a company can demonstrate the ability to achieve net positive power generation with the potential to be cost competitive. If commercially successful, fusion power has the potential to unlock enormous amounts of carbon-free heat and power ideal for complementing fission, wind, and solar energy.

The overall purpose of this study is to assess the state of progress on nuclear fusion. This study assesses the current state of fusion energy development, including public sector programs, status of private investment in the nascent industry, the commercial and technological maturity of the technology, and key barriers to commercialization. The study was developed using publicly available reports, academic and industry research, regulatory materials, industry databases, and information obtained through stakeholder outreach. The analysis is intended to reflect the current state of a rapidly evolving industry.

The Fusion Energy Study includes the following sections:

- **Section 2, Introduction to Fusion Energy,** reviews the principles of fusion energy, different technology approaches to commercial fusion, and factors contributing to the recent acceleration of fusion development,
- **Section 3, Public Sector Developments,** provides details on public research and programs at the national the national level in the U.S. as well as other countries.

- **Section 4, Private Sector Developments,** provides details on the technology developers currently pursuing commercial fusion machines and private investment in this budding industry.

- **Section 5, Commercialization Pathways and Challenges,** identifies key milestones and challenges as the industry moves towards commercialization.

Other aspects of fusion energy are examined as part of the broader collection of studies supporting the Master Plan. In particular, the Master Plan Supply Chain Study identifies areas where the state may have comparative fusion supply chain advantages and emerging capabilities, the Master Plan Research and Development (R&D) Study identifies technical challenges to deployment and considers what roles New York State could play in the fusion R&D ecosystem, and the Master Plan Regulatory Issues and Safety Study reviews the safety and environmental considerations of fusion, provides an overview of the developing federal framework and subsequent responsibilities of New York State entities.

2. Introduction to Fusion Energy

Meeting growing energy demand, while achieving deep decarbonization within practical economic, technological, and infrastructural constraints represents a major challenge for energy systems. Fusion energy has long been viewed as a potential source of abundant, low-carbon electricity, but for seven decades it remained primarily a scientific endeavor rather than a near-term energy option. In recent years, several developments, including achievement of scientific energy gain, advances in enabling technologies, and sharply increased investment in fusion commercialization, have shifted the field from incremental and theoretical research toward a more accelerated phase of technological and commercial exploration for electricity production.

This section reviews the principles of fusion energy, different technology approaches to commercial fusion, and factors contributing to the recent acceleration of fusion development.

2.1 Overview of Fusion

Fusion is the process by which two light atomic nuclei combine to form a single heavier nucleus, releasing energy. This process occurs naturally in stars, where immense gravitational pressure and extremely high temperatures create the conditions necessary to sustain fusion reactions.

On Earth, scientists and engineers seek to create and control these conditions artificially. However, replicating such conditions is challenging and requires achieving sufficient temperature, density, and confinement time, commonly referred to as the Lawson criterion or triple product. A plasma of fusion fuel must be heated to extremely high temperatures (often exceeding 100 million degrees Celsius) so that atomic nuclei have sufficient kinetic energy to overcome their electrostatic repulsion.[a,2] At the same time, the plasma must be maintained at a particle density and confined for a sufficient duration such that fusion reactions occur frequently enough to produce net energy. For fusion approaches using the commonly pursued deuterium–tritium (D-T) fusion reaction (discussed in the following section), the required combination of plasma density and confinement time depends strongly on the fusion approach (discussed in detail in the next section).

Most fusion concepts under development rely on the D-T reaction. This reaction uses two isotopes of hydrogen—deuterium and tritium—as fuel, with lithium playing a supporting role in sustaining the fuel cycle. When deuterium and tritium fuse at high energy, they produce helium and a high-energy

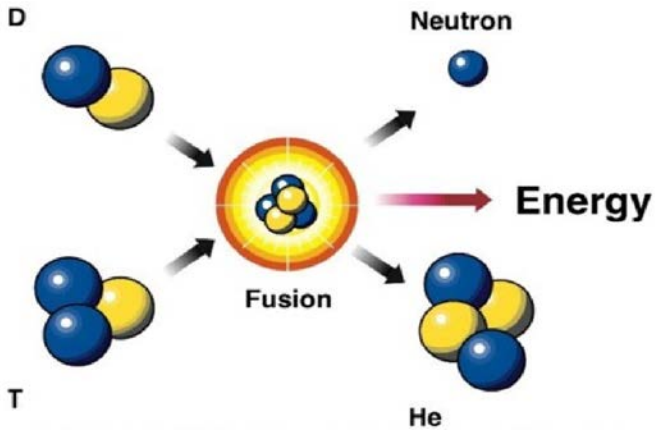
[a] This discussion focuses on fusion concepts that rely on high-temperature plasma confinement and does not address less-established or less widely studied approaches, including lattice confinement, low-energy nuclear reaction concepts, or "cold fusion," which remain outside the mainstream basis for current fusion power-plant designs.

neutron (Figure 1).[b,3] These neutrons carry most of the energy released in the reaction. In many fusion power plant designs, this neutron energy is absorbed by surrounding blanket materials, generating heat that can be used to produce steam and drive turbines for electricity generation.

Figure 1. Illustrative Deuterium-Tritium Fusion Reaction

Deuterium (D) with one proton (yellow) and one neutron (blue) combines with tritium (T) with one proton and two neutrons to release a neutron and helium atom.[4]

***Source**: U.S. Department of Energy, "DOE Explains...Fusion Reactions."*



Deuterium, tritium, and lithium have distinct physical properties that influence how fusion reactions occur, how fuel is handled, and how byproducts are generated and managed.

- **Deuterium** is a stable, non-radioactive isotope of hydrogen that is naturally abundant and can be extracted from seawater. It serves as one of the two primary fuel components in most fusion systems. Because it is non-radioactive and widely available, deuterium does not present significant technical challenges in terms of sourcing or handling, and its use is relatively straightforward compared to other fuel cycle elements.

- **Tritium** is the second primary fuel component and plays a central role in enabling fusion reactions. Unlike deuterium, tritium is radioactive, scarce, and difficult to contain due to its ability to permeate materials. Sustained fusion operation will depend on producing tritium within the reactor itself. In most designs, this will be achieved through a process known as "tritium breeding," in which high-energy neutrons from fusion reactions interact with lithium-containing materials in a surrounding blanket to generate new tritium.[5] Though tritium

[b] Other reactions being explored include the Deuterium-Helium-3 and Proton-Boron-11 reactions. Though they are both considered aneutronic (meaning they produce significantly less radioactive waste compared to D-T fusion), they require substantially higher ignition temperatures that have been difficult to achieve.

breeding has been demonstrated at a proof-of-concept level, large-scale, continuous tritium breeding remains theoretical.[6]

- **Lithium** is incorporated into the breeding blankets surrounding the plasma to enable in-situ production of tritium. In breeding blankets, high-energy neutrons generated during fusion reactions interact with lithium to produce new tritium. This process will allow fusion systems to partially or fully sustain their own fuel supply.

Table 1. Summary of Nuclear Fusion Characteristics

Feature	Characteristic
Basic Process	Combining two light nuclei to form a single, heavier nucleus.
Typical Fuel	Light elements, typically Hydrogen isotopes (Deuterium and Tritium).
Energy Yield (Fuel Energy Only)	Extremely high energy density. D-T fusion releases roughly 340 TJ/kg of fuel consumed, or about 3 to 4 times more energy per unit of mass than fission.
Conditions Required	Requires extreme temperatures (100 + million degrees) and high pressure to overcome the electrostatic repulsion between nuclei.
Radioactive Waste	Produces mostly harmless Helium. The reaction does release neutrons which can make reactor walls radioactive (activated materials), but it creates no long-lived nuclear waste.
Safety	If containment is lost, the plasma cools down and the reaction stops. Reaction requires external energy to occur and cools down if stopped

2.2 Technology Approaches to Fusion Energy

Fusion development is currently being pursued through several distinct technological approaches, which differ in how they create and maintain the plasma conditions (e.g. temperature, density, and confinement time) required to achieve fusion reactions. They can be broadly categorized into three groups: magnetic confinement fusion (MCF), inertial confinement fusion (ICF), and magneto-inertial fusion (MIF).

2.2.1 Magnetic Confinement Fusion

MCF uses powerful magnetic fields to confine high-temperature plasma within a vacuum chamber. Because fusion plasmas can exceed temperatures of 100 million degrees Celsius, they cannot come into contact with reactor walls. Magnetic fields therefore act as a “magnetic bottle” to confine and control the plasma. Magnetic confinement systems typically operate at relatively low plasma densities with confinement times ranging from fractions of a second to several seconds.

MCF systems generally fall into two primary configurations: tokamaks and stellarators. These two configurations use different engineering approaches to generate the twisted magnetic fields needed

to stabilize the plasma. The **tokamak** (Figure 2) generates this helical magnetic field using a combination of external magnetic coils and a powerful electrical current driven through the plasma itself. They have historically been easier to design and construct than other magnetic confinement concepts, however, the plasma current that enables confinement can also introduce instabilities. The **stellarator** (Figure 3) uses complex external magnet coils that are carefully shaped to produce a three-dimensional helical magnetic field. This configuration eliminates the risk of instabilities and allows for inherently steady-state operation. However, the complex geometry makes stellarators significantly more difficult to design, manufacture, and construct.

Figure 2. Tokamak

A tokamak generates a helical magnetic field using a relatively symmetrical, toroidal plasma chamber[7]

Source: *Francesco Romanelli, "Fusion Energy," 2020;*

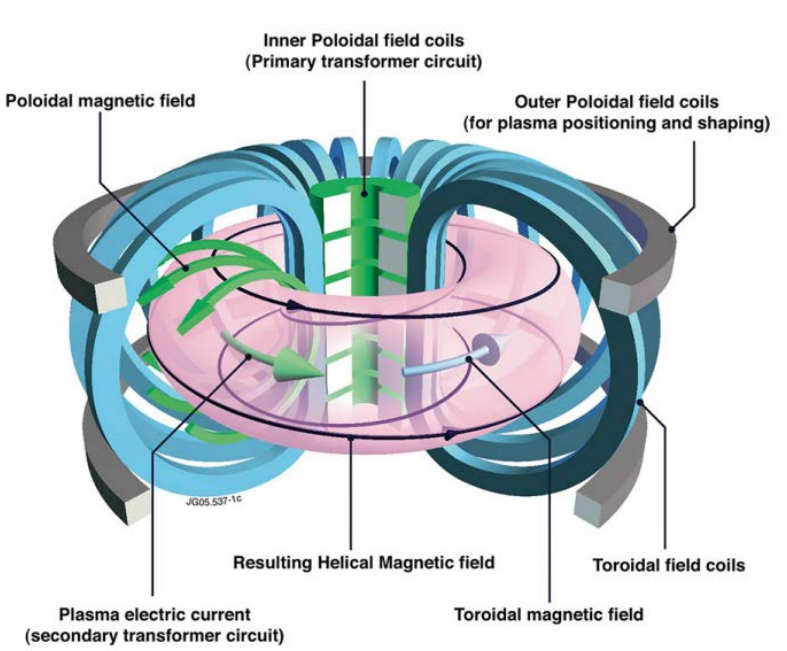
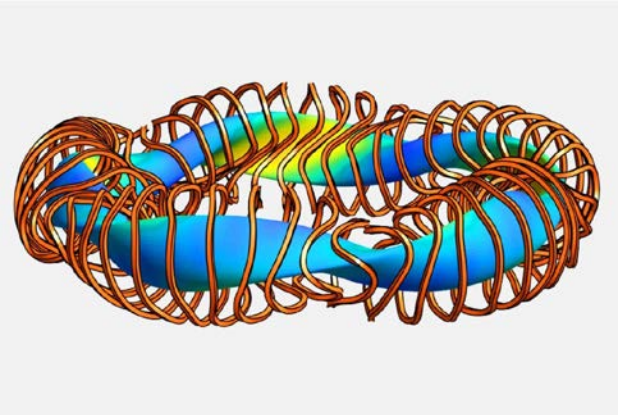


Figure 3. Stellarator

A stellarator has magnets carefully shaped and twisted in such a way as to direct the magnetic field lines around the stellarator's torus (the doughnut-shaped area of the reactor where the plasma is contained). This produces a 3D helical magnetic field[8]. The plasma is contained in a twisted circle with coils representing magnets.

Source: John Greenwald, "PPPL Researcher's Work Yields a Breakthrough For a Promising Fusion-Energy Device," 2022.



2.2.2 Inertial Confinement Fusion

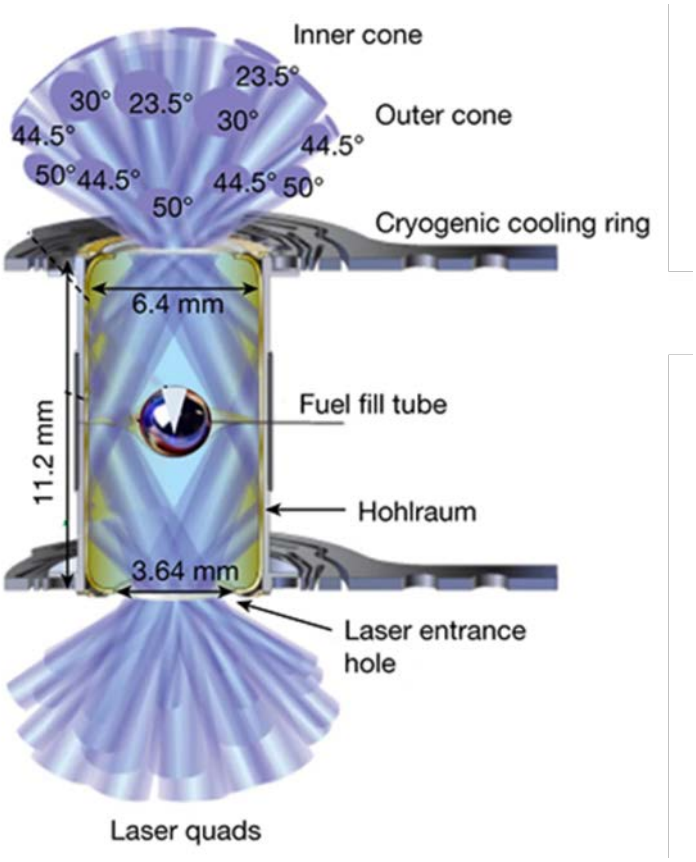
ICF takes a fundamentally different approach than MCF. ICF seeks to achieve fusion conditions by rapidly compressing a small fuel pellet to extremely high densities, but for very short confinement times, typically on the order of nanoseconds (one billionth of a second, 10^{-9}) (Figure 4).[c] Because many systems use high-powered lasers to drive this compression, the approach is often referred to as "laser fusion," though some developers are pursuing alternative drivers.[9]

[c] For reference, at sea level (room temperature, 1 atm), air has roughly 2.5×10^{25} particles per cubic.

Figure 4. Inertial Confinement Fusion Diagram

Lasers are used to compress a fuel pellet to extremely high densities.[10]

Source: Lawrence Livermore National Laboratory, "Fusion Ignition and the Path to Inertial Fusion Energy," 2024.



2.2.3 Magneto-Inertial Fusion /Magnetized Target Fusion

MIF, sometimes referred to as magnetized target fusion, is a hybrid approach that combines aspects of both MCF and ICF systems. In these systems, plasma is first generated and magnetized to reduce heat losses. The plasma is then rapidly compressed to reach the temperature and density conditions required for fusion reactions. Different MIF concepts employ a range of compression and confinement techniques. For example, some approaches use pulsed magnetic fields to accelerate and collide magnetized plasma rings,[11] while others use mechanically driven pistons to compress a sphere of liquid metal containing the plasma.[12] Alternative concepts rely on sheared-flow stabilization (Z-pinch) to confine plasma without external magnetic coils.[13] By combining magnetic insulation with rapid compression, MIF concepts seek to achieve fusion conditions using potentially smaller and less complex devices than traditional magnetic confinement reactors or large laser facilities.

2.3 Factors Contributing to the Recent Acceleration of Fusion Development

Fusion energy is transitioning from a long-standing scientific research effort toward an emerging field of engineering development and early-stage commercialization. This section reviews the recent technical advances that offer the prospect of commercialization, the process of commercialization, and the market participants driving it. It concludes with findings including on New York State's role on nuclear fusion as considered across the Master Plan including in the Supply Chain, Regulatory Issues and Safety, and R&D studies.

Two key areas of technological development have increased confidence in fusion's viability and have shifted fusion from a primarily exploratory scientific domain toward a more integrated, engineering- and deployment-oriented field:

- Recent experimental results have reduced uncertainty in technical feasibility, and
- Advances in enabling technologies have improved the ability to design and control fusion systems.

In addition, as discussed in the Master Plan R&D Study, policy frameworks along with public and private investments over the past few decades have continued to prepare the ground for commercial implementation.

2.4 Validated Fusion Performance and Transition to Engineering Systems

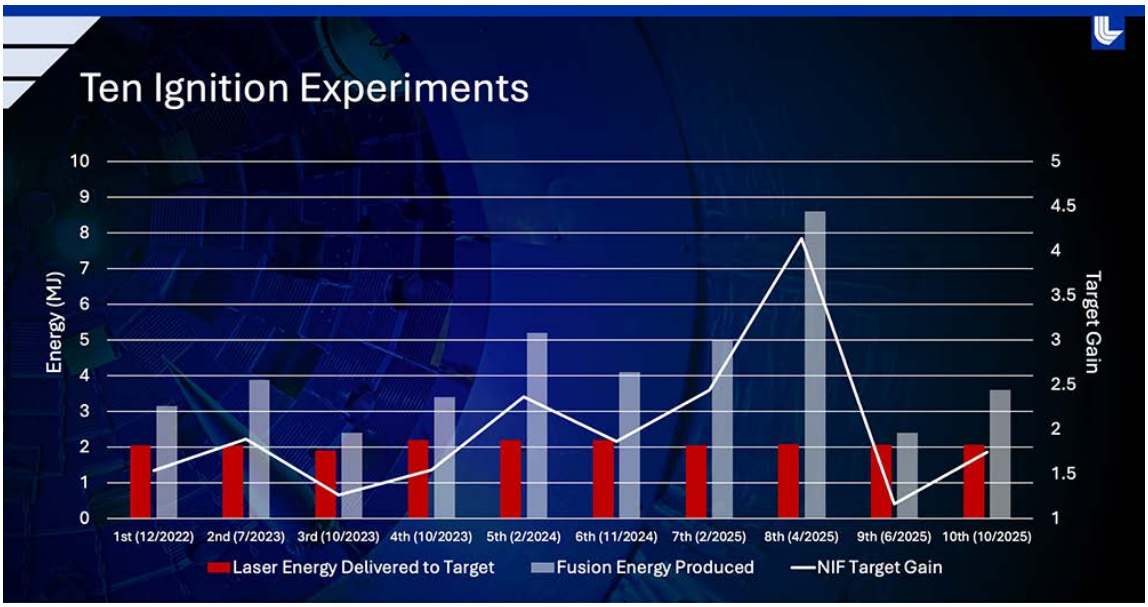
Recent milestones have demonstrated producing energy through fusion is physically achievable, but they have not yet demonstrated a complete energy system capable of producing net electricity. Nearly seven decades of fusion research have advanced foundational knowledge in plasma physics, experimental validation, and computational modeling. More recently, experiments have validated fusion performance, reduced long-standing scientific uncertainties, and demonstrated key conditions required for fusion energy production. The transition now underway is from scientific validation toward engineering-relevant systems that can repeat, control, integrate, and convert fusion reactions into useful energy production.

A major milestone for ICF research occurred in December 2022 at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) in the United States. In this experiment, 192 high-energy lasers delivered approximately 2.05 megajoules of energy to a small D-T fuel target, producing 3.15 megajoules of fusion energy.[14] This was the first demonstration of scientific energy gain in a laboratory fusion experiment. Since that time, NIF has reproduced those results more than 10 times,

with later experiments producing higher energy yields approaching four times the laser energy delivered to the target (Figure 5). Though this is the only demonstration of scientific energy gain globally to date, this progress reduces scientific risk and confirms that fusion energy gain is physically achievable.

Figure 5. Experimental Fusion Ignitions and Energy Yield achieved at NIF at LLNL

Laser energy delivered and energy produced from fusion at ignition shots at NIF at LLNL from 2022 to 2025.[15]



These results do not reflect energy gain at the facility level. A commercially viable fusion power plant must deliver net electricity to the grid, accounting for all plant systems, conversion losses, and auxiliary power consumption. This system-level measure of performance is often referred to as "engineering gain." For ICF, scientific gains around 10 are expected to be required to achieve net engineering gain, while scientific gain on the order of 30 to 100 is commonly cited as potentially necessary for cost-effective power production.[16]

Unlike ICF experiments, MCF systems have not yet demonstrated net energy gain. Instead, MCF systems are making steady progress toward plasma confinement, or maintaining a hot, unstable plasma within magnetic fields for extended periods without significant energy loss.[d] This is a central challenge for sustained operation.[17]

[d] The longest reactor-relevant magnetic-confinement fusion plasma duration commonly cited today is 1,337 seconds, or just over 22 minutes, achieved by the WEST tokamak in 2025.

It is a critical step because it enables examination of how fusion reactions begin to influence system performance. This provides a bridge between scientific gain and the integrated performance characteristics needed for practical fusion energy systems.

Though many scientific challenges still remain, these developments are driving a broader shift in fusion research from fundamental plasma science toward integrated, engineering-relevant system regimes. Increasingly, physical experiments are designed to approximate power plant–relevant conditions And Research efforts are increasingly focused on system integration, operational reliability, and performance under sustained conditions. These are essential considerations to translate experimental progress into viable energy technologies.[18]

2.5 Advances in Enabling Technologies

In parallel, a set of enabling technologies has matured to support the practical realization of fusion systems. Spanning computational tools, advanced materials, and precision energy delivery and control systems, these developments have improved the ability to design, build, and operate fusion devices with greater accuracy and reliability. They have reduced experimental uncertainty, accelerated development timelines, and supported the transition from physics experiments to integrated, reactor-scale systems.

Advances in high-performance computing (HPC), artificial intelligence (AI)/machine learning (ML)-enabled modeling and multi-physics simulation have played a central role in this shift. Researchers are now able to model plasma behavior with increasing fidelity and accelerate optimization and control-oriented prediction.[19] These tools support a more design-driven approach to development.[e,20]

At the same time, progress in materials science, particularly the development of high-temperature superconductors (HTS) and plasma-facing materials, is expanding the feasible operating space for fusion systems. Stronger magnetic fields enabled by HTS magnets support improved plasma confinement and more compact reactor designs, while advances in materials resilience address challenges associated with extreme heat loads and neutron flux.[21]

In addition, improvements in energy delivery and control systems have enabled more precise operation of fusion experiments. Advances in high-power laser systems and pulsed energy technologies have made possible the ignition-scale experiments at NIF.[22] Enhanced diagnostics and

[e] More recently, researchers have begun exploring hybrid quantum-classical computing as a potential extension of HPC-based fusion modeling, particularly for computationally intensive plasma simulation and optimization problems, although these applications remain early-stage and have not yet displaced classical supercomputing approaches.

real-time control systems have allowed for more accurate measurement and stabilization of plasma behavior, supporting operation in increasingly complex and high-performance regimes.[23]

Collectively, these enabling technologies have helped make fusion development more predictable and design-driven. They reduce uncertainty in system behavior and support faster iteration between design and experiment. Though substantial scientific, technical, and engineering challenges remain (discussed in a subsequent section), these advances help move fusion development beyond experimental validation toward the engineering and optimization of fusion systems intended for practical energy applications.

3. Public Sector Developments

Fusion development is supported by a global ecosystem that includes publicly funded research institutions, universities, and a rapidly growing set of private technology developers. Historically, progress in fusion has been driven primarily by national laboratories and government-funded research programs, which established the scientific foundations of plasma physics, developed key technologies, and built large-scale experimental facilities. Public programs continue to support foundational research, large-scale infrastructure, and long-term capability development, while a growing number of private companies are focused on system integration, prototype development, and demonstration of commercially relevant designs. The following sections outline the respective roles of public institutions, private developers, and public–private collaboration mechanisms in shaping the current fusion development landscape.

This section is based on publicly available information and is intended to review the current state of public and private research and investment at the state and national level in the U.S. as well as other countries, as well as to identify the roles each party plays to advance the industry.

3.1 Federal and International Programs

Historically, public funding for fusion development has focused on advancing scientific understanding and supporting large-scale experimental facilities. These investments have enabled the construction and operation of complex research infrastructure, such as tokamaks, laser systems, and HPC capabilities, that form the foundation of modern fusion science. These activities are primarily funded and directed by governments and international partnerships, reflecting the scale, technical complexity, and long development timelines associated with fusion energy. National laboratories, universities, and international collaborations operate many of the experimental facilities used to study plasma behavior, materials performance, and reactor design, while also maintaining the computational and experimental infrastructure that underpins the broader research ecosystem.

In recent years, public-sector funding programs are placing greater emphasis on programs that bridge early-stage research and system-level development, with funding increasingly targeted toward technology maturation, engineering validation, and early demonstration efforts rather than basic science. These programs also coordinate development pathways around defined technical milestones and help focus activity on challenges to scaling fusion systems toward pilot and demonstration stages.

3.1.1 United States

In the United States, fusion research is supported primarily through the U.S. Department of Energy's (DOE's) Fusion Energy Sciences (FES) program, which funds work at national laboratories such as LLNL, Princeton Plasma Physics Laboratory (PPPL), and Oak Ridge National Laboratory (ORNL), as well as university-based research programs, including the University of Rochester's Laboratory for Laser Energetics (LLE). These institutions conduct research comprising plasma physics, high-energy-density physics, materials science, and reactor technology, and provide critical capabilities in HPC and advanced modeling. These publicly supported capabilities enable large-scale simulation, experimental validation, and long-term research efforts that are not typically feasible within private-sector development models. Selected major U.S.-based fusion research facilities are summarized in Table 2.

Table 2. Select U.S.-Based Public Fusion Research Facilities and Programs

Institution / Operator	Program	Technology Type	Focus & Achievements
Lawrence Livermore National Laboratory	National Ignition Facility (NIF)	ICF	Achieved ignition and target-level energy gain
Princeton Plasma Physics Laboratory	NSTX-U	Tokamak (MCF)	Spherical tokamak; confinement and plasma physics research
Oak Ridge National Laboratory	Materials / neutron research programs	Cross-cutting	Fusion materials and neutron effects research
Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center (DOE-supported)	Alcator C-Mod (concluded in 2016)	Tokamak (MCF)	High-field tokamak; informs modern HTS designs
University of Rochester	Laboratory for Laser Energetics (LLE)	ICF	Laser-driven fusion research supporting NIF and direct-drive concepts
Brookhaven National Laboratory	Superconducting Magnet Division; National Synchrotron Light Source II (NSLS-II) and Center for Functional Nanomaterials	Cross-cutting / MCF-enabling technology	High-field superconducting magnets and radiation tolerant materials development.
Sandia National Laboratories	Z Pulsed Power Facility	MIF	Focused on defense applications for high energy density plasma Magnetized liner inertial fusion

In the United States, the DOE's Fusion Science and Technology Roadmap outlines coordinated activities across near-, mid-, and long-term horizons, aligning public research programs, private-sector development, and pilot plant goals. The DOE's Fusion Energy Sciences program has expanded funding for programs to accelerate the development and validation of technologies needed for fusion energy systems.[24] These include:

- **Innovation Network for Fusion Energy (INFUSE):** Provides cost-shared funding to connect private developers with national laboratories and universities, supporting targeted R&D projects in areas such as materials, plasma physics, and system components. In 2025, DOE announced $6.1 million in funding for 20 projects selected under this program.

- **Fusion Innovative Research Engine (FIRE) Collaboratives:** Supports coordinated, multi-institution research efforts focused on advancing critical technologies needed for fusion systems. In 2025, DOE announced $128 million in funding for seven teams

- **Fusion Milestone Program:** Provides cost-shared, milestone-based funding to private companies developing pilot-scale fusion systems, with awards tied to achieving specific technical and engineering objectives. In 2023, DOE announced approximately $46 million in initial awards to eight fusion companies, reflecting a shift toward funding structures that directly support system-level development and commercialization-relevant outcomes. [xxxix]

3.1.2 International and Multi-national

The International Thermonuclear Experimental Reactor (ITER) project in southern France is the largest international fusion collaboration currently underway; it involves 33 participating nations, including the United States, European Union, China, India, Japan, Russia, and South Korea. ITER is designed to demonstrate sustained "burning plasma" operation in a large tokamak device and is intended to generate data on plasma behavior, materials performance, and system integration under reactor-scale conditions, which is important information for designing and developing future fusion power plants. [25] As a publicly funded, multinational project, ITER represents a coordinated effort to address scientific and engineering challenges that exceed the capacity of individual national programs.

Several other countries maintain national fusion research programs, supported by large-scale experimental facilities and long-term public investment. The United Kingdom's Spherical Tokamak for Energy Production (STEP) program is a long-term, government-led effort to demonstrate a prototype fusion power plant and facilitate industrial participation. Germany's Max Planck Institute for Plasma Physics operates the Wendelstein 7-X stellarator, one of the most advanced devices of its kind. Japan supports fusion research through the JT-60SA tokamak and related programs managed by the

National Institutes for Quantum Science and Technology, and China has significantly expanded its capabilities through facilities such as the Experimental Advanced Superconducting Tokamak (EAST) and planned next-generation systems. In addition to these active programs, the Joint European Torus (JET) is the most advanced completed D-T tokamak experiment and serves as a reference for ITER. Selected major international fusion research programs are summarized in Table 3.

Table 3. Select International Public Fusion Research Facilities and Programs

Institution	Country	Project	Technology Type	Status	Objective
ITER	International (EU, US, China, India, Japan, Russia, Korea)	ITER	Tokamak (MCF)	Under construction	Produce/study sustained burning plasma
UK Atomic Energy Authority (UKAEA) / EUROfusion	EU, UK, Several other European countries	JET	Tokamak (MCF)	Completed	Until recently, largest and only operational D-T tokamak experiment; Provided key data for ITER
UKAEA	UK	STEP	Tokamak (MCF)	Planned (concept design phase)	Prototype fusion power plant
Chinese Academy of Sciences (ASIPP)	China	EAST	Tokamak (MCF)	Operational	Advanced superconducting tokamak; long-pulse operation
China National Nuclear Corporation / SWIP	China	CFETR (planned)	Tokamak (MCF)	In Design/Under Preliminary Evaluation	Demonstration reactor-scale device
National Institutes for Quantum Science and Technology (QST)	Japan	JT-60SA	Tokamak (MCF)	Commissioning/ Testing	Superconducting tokamak supporting ITER physics and advanced scenario development
Max Planck Institute for Plasma Physics	Germany	Wendelstein 7-X	Stellarator (MCF)	Operational	Advanced stellarator; steady-state confinement research

Table 3. (Continued)

Institution	Country	Project	Technology Type	Status	Objective
National Institute for Fusion Science (NIFS)	Japan	LHD	Stellarator (MCF)	Completed	Long-running heliotron-type stellarator experiment
Korea Institute of Fusion Energy (KFE)	South Korea	KSTAR	Tokamak (MCF)	Operational	Advanced superconducting tokamak; long-duration plasma experiments

3.2 Public-Private Collaboration

The interaction between public research institutions and private developers has become a defining feature of the modern fusion ecosystem. While public programs continue to provide the scientific foundation, large-scale infrastructure, and long-term research continuity required for fusion development, private companies are increasingly focused on translating these advances into integrated systems and commercially relevant designs. As a result, there is increasing collaboration between the public and private sectors. In some cases, private entities operate publicly funded research infrastructure. For example, General Atomics operates the DOE–funded DIII-D National Fusion Facility, providing a platform for publicly supported research under a privately managed model. In other cases, public research institutions serve as the basis for private-sector development through technology transfer and spinout companies. The relationship between MIT's Plasma Science and Fusion Center and Commonwealth Fusion Systems illustrates this model.

At the project level, collaboration increasingly occurs through partnerships between private developers and public institutions or regional stakeholders. For example, Colorado State University has partnered with Marvel Fusion to develop a laser research facility supporting inertial fusion development.[26] In New York State, the University of Rochester's LLE engages with private inertial fusion developers, including Focused Energy who, in 2026 entered into a $6.9 million research collaboration with LLE to tackle ICF-related laser-plasma interaction challenges.[27]. These models emphasize co-location of research and industry, shared infrastructure, and cost-shared development. DOE has explicitly identified public-private partnerships and shared R&D infrastructure as mechanisms to close remaining science and technology gaps.

4. Private Sector Developments

Alongside public programs, a growing number of private companies are developing fusion technologies with a focus on accelerating engineering progress toward commercial systems.

4.1 Technology Developers

More than fifty private fusion companies are currently active worldwide, with activity concentrated primarily in the United States and Europe. These companies span several technological pathways including MCF, ICF, and MIF concepts. Selected private fusion developers and their associated technologies are summarized in Table 4.

Table 4. Select Private Fusion Developers and Technologies

Technology	Country	Sample Companies
MCF: Tokamak	United States	Commonwealth Fusion Systems (CFS)
	United Kingdom	Tokamak Energy
MCF: Stellarator	United States	Thea Energy Type One Energy
	Germany	Proxima Fusion
MCF: Other	United States	TAE Technologies
ICF	United States	Pacific Fusion Blue Laser Fusion Inertia Enterprises Longview Fusion
	Germany	Focused Energy Marvel Fusion
	Japan	Ex-Fusion
MIF	United States	Helion Energy Zap Energy
	Canada	General Fusion

Compared to public research institutions, private fusion companies typically emphasize shorter development cycles, prototype systems, and integrated engineering validation. Rather than focusing primarily on isolated scientific questions, these firms are developing complete systems intended to demonstrate performance under increasingly realistic operating conditions. Multiple technology developers are targeting technology pilot or demonstration projects (Table 5).

Table 5. Select demonstration systems and pilot plants currently in development in the U.S.

Company	Technology	Demonstration or Pilot Plant	State
Commonwealth Fusion Systems (CFS)	MCF	Technology Demonstration	MA
		Pilot Plant	VA
Type One Energy	MCF	Technology Demonstration	TN
TAE Technologies	MCF	Technology Demonstration	CA
Pacific Fusion	ICF	Technology Demonstration	NM
Helion Energy	MIF	Pilot Plant	WA
Zap Energy	MIF	Technology Demonstration	WA
Realta Fusion	MCF	Technology Demonstration	WI

Private sector activity extends beyond developers to include an evolving supply chain ecosystem. The Master Plan Supply Chain study identifies the relevant supply chain categories and provides a targeted overview of the landscape in New York State.

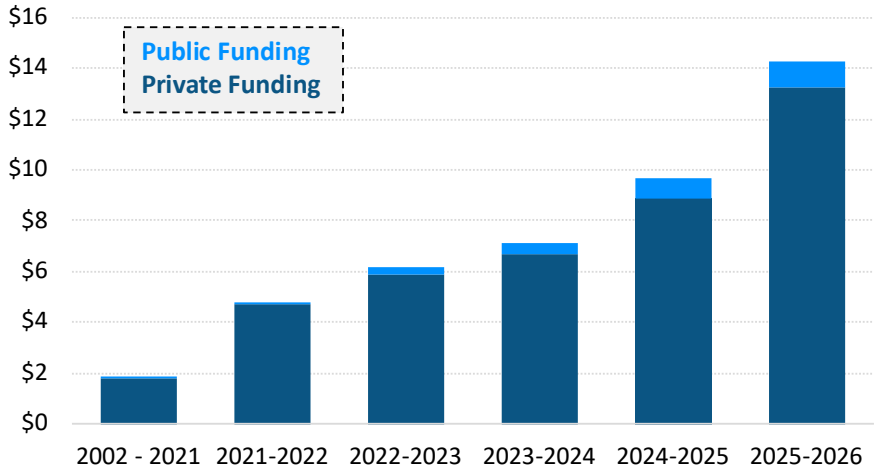
4.2 Private Investment

Private investment has become an important driver of fusion development, enabling companies to pursue engineering validation, prototype systems, and alternative design approaches on accelerated timelines. Investment has grown rapidly, with cumulative industry-reported funding increasing by over 7.5-fold between 2021 and 2026 to now exceed $14 billion globally (Figure 6). Within the funding captured by the Fusion Industry Association's (FIA's) industry survey, private sources account for the vast majority of cumulative investment, while public funding represents approximately 7%.[f]

[f] This measure does not capture the full value of government-supported fusion research infrastructure and programs as this is based on industry reporting.

Figure 6. Cumulative Fusion Industry Funding

Source: Fusion Industry Association, 2026 Global Fusion Industry Report (2026), https://www.fusionindustryassociation.org/wp-content/uploads/2026/07/FIA-Industry-report-2026_d9.pdf.



Despite the rapid growth in private investment, capital is not necessarily broadly available across the fusion ecosystem. As highlighted by the FUS-TWG, private funding has been concentrated in a relatively small number of fusion developers, while applied university research, shared testing infrastructure, and early-stage technology development are under-resourced. Furthermore, many component and manufacturing suppliers likely require comparatively modest but patient capital to develop, qualify, or scale fusion-specific products, while lacking the potential returns or growth profiles typically sought by venture investors.

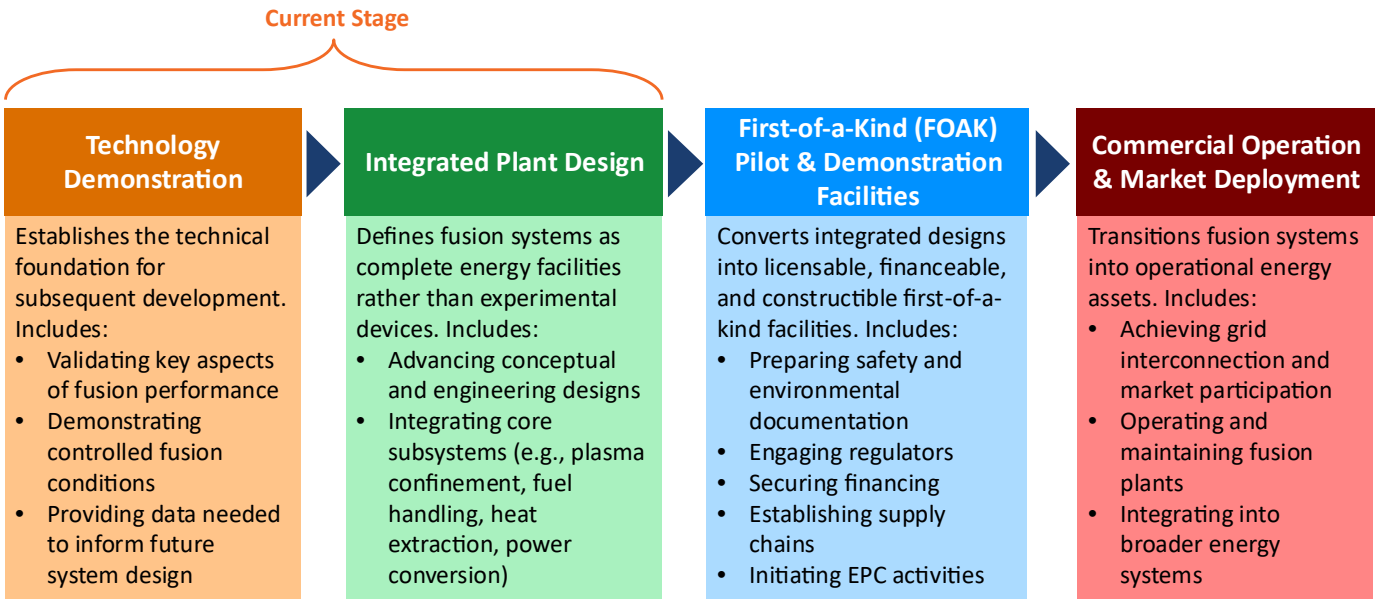
5. Commercialization Pathways and Challenges

Fusion energy is transitioning from a long-standing scientific research effort toward an emerging field of engineering development and early-stage commercialization. This section reviews the commercialization challenges and industry priorities.

5.1 Development Stages

Fusion commercialization is expected to proceed through several stages as shown in Figure 7: technology demonstration, integrated plant design and engineering, first-of-a-kind (FOAK) pilot or demonstration project development, and eventual commercial operation. Demonstration systems establish the technical foundation by validating key aspects of fusion performance, testing components and control approaches, and generating data needed to inform future designs. Integrated plant design then translates these results into complete energy-facility concepts, incorporating core subsystems such as plasma confinement, fuel handling, heat extraction, power conversion, controls, and safety systems. FOAK pilot and demonstration projects are the next step: converting integrated designs into licensable, financeable, and constructible facilities that can test fusion systems under power-plant-relevant operating conditions. Commercial deployment would follow only after these systems demonstrate reliable operation, grid integration, maintainability, and performance at scale.

Figure 7. Fusion Development Stages



The fusion sector is currently moving from experimental validation toward integrated plant design and early FOAK project development. While recent experiments have demonstrated meaningful progress

in producing and controlling fusion reactions, no fusion system has yet operated as a complete electricity-generating facility with sustained, integrated performance across the plasma system, fuel cycle, heat extraction system, power conversion equipment, and supporting plant infrastructure. This creates a commercialization gap between demonstrating fusion conditions and deploying fusion as a reliable energy asset.

5.2 Commercialization Challenges

There remain challenges moving through this pathway. Bridging the gap between experimental fusion systems and commercially deployable fusion plants will require advances across several technical and engineering domains, and several critical components remain underdeveloped with limited analogs in other industries and will require dedicated development. These technical gaps are evaluated alongside the capabilities of New York State research institutions in the Master Plan R&D Study.

Supply chain and workforce constraints will also play a central role in determining the pace, cost, and feasibility of commercialization. Fusion systems must be supported by supply chains capable of producing specialized components at scale. A significant portion of the fusion supply chain overlaps with existing industries that support applications in aerospace, advanced nuclear, defense, and scientific research. However, fusion applications impose more demanding performance requirements. The fusion supply chain is evaluated in more detail in the Master Plan Supply Chain Study. Fusion systems will also require a workforce able to design, construct, and operate complex facilities. Currently, those needs are concentrated in research and early-stage engineering, but as the industry progresses needs are expected to shift to a broader set of capabilities associated with power plant design, construction, and operation.

These challenges do not carry equal weight across all stages of fusion development. Industry perspectives provide insight into how these challenges are prioritized over time, particularly as technologies transition from experimental systems to pilot plants and commercial facilities. This prioritization provides a basis for understanding how fusion development may progress over time.

Survey data from the FIA indicate that developers place the greatest emphasis on near-term challenges that directly affect demonstration and pilot-scale systems, such as achieving reliable fusion performance and advancing engineering validation. At the same time, several industrial constraints, particularly supply chain readiness, manufacturing capacity, and supplier availability, are also identified as high-priority near-term challenges. System integration and engineering validation remain high priorities across both time horizons, underscoring the importance of developing fully integrated plant designs that combine plasma performance, materials, fuel cycle systems, and balance-of-plant

infrastructure. This reflects the central role of pilot plants as a bridge between experimental devices and commercial deployment. Table 6 summarizes these challenges.

Table 6. Fusion Commercialization Challenges and Industry Priorities

Select commercialization challenges of the fusion industry are viewed as either high (dark blue) or medium (blue) priority in the near and longer term.[28]

Commercialization Challenge	Relevant Fusion Technologies	Industry Priority (Near Term)	Industry Priority (Longer Term)
System Integration and Net Plant Performance	MCF, ICF, MIF	**High**	**High**
Tritium Fuel Cycle and Fuel Self-Sufficiency	MCF, ICF, MIF	**Medium**	**High**
Materials and Component Performance	MCF, ICF, MIF	**Medium**	**High**
Plasma Stability and Confinement	MCF, MIF	**High**	**Medium**
Plasma-Facing Components and Divertor Operations	MCF	**Medium**	**High**
Fuel Target Fabrication and Injection	ICF	**Medium**	**Medium**
Repetitive Driver and Pulsed-System Performance	ICF, MIF	**High**	**Medium**
Synchronized Magnetization, Compression, and Control	MIF	**Medium**	**Medium**
Supply Chain Readiness and Manufacturing Capacity	MCF, ICF, MIF	**High**	**High**
Workforce Availability and Skills Development	MCF, ICF, MIF	**Medium**	**High**

There is currently no clear indicator which technology approach (MCF, ICF, MIF, or other) will ultimately produce a commercially-viable power plant. Both industry perspectives and public-sector projections indicate that fusion deployment timelines are not defined by a single milestone, but by progress across a set of interdependent challenges, particularly those associated with system performance, integration, and supply chain readiness in the near term, and materials, fuel cycle systems, and operational reliability over longer time horizons. The pace at which these challenges are addressed will ultimately determine the timing and scale of fusion's transition from demonstration systems to commercially deployed energy infrastructure, but FUS-TWG participants emphasized that external factors, including supply chain disruptions, the availability and cost of key materials, and continued access to private and public financing, could materially affect development timelines.

Both the costs and risks involved in overcoming these uncertainties are significant, and government action to continue to push fusion technology forward to overcome these challenges therefore has a long history of proceeding primarily at the level of national governments or multi-national initiatives (as discussed in more detail in the Master Plan R&D Study). A transition to state-led action to pursue deployment may become opportune when further progress has been achieved. In the meantime, State investments should focus on creating durable public value (such as action aimed at economic benefits and supply chain development) and offering enabling actions (such as by reviewing regulatory structures to ensure they are ready to respond to the specific characteristics of fusion projects). The State's objective should be to capture the economic and institutional upside of becoming a fusion-ready location. These types of opportunities are discussed further in the Master Plan Supply Chain, Regulatory Issues and R&D studies.

5.3 Findings

Fusion has made progress and investment is accelerating. Recent advances in plasma physics, enabling technologies, federal funding programs, and private investment have contributed to this increased momentum for the growing fusion ecosystem. A key feature of the industry is public-private interactions with public research institutions and private developers advancing multiple technological pathways in parallel.

There remain significant hurdles to commercialization. Fusion remains in a pre-commercial phase, with significant technical, industrial, regulatory, and market challenges to be addressed before it can be deployed as a reliable source of electricity. As fusion technologies continue to advance, their role within future energy systems will depend on the pace at which these challenges are addressed. Given these dependencies, deployment timelines remain uncertain.

For New York State, near-term action can most meaningfully focus on readiness and option value, such as strengthening research and industrial capabilities and monitoring technology pathways (considered in the Master Plan R&D Study); maximizing economic benefits from supply chain opportunities (considered in the Master Plan Supply Chain Study) and ensuring the regulatory framework is ready to enable developments as the market progresses (considered in the Master Plan Regulatory Issues and Safety Study).

Acronyms and Abbreviations

AEA	Atomic Energy Act
AI	artificial intelligence
CFS	Commonwealth Fusion Systems
D-T	deuterium–tritium.
DOE	U.S. Department of Energy
FIA	Fusion Industry Association
FIRE	Fusion Innovative Research Engine
FOAK	first-of-a-kind
FUS-TWG	Fusion Technical Working Group
HPC	high-performance computing
HTS	high-temperature superconducting
IAEA	International Atomic Energy Agency
ICF	inertial confinement fusion
INFUSE	Innovation Network for Fusion Energy
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
LLE	Laboratory for Laser Energetics
LLNL	Lawrence Livermore National Laboratory
MCF	magnetic confinement fusion
MIF	magneto-inertial fusion
MIT	Massachusetts Institute of Technology
ML	machine learning
NIF	National Ignition Facility
NSLS-II	National Synchrotron Light Source II
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
PPPL	Princeton Plasma Physics Laboratory
R&D	research and development
STEP	Spherical Tokamak for Energy Production
UKAEA	UK Atomic Energy Authority

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