DOE | MEETING THE SUPPLY CHAIN NEEDS FOR COMMERCIAL FUSION

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1.0 Introduction

With global concerns about climate change ever increasing, the search for new, carbon-free methods to power the grid has taken on a heightened sense of urgency. Internationally, the public and private sectors, encouraged by recent advances in fusion technologies are combining financial resources on a scale rarely seen. The goal is nothing less than the successful commercialization of fusion technology to power the grid by the early 2030's.

The Plasma Science and Fusion Center (PSFC) at the Massachusetts Institute of Technology is playing a central role in the design of SPARC, working in collaboration with a private company, the Commonwealth Fusion Systems (CFS). SPARC is a tokamak, focused on speeding up the commercialization of fusion by the use of high-temperature superconducting (HTS) magnets. Building on the federal government's long-standing investment in fusion research, the private sector is focusing on what it does best - commercialization.[1]

Figure 1: Introducing Commonwealth Fusion Systems
Click here to see video

Initiatives such as this are growing rapidly in all regions and are showcased in numerous publications made available by the Fusion Industry Association (FIA), founded in 2018 by

16 member companies which jointly invested over a billion dollars to transform fusion energy into clean energy that would power the grid.[1] Fueled by the advances in scientific achievements between 2018 and 2023, FIA membership has grown to 34 private fusion companies and over 80 affiliate members working to support the emerging fusion industry. By 2023 over $6 billion had been invested globally in fusion with $6⁺ billion from the private sector and over $270 million from the public sector.[2] Globally, the U.S. remains the leader in both the number of private fusion companies (25) and at generating the most investment. However, significant growth has been observed in Japan, China, Australia, New Zealand, Germany, and Israel, while the UK and Canada have advanced contenders.[3] To stay current on news related to fusion, FIA releases a monthly video usually delivered by a graduate student working at an affiliate member organization.

Figure 2: Fusion News, February 24, 2024

Click here to see video

Some may be wondering: how far fusion is from powering the grid? According to a recent publication by FIA, 25 companies participating in the 2023 annual FIA survey believed that the first fusion plant will deliver electricity to the grid before 2035; while 14 additional respondents anticipate that it will take longer – extending out to 2050. To get there will

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[1] The original 16 members were: (1) General Atomics, (2) Lockheed Martin, (3) Commonwealth Systems, (4) TAE Technologies, (5) Tokamak Energy, (6) First Light Fusion, (7) Helion Energy, (8) Princeton Plasma Physics Laboratory, (9) MIT Plasma Science and Fusion Center, (10) University of Washington Plasma Science and Innovation Center, (11) General Fusion, (12) Sustained Nuclear Fusion, (13) Ad Astra Rocket Company, (14) CFS Energy, (15) Empowery and (16) First Principles

require meeting mid-term milestones, taking risks in parallel development pathways, forming new partnerships and additional financial resources. The next ten years will be focused on scale-up of proof-of-concept machines.[4]

"The global fusion industry in 2023," report also includes profiles of today's fusion players each of which contains considerable information. Profiles include the company's location, the founders' names, primary target markets, declared funding to date, the technical approach, fuel sources and their pilot plant timescale. In addition to electricity generation, other primary markets of interest include, in no particular order, space and marine propulsion, medical, industrial heat, off-grid energy and hydrogen/clean fuels. When asked what these companies considered to be the greatest near-term challenges – most respondents cited (1) fusion power efficiency, (2) plasma science, (3) tritium self-sufficiency, (4) neutron resilient materials, (5) funding and (6) eventually full life-cycle issues such as maintenance, waste, recycling, and decommissioning.

2.0 The Supply Chain – Looking Ahead

A companion report also released in 2023 entitled "The Fusion Industry Supply Chain Opportunities and Challenges," sets the stage for this report. As noted earlier, it is hard to predict when fusion will become commercially viable. Most of the respondents to the 2023 FIA survey agreed that for the near term, the supply chain is adequate. However, once fusion technology matures to the point where it can be reliably used to generate electric power, it is anticipated that the demand will instantly outstrip supply of both trained personnel and needed materials. The reason for the anticipated sudden demand is that fusion does not create greenhouse gases and therefore could solve many of the problems that plague the earth's climate today. What sets the stage for the supply chain challenge are the different methodologies used to create fusion energy. It is reasonable to assume that the supply chain demands will vary depending upon the approach to creating fusion energy.

There are two major approaches which can be described as **magnetically confined fusion** and **inertially-confined fusion** approaches. The first requires magnets and superconducting wires, while the latter requires lasers and associated component parts. Another split or divide is between **steady-state** and **pulsed approaches.** A pulsed approach will require precision power-supply management components, and particularly power semiconductors. "Common across many fusion technologies are the advanced and specialized components for heat management, the first wall and vacuums – all the parts that will be needed to create a plasma and then to transfer the energy created into a usable power source, either electricity of process heating.[5]

2.1. Different Types of Fusion Reactors

Of the many types of fusion devices, the International Atomic Energy Association (IAEA) distilled the information into one comprehensive figure.[6] This figure illustrates the status of over 140 public and private fusion devices. The bar graph at the top of Figure 3 represents the number of fusion devices that are planned, under construction or operating, while the colors of the bars reflect the type of funding (i.e., public, public-private, or private). The figure also graphically represents the device configuration (i.e., tokamaks, laser/inertial, stellarators/heliotrons, or alternative concepts), and the design (i.e., demo or experimental –meaning demonstration fusion power plants or experimental fusion facilities). DEMO-type devices are designed to achieve net engineering gain (Qeng>1); while experimental facilities optimize different processes and facilitate information exchange of scientific data generated under experimental conditions.

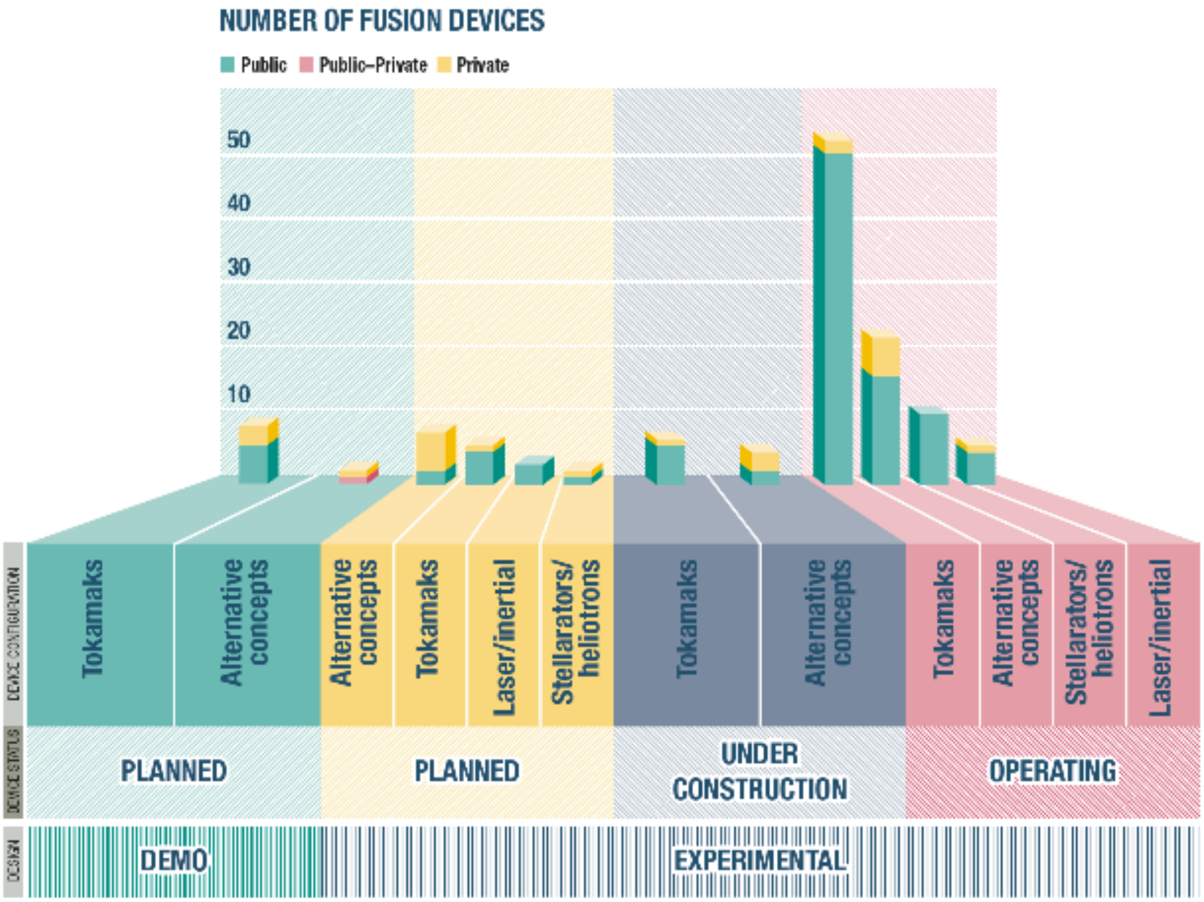

Figure 3: Configuration of More than 140 Fusion Devices
Source: International Atomic Energy Association

"The Fusion Device Information System (FusDIS), developed and maintained by the IAEA, focuses on fusion devices worldwide. FusDIS contains information in the form of a map with selectable filters about public or private fusion devices with experimental and demonstration designs, currently in operation, under construction or being planned, as well as their locations, websites, technical data of these devices and country statistics, including research statistics from the Fusion Energy Conference series. The devices are organized in four main configuration categories:

- **Tokamaks;**
- **Stellarators and heliotrons;**
- **Laser/inertial;**

- **Alternative concepts**, including dense plasma focus; field reversed configuration; inertial electrostatic fusion; levitated dipole; magnetic mirror machine; magnetized target fusion; pinch; reverse field pinch; simple magnetized torus; space propulsor; spheromak."[7]

2.1.1. Tokamaks (Magnetically Confined Fusion)

Tokamaks use gaseous hydrogen as the fuel which is subjected to extreme heat inside a toroidal chamber with magnetic coils[8] in order to create a plasma. Tokamaks use a magnetically confined fusion approach. The changing magnetic fields create a high intensity electrical charge through induction. There are two noted tokamak facilities in the U.S.: **DIII-D National Fusion Facility** and the **National Spherical Torus Experiment Upgrade (NSTX-U).** The DIII-D tokamak, located in San Diego, CA has been operated by General Atomics for the U.S. Department of Energy since the 1980's. The National Spherical Torus is operated by the Princeton Plasma Physics Laboratory and sponsored by the U.S. Department of Energy.

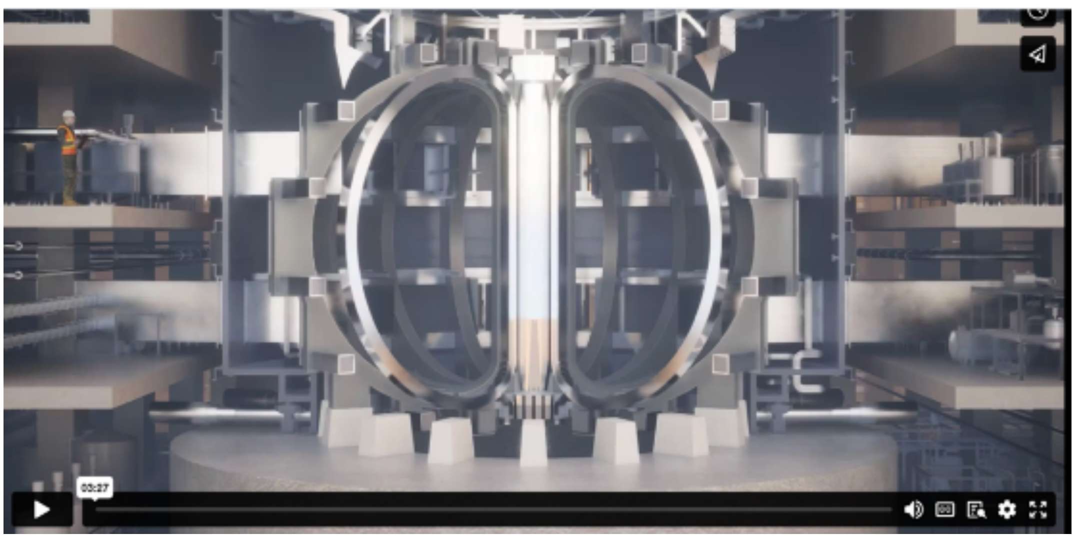

Figure 4: General Atomics Fusion Power-Plant

Click here to see video

The world's largest tokamak, ITER ("the Way" in Latin) is under development in France and is the result of over 35 nations collaborating, many of which have worked together since 1985. The goal of this Tokamak is to produce six times the plasma volume of the largest tokamak machine used today. This will be a research tool, that has been designed to:

- "Achieve a deuterium-tritium plasma in which the fusion conditions are sustained mostly by internal fusion heating,
- Generate 500 MW of fusion power in it plasma,
- Contribute to the demonstration of the integrated operation of technologies for a fusion power plant,
- Test tritium breeding, and
- Demonstrate the safety characteristics of a fusion device."[9]

The ITER projects will be housed in 39 buildings and technical areas on a 180- hectare site. The Tokamak building will be a seven-story structure in reinforced concrete that sits 13 meters below the platform level and 60 meters above. Over one million components are being built in ITER Members' factories and delivered to the ITER site for integration.[10]

Figure 5: Manufacturing the ITER Toroidal Field Coils

Click here to see video

2.1.2. Laser/Inertial Confinement Fusion

The U.S. has invested heavily in Inertial Confinement Fusion (ICF), commonly known as laser fusion which initiates fusion reactions by using lasers to compress and heat small, spherical targets (usually 1 to 10 mm in diameter) containing the hydrogen isotopes – deuterium and tritium.

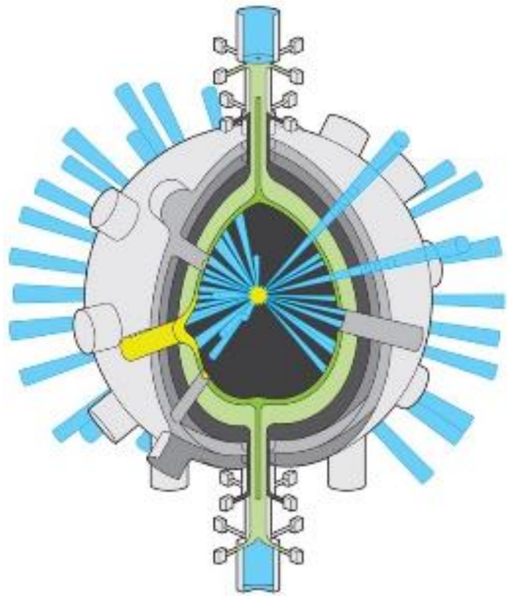

Figure 6: Artist Rendering of ICF Containment Chamber Concept
Illustration courtesy of Chris Philpot

Two methods are used to compress deuterium and tritium gas (DT) pellets: direct-drive laser fusion and indirect-drive laser fusion. **Direct-drive** involves intense laser beams focused on a hollow plastic pellet filled with a mixture of DT and tritium gas. The intense focus ablates the shell, compressing the gas and resulting in substantial nuclear energy gain. **Indirect-drive** involves a pellet centered within an enclosure, a hohlraum. Laser beams enter the hohlraum, creating a cloud of x-rays that symmetrically ablate the pellet shell, producing compression and heating.[11]

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is the leading center for indirect-drive research.[12] At NIF, 192 powerful laser beams fire into a target the size of a pencil eraser, delivering over 2 million joules of ultraviolet energy and 500 trillion watts of peak power.[13]

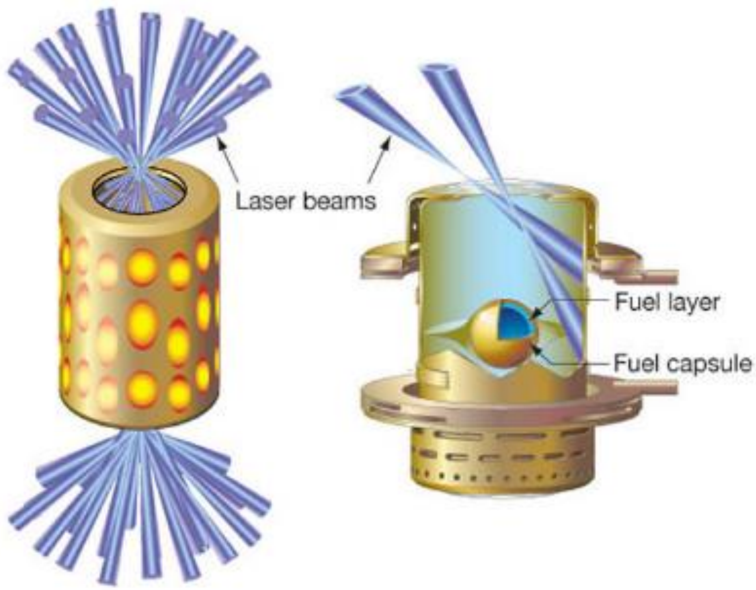

Figure 7: Indirect-drive Laser Fusion Approach as used by NIF at LLNL[14]

Click here to see video

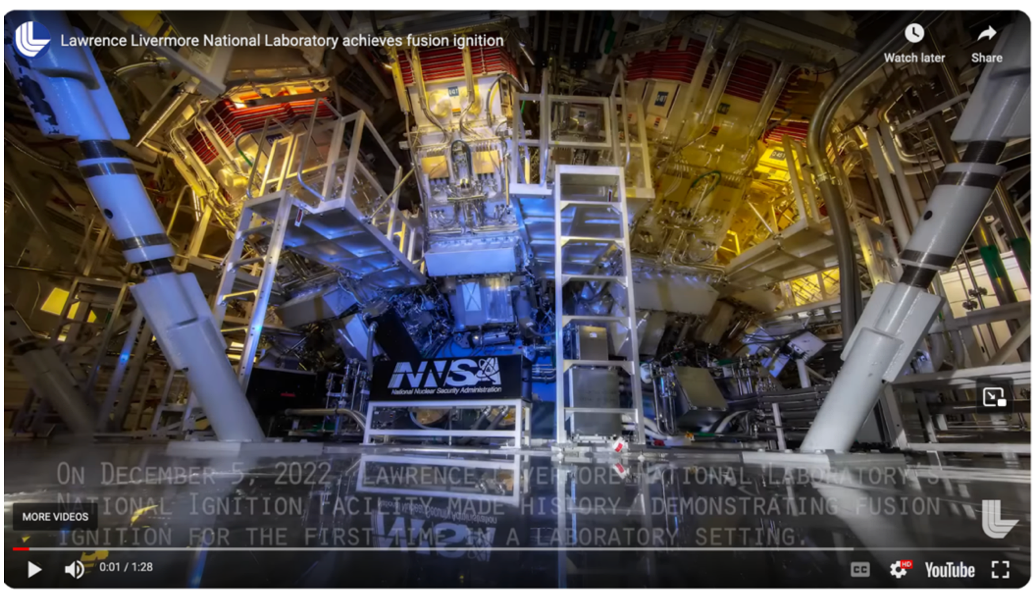

Figure 8: Lawrence Livermore National Laboratory Achieves Fusion Ignition

Click here to see video

The Laboratory for Laser Energetics (LLE) at the University of Rochester is the world's leading experimental facility for the direct-drive approach. The OMEGA laser system produces 60 laser beams, yielding over 30,000 J focused on a pellet.[15]

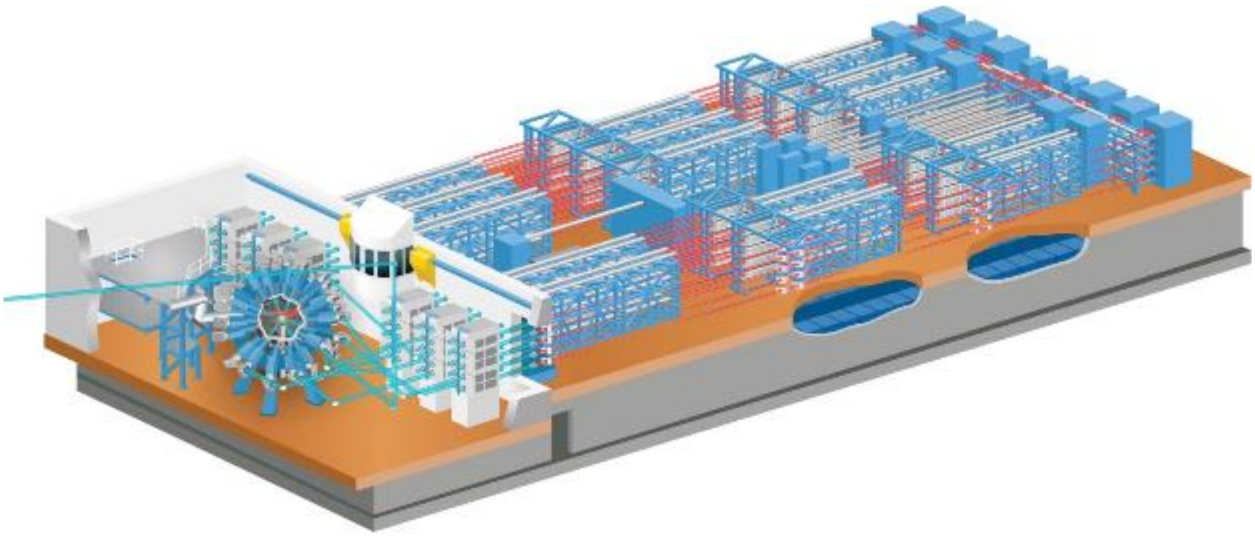

Figure 9: Direct-drive Laser Fusion Approach as used by LLE at U of R
Source: Laboratory for Laser Energetics at the University of Rochester

2.1.3. Stellerators/Heliotrons

A stellarator also uses magnetic fields to contain plasma but in a different configuration than a tokamak. According to the Department of Energy "Stellarators require less injected power to sustain the plasma, have greater design flexibility, and allow for simplification of some aspects of plasma control. However, these benefits come at the cost of increased complexity, especially for the magnetic field coils."[16]

Figure 10: Stellerator Fusion Energy
Click here to see video

A variation of a stellarator is a heliotron which twists the confinement chamber into a helix. The Institute of Advanced Energy at Kytoto University is heading up the Heliotron J Project.[17]

2.1.4. Alternative Concepts

Alternative fusion concepts are those that are not well-aligned to the mainline magnetic or inertial confinement approaches. These alternative concepts include (but are not limited to) the following types: dense plasma focus; field reversed configuration; inertial electrostatic fusion; levitated dipole; magnetic mirror machine; magnetized target fusion; pinch; reverse field pinch; simple magnetized torus; space propulsor; and spheromak.[18]

3.0 Growth of Fusion Energy Within the United States

As of 2023, globally there were 43 fusion companies, an increase from 33 in 2022.[19] The following map shows the location of fusion projects by primary headquarters and indicates how many fusion companies currently exist in each country. As previously mentioned, the U.S. is the front-runner with 25 companies – with many focused on alternative applications.

Figure 11: Locations of Major Fusion Projects, by Primary Headquarter
Source: Fusion Industry Association[20]

Many concerns for the global fusion supply chain were identified in FIA's 2023 global supply chain report. These concerns included the need for: investment for the scale up of suppliers; regulatory frameworks and best practices; and the need for engineering, procurement, and construction (EPC) firms. Concerns were also expressed regarding the availability of certain materials and necessary components.[21]

In addition, concerns expressed by those responding to the FIA Supply Chain survey highlighted the lack of investment in fusion suppliers that would need to scale-up in order to meet the future demands of the industry. The challenge is that companies within the potential supply chain may not have the money to invest, nor know where to place such investments, since fusion technologies are not yet ready. The FIA report recommends a shared-risk structure, where investors would invest in suppliers, as well as fusion developers. This shared-risk framework would be supported by governments, where fusion programs and national labs would work hand-in-hand with private companies instead of competitively.[22]

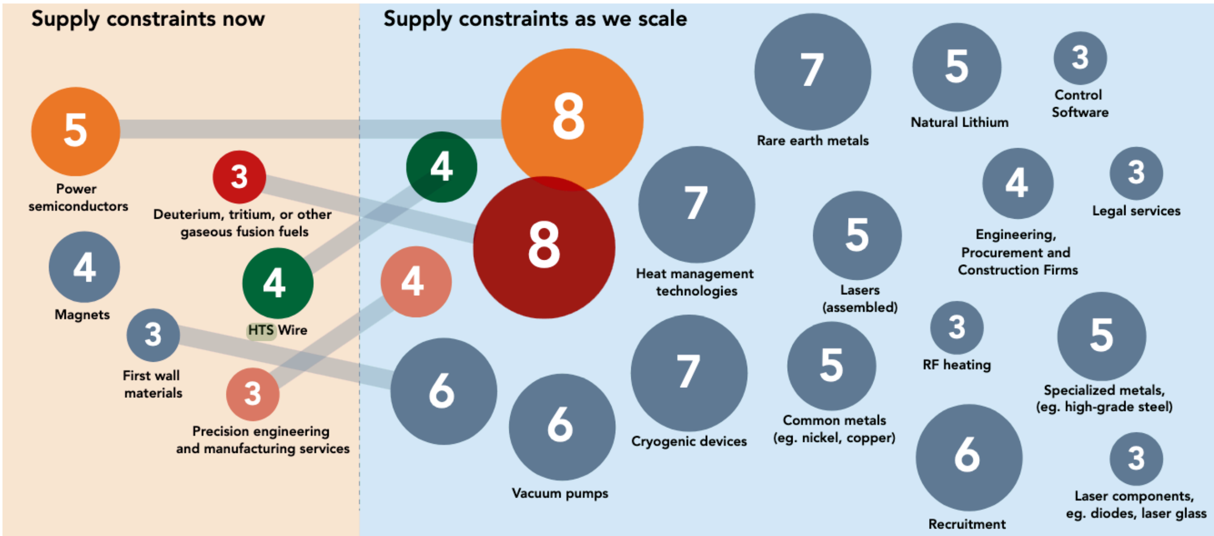

Figure 12: Number of Companies in the FIA Supply Chain Report Expressing Near-term (to 2030) and Long-term (2030-2050) Supply Chain Concerns[23]

Note: Numbers indicate the number of respondents

Figure 12 represents the diversity of needs of both magnetically- confined fusion and inertially-confined fusion approaches. These near-term concerns continue into the early 2030s and merit attention near term in order to facilitate rapid growth in the future.

In Appendix A, a comprehensive table is provided which contains a brief look at those U.S. companies which provided responses to FIA's supply chain study. The specific concerns of each firm were not identified by company name or location in the FIA report. However, the table provides a sense of the investment from both the public and private sectors in these firms. Information was available for most, but not all of the twenty-six companies that responded to the survey on supply chain needs which is discussed in the next section.

4.0 Supply Chain Needs

4.1 Fusion Industry Supply Chain Report

This section begins with an initial discussion of the top four needs listed as critical over the next ten years by companies participating in the FIA survey. These include **(1) vacuum**

pumps, (2) precision engineering and manufacturing services, (3) control software and (4) power electronics. The complete list of critical and important needs is available on page 9 of the Fusion Industry Supply Chain report of 2023.[24]

4.1.1. Vacuum Pumps

A large contributor to the cost of a fusion reactor are components such as vacuum vessels.[25] Because of the helium-based emissions that fusion energy can produce, there is a need for the removal of that helium, plus any impurities, for "stable fusion." This is carried out by pumps that facilitate a high vacuum and remove plasma exhaust. There are a few problems that lie with current vacuum pump design compositions. These problems are expanded upon in a recent report published by the Massachusetts Institute of Technology (MIT):

> "Due to tritium accumulation in pump components and fluids, and to leakage through clearances, existing pump designs are not sufficiently tritium-compatible for a commercial fusion plant. Additionally, pumps that are located on the interior of fusion devices must also be resistant to the effects caused by high magnetic fluxes, extreme temperatures, and radiation. The pumps that are currently available aren't designed for use in fusion devices; they aren't durable enough, they can't withstand tritium infiltration, and it's difficult to effectively modify them to overcome these issues."[26]

MIT has provided information on different types of pumps that have been/ or are being explored for fusion. These are listed below.

- **Vapor diffusion pumps:** These pumps are described as doing "moderately well in the presence of tritium" and are designed for high vacuum uses.
- **Non-evaporable getter pumps and cryopumps:** These two pumps fulfill through-put requirements, although cryopumps necessitate high energy, in turn increasing the challenges for implementing at high scale.
- **Metal foil pumps:** These high-performing pumps enable Direct Internal Recycling by splitting plasma exhaust and tritium. Metal foil pumps are not currently technologically advanced.[27]

Additionally, oil containing vacuum pumps have been explored in a recent study from Savannah River National Laboratory (SRNL), Hydrogen Isotope Processing Science and Clemson University, Center for Nuclear Environmental Engineering Sciences and Radioactive Waste Management Center. These pumps can manage the flow rate requirements, yet the vacuum fluids cannot withstand tritium exposure and high-energy radiation. This work illuminated a variety of oils that could be used for vacuum pumping: phenyl silicone oil, highly purified mineral oil, and a polyphenyl ether.[28] Other work out of SRNL (funded by ARPA-E) began in 2021. The intention of this project is to:

> "[…] demonstrate a hydrocarbon pump oil-recycling loop process that can selectively remove heavier hydrogen isotopes from pump oil (target of 99.5 % removal, with an uptake of 0.01% of tritium throughput), while also purifying the oil of radiation-induced damage. The recycled oil will retain its pumping characteristics, and hydrogen isotopes and impurities will be extracted in gaseous form for further processing in the tritium plant. The project's successful execution would potentially enable fusion pumping solutions capable of reducing pump operational costs >100X, pump electric-power consumption by 10X, and tritium inventory by more than 4X."[29]

This work is a part of the Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts (GAMOW) program, overseen by the Office of Fusion Energy Sciences and ARPA-E, to fund as much as $15 million over three years to a variety of R&D related to fusion.[30, 31]

Agilent, headquartered in the U.S., has worked with academic institutions conducting nuclear experiments for several decades. The company's products include, but aren't limited to, high vacuum pumps. According to Agilent:

> "Vacuum pumps for fusion technology must guarantee compatibility with tritium, nuclear radiation, magnetic fields, shock, and air inrush accidents, without contamination of pumped gases. A leak-tight operation with metal-based sealings alone must also be ensured. These pumps must provide a high pumping speed for light gases like hydrogen, tritium, and deuterium, guaranteeing a base pressure of < 1x10-8 mbar. When used to recycle helium in cryostats, the pumps must move huge quantities of helium in the 1x10-5 pressure range."[32]

4.1.2. Control Software

Control software for fusion energy spans a wide variety of applications for scientific research and development, as well the commercialization and decommissioning phases. One application example is the anticipated use of software to work with the ITER Tokamak. Thousands of diagnostic devices will be used to measure the magnetic fields developed by ITER and the plasma. "The data-analysis software for magnetics diagnostics will bring all these measurements together and derive the parameters that other systems, scientists and engineers will use to control the plasma, interpret what happens in the machine and operate it accordingly. The design of this software has recently been validated and the coding stage has started.[33]

> "F4E [Fusion for Energy] awarded a contract in 2018 to prepare the design of these software modules. The CREATE consortium collaborated with Consorzio RFX and ENEA (all three from Italy), as well as with ASIPP (China) and SPC-EPFL (Switzerland), to produce a set of state-of-the-art algorithms with a variety of functions. Alfredo Pironti, CREATE, gives us more details. "Starting from the output of the magnetic sensors, these algorithms allow to extract information about the plasma state, such as the total current, the position and the shape of the plasma, its distance from the wall, the stored magnetic energy and plasma instabilities. These are examples of quantities that need to be estimated and controlled in real time by the plasma control system, a fundamental component in making ITER a unique experimental device, capable of longer plasma discharges and better confinement."[34]

A study conducted by Sygensys and United Kingdom Atomic Energy Authority (UKAEA) spanning six-months studied 'MARTe,' a fusion control software framework.[35, 36] "MARTe was first developed in 1995 at UKAEA and has been continuously improved since then to provide plasma control and protection systems for record-breaking fusion energy machine JET (Joint European Torus). It was made open-source in 2010 and has been adopted internationally for fusion research programmes, including ITER, the larger and more advanced version of JET."[37].[38]

Software is also used to design new systems such as the ITER remote maintenance devices for testing before implementation in ITER. This work was conducted at the VTT research center in Finland. They developed two remote maintenance devices for testing using LabVIEW, LabVIEW Real-Time and NI data acquisition devices for their control systems.[39]

4.1.3. Precision Engineering

There is a need for additive manufacturing (AM) to build components in fusion that have complicated internal structures (e.g., waveguides and fusion plant cooling channels) using metal alloys. AM possesses a number of benefits, including the production of stronger structures due to the annealing process. This manufacturing also removes the need for brazing and welding resulting in a smaller chance of structural failure. Since fusion can be described as an "experimental field," the ease with which AM can change from material to material when producing alloys, and its ability to produce many components from various designs is helpful. In addition, AM allows for lower production time, increased efficiency in logistics, and utilizes a smaller amount of energy as opposed to established methods of manufacturing.[40]

Examples of precision manufacturing applied in fusion components include the toroidal field radial plate, toroidal field magnets, and cryostat manufactured for ITER.[41, 42, 43] ITER's toroidal field magnets need extreme precision engineering. The magnetic field which encloses the plasma is derived from superconducting coils. The ultimate goal is that the plasma will be symmetrical, which is made possible by a surface that doesn't have any bumps. These elements need to be just so in order for fusion to work.[44]

4.1.4. Power Electronics

High powered semiconductors are part of the group of "specialized manufactured components" that need to be specially manufactured for fusion, as opposed to components that are already manufactured through established supply chains.[45] MIT has noted that semiconductors are "foundational to electronics" and are undergoing developments to increase their tolerance to radiation. The space industry has transferred from using "standard silicon" to gallium nitride and silicon carbide. There are also new manufacturing methods, including fin field-effect transistors and silicon-on-insulator. Substantial investments have been based out of the U.S. for semiconductors that can withstand radiation for nuclear implementation. That being said,

> "Despite these advances, rad-hardness is still a major unsolved issue for commercial fusion. In D-T experimental tokamaks for example, electronics embedded in the toroidal magnets can become damaged within mere minutes. Developing rad-hard sensors and electronics will require extensive collaboration between the fields of semiconductors and nuclear materials; the advent of these components would be significant to the fusion industry and many other established industries as well."[46]

Also called out in the FIA report were other electronics - considered important and potentially in short supply. These included:

- Capacitors
- Power semiconductors
- High voltage switches
- High density energy storage
- Ignitrons
- Thyristors[47]

In addition to FIA's survey of supply chain needs, a number of additional publications from academia, fusion projects, companies, and government have also presented supply chain needs as they see them.

4.2 DOE Office of Supply Chain Roundtable Report (2021)

Although this Department of Energy (DOE) report[48] focused on supply chain issues that could affect scientific facilities, with respect to fusion it echoed many of the same concerns that surfaced in the FIA report. Of specific note are the domestic supply chain for high-temperature superconducting (HTS) tape, and fusion structural steels (first wall).

4.2.1. HTS tape (REBCO)

HTS is a key enabler for fusion technologies that use magnets and can also be used in other applications such as medical equipment, turbines, and electric aircraft. The term REBCO stands for rare earth barium copper oxide, a combination which yields the needed performance in HTS wire and tape for fusion applications. The world's largest suppliers of HTS tape for fusion applications include **Faraday Factory** and **Fujikura Ltd.** in Japan. Faraday Factory has recently partnered with **Coherent**, an American firm which manufactures the LEAP excimer lasers that provide the pulsed laser deposition that enables the manufacturing of HTS tape.[49] There is limited domestic supply of HTS tape. Domestic suppliers include **SuperPower, Inc**. a wholly owned subsidiary of Furukawa Electric Co, Ltd. located in Grenville, NY, **High Temperature Superconductors Inc** located in Santa Barbara, CA and **MetOx Technologies** located in Houston, TX. These newer companies are to some extent considered unproven. A concern raised in the DOE roundtable report is that *"There is also no domestic capability to perform tests on these materials under high magnetic fields outside of select universities, the National High Magnetic Field Laboratory, and Commonwealth Fusion Systems. Previous high-field testing had to be done in New Zealand (Rogers Research Institute).*[50]

4.2.2. *Fusion Structural Steels*

The DOE report also calls out that for applications such as fusion, specific alloys may need to be developed and produced that operate to spec in high-radiation environments. Testing facilities will also be required to validate the performance of new materials.

> "Development and testing of new materials for high-radiation environments will require testing facilities for high-does, high-volume, and accelerated radiation damage. These could serve the accelerator targetry fusion and fission communities."[51]

Within DOE fusion structural research is carried out in the ORNL Fusion Materials Program which is embedded in the Nuclear Materials Science and Technology (NMST) group of the Materials Science and Technology Division[52]. Annual and Semi-Annual Reports on progress made with respect to fusion materials are available at this site.

4.3 Enabling Commercial Fusion Report

In February 2024, Proto Ventures and the Plasma Science and Fusion Center at MIT, released a report which provides an overview of the needs for (1) fusion materials, (2) components and consumables, (3) subsystems and (4) software, services, and facilities. A high-level summary of those needs is provided below. The reader is referred to this report for more details.[53]

4.3.1. *Fusion Materials*

Called out are the needs for plasma-facing materials that can withstand extremely high temperatures, mechanical loads, and radiation; as well as advanced materials that can be used to create numerous components of the fusion system. SPARC is using a relatively new, high-temperature superconducting material which presents a different set of challenges for plasma facing component (PFC) materials.[54] Also noted are prescribed needs for superconducting electromagnets and tritium permeation barriers.

> "Carbon-based PFC materials would be preferred for meeting SPARC's mission goals due to improved manufacturability, reduced eddy current torques and increased resistance to damage from thermal transients, relative to tungsten. However, the tritium retention and high erosion rates in carbon-based materials do not project well towards a pilot plant,and would

create a risk for the timely achievement of SPARC's goals within limited tritium inventory. Therefore, SPARC will feature a divertor made of tungsten-based tiles."[55]

4.3.2. Components and Consumables

The report highlights the needs for enriched lithium supply; sensors that can withstand irradiation, vacuum pumps that can handle plasma exhaust; separation systems with element selectivity; supplying molten salts such as FLiBe; and transistor chips for plasma heating.

4.3.3. Subsystems

Four subsystems are highlighted including the tritium fuel cycle, plasma heating and drive actuators, cryogenic cooling systems and heat exchangers which can withstand both radiation and high temperatures.

4.3.4. Software, Services and Facilities

Easy-to-use software that can earn the trust of plasma scientists, as well as control and maintenance of robotic tools are needed. Also required are a number of services such as high precision engineering, component manufacturing using additive manufacturing and workforce training.

4.4. U.S. Nuclear Regulatory Commission (NRC)

Tritium is produced during the fusion reaction through contact with lithium. In the case of magnetic fusion systems such as tokamaks, tritium is said to be "bred" when neutrons escape the plasma and interact with lithium contained in the blanket wall.[56] Irrespective of the fusion method used, small amounts of tritium are produced during the fusion process. Although tritium is radioactive, its' half life is short and is used only in small amounts. For this reason, it cannot produce any serious danger.

Tritium in any quantity is regulated. In the U.S. this responsibility falls to the U.S. Nuclear Regulatory Commission (NRC). In the FIA Supply Chain report the need was also called out for a regulatory framework to be articulated and for fusion to be regulated in a different manner than fission. A white paper on this topic was released by the NRC in 2021 and is available here.

4.5. White House Concerns and Solutions

The White House has shed light on the domestic fusion supply chain in a 2022 publication. The White House notes that the U.S. should not become dependent on other countries to provide components and materials critical to the U.S. fusion technologies in development:[57]

> "[…] one pathway to fusion is enabled by high-temperature super-conducting magnets made with the rare-earth element yttrium. You may not know what yttrium is, but you need to know that we import nearly 100% of our yttrium consumption from one country. We also import 100% of the niobium used to generate the magnetic fields for other fusion pathways. From high temperature superconductors to high voltage power electronics, the U.S. is far too dependent on supply chains with single points of failure. As fusion technology develops, we must also concurrently identify the supply chain vulnerabilities and bottlenecks, build a resilient fusion supply chain, build a robust U.S. fusion manufacturing base, and build international partnerships to diversify production of critical materials and components. Fusion can be a part of a clean energy future that's made in America, and we must build the secure supply chains that underpin the clean energy transition."[58]

Currently the U.S. has one mine, Mountain Pass in CA that can produce yttrium and other rare earth minerals. Story has it that the rare earth elements in the mine were discovered quite by accident, as it was started in the search for uranium.[59] A 2024 publication entitled "Exploring the Unexpected: An AI Model Uncovers Rare Earth Elements" reports on research conducted by DOE's National Energy Technology Laboratory to use AI to develop a new geologic resource assessment model. This was tested on Wyoming's Powder River Basin and "revealed the largest unconventional deposit of magnetic REEs discovered in the US, estimated to have 1.2 million tons of rare earth oxides.[60]

4.5.1. White House Solutions

In June 2022 the White House released "Parallel Processing the Path to Commercialization of Fusion Energy". To accelerate the transition from proof-of-concept to commercialization, participants in the White House Fusion Summit recommended a model that should expedite the commercialization of fusion energy technology. The acceleration path referred to as "parallel processing" should reduce the time for commercialization from the historic norm of 30 to 50 years to 10 years. The model requires concurrent attention to multiple factors and public support. A key element of this model is the supply chain, which goes hand-in-hand with workforce development.[61]

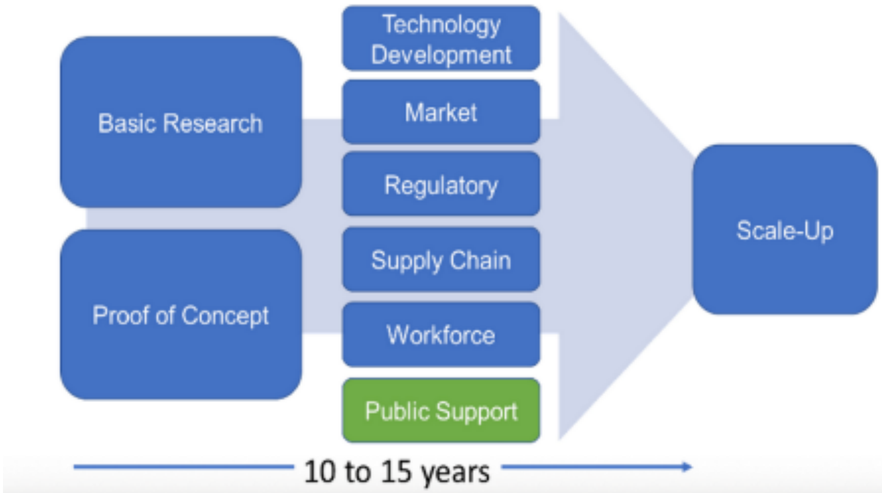

Figure 13: Parallel Processing Path to Fusion Commercialization

5.0 Learning From Others

The largest fusion initiatives in Europe are the [Joint European Torus (JET)]() and [ITER]() ("the Way"). JET is a tokamak which began operation in 1983 at the Culham Laboratory in Oxfordshire, England. It is jointly owned by the European Community[62] and was built to enable the study of fusion in conditions approaching those needed for a power plant. "It was the only tokamak fusion machine in operation capable of handling tritium fuel, and was a key device in preparations for the multinational ITER fusion research project which is currently under construction in southern France."[63] JET has completed its mission and "has produced a **record-breaking** 59 megajoules of sustained fusion energy over a five second period (the duration of the fusion experiment) using deuterium and tritium – the same fuel mix that will be used in future powerplants. During this experiment, JET averaged a fusion power of around 11 megawatts."[64] The process of decommissioning JET[65] to give way to the ITER began in early 2024.

To facilitate the decommissioning process, the remote Handling Control Room at the Joint European Torus has been upgraded. “Due to safety precautions, personnel have not been able to enter the tokamak for over 30 years.”[66]

Figure 14: JET’s Decommissioning and Repurposing
Click here to see video

5.1. ITER (The Way)

The ITER, the next generation tokamak, has an interesting beginning: The idea for this collaborative, international project was actually proposed by General Secretary Gorbachev of the former Soviet Union to U.S. President Ronal Reagan almost 40 years ago.[67] An agreement was signed a year later that the ITER project would begin and initially included the European Union, Japan, the Soviet Union and the United States. Later the People’s Republic of China and the Republic of Korea joined in 2003, followed by India in 2005. What became known as the **ITER Agreement** was put in place in 2006 by representatives from the seven ITER members. This agreement laid out the responsibilities for this international entity regarding responsibilities for building, operating, and decommissioning the project to be located at the Saint Paul-lez-Durance site in France. Announcement of the new schedule for ITER will be made later in 2024.

Figure 15: From JET to ITER: The Future of Fusion

Click here to see video

In a 2023 article[68], Roberto Hinojosa, the Acting Section Leader for Building & Construction Project Control at ITER provided insight into this unique international endeavor. Hinojosa clarified that ITER is not a company or a federal lab but an international collaboration. There are no suppliers – only partners. The host, the European Union agreed to pay 45.5% of the costs, while the other members each agreed to pay 9% of the construction costs. “The lion’s share of Member contributions to ITER (90 percent) will be delivered in-kind.”[69]

Mr. Hinojosa provided an example of how the partnership works.

> “For example, a vacuum vessel sector was sent to us from Korea. We did not pay for that; we don't have a contract with the Korean company that will give us that component. The Korean government is paying for it—they have a contract with the company that built it, they paid for the shipping, they paid for everything that showed up on our doorstep.”

The fabrication of ITER key components reflects the interests of the Members and are distributed in the following fashion:

1. Europe and Korea share the responsibility for the fabrication of the numerous vacuum vessel sectors;
2. the central solenoid is the result of a collaboration between the United States and Japan;

3. divertor manufacturing and testing is conducted by Europe, Russia and Japan;
4. responsibility for the ITER water cooling system is shared by India and the United States;
5. China, Europe, Korea, Russian and the United States are producing the blanket system and (6) lastly the production of ITER magnets is being conducted by all ITER members with the exception of India.[70]

Information on the ITR Procurement and Contracts division is readily available.[71]

The **US ITER** office is managed by Oak Ridge National Laboratory which partners with the Princeton Plasma Physics Laboratory and Savannah River National Laboratory. In exchange for its contribution to ITER the U.S., like the other Members, has access to all ITER technology and scientific data as well as the opportunity to conduct experiments and design and construct parts. The U.S. is providing six solenoid modules.[72]

ITER provides an excellent site which provides information on the main ITER components and key technologies. Each section provides figures or videos showing the component and information regarding who is manufacturing that particular component.[73] A partial image of that site is provided in the following figure.

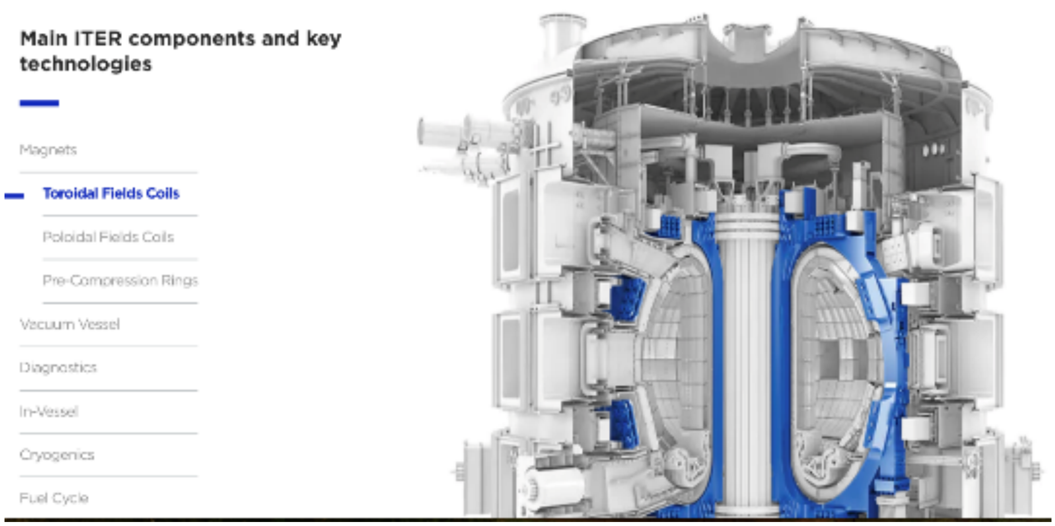

Figure 16: Access to information on ITER key components and technologies

Source: Fusion for Energy[74]

5.2. Public-Private Partnerships in the UK

With the advances being made with fusion in 2021, the UK published its first fusion energy strategy for commercialization. The three pillars of this strategy are (1) international collaboration, (2) scientific and technical expertise and (3) commercialization. In 2023, the UK Department for Energy Security and Net Zero (DESNZ) updated its strategy and created the Fusion Futures programme with three core areas infrastructure, skills and iIndustrial and commercial opportunities.[75] Infrastructure is focused on the supply chain and providing infrastructure and facilities for fusion companies, while the Skills category will create a new Fusion Skills Centre that will work with universities, colleges, and employers.

An interesting report commissioned by DESNZ in 2023 utilized a unique method to surface and represent the UK fusion sector.[76] The methodology was provided by glass.ai using a technology they developed which can read and interpret text at scale. Using this approach London Economics in combination with glass.ai developed a taxonomy for the fusion sector comprised of keywords and phrases combined with other search criteria that were representative of the fusion sector and its supply chain.

The full taxonomy of words used is presented in the Appendix to that report. The sources that were searched include company websites, social media, official sources, news and blogs, academic papers, and others. The approach and the results were validated by DESNZ and interviews with experts. As a result of applying this technology, the team was able to identify and classify UK fusion companies. The following figure is taken from this report. A geographic cluster map is also available in this report.

Table 2: Breakdown of UK Fusion Companies

Type	No. of organisations identified
Core fusion companies	31
Supply chain companies	480
Wider ecosystem	55
Total active in the fusion sector	**566**
Potential supply chain	185
Total including potentials	**751**

Source: glass.AI

In another 2023 article entitled Public-private partnership in the UK fusion program, two different approaches to commercialization were presented and discussed: the **"schedule-driven"** approach and the **"evidence-driven"** approach. The schedule-driven approach is focused on developing a prototype as rapidly as possible to demonstrate the ability to develop powerplants at the prototype level. The goal is to drive innovation, investment, and competition. By comparison the evidence-based approach takes its time in addressing uncertainties before beginning construction. The pros and cons of each approach are discussed.

The UK appears to be implementing both models. A new initiative called the Spherical Tokamak for Energy Production (STEP) is currently in the design phase. STEP will be a spherical tokamak, connected to the grid and producin net energy. This program will work with a number of industrial partners and build the prototype by 2040 which will be delivered through a new organization called UK Industrial Fusion Solutions Ltd.

5.3. Partnerships Between the UK and the U.S.

As part of the UK and the U.S. strategies to continue to develop and foster international relationships, in November, 2023 representatives from the U.S. Department of Energy and the Department for Energy Security and Net Zero (UK) agreed to form a new partnership to focus on advancing the U.S. Bold Decadal Vision for Commercial Fusion Energy and the UK's Fusion Strategy.[77] One of the numerous goals identified in this release is to "Identify and support the development of resilient supply chains that will be necessary for commercial fusion deployment." Excluded from the agreement were major plant design projects such as STEP in the UK or those part of the U.S. Milestone-Based Fusion Development Program. These projects, however, may inform priority research areas of the partnership.

5.4. DOE Milestone-Based Fusion Development Program

The Department of Energy (DOE) Milestone-Based Fusion Development Program is a public-private program that will provide funding of $46 million to Commonwealth Fusion Systems (Cambridge, MA), Focused Energy Inc. (Austin, TX), Thea Energy (previously known as Princeton Stellarators Inc.) located in Branchburg, NJ, Realta Fusion Inc. (Madison, WI), Tokamak Energy Inc. (Bruceton Mills, WV), Type One Energy Group (Madison, WI), Xcimer Energy Inc. (Redwood City, CA), and Zap Energy Inc. (Everett, WA). These eight companies are working to advance designs, as well as research and development, for fusion power plants.[78] The companies involved in this program will develop designs for fusion pilot plants that will enable the commercialization of fusion, by overcoming technological and scientific challenges within a five-year timespan, of which the outyear is dependent on various factors.[79]

6.0 Summary and Conclusions

This report provides an introduction to the dynamic and exciting advances that are being made with fusion as it approaches true commercialization. To keep apprised of this journey, the Fusion Industry Association provides monthly videos and press releases that update advances being made globally. There are numerous challenges which this emerging market is addressing with both public and private funds. A number of these have been highlighted in this report. The advances made with new materials, electronics, lasers, cryogenics and countless other inventions will not only serve the fusion market but enable new advances in medicine, aerospace and manufacturing.

APPENDIX A

This Appendix contains information on U.S. companies that participated in the FIA Supply Chain Survey. The number of employees in each company reflects the data at the time of publication of the FIA report and are likely to have changed since then. The number of investors in each company has been expanded in the research conducted for this current report. Noted under each company name are the number of employees as cited in the FIA Supply chain report, as well as the primary target markets the company planned to pursue, noted in italics.[80]

Table 1: U.S. Companies Participating in FIA Supply Chain Survey

Company	Location	Total declared funding to date	Investor
Avalanche Energy **The company has 27 employees and is developing a modular 5kWe fusion microreactor.** ***Their primary target markets include space propulsion, marine propulsion, and mobility.***	Tukwila, Washington, USA	$53,000,000	• Autodesk Foundation[81] • Lowercarbon Capital • Founders Fund • Toyota Ventures • Azolla Ventures • Congruent Ventures • Grantham Foundation • Clear Path • MCJ Collective • Climate Capital Syndicate[82] • Prime Impact Fund[83]
Commonwealth Fusion Systems **CFC utilizes an open innovation model and is building SPARC- "the world's first commercially relevant net energy (Q>1) fusion system."** ***Commonwealth Fusion Systems' primary target market is electricity generation.***	Devens, Massachusetts	> $2,000,000,000	• Tiger Global Management • Bill Gates • Coatue • DFJ Growth • Department of Energy (DOE) Fusion Milestone Program[84] • Emerson Collective • Footprint Coalition • Google • JIMCO Technology Fund • John Doerr • JSCapital • Marc Benioff's TIME Ventures • Senator Investment Group • Breakthrough Energy Ventures • The Engine • Eni

			• Equinor Ventures • Fine Structure Ventures • Future Ventures • Hostplus • Khosla Ventures • Lowercarbon • Moore Strategic Ventures • Safar Partners • Schooner Capital • Soros Fund Management LLC • Starlight Ventures • Temasek • Major university endowment • Pension plan • Others[85]
CTFusion	Although CTFusion provided feedback to the survey, they have since gone out of business.[86]		
Electric Fusion Systems **The company has 5 employees and is developing "a compact and portable fusion power generator capable of delivering kilowatts, yet scalable to many megawatts."** ***The primary target markets include electricity generation, space propulsion, off-grid energy, and compact portable power.***	Broomfield, Colorado, USA	$400,000	Not identified

General Fusion **The company has 150 employees and is developing magnetized targeted fusion.** ***The primary target market is electricity generation.***	Vancouver, Canada; London, UK; Tennessee, USA	$300,000,000+	• BDC (Business Development Bank of Canada) • Braemar Energy Ventures • Segra Capital • JIMCO Technology Fund • Khazanah Nasional Berhad • SET Ventures • GIC • Chrysalix Venture Capital[87] • Temasek • Financial support from the Canadian, U.K., and U.S. governments • Jeff Bezos • Tobias Lütke • Kam Ghaffarian • U.S. state pension plan[88] • Government of British Columbia[89]
HelicitySpace **The company has 5 employees.** ***The primary target market is space propulsion.***	Pasadena, California, USA	$2,400,000	• Airbus Ventures • TRE Ventures • Voyager Space Holdings • E2MC Space • Urania Ventures • Gaingels[90]
Helion Energy **The company has 170 employees** ***The primary target market is electricity generation.***	Everett, Washington, USA	$577,000,000	• Dustin Moskovitz • Mithril Capital Management • Capricorn Investment Group • Y Combinator • Sam Altman[91] • ARPA-E[92]
Horne Technologies **The company reported 4 employees.** ***The primary target markets include electricity generation, marine propulsion, and off-grid energy.***	Longmont, Colorado, USA	$2,000,000	• Free Radical Ventures • Cottonwood[93]
HyperJet Fusion			• DOE ARPA-E (Advanced Research Projects Agency-Energy)

			• DOE OFES (U.S. Department of Energy Office of Fusion Energy Sciences) • Strong Atomics[94]
Kyoto Fusioneering **The company reported 80 employees** ***The primary target markets include electricity generation and industrial heat.***	Tokyo, Japan (Headquarters); Kyoto, Japan (Laboratory); Reading, UK (Regional office); Seattle, WA, USA (Regional office)	$91,000,000	• Coral Capital, Inc. • Daiwa Corporate Investment Co.,Ltd. • DBJ Capital Co., Ltd. • JAFCO Group Co., Ltd. • JGC MIRAI Innovation Fund L.P. • JIC Venture Growth Investments Co., Ltd. • Kyoto University Innovation Capital Co., Ltd.[95] • Electric Power Development Co.,Ltd.（J-POWER） • INPEX CORPORATION • JAPAN CO-INVEST IV LIMITED PARTNERSHIP / SUMITOMO MITSUI TRUST INVESTMENT CO., LTD. • JGC MIRAI Innovation Fund / JGC JAPAN CORPORATION • JGC MIRAI Innovation Fund / General Partner Global Brain Corporation • K4 Ventures GK（Kansai Electric Power Group） • Mitsubishi Corporation • Mitsubishi UFJ Capital Co., Ltd. • MITSUI & CO., LTD. • MOL PLUS Co., Ltd. • MUFG Bank, Ltd. • SMBC VENTURE CAPITAL CO., LTD.[96]
LPPFusion **The company reported 4 employees.** ***The primary target markets include electricity generation, space propulsion, marine propulsion, off-grid energy, and industrial heat.***	Middlesex, New Jersey, USA	$10,000,000	• 1,000 private investors (Wefunder) • 1 institutional investor[97] • Abell Foundation[98]

Magneto-Inertial Fusion Technology (MIFTI) **The company reported 6 employees** ***The primary target markets include electricity generation, space propulsion, medical, and hydrogen/clean fuels.***	Tustin, California, USA	$12,000,000	• DOE ARPA-E[99] • Strong Atomics[100]
NearStar Fusion **The company reported 7 employees.** ***The primary target markets are electricity generation and spacecraft propulsion.***	Chantilly, Virginia, USA	$500,000	• Fairfax Founders Fund[101] • National Science Foundation Phase I SBIR grant[102] • Commonwealth Commercialization Fund (CCF) grant[103]
Princeton Fusion Systems **The company reported 6 employees.** ***The primary target market is off-grid energy.***	Plainsboro, New Jersey, USA	$3,600,000	• DOE ARPA-E[104]
Princeton Stellarators (now Thea Energy[105]) **The company reported 20 employees.**			• Anglo American • U.S. DOE Milestone-Based Fusion Development Program[106] • U.S. DOE Innovation Network for Fusion Energy (INFUSE) Program[107] • Prelude Ventures • 11.2 Capital • Hitachi Ventures • Lowercarbon Capital • Mercator Partners • Orion Industrial Ventures • Starlight Ventures[108]
Realta Fusion **The company reported 5 employees** ***The primary target markets are off-grid energy and industrial heat.***	Madison, Wisconsin, USA	$12,000,000	• DOE Fusion Milestone Program[109] • Khosla Ventures • DOE ARPA-E[110] • Wisconsin Alumni Research Foundation[111]

TAE Technologies **The company reported >600 employees.** ***The primary target market is electricity generation.***	Foothill Ranch, California, USA; Locations in UK, EU, and Switzerland	>$1,200,000,000	• Chevron (Technology Ventures unit) • Google[112] • Venrock • Kuwait Investment Authority • New Enterprise Associates[113] • Reimagined Ventures • TIFF Investment Management • Sumitomo Corporation of Americas • U.S. West coast based mutual fund manager (unnamed) • U.S. pension fund[114] • Vulcan • Rusnano Group • Wellcome Trust • Google • Family office of Charles Schwab • Family office of Addison Fischer • Family office of Art Samberg[115]
Tokamak Energy **The company reported 255 employees.** ***The primary target markets include electricity generation, marine propulsion, off-grid energy, hydrogen/clean fuels, and industrial heat.***	Oxford, UK; Bruceton Mills, West Virginia, USA	$250,000,000	• Legal & General Capital • IMechE through the Stephenson Fund[116] • Department for Business, Energy, and Industrial Strategy (BEIS) - UK Government's Advanced Modular Reactor project[117] • DOE Fusion Milestone Program[118] • Oxford Instruments • UK Innovation & Science Seed Fund (fund is managed by Future Planet Capital[119]) • Future Planet Capital • Winton Capital[120] • Sir David Harding • Dr. Hans-Peter Wild • Lord Simon Wolfson[121] • Furukawa Electric Co., Ltd.[122] • BEIS Energy Entrepreneurs Fund • UKI2S Accelerator Programme for Technology Development (Innovate UK)

			• UK government[123] • U.S. government[124]
Zap Energy **The company reported 140 employees.** **The primary target markets are electricity generation and industrial heat.**	Everett & Mukilteo, Washington, USA	$208,000,000	• Lowercarbon Capital • Breakthrough Energy Ventures • Addition • Chevron Technology Ventures • DCVC • DOE Fusion Milestone Program[125] • Energy Impact Partners (EIP) • Shell Ventures • Valor Equity Partners[126] • DOE ARPA-E[127] • GA Capital • Fourth Realm[128]

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