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U.S. Fusion Supply Chain Report

CALEB BARNES

SPECIAL COMPETITIVE STUDIES PROJECT

U.S. Fusion Supply Chain Report

Executive Summary

Supply chain challenges could stall a burgeoning fusion industry, and addressing them effectively will be vital for the industry to rapidly grow. As the Special Competitive Studies Project's (SCSP) Commission on the Scaling of Fusion Energy outlined in their report Fusion Forward: Powering America's Future, securing a future for fusion energy is of utmost importance.[1] Lessons from other high-tech sectors, such as semiconductors and advanced batteries, underscore the risks of supply chain vulnerabilities and over-reliance on foreign sources, particularly from strategic competitors like China. In this report, we determine a ranking of the most widely used supply chain components within the fusion industry, then provide detailed analysis of each major system and its subsystems, including current locations of manufacture, dominant players in the space, and potential remedies for the most vulnerable components.

A few fusion ecosystem inputs in particular stand out. Tritium, which makes up half of the fuel that most fusion companies plan to use, is a scarce material, with only 25-30 kg available worldwide. To breed more tritium and ensure a closed fusion fuel cycle, companies will likely require lithium enriched in lithium-6, for which there is no domestic commercial supply. Laser diodes are crucial to a subset of inertial fusion companies, and China leads in producing the necessary gallium and germanium, and is making strong progress in the diodes themselves. High-temperature superconductors, necessary for compact magnetic fusion approaches, lack reliable American producers, and China has recently taken the lead in global production volume with plans to massively scale up. Both neutral beam injectors and radiofrequency heaters, used to heat plasma in magnetic fusion devices, are specialized machines that rely on scarce materials and unique expertise.

Our analysis of the fusion supply chain also found some areas where China is potentially vulnerable relative to the United States and Europe. For example, the United States is the world's leading supplier of beryllium, which will likely be important as a neutron multiplier for breeding tritium, and as a component of FLiBe molten salts. Cryogenics, particularly the helium cryogenics needed for low-temperature superconductors, stand out as another area where the dominant manufacturers reside not in China, but in Europe.

[1] Fusion Forward: Powering America's Future, Commission on the Scaling of Fusion Energy, Special Competitive Studies Project (2025).

This method was to observe fourteen major fusion supply chain components, sort them by the number of companies that use them and those companies' raised funding, and present recommendations for addressing the most vulnerable components. Further details of the ranking methodology and risk level analysis can be found in the Methodology section. For a table of fusion supply chain inputs, ranked by their threat level, see Appendix 1. For a table of nations and their relevant fusion supply chain production, see Appendix 2. Select policy mitigations from the full report are presented here.

Key Recommendations:

Create a Stable Demand Market for Fusion. Federal support to accelerate deployment of a fusion pilot plant through the National Fusion Goal and the Milestone-based commercial demonstration program would provide a powerful demand signal for the supply chain.

- Elevate fusion to a national security priority, as recommended in the final report of SCSP's Commission on the Scaling of Fusion Energy. This would allow fusion companies to bypass traditional roadblocks in procurement and signal demand, as happened with the CHIPS and Science Act.

Onshore and Friendshore Manufacturing Capacity. Manufacturing components for fusion power plants on friendly shores would shelter the industry from foreign influence and provide markets for our allies. The United States can both partner with existing companies and support novel industrialists to accomplish this goal.

- Tax credits (such as 45X and 48C) are a valuable tool for the U.S. government (USG) to encourage domestic development of manufactured parts.
- The Department of Energy's Office of Energy Dominance Financing (formerly the Loan Programs Office), a multi-hundred-billion-dollar government lending program, stands out as another avenue for the government to facilitate a fusion supply chain, particularly for applications like critical minerals development, capacitor and switch manufacturing critical for pulsed fusion applications, an isotope separation facility for lithium-6, or domestic steel forging.
- Including fusion as a priority technology for investment in existing and potentially new place-based innovation organizations, such as the National Institute of Standards and Technology (NIST)-led Manufacturing USA Institutes, NIST Manufacturing Extension Partnerships, and the Economic Development Administration's Regional Tech Hubs, would help grow innovation ecosystems that can contribute to the emerging fusion supply chain.
- In the near and medium term, strategically partnering with like-minded nations like the United Kingdom, Japan, and Germany and including specialized fusion components like cryogenics and gyrotrons in trade deals and tariff exemptions would help stave off

potential chokepoints. Recent bilateral tech partnerships with the UK and Japan have already begun this process.
- Create a third-party data hub for creating training sets for the robotics that will be used in fusion machines.

Prioritize R&D to Mitigate Challenges. Funding American researchers can help American supply chain leverage by both spawning industries and innovating our way out of dilemmas. Fusion suppliers can be the next in a long history of successful spinouts from research labs.

- Federal research funding should prioritize fusion energy projects.
- Research into fusion fuel cycles and tritium breeding can create self-sustaining fuel cycles, eliminating the pressure to supply tritium from external suppliers.
- Research into radiation-resistant materials and robotics, as well as molten salt and liquid metal systems, can bring the United States early-mover advantages.

Strategic Management of Critical Materials. A fusion machine will require a number of specialized materials with unique properties. Securing an adequate supply, domestically or from allies, will be essential to building the necessary components.

- Ensure domestic and friendly nation production of maximally threatened raw materials.
  - Leverage domestic capabilities of to expand American production of fusion-relevant critical minerals (including gallium, germanium, gadolinium, and yttrium). MP Materials is the only domestic rare earths producer, and the Department of War is its largest shareholder, giving the United States Government unique influence.
  - Create an American supply of enriched lithium-6 by helping to establish a domestic commercial supply chain.

- Canada looks to be the world's top tritium producer until fusion machines begin to breed their own tritium, or other countries build more heavy water fission reactors. The United States should ensure continued flexible trade to maintain access to the tritium supplies that will be needed for fusion-plant startup.

- For materials like beryllium, the United States should ensure that it maintains and expands its current lead in production. The USG should consider leveraging the Defense Production Act, as it has done so in the past, for production of beryllium and beryllium fluoride as well as other minerals and metals important for fusion energy.

- A coordinated fusion fuel strategy from the United States government would provide a structured plan for availability of fusion fuels.

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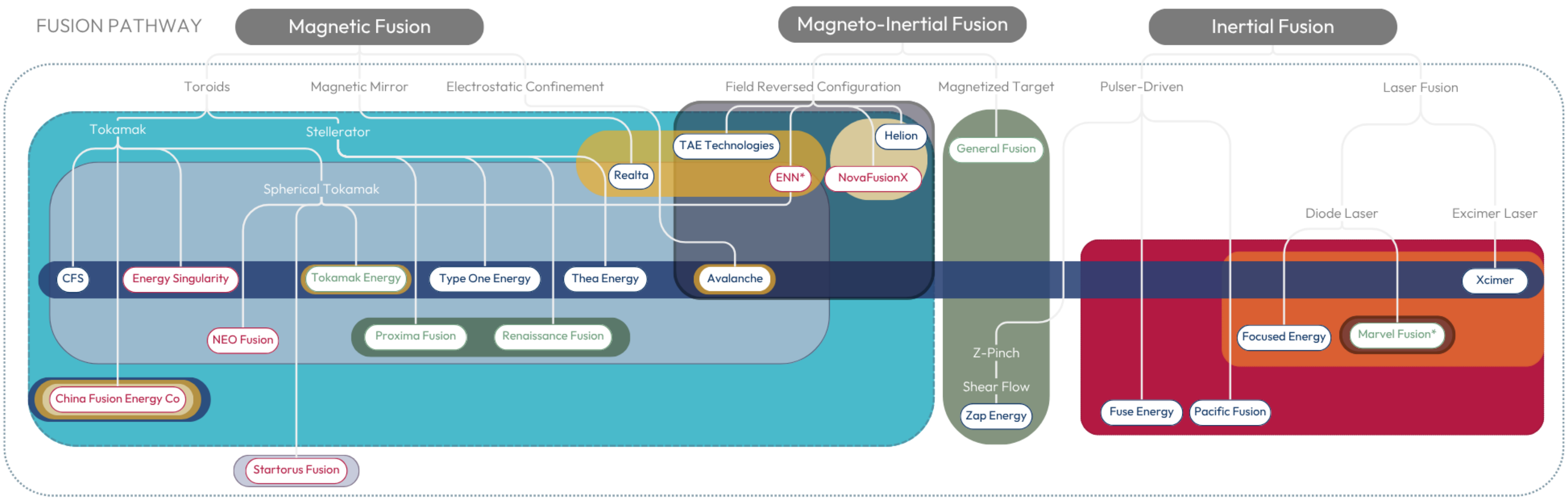
Commercial Fusion Ecosystem Map

The companies shown are those with known funding of at least USD 50 million or participants in the DOE Milestone Program.



*Note: ENN is attempting both a spherical tokamak and field reversed configuration approach to fusion energy. Marvel Fusion and ENN have not announced the use of tritium, but it could be part of an intermediate step, as it is for the other advanced fuels companies. For some Chinese companies, data on the specific components used in their design is not forthcoming. For the case for NovaFusionX and Energy Singularity, some component dependencies are implied based on similarity to the American companies whose designs are closest. China Fusion Energy Co's dependencies have basis on the design of HL-3, a tokamak built by the controlling China National Nuclear Corporation, but their future work will almost definitely have different dependencies.

A map of the fusion technology ecosystem, with various supply chain needs overlaid. Included in the graphic are all fusion companies with funding of $50M USD or higher, plus members of the DOE Milestone program.

Research Methodology

As the first step in our analysis, we have developed an ecosystem map showing the various supply chain components (or fuel inputs) for fusion machines along different technology pathways. The diagram represents every global fusion power company with a known amount of funding $50M USD or higher, plus the members of the Department of Energy (DOE) Milestone Program.[2] It displays a tree diagram that begins by distinguishing the underlying plasma management technology–– inertial vs. magnetic vs. magneto-intertial––and branches into more specific technical approaches. Overlaid on top of the flow chart is a color-coded map displaying specific supply chain components of each company. The full data set of components and companies includes all companies with known valuations, not just those under $50M.[3]

Next, we determined the most widely used components in the supply chain based on all of the American companies within the data set.[4] Given the wide variety of fusion energy approaches underway, something more sophisticated than a simple percentage of companies that use a component is needed.[5] Therefore, we first use the total amount of funding raised by each company as a proxy for each company's significance to the U.S. commercial fusion ecosystem. To determine the most critical supply chain components, the fraction of companies that use a component is weighted by the total funding raised by those companies.[6] Forgings, advanced robotics, and electronics are considered universal components that any company will require,

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[2] For funding data, see 2025 FIA Global Fusion Industry Report, Fusion Industry Association (2025); Fusion Energy Base (last accessed 2025); or Pitchbook (last accessed 2025), in that order of preference.

[3] This is based on preliminary SCSP analysis and can be shared upon request. Publicly available data about every supply chain component's use is not available for every company.

[4] Another 'component' of the supply chain will be workforce, which is briefly touched on in the forgings/steel analysis. This was not included in the original data analysis of official components, but will be considered in future discussions of this working group regarding workforce and talent.

[5] By simple percentage, the most used components globally for the fusion supply chain are:
1(t). Electronics / Forgings / Robotics (100%), 4. Deuterium-Tritium (77%) 5. Molten Salts (67%), 6. High temperature superconductors (48%) 7. RF Heating (47%) 8. Liquid Metals (33%), 9. Alternative Fuels (28%), 10. High Purity Optics (24%), 11. Targets (23%), 12. Neutral Beam Heating (24%), 13. Laser Diodes (22%), and 14. Copper (15%).
When the supply chains are weighted by international company funding, as they are for the U.S. fusion supply chain highlighted on the next page, the ranking becomes:
1(t). Electronics / Forgings / Robotics, 4. Deuterium-Tritium, 5. RF Heating, 6. Molten Salts, 7. Copper, 8. Alternative Fuels, 9. High-Temperature Superconductors, 10. Neutral Beam Heating, 11. Liquid Metals, 12. Targets, 13. High Purity Optics, and 14. Laser Diodes.

[6] If a company's potential use of a component is unknown, it is not included in the fraction. There are some difficulties with this as a weighting method. While it is somewhat effective at separating the serious industry players from more fringe designs, it ignores government funding, underweighting laser inertial fusion. In reality, not all funding is equally valuable. For example, Pacific Fusion has raised $900M in commitments in their seed round, and that is the number used in their weighting. Much of that funding, however, is only accessible once milestones are met, meaning that their accessible cash is lower.

placing them at the top of the list.[7] Similarly, copper should be used in all approaches (including in the fabrication of high-temperature superconducting tape), but only the companies that use it as their primary electromagnetic plasma control system are counted in this ranking. In a different methodology with no such threshold, the importance of copper would be higher.

This ranking system values breadth of use, rather than depth. Due to the weighting mechanism, any component that is specialized to an approach will fall down the ranking list here, but this does not mean that a component would not be needed in a future fusion ecosystem. We still don't know which technical approaches will work for an advanced fusion economy. If one approach ends up being the technological and economic winner, its components will end up being the most important ones, even if they appear relatively low in this ecosystem-level analysis. In most cases, it's true that the technological approach will live and die with the availability of a component. For example, there could be no laser fusion companies without access to optics. There are also some cases where this methodology fails to take into account possible alternatives. Companies might have some degree of choice between banks of capacitors and banks of batteries, a choice between neutral beam heating and radio frequency heating, and a choice between liquid metals, molten salts, and solid walls. For the purpose of this analysis, it's assumed that companies will continue to pursue the approaches that they currently have planned. What this list favors is universality, and manufacturing and maintenance-related components therefore take the top position.

Based on this weighting, the most important supply chain components[8] for American fusion companies are (in order from most to least used, weighted by the total funding raised by the company[9]):

[7] Some other notable supply chain components not included in this list: tungsten (for use as a wall material or divertor, and is mentioned in the RF heating section), and (enriched) lithium, which could have been considered in its own category instead of as a sidenote about tritium.
[8] The choices of components to consider were adapted from the directory found at Supply Chain, Fusion Energy Base (last accessed 2025).
[9] This is an imperfect method for determining the importance of a company, the number of components they will require, or their likelihood of success. Unfortunately, there is no independent review board for the fusion industry or significant technical barrier to joining FIA. As such, funding raised is the most objective measure currently available of the company's significance to the overall fusion ecosystem and their level of technological progress. This approach tends to undervalue inertial fusion approaches. A company planning an approach most similar to well-established public research might need to spend less on their initial steps. Private investment has also been increasing for inertial approaches in the last year, with companies like Marvel Fusion becoming the largest fusion company in the EU. In the future, one could imagine a review of fusion companies based on a combination of funding raised and objective technical milestones, but that is outside the scope of this publication.

1(t). Electronics/Forgings/Robotics	4. Deuterium-Tritium	5. RF Heating
6. Molten Salts	7. High-Temperature Superconductors	8. Alternative Fuels
9. Neutral Beam Heating	10. Targets	11. Copper
12. Liquid Metals	13. Laser Diodes and Optics	

We then evaluate the current supply chain picture for the United States, with a particular eye on Chinese reliance, for all components. Additional consideration is given to the volume of a component needed for a fusion power plant. The risk level for a component (or subcomponent) is rated by the following metric:

None

The component is readily available, has a nearly unconstrained natural supply, and has multiple domestic producers (e.g. hydrogen).

Low

The component has significant natural resources and multiple domestic producers or a very small amount of the component will be needed.

Medium

The United States may be mostly reliant on imports of a component, but is dependent on allies or neutral countries, with multiple providers. There may be some American industry of the component, but it is not currently capable of meeting the industry's needs alone (e.g. high-temperature superconducting tape).

Medium-High

The United States is largely reliant on a single non-allied country to provide a component, perhaps with a small American commercial industry. The technology to produce the component is known, but not at scale in the United States (e.g. gyrotrons).

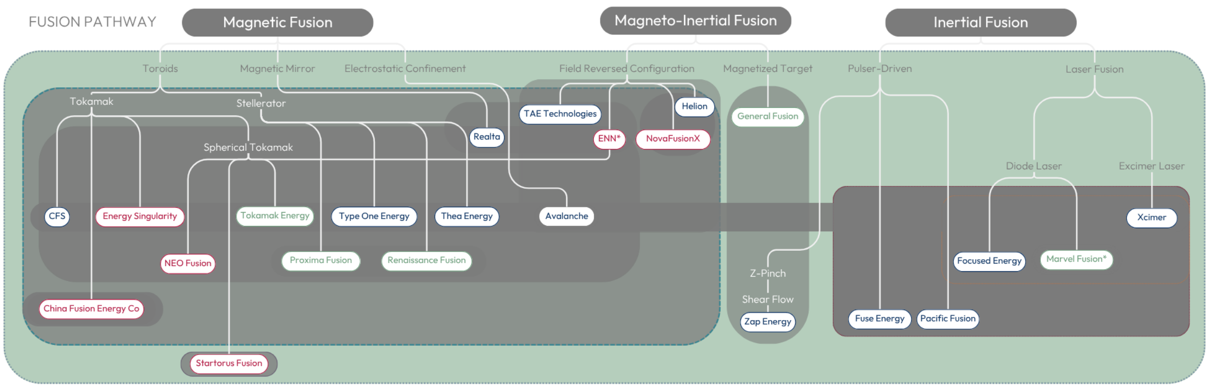
High

The United States is reliant exclusively on non-allied countries for a component (e.g. enriched lithium), or the technology does not yet exist to produce a component.

We offer examples of policy levers that could be explored to improve the supply chain for components with a supply chain risk level at or above "Medium." Notably, the risk levels do not account for the ubiquity of use; that is left up to the ranking system. As such, a component that only one company uses could still be called high-risk, and it would appear towards the bottom of the list.

Fusion Supply Chain Component Analysis

Electronics



Every fusion company (much like any industrial facility of a similar size) will use a considerable number of electronic components. Both conventional semiconductors and high power electronics (HPE) will feature heavily throughout a fusion machine, particularly in the implementation of diagnostic and control software.

Conventional Chips

Conventional computer chips will likely be a major part of the success of a commercial fusion plant. A number of major advances in plasma control have been due to the development of advanced artificial intelligence (AI) systems.[10] The planning and construction of future fusion plants will also be highly dependent upon simulations, perhaps with the utilization of AI to construct device parameters, or creating digital twins of components of fusion machines (and, in time, of the full machines themselves).[11] These chip applications will be fairly conventional for large amounts of data processing. Advanced AI chips will likely be used for this capacity, putting the demands of this supply chain similar to a data center (or perhaps requiring the renting of time on data centers and/or supercomputers, potentially including those at our national labs). Fortunately, the United States is the global leader in advanced computing chip design and

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[10] Colton Poore, AI approach elevates plasma performance and stability across fusion devices, Princeton Plasma Physics Lab (2024).

[11] See Building a Fusion Reactor Digital Twin in NVIDIA Omniverse, NVIDIA Omniverse (2022); Michael I. Battye & Suresh Perinpanayagam, Digital Twins in Fusion Energy Research: Current State and Future Directions, IEEE (2025).

development (but not production, which currently comes predominantly from Taiwan).[12] Reshoring domestic chip manufacturing was identified as a need in the CHIPS and Science Act,[13] and has been further cemented by the federal government's purchase of a 9.9% stake in Intel, the only major company that both designs and manufactures advanced chips in the United States.[14] There are real threats that extend far beyond fusion from not having a domestic chip manufacturing ecosystem. The problem has been taken seriously over the last several years, and the computing industry's demand represents a much larger market than that which will be needed for fusion energy.

Semiconductor Chips Risk Level: Medium. Advanced chips are still generally manufactured overseas, but several mechanisms are in place to reshore domestic construction as-is. On the whole, it's worth noting that this is not a fusion-specific component, and a chip shortage would be felt by a large share of the American economy.

Possible Mitigation(s): Continue the buildout of domestic chip manufacturing proscribed in the CHIPS and Science Act. Fusion companies can partner with National Labs and lease out their supercomputing infrastructure for specific projects. Fusion companies can also negotiate for access to hyperscalers' compute resources as part of Power Purchase Agreements (PPAs).

High Power Switches

The area most requiring fusion-specific electronic components is in high power electronics. Pulsed fusion power companies, which form roughly half of all U.S. fusion companies, rely on pulses surges of energy to initiate fusion reactions and are dependent upon power electronics. These are the driving costs for many of these machines.

High power switches, in this context, includes semiconductors and spark-gap switches for the control and conversion of electric power, specifically those capable of withstanding extraordinarily large currents. These can be used in both pulsed and steady-state confinement approaches, although the pulsed fusion requires significantly higher requirements for current and peak voltage.[15] For pulsed power (like lasers, Z-pinch, or FRC), these high power electronics are needed to survive the significant surge of electricity that comes through with each pulse or shot. For magnetic confinement approaches like tokamaks, these switches are used when activating an individual magnet–the abrupt nature of plasma whips necessitates significant surges of electricity be delivered to the controlling magnet, and the power electronics for confinement magnets will need to withstand tens of kiloamperes per AC/DC converter, and be

[12] Chips For America, National Institute of Standards and Technology (last accessed 2025).
[13] H.R. 4346, CHIPS and Science Act (2022).
[14] Intel and Trump Administration Reach Historic Agreement to Accelerate American Technology and Manufacturing Leadership, Intel (2025).
[15] Fusion Energy, Dynex (last accessed 2025).

able to quickly turn off and on.[16] They will also be used to power the plasma heating systems[17] that create fusion conditions.

Traditional power electronics are usually made of silicon, but a new generation of wide-bandgap power electronics, made of materials like silicon carbide (SiC) or gallium nitride (GaN), offer the promise of higher operating temperatures and switching voltage.[18] There may be additional components, such as copper and tungsten, that could be challenging to supply at scale.

Most high power switch providers are based in Europe, although the most prominent supplier, Dynex, is now owned by a Chinese company.[19] Other suppliers include OCEM Power Electronics (Italy),[20] JEMA (Spain),[21] Siemens (Germany),[22] and Hitachi Energy (Japan).[23] The United States' contribution to the International Thermonuclear Experimental Reactor (ITER) project's power supplies came courtesy of Princeton Plasma Physics Lab,[24] and Princeton Satellite Systems (doing business as Princeton Fusion Systems) attempts to commercialize that technology.[25] Generally, high power electronics for fusion are not a mature industry, and instead are a small, bespoke field driven by individual projects.

High Power Switches Risk Level: Medium-High. The engineering expertise and facilities for HPE are currently spread globally, and no one country has a dominant share of the niche and nascent market. Depending on actions taken in the next few years, this could become a supply chain chokepoint for U.S. fusion companies, or could serve as an opportunity to position U.S. innovators at the forefront of an emerging industry.

Possible Mitigation(s): Public-private partnerships, such as the Advanced Research Project Agency-Energy's (ARPA-E) collaborations with the private sector, are already helping to

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[16] E.K. Sato, et al., Power Electronics: Critical Technology for Control and Operation of Fusion Power Plants, 13th International Conference on Power Electronics, Machines and Drives (2024).
[17] See the 'RF Heating' and 'Neutral Beam Heating' sections.
[18] Giovanni Di Maria, Wide Bandgap (WBG) Semiconductors, Power Electronics News (2024).
[19] Paul Shepard, Zhuzhou CRRC Times Electric to Acquire Dynex Power for 160% Premium, EE Power (2019).
[20] OCEM, OCEM (last accessed 2025).
[21] JEMA, JEMA (last accessed 2025).
[22] Power Electronics, Siemens (last accessed 2025).
[23] Frede Blaabjerg & Simon Round, Power Electronics: Revolutionizing the world's future energy systems, Hitachi (2021).
[24] Jeanne Jackson DeVoe, PPPL completes shipment of electrical components to power site for ITER, the international fusion experiment, Princeton University (2017).
[25] Power Electronics Development for Plasma and Nuclear Fusion Systems, Princeton Satellite Systems (last accessed 2025).

cultivate an American HPE industry.[26] These programs should continue and can provide an example of future programs to create American vendorship of HPE technology.

Capacitors

Capacitors are a standard electronic that can release a significant charge very quickly. For fusion machines, capacitors will be an integral part of nearly all pulsed-power approaches. They will also see use in some magnetic confinement designs to quickly turn on a controlling magnet.

Capacitors are in constant use in modern devices, but those for a fusion machine will require stringent operating standards, tolerating higher voltages and currents than in consumer electronics. Large pulsed power facilities will require a world-class capacitor bank. The National Ignition Facility (NIF) power bank, for example, delivers more than 330 MJ of energy for each laser shot fired, making it the most energetic capacitor bank in existence.[27] Private companies' needs are more modest, but still noteworthy. Zap plans on using a ~2 MJ capacitor bank for a power plant, Pacific Fusion plans on using 80 MJ for a demonstration plant,[28] and Helion plans on using a 50 MJ capacitor bank for their Polaris facility, requiring 150 shipping containers' worth of capacitors,[29] and estimates capacitors to be the second-largest component by cost in their system.[30]

Capacitor banks often have long lead times on the order of 18-24 months, and a fully functional power plant will require more stringent operational specs (the rapid sequence of firing multiple shots per second will likely require active cooling, and last for hundreds of millions of shots). In Helion's case, only one supplier was capable of producing capacitors at the scale, quality, and cost required for even their preliminary machines, and that supplier was based in China. As a result, Helion set up their own capacitor factory in Washington, and have been capable of producing 5 MJ worth of capacitors per week, when operating. Zap, similarly, has acquired the machines to facilitate their own capacitor production.[31]

Capacitor Risk Level: Medium. The current supply of fusion-relevant capacitors is quite limited, and mostly overseas, but does not feature specialized materials or components that cannot be recreated here.

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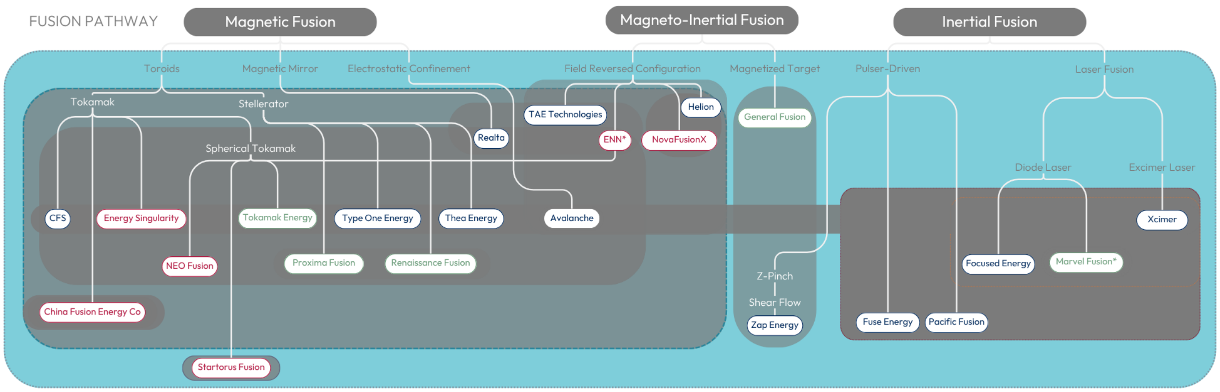
[26] Princeton Fusion Systems, Advanced Research Project Agency-Energy (last accessed 2025).
[27] Power Conditioning System, National Ignition Facility & Photon Science (last accessed 2025) and Facility Operations, National Ignition Facility & Photon Science (last accessed 2025).
[28] SCSP Engagement with Pacific Fusion representatives.
[29] Mark Harris, "Welcome to Fusion City, USA", IEEE (2023).
[30] SCSP engagement with Helion representatives (2025).
[31] SCSP engagement with Zap representative (2025).

Possible Mitigation(s): Tax credits for capacitor manufacturing would increase the economic viability of domestic production. Vertically integrating capacitor production is not economically feasible or strategically wise for every company, especially using venture capital, but has been appropriate for some. If companies who have vertically integrated their capacitor supply chain decided to sell them to other fusion companies with similar needs, this risk level would decrease.

High Strength Forgings



Like many other advanced industries, steel will be a major structural component of fusion machines. The steels used in fusion plants will likely need to survive extreme conditions, including very high temperatures, very low temperatures, neutron irradiation, corrosion, and significant mechanical stress.[32] Steels used near the plasma chamber will likely need to be reduced-activation steel, which can better survive a lifetime of neutron bombardment.[33] The other industry that shares most of these requirements, the fission power industry, is also in a difficult position for sourcing their steel—only Framatome (France) and Japan Steel Works are capable of producing reactor vessel forgings for American companies.[34] Fusion power plants should be able to suffice with smaller forges, but still require very rigorous materials standards and a workforce capable of producing them. A 50% tariff was added on foreign steel imports, increasing the necessity of creating a domestic supply of steel.[35]

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[32] The plasma inside a fusion machine will reach over a hundred million degrees. The steel components will need to regularly survive temperatures above 1000 degrees F. High-temperature superconductors, despite the name, need to operate at about -300 degrees F. Low-temperature superconductors are even more stringent, at less than -400 degrees F, or 4 to 20 Kelvin. For more, see the “High Temperature Superconductors” section. Low-Temperature Superconductors, National High Magnetic Field Laboratory (last accessed 2025).

[33] Reduced-activation steels are one of three likely candidate materials for the structural components of a breeding blanket, alongside vanadium alloys and silicon carbide composites. See T. Muroga, et al., History, present status, and future directions for vanadium alloys in fusion reactors, Current Opinion in Solid State and Materials Science Vol. 36 (2025) and M.J. Gorley, Critical Assessment 12: Prospects for reduced-activation steel for fusion plant, Materials Science and Technology Vol 31 (2015).

[34] China (China First Heavy Industries, China Erzhong, and Shanghai Electric Group Company) and Russia (OMZ Izhora) both have access to their own steel production at this scale, making this more of a problem for America than our competitors. See Heavy Manufacturing of Power Plants, World Nuclear Association (2021).

[35] Donald J. Trump, Adjusting Imports of Aluminum and Steel into the United States, The White House (2025).

Major advances have happened overseas, with the UK's Neurone Consortium (a collaboration of the UK Atomic Energy Authority, and academic and industrial partners both in the UK and internationally) capable of high-temperature-resistant steel production at scale,[36] and Chinese scientists have formulated a steel capable of withstanding much higher temperatures and magnetic field strengths.[37]

Supply Chain Risk Level: Medium. U.S. fusion companies are not currently dependent on China for high strength steel production, but the lack of a domestic steel manufacturing industry and workforce, especially for specialty steels such as those needed for fusion, could significantly extend lead times and costs for the basic building blocks of fusion power plants as the industry scales.

Possible Mitigation(s): The materials vulnerability could be partially alleviated through government incentives to reshore American high strength steel production, along with tariff exemptions for fusion companies (and others) as a national security priority. However, this alone will not address the forging skill and infrastructure gap. To mitigate this, nearshoring or friendshoring with key allies and partners should be considered as a short- to medium-term mitigation.

To sustain the long-term growth of a U.S. fusion industry alongside those of many other advanced technologies, the United States must invest in workforce development for the domestic steel industry. One approach is to designate steel production as a priority area within the Manufacturing USA Institutes, while another is to explore foreign direct investment as a strategy to address steel shortages. Expanding Manufacturing USA's funding and eliminating restrictive five-year term limits, along with modernizing the Manufacturing Extension Partnership (MEP) program to help small manufacturers adopt advanced technologies, could further strengthen domestic steel production and supply chain resilience.[38] Further, the tax code can be leveraged to benefit the fusion industry, with the addition of 45X and 48C tax credits for fusion-capable high-strength forgings. The Office of Energy Dominance FinancingOffice of Energy Dominance Financing could be a valuable tool for funding the initial stages of reshoring the kind of steel manufacturing needed.

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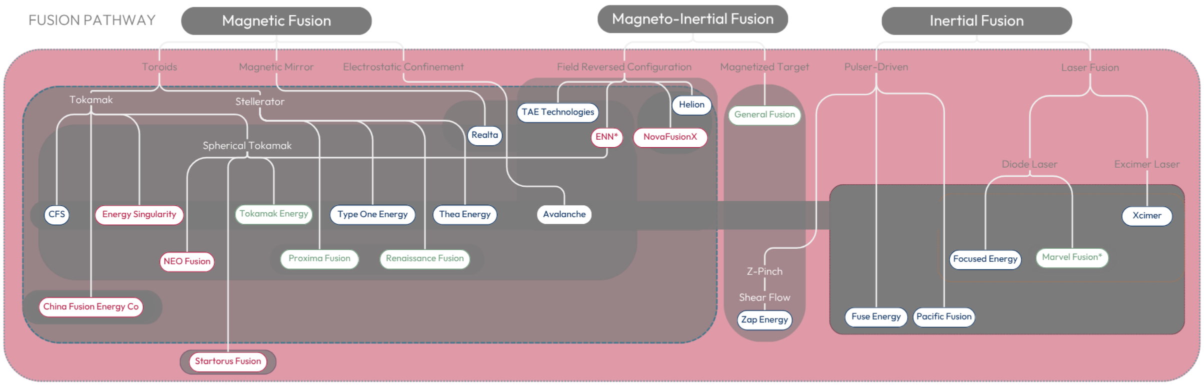
[36] Thomas Johnson, Fusion-grade steel able to withstand 650 C produced at industrial scale for first time in UK, New Civil Engineer (2025).
[37] Darren Orf, Scientists Developed 'Super Steel' That Could Take Fusion to the Next Level, Popular Mechanics (2025).
[38] Advanced Manufacturing Transition Memo, Special Competitive Studies Project at 3 (2025).

Advanced Robotics



While not strictly necessary for a fusion machine to exist, advanced, radiation-resistant robotics will be highly likely to be integrated in all fusion approaches. Any human interaction in a tokamak requires a difficult cleaning process. For example, the recently decommissioned Joint European Torus (JET) required a three-month process for any human activity in the chamber, not including the time of performing the upgrades or repairs.[39] As such, and considering the radioactive activation of fusion, no human entered the chamber for thirty years.[40] This led JET to become a leader in advanced robotics, creating mechanical arms sensitive enough to allow an operator to feel if a bolt is correctly threaded. As a result, the UK is a major leader in fusion-specific robotics applications.[41]

Robotics would also incur a design advantage. A fusion machine built around robotic maintenance wouldn't need human-sized spaces or human-amenable environments, significantly freeing up design criteria. After a fusion machine's operational life ends, radiation-resistant robotics will be of use in site cleanup.

The United States is a global leader in advanced robotics technology today, but China's significant investments, strategic initiatives, and lower manufacturing costs pose a serious competitive challenge as the industry scales. An example of this can be seen in the Boston Dynamics 'robot dog,' Spot, which has been used for high-radiation work in the UK.[42] The

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[39] Arthur Turrell, The Star Builders, Scribner at 105-106 (2021).
[40] UK Atomic Energy Authority, JET's Remote Handling upgrades among the world's most advanced, Gov.UK (2024).
[41] The United States and United Kingdom recently signed a memorandum of understanding to collaborate in various technologies, including fusion energy. The UK's leadership in radiation-resistant robotics is a likely target for that collaboration to take hold. See Memorandum of Understanding Between the Government of the United States of American and the Government of the United Kingdom of Great Britain and Northern Ireland Regarding the Technology Prosperity Deal, The White House (2025).
[42] Data Collection and Sensing in Nuclear Environments, Boston Dynamics (last accessed 2025).

Chinese equivalent, the Unitree B2, is available for half the price (pre-tariff), with greater payload capacity, battery life, speed, temperature range, and climb angle.[43] Another major facet of competition will be robotics adoption. China leads in installations of industrial robots, with a majority of all new installations coming in China.[44] That industrial experience is paying off in the fusion sector, as China has revealed the successful testing of a class-leading robotics system at the CRAFT campus, capable of lifting 60 metric tons, with positioning accurate to a fifth of an inch.[45]

Other countries have made investments in radiation-hardened robotics. Russia recently announced the development of Rosatom's "nuclear spider", which analyzes reactor welds.[46] Mitsubishi Heavy Industries also has an inspection robot, the A-UT, for underwater operation.[47] In the United States, Idaho National Laboratory has done some work in developing radiation-resistant robotics.[48]

Advanced Robotics Risk Level: Medium. China and Russia have both made notable strides in radiation-resistant robotics, but the United States has significant experience in robotics overall, and has close ties with the overall industry leader in the United Kingdom.

Possible Mitigation(s): Policy recommendations to accelerate U.S. leadership in advanced robotics broadly would have downstream positive impacts on the fusion industry. For example, the creation of voluntary, third-party dataset hubs would help offset China's ability to compel data sharing across its innovation ecosystem.[49] For fusion, such a hub could enable companies to access data related to the training and deployment of robots in fusion facilities and for associated manufacturing processes, accelerating adoption readiness. Additionally, radiation-hardened robotics should be an area of priority in government-funded fusion R&D.

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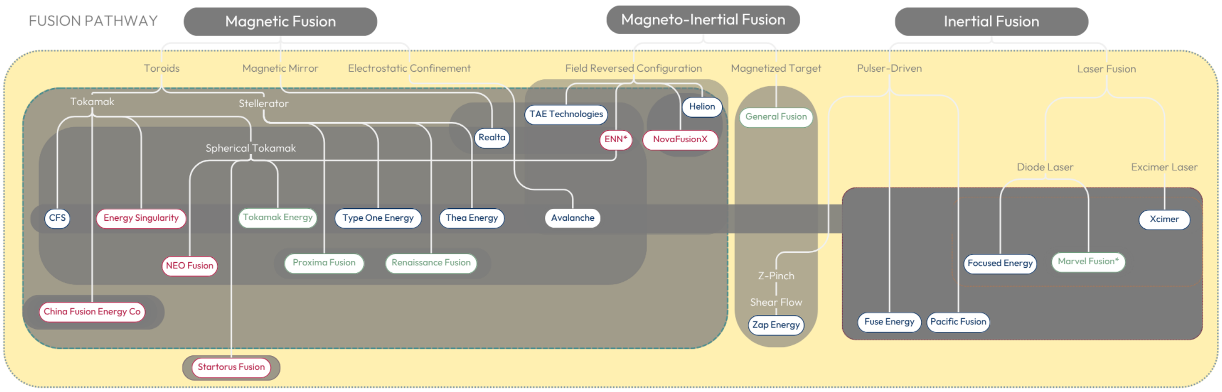
[43] Don Garland, Unitree B2 vs. Boston Dynamics' Spot Robot Dog: A Detailed Comparison, Drones Plus Robotics (last accessed 2025).
[44] World Robotics 2024, International Federation of Robotics at 17 (2024).
[45] Dannie Peng, China unveils largest known radiation-proof robot for nuclear fusion power plant, South China Morning Post (2025).
[46] Rosatom deploys robotic "spider" for reactor weld inspections, Nuclear Newswire (2025).
[47] David Elliot, This robot swims inside nuclear reactors to keep them safe, Mitsubishi Heavy Industries Spectra (2025).
[48] Idaho successfully tests robot to help retrieve radioactive waste, Nuclear Newswire (2025).
[49] Memos to the President: National Robotics Strategy, Special Competitive Studies Project (2025). Also relevant: Advanced Manufacturing Action Plan, Special Competitive Studies Project (2024).

Deuterium-Tritium



Almost every fusion company plans to use deuterium-tritium (D-T) fuel in some capacity, whether as the intended final fuel source (like Commonwealth Fusion Systems (CFS), Zap, and most other companies), or as a bridge in the phase before their final plant design is realized (like Helion[50] and TAE[51]).

Deuterium is plentiful, making up one out of every 6500 hydrogen atoms in seawater, and costing about $13 per gram. There are at least three[52] different suppliers of deuterium based in the United States, but none currently enrich their deuterium from natural water. Current suppliers like Cambridge Isotope Laboratories and Isowater don't currently enrich deuterium from natural water, but instead purify existing stocks of deuterium oxide. Isowater has proposed an intention to make a plant to produce 20 metric tons of D_2O per year from natural water.[53]

Deuterium Supply Chain Risk Level: Low-Medium. The natural supply of deuterium in water is enough to last for over a billion years of energy production, so that is of no concern, but the United States currently lacks the capability to produce deuterium from water.

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[50] Helion's endgame fuel approach, D-He^3 fusion, will end up producing tritium from D-D reactions. While a final-form Helion reactor wouldn't require tritium for startup, it would require capture and storage of tritium, and could potentially be a seller. See David Kirtley, Explaining Helion's fusion fuel: D-He-3, Helion (last accessed 2025).
[51] Jonathan Shieber, Claiming a landmark in fusion energy, TAE Technologies sees commercialization by 2030, TechCrunch (2021).
[52] Cambridge Isotope Laboratories, Sigma-Aldrich, and Isowater Corporation.
[53] See Isowater Deuterium Oxide Refinery, Isowater (2025); D2O Recovery Program, Cambridge Isotope Laboratories, Inc (last accessed 2025).

Tritium, however, is a different story, and has been consistently cited by industry as a future supply constraint.[54] Within a fusion machine, tritium can be bred from enriched lithium,[55] and commercial tritium exists as a byproduct from CANada Deuterium-Uranium (CANDU) fission reactors, which operate using heavy (deuterium-rich) water. Commercial tritium is expensive ($30,000–50,000 per gram) and scarce, with only around 25–30 kg currently available, mostly sold through Canada's Ontario Power Generation (OPG).[56] ITER plans to consume 12 of those kilograms in its experimental regime when it comes online, intended to be in the late 2030s.[57] Fusion is also not the only industry use for tritium, which is also used in medical tracing, nuclear weapons, and luminescent devices. It has a half-life of around 12 years, so new tritium needs to be bred as extant supplies decay. Once fusion machines are operating, the industry expects blankets of lithium inside the machines to produce tritium above replacement levels, helping to close the fusion fuel cycle as well as create startup tritium for new fusion power plants. Should this work as planned, the major tritium-related hurdle will be in acquiring the startup supply for initial fusion machines and the early stages of commercial scale-up.[58] A tritium fuel cycle may also require specialized oil-free pumps, which are not currently commonly available.[59]

Private fusion companies do not expect to need as much tritium as ITER requires to set up a machine. An ARC-class power plant, for example, has a startup inventory "on the order of kilograms."[60] If a mature fusion industry pursues plant designs of a similar size, then tritium inventory would affect the rate of scale-up, as tritium-doubling times limit how fast you can increase the number of new constructions. Even so, those fusion plants could run on deuterium-deuterium (D-D) fuel for a few months to create their tritium supply. While doing so would be expensive, a lack of available tritium capacity would not be a technical showstopper for the industry.

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[54] 2025 FIA Supply Chain Report, Fusion Industry Association (2025).
[55] See sidenote at the end of this section.
[56] David Matthews, UK and Canada team up to solve nuclear fusion fuel shortage, Science Business (2024).
[57] ITER has not yet obligated funding to a purchase order, and OPG sells on a first-come, first-served basis.
Several other countries (South Korea, Romania, China, and India) have CANDU or similar reactors, but none sell tritium commercially. See Daniel Clery, Out of Gas: A shortage of tritium fuel may leave fusion energy with an empty tank, Science (2022) and Daniel Jassby, The fuel supply quandary of fusion power reactors, Bulletin of the Atomic Scientists (2024).
[58] As time passes, the conventional tritium supply may grow more scarce, as nearly half of the CANDU reactors that produce tritium were scheduled to shut down before 2030. As that supply decreases, demand is expected to increase due to the rise of private fusion companies and the construction of ITER, which will use approximately 1 kg of tritium per year. ITER projects that, when they finish their work in the 2050s, the global tritium supply could be down to 5 kg or less. See Daniel Clery, Out of Gas, American Association for the Advancement of Science, Science (2022).
[59] Lucas M. Angelette & James E. Klein, Logical approach to tritium vacuum pump selection for fusion applications, Fusion Engineering and Design (2025).
[60] Samuele Meschini, et al., Modeling and Analysis of the Tritium Fuel Cycle for ARC and STEP-Class D-T Fusion Power Plants, Nuclear Fusion Vol. 63 Num. 12, (2023).

The current method that the United States uses to produce tritium is the use of Tritium Producing Burnable Absorber Rods (TPBARs), which have been installed at Watts Bar Nuclear Plant in Tennessee (a conventional fission reactor) and processed at the Savannah River National Lab.[61] While this concept theoretically could be used in a purely commercial application, TPBARs are not available for commercial use today and would require significant policy changes to become so.

Tritium Supply Chain Risk Level: Medium. Tritium is currently quite scarce and is commercially supplied by only one foreign company, but can be created in existing machines. Functional breeding blankets will allow future fusion machines to create their own supply of tritium fuel.

Possible Mitigation(s): The most important action the DOE could take is to derisk tritium breeding and closing the fusion fuel cycle through a mixture of research and the construction of high priority test stands or R&D facilities. Setting up a new facility exclusively to create a commercial tritium supply would likely be far more expensive than the combined opportunity and electricity cost of simply running a fusion machine on D-D fuel to breed a startup supply of tritium or the use of TPBARs or similar technology, for a relatively limited need. Alternatively, the USG could signal interest in companies building U.S.-based heavy water reactors of, or similar to, the CANDU design, which would not only supply tritium, but also be a new source of electricity to the grid.

Sidenote: Beryllium

A lithium blanket should produce more tritium than is consumed by the fusion machine. A neutron multiplier is required for this process. Beryllium is the best low-Z[62] candidate material for this,[63] and also is one of the few materials where the United States has a clearly defined

[61] TPBARs were designed by Pacific Northwest National Lab and fabricated by WesDyne (owned by Westinghouse). Savannah River National Lab handles the tritium extraction, as well as the He-3 made by tritium decay. See KA Burns, et al., Description of the Tritium Producing Burnable Absorber Rod for the Commercial Light Water Reactor, Pacific Northwest National Laboratory (2012); DJ Senor, Science and Technology Supporting the Tritium Sustainment Program, Pacific Northwest National Lab (2018); and Savannah River Tritium Enterprise, Savannah River Site (2020).
[62] Where Z refers to atomic number, meaning this is a lighter element. One high-Z alternative option for tritium production would be to construct a fission-fusion hybrid reactor with one or more layers of subcritical blankets. A 50-100 MW fusion driver could produce a surplus of a few kilograms of tritium per year, but would come with the additional regulatory and supply constraints of building a novel fission reactor. Vladimir Khripunov, et al., Enhanced tritium production in fusion-fission hybrids for the external consumption, Fusion Engineering and Design Vol 146 Part B at 1569-1573 (2019).
[63] Another high-Z alternative being considered is mercury-197, which could theoretically be transmuted into gold, according to a recent paper. Adam Rutkowski, et al., Scalable Chrysopoeia via (n,2n) Reactions Driven by Deuterium-Tritium Fusion Neutrons, Marathon Fusion (2025).

advantage in mining and production. Building fusion power plants will require a dramatic increase in beryllium production. One estimate suggests that 1 GW of fusion electricity could require almost 500 tons of beryllium, higher than the 360 tons currently produced worldwide per year (but much lower than total identified resources of 100,000 tons).[64] It is a difficult material to work with, as it is known to cause an increase in lung cancer.[65] The American company Materion, the world's most notable beryllium supplier, recently signed a deal to provide beryllium fluoride for fusion power plants.[66]

Only a few nations (the United States, China, Brazil, and Kazakhstan)[67] have meaningful beryllium production capabilities.[68] Of these, Kazakhstan sources their ore from a shrinking Cold War stockpile, Brazil has only recently scaled up production, and China mines a fraction of its production, but the United States creates by far the largest volume of production from fresh ores.[69] While China is a net importer of beryllium, their imports today are generally Kazakh and other foreign sources rather than American.[70] While they do have natural reserves, China will need to look further than their current supply chain to meet the demands of a fusion industry.

Beryllium Supply Chain Risk Level: Low-Medium. In tallies of American leverage and policy options, beryllium is one critical component from which we have an advantage in both import and export today, and possess 60% of the world's known beryllium reserves for future production.[71] The world does not yet produce enough beryllium that a fusion ecosystem will need, but the United States can maintain and expand its leadership if it appropriately increases production.

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[64] Estimate courtesy of Timothy Pickarski and Dr. Raluca O. Scarlat, presuming an ARC-style fusion machine. See also Ricardo Vidrio, et al., Density and Thermal Expansivity of Molten 2LiF-BeF2 (FLiBe): Measurements and Uncertainty Quantification, Journal of Chemical & Engineering Data Vol. 67 (2022), Lorenzo Vergari, et al., The corrosion effects of neutron activation of 2LiF-BeF2 (FLiBe), Nuclear Materials and Energy Vol. 34 (2023), and Brian W. Jaskula, Mineral Commodity Summaries 2025: Beryllium, U.S. Geological Survey (2025).

[65] Beryllium, National Institute of Health, National Cancer Institute (last accessed 2025).

[66] Materion Signs Agreement with Commonwealth Fusion Systems to Provide Beryllium Fluoride for Fusion Energy Technology, BusinessWire (2025).

[67] Graham Lederer, et al., Beryllium-A Critical Mineral Commodity-Resources, Production, and Supply Chain, U.S. Geological Survey (2016).

[68] There is limited production from a few other African nations as well, including Madagascar, Mozambique, Rwanda, and Uganda, but most produce a ton or less of beryllium per year. Brian W. Jaskula, Mineral Commodity Summaries 2025: Beryllium, U.S. Geological Survey (2025).

[69] Meeting Growing Demand for Beryllium as Worldwide Supplies Tighten, Materion (2024).

[70] Brian W. Jaskula, 2020 Minerals Yearbook: Beryllium, U.S. Geological Survey (2025).

[71] Brian W. Jaskula, Mineral Commodity Summaries 2025: Beryllium, U.S. Geological Survey (2025).

Sidenote: Enriched Lithium

The lithium required to breed tritium fuel would be enriched in lithium-6 (^{6}Li).[72] At present, the United States lacks any commercial lithium enrichment capabilities. The Y-12 facility at Oak Ridge National Lab has begun construction of a lithium processing facility, projected to be completed in the early 2030s for $0.96-1.6 billion,[73] but this would be targeted for non-commercial use. Chile and other South American countries have considered installing lithium enrichment facilities, but have not yet.

Some advanced fission companies require lithium highly enriched in the other naturally occurring lithium isotope, lithium-7. Creating this, as Kairos Power is doing at their Molten Salt Purification Plant in New Mexico, will inherently create a feedstock of lithium enriched in the ^{6}Li that fusion reactors will need, although likely not to the enrichment levels required. As of November 2025, Kairos has no plans to sell their ^{6}Li-heavy feedstock externally.[74]

Support for domestic commercial lithium enrichment capacity could leverage a number of newer technologies, which could potentially be more cost-effective[75] and reduce the environmental wastes of the standard COLEX process.[76] The U.S. Government should incentivize avenues to make a supply of enriched lithium available to private fusion companies, and leveraging incentives such as tax credits and/or the Office of Energy Dominance Financing to facilitate construction of one or more modern lithium enrichment facilities. A coordinated fusion fuel strategy from the U.S. Government would provide a structured plan for availability of fusion fuels. Until commercially accessible lithium enrichment facilities are constructed and completed, ^{6}Li access is very limited. **Enriched Lithium Supply Chain Risk Level: High.**

Raw lithium has more exporters who produce a much greater volume (as is required for global battery production), but China is still a major lithium exporter. The amount of lithium required for a fusion plant (10 to 100 tonnes to start and sustain a machine[77]) is significantly less than will be needed in the battery and EV industries, for example, and there are over a hundred million tons of lithium reserves worldwide.[78] **Raw Lithium Supply Chain Risk Level: Low.**

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[72] The level of enrichment required is still debated and design-specific. CFS's ARC plans on a 90% enriched blanket, although one paper claims that the optimal enrichment level is approximately 25%. Different designs could incorporate regular replenishment of the enriched lithium, or the blanket could be a lifetime component. Different salts will also require different enrichment levels. See Lorenzo Vergari, et al., The corrosion effects of neutron activation of 2LiF-BeF2 (FLiBe), Nuclear Materials and Energy Vol. 34 (2023).

[73] See Site work begins for Y-12 Lithium Processing Facility, Y-12 (2023) and Darryl Creasy et al., Lithium Processing Facility, Y-12 (2023). This site is not for enriching lithium from mined stock, but rather for processing enriched lithium from extant stockpiles.

[74] Bringing Flibe Back: How Kairos Power is Producing a 1960s Molten Salt Coolant for 21st Century Reactors, Kairos Power (2025).

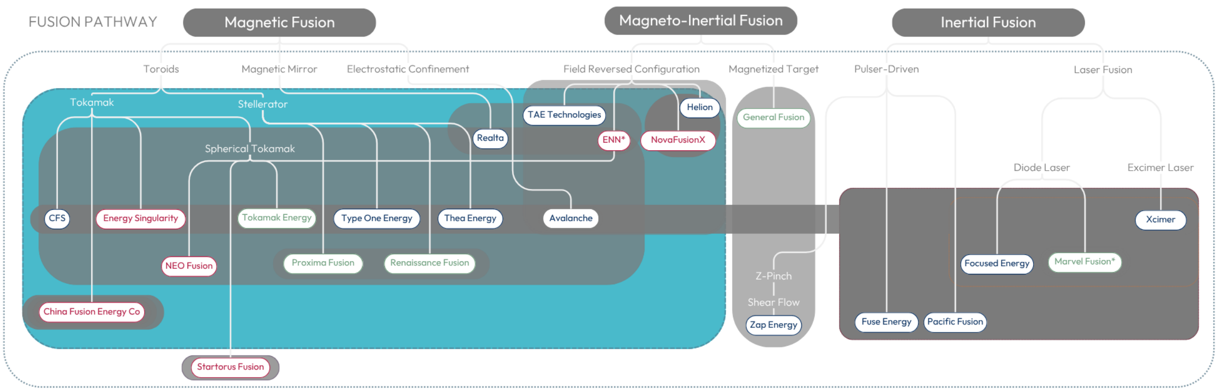
[75] Jackie Park, Enriched lithium and the race for advanced nuclear technologies, Power Technologies (2025).

[76] Silviu-Laurentiu Badea, et al., New Trends in Separation Techniques of Lithium Isotopes: A Review of Chemical Separation Methods, Materials (Basel) (2023).

[77] Jeremy Hsu, Fusion power may never happen if we don't fix the lithium bottleneck, New Scientist (2025).

[78] Brian W. Jaskula, Mineral Commodity Summaries 2024: Lithium, U.S. Geological Survey (2024).

RF Heating



To achieve the more than 100-million-degree temperatures needed in a fusion machine, most fusion energy approaches require heat to be delivered into a plasma without physical contact with walls. For magnetic methods, the most common approach is radio-frequency heating, akin to how a microwave oven works. The machines used to generate radiofrequencies are typically gyrotrons,[79] which are used to heat the electrons or ions[80] inside the plasma of the fusion chamber. Gyrotrons for RF heating were the most-noted present-day supply chain constraint noted in the industry survey of the FIA 2025 Supply Chain Report.[81]

In addition to being a component themselves, gyrotrons rely on critical materials like tungsten, copper, graphite, boron, and molybdenum for specialized vacuum components, as well as superconducting materials[82] and advanced ceramics. Gyrotrons demonstrate both a level of complexity and a reliance upon other nations (including China) that may create significant vulnerabilities for the fusion supply chain later down the line. Russia has historically dominated the gyrotron industry, due to decades of sustained investment in high-power microwave technologies. In recent years, Japan's Kyoto Fusioneering has also become a major supplier in

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[79] Klystrons, a type of oscillating vacuum tube, can also be used. Their largest manufacturer is Canon (Japan), although there are also three American klystron manufacturers. See A. Beunas, et al., High power CW klystron for fusion experiments, 2008 IEEE International Vacuum Electronics Conference (2008) and Klystron Manufacturers, everythingRF (last accessed 2025).

[80] For steady-state operation, the RF heating type must be non-inductive, as inductive methods are inherently pulsed. Ion Cyclotron Resonance Heating (ICRH) and Electron Cyclotron Resonance Heating (ECRH) produce radio waves at the resonant frequencies of the ions and the electrons, respectively. Lower Hybrid Current Drive (LHCD) uses a frequency in the range between ion and electron resonances. To continue the microwave oven simile, LHCD is like how microwaves are tuned to a frequency near, but not at, the resonant frequency of water. See Pat Brans, How to pump 20 MW of power into 1 gram of plasma, ITER (2020).

[81] FIA Supply Chain 2025 Report, Fusion Industry Association (2025).

[82] For more about superconducting materials, see the "High-Temperature Superconductors" section.

the gyrotron space.[83] Separate from fusion, gyrotrons also play a critical role in industrial heating, enabling ceramic sintering, glass processing, and semiconductor manufacturing,[84] and are also being explored for directed-energy weapons[85] and as tools for deep borehole drilling for geothermal plants.[86]

RF Heaters Supply Chain Risk Level: Medium-High. The gyrotron industry is still in early stages of growth relative to other markets within the fusion ecosystem. With key dependencies on other nations for both materials and expertise, the United States will need to invest in domestic gyrotron capacity and/or deepen strategic partnerships with friendly nations that can meet future supply chain needs.

Possible Mitigation(s): Elevating fusion energy to a national security priority and articulating key components in the fusion supply chain could provide an early demand signal for a domestic gyrotron industry. To mitigate potential vulnerabilities in the gyrotron supply chain, the United States could, in support of the National Fusion Goal, leverage the Defense Production Act to secure enough supplies of tungsten, molybdenum, and graphite[87] for the construction of the first fusion plant. This would also help shore up supply chains for other industries that use these components, including aerospace, defense, and medical industries.

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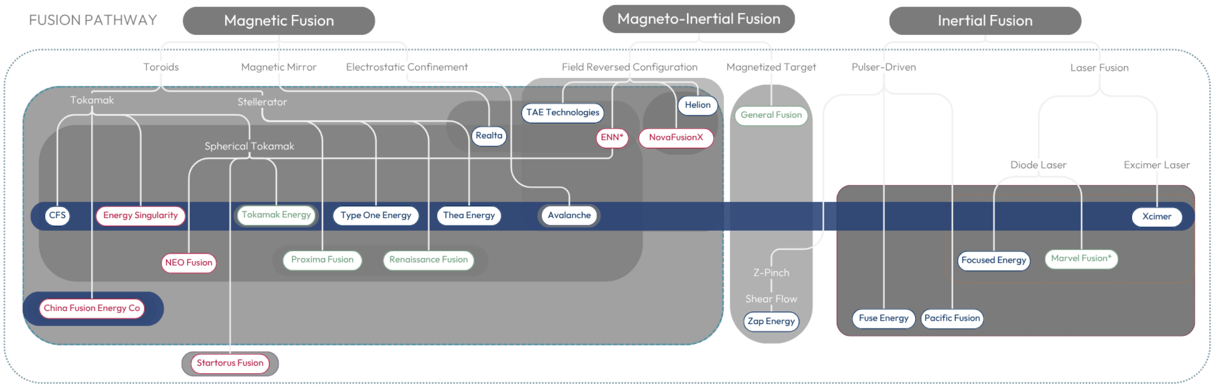
[83] In the past few years, Kyoto Fusioneering has signed major deals with Tokamak Energy and General Atomics to provide essential gyrotron technology to support fusion experiments. See Kyoto Fusioneering's Advanced Gyrotron Technology to Support Fusion Experiments on Tokamak Energy's World-Leading ST40 Facility, Kyoto Fusioneering (2025) and Kyoto Fusioneering to Supply Advanced Gyrotron Systems to General Atomics, Kyoto Fusioneering (2023).
[84] Richard Temkin, High Frequency Gyrotrons and Their Applications, Applied Physics and Applied Math Dept., Columbia University (2014).
[85] Chris Chatwin, et al., Gyrotron Power Beams for Defence Applications, University of Sussex (2016).
[86] Zach Winn, Tapping into the million-year energy source below our feet, MIT News (2022).
[87] Each of these materials can be justified as defense materials for their conventional military purposes. Tungsten is a leading metal for armor-piercing bullets, molybdenum is used for armor and aerospace, and graphite is used in firearms, aircraft, naval craft, and missiles. See The Unique Defense Applications of Tungsten Metal, Tungsten Metals Group (last accessed 2025), Refractory Metals and Alloys, Refractory Metal (last accessed 2025), and Understanding Graphite as a Material for Military Components, Mor-Wear Industries (2024).

Molten Salts



Molten salts, which are also under consideration for advanced fission reactors,[88] are a solution to a number of problems inside a fusion machine. A primary purpose, in both fusion machines and fission reactors, would be for heat extraction. In a typical fusion plant design, neutrons would deposit their energy in the molten salt layer, which flows out of the fusion chamber and to a heat exchanger, which eventually leads to making steam to spin a turbine. For D-T fusion, the molten salt blanket can serve as a form of shielding for other components of the machine, which will need protection from the 14 MeV neutrons. These molten salt blankets will also be used as the location to breed additional tritium. The most commonly considered salt would be FLiBe, a combination of fluoride **(Supply Chain Risk Level: None)**, lithium, and beryllium, which would include both a neutron multiplier and a source for tritium to be bred from (see the "Enriched Lithium" and "Beryllium" sidenotes above). Other molten salts, like FLiNaK, are under consideration, but FLiBe has a longer research history,[89] exceptional heat capacity,[90] and contains a neutron multiplier that makes tritium breeding easier.[91] Most fusion companies plan to have a liquid component in their machines, whether it be molten salts or liquid metals.

Similarly to liquid metals (see "Liquid Metals"), molten salts are also under consideration for some designs of advanced nuclear fission reactors. Current advances in handling, pumping, and engineering molten salt systems for fission reactors will assist the fusion industry.[92] The most critical challenges around molten salts regard salt chemistry and materials. Molten salts will need to be of a very high purity, as is the case with many materials in a fusion machine, to

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[88] One small difference here is that a molten salt for fission reactors would likely be enriched in ^{7}Li, whereas a molten salt for fusion would likely be enriched in ^{6}Li.
[89] James A. Lane, et al., Fluid Fuel Reactors, Addison-Wesley at 569-594 (1958).
[90] T. Lichtenstein, et al., Thermochemical Property Measurements of FLiNaK and FLiBe in FY 2020, Argonne National Lab (2020).
[91] Beryllium is that multiplier, which is not present in FLiNaK salts. The presence of a neutron multiplier will allow for much more efficient tritium breeding and less enrichment of ^{6}Li.
[92] As mentioned in the above sidenote about enriched lithium, Kairos Power is developing a molten salt production facility, as they are one of the advanced reactor companies pursuing molten salt designs. See Bringing Flibe Back: How Kairos Power is Producing a 1960s Molten Salt Coolant for 21st Century Reactors, Kairos Power (2025).

prevent radioactive activation and corrosion.[93] One particular corrosion concern for FLiBe salts (or any fluoride-containing salt) is the creation of tritium fluoride, which is highly corrosive.[94] Some open research questions will affect the operation of a tritium stripping and gas supply system within the blanket.[95]

Designing around molten salts carries a number of difficulties, including high operating temperatures. There is still work to be done to ensure that a molten salt system would flow smoothly, but this is more of a matter of research and development than it is of sourcing of parts and raw materials. As long as that R&D continues, molten salt pumps and equipment should be relatively easy to scale.

Molten Salts Supply Chain Risk Level: Low-Medium. Molten salt systems are still in early stages of development, but are more likely to depend on the manufacturing of advanced pumping systems and corrosion-resistant piping than on scarce metals.

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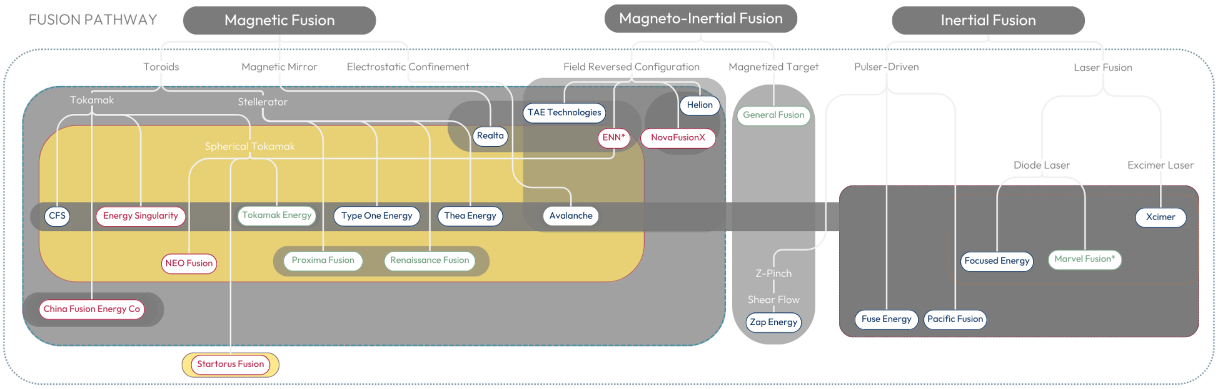
[93] Status of Molten Salt Reactor Technology, International Atomic Energy Agency at 19 (2023).
[94] Haoyang Li, et al., Study on tritium transport characteristics in fluoride-salt-cooled high-temperature advanced reactor, International Journal of Hydrogen Energy (2024).
[95] Thomas Fuerst, et al., The Molten Salt Tritium Transport Experiment: A Pumped Fluoride Salt Loop for Hydrogen Isotope Experimentation, Social Science Research Network (2024).

High-Temperature Superconductors



High-temperature superconductors (HTS), which were discovered in the 1980s, can deliver uniquely strong magnetic fields with no resistance, which can enable fusion reactors to be much smaller. For fusion, HTS will most likely be used to its greatest degree in magnetic confinement approaches for plasma control, but are also often found in particle accelerators, as would be seen in a neutral beam heater.[96] HTS could also be important for future data centers and electric transmission lines.[97]

The standard form of superconducting wire/tape used by fusion companies is Rare-Earth Barium Copper Oxide (REBCO). REBCO wire/tape features a major advantage in its critical temperature, which can be over 77 K.[98] High-temperature superconductors make the challenges of cryogenics much easier by operating at temperatures above that of liquid nitrogen, which is relatively common and cheap, whereas low-temperature superconductors require liquid helium, which is much more expensive.[99]

The potential difficulties of acquiring HTS are more than just the sum of the materials. Superconducting tape and superconducting wire are complicated and expensive, needing to

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[96] Fritz Caspers & Sergio Calatroni, Superconducting RF Cavities, CERN (2024).
[97] This is where some companies, like those in South Korea, specialize. See Will Reynolds, Beyond voltage: Rethinking data center density with HTS, Data Center Dynamics (2025), HTS Cables Speed Up the Electric Superhighway, Power Mag (2009), and LS Superconducting System, LS Cable & System (2021).
[98] Alternative (low-temperature) superconductors, like Niobium Titanium (NbTi) and Niobium Tin (Nb3Sn), have a lower critical temperature of 9 K and 18 K, respectively. Those temperatures, just above absolute zero, create significant challenges in cryogenics, the systems that chill components down to the necessary temperatures.For a comparison of these three superconducting materials, see HTS REBCO, Canyon Magnet Factory (last accessed 2025).
[99] Naila Moloo, Why High-Temperature Superconductivity Cannot Be Explained Without Quantum, Medium (2021).

withstand high thermal stress and electromagnetic forces[100] and a commercial fusion power plant will require more than has ever been produced before.[101] A number of stellarator companies seek to have delicate superconductor shapes surrounding their vessels in a design to facilitate steady-state operation.[102] Tokamaks will generally have a simpler HTS geometry, needing circular coils of superconductor. In stellarators, the complexities are more likely to be resolved in the design and construction process, and advanced manufacturing techniques (like additive manufacturing) had to be innovated for stellarators to become a viable concept.[103]

The world's top consumer of REBCO magnets is the U.S. fusion company Commonwealth Fusion Systems, which has already acquired 'nearly all' of the 10,000 km of superconducting tape required by their upcoming SPARC demonstration machine.[104] CFS produces REBCO magnets primarily for their own machines, but has delivered magnets to the University of Wisconsin[105] and has inked a deal to exclusively license their superconducting magnet technology to Type One Energy.[106] CFS generally sources their HTS tape through Japanese suppliers like Faraday Factory, which have historically led the world in HTS production and produce about 3,000 km of HTS tape per year.[107] Faraday Factory has also signed further agreements to become the HTS provider for additional companies like Proxima Fusion,[108] despite international concerns about its majority owner and chairman, Andrey Vavilov.[109]

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[100] You-He Zhou, et al., Review of progress and challenges of key mechanical issues in high-field superconducting magnets, National Science Review Vol. 10, Issue 3 (2023).
[101] Lara Pierpoint & Rick Needham, The superconducting tape set to make fusion power plants possible, Latitude Media (2025).
[102] There are ways to do this other than producing spools of HTS tape or wire. Renaissance Fusion, for example, plans to coat the vessel surface with superconducting films, then engrave the HTS coil pattern directly onto the surface with lasers. This approach would have greater usage of HTS materials, but, should it work as promised, greater simplicity in HTS construction.
[103] Vicente Manuel Queral, et al., Evaluation of metal additive manufacturing for high-field modular-stellarator radial plates and conductors, Nuclear Materials and Energy Vol 30 (2022).
[104] Stephen Shankland, How CFS is building a fusion factory, not just a single fusion machine. Commonwealth Fusion Systems Blog (2025).
[105] Commonwealth Fusion Systems delivers superconducting magnets to Wisconsin University, Nuclear Engineering International (2024).
[106] As a result of this deal, Type One is currently the only stellarator company with an agreement to use CFS tape. Type One Energy inks expanded fusion development deal with TVA, Nuclear Newswire (2025).
[107] See Faraday Factory Japan: High-quality HTS tapes for a greener future, Innovation News Network (2025) and LinkedIn Post, Faraday Factory Japan (2025). Other Japanese suppliers of note are the smaller Fujikura and Sumitomo.
[108] Faraday Factory Japan signed an agreement to deliver superconductor tape for the demo stellarator magnet of Proxima Fusion, PR Newswire (2025).
[109] Stephanie Saul & Louise Story, At the Time Warner Center, and Enclave of Powerful Russians, New York Times (2015).

There are a few companies in the United States[110] producing HTS tape/wire, but in small volumes and with long lead times. Two of the three American HTS companies pursue the Metal-Organic Chemical Vapor Deposition (MOCVD) approach, which has so far struggled to achieve the price point, quality, and consistency of the Pulsed Laser Deposition (PLD) approach pursued by overseas manufacturers. The last, High Temperature Superconductors, Incorporated, has yet to produce complete tape, but is positioning for completely American supply sourcing.[111]

Recently, China has begun to significantly ramp up its efforts in the production of HTS tape. There are now four notable Chinese HTS suppliers,[112] and they have set a price target under half of what Japan's tape sells for.[113] The largest of these companies, Shanghai Superconductor, is undergoing an expansion that will bring their annual capabilities to double that of Faraday Factory.[114] These Chinese companies claim similar levels of product quality as their Japanese competitors, and aim to quintuple their output by 2027.[115]

HTS Risk Level: Medium-High. HTS production is difficult and expensive, and American companies currently lag behind manufacturers in the East in volume, price, and consistency. China has taken steps to try to dominate this industry, and the Japanese industry leader is owned by a Russian oligarch. Accelerating American production of HTS tape would benefit a number of magnetic fusion companies, particularly as they scale.

Possible Mitigation(s): Ensure that HTS tape is eligible for tax credits. Additionally, to ensure short- and medium-term needs are met, HTS tape should be a priority area in supply chain cooperation between the United States and Japan.

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[110] MetOx International, based in Texas, and SuperPower, a subsidiary of the Japanese company Furakawa, are examples. See MetOx International, MetOx (last accessed 2025) and SuperPower, Inc, SuperPower (last accessed 2025).
[111] High Temperature Superconducting Wire, High Temperature Superconductors, Inc. (last accessed 2025).
[112] Shanghai Superconductor, EastSuper, Shanghai Creative Superconductor, and SuperMag are the major Chinese superconducting tape manufacturers. Lianovation Superconductor (a subsidiary of Jiangxi Electronic Group) also exists, and is one of the two main companies responsible for the Xinghuo fission-fusion hybrid reactor in Nanchang. See Shanghai Superconductor, Fusion Energy Base (last accessed 2025); Shanghai Creative Superconductor, Fusion Energy Base (last accessed 2025); Jeff Pao, China's Jiangxi to build a fusion-fission reactor, Asia Times (2023).
[113] $7/m, relative to the approximately $20/m that Faraday Factory sells.
[114] 6000 km of 12mm tape per year, relative to Faraday Factory's 3000 km per year. Tongling Jingda Special Magnet Wire (600577): Participating company Shanghai Superconductor filed an IPO, Futubull (2025).
[115] SCSP engagement with anonymous representatives.

Sidenote: Rare Earth minerals[116]

Rare Earth minerals are definitionally required to create REBCO magnets, and some, like gadolinium, are used in laser diodes as well (see the "Laser Diodes" subsection below). Most extant REBCO magnets use yttrium, but lanthanum, samarium, neodymium, gadolinium, and europium can also be used.[117] Yttrium production is almost entirely dependent on China, which provides 94% of the United States' inventory, as well as 74% of the total rare earths inventory.[118] Over the course of the past year, China has exerted additional controls over supplies of rare earths,[119] but as of November 2025, has suspended a number of export control regulations on rare earths and other fusion-relevant critical minerals for the coming year.[120] There is some domestic rare earth mining through the Mountain Pass mine in California, the only rare-earths mine in the United States. MP Materials, the company in charge of Mountain Pass, initially had to send their mined ores for processing in China,[121] but now processes their own neodymium and praseodymium domestically.[122] In July 2025, the Department of Defense acquired $400M in stock, becoming the largest shareholder, and provided $150M in loans for upgrading MP's processing facilities.[123]

Fortunately, the amount of yttrium in HTS tape is very small, with the Y_2O_3 layer being less than a micron thick.[124] To build an entire fusion plant, the volume of yttrium would be on the order of just 100 kg.[125] That consumption would be less than a ten-thousandth of 2022 yttrium oxide imports. As a result, threats of crackdowns on rare earth exports are likely not an existential threat to the nascent fusion industry, and HTS producers should be able to scale to meet growing industry needs. **Yttrium/Rare Earths Supply Chain Risk Level: Low-Medium.**

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[116] "Rare earths" generally refers to the lanthanide series, but here we include yttrium and scandium, which are typically found in the same ores and have similar chemical properties. Gallium is another critical mineral, used in laser diodes, that is often grouped with rare earths while not technically being one.
[117] Rare-earth Barium Copper Oxide, ReBCO, Energy Encyclopedia (last accessed 2025).
[118] Marcus Lu, Charted: China Dominates the Supply of U.S. Critical Minerals List, Visual Capitalist (2024).
[119] Keith Bradsher, Step by Step, How China Seized Control of Critical Minerals, New York Times (2025).
[120] Keith Bradsher, China Suspends Some Export Controls on Critical Minerals but Retains Others, New York Times (2025).
[121] Mineral Commodity Summaries 2024, U.S. Geological Survey (2024).
[122] Joelle Anselmo, MP Materials begins rare earth metal production, Utility Dive (2025).
[123] MP Materials Announces Transformational Public-Private Partnership with the Department of Defense to Accelerate U.S. Rare Earth Magnet Independence, MP Materials (2025).
[124] Technology, Superconductor, Nano, and Advanced Materials (last accessed 2025).
[125] SCSP staff engagement with CFS supply chain team (June 2025).

Sidenote: Cryogenics

Despite the name, high-temperature superconductors need to be quite cold, but to different degrees. Superconductors with a critical temperature above 77 K, like REBCO, can be cooled by liquid nitrogen, which is cheaper and more available than the liquid helium needed to reach lower temperatures. Cryogenics are used not only for reaching superconductor temperatures in magnetic fusion, but also for freezing the fusion fuel in inertial fusion approaches.[126]

Cryogenics is one of the few fields where China clearly lags behind American allies. The leading companies in cryogenics are mostly European, including the French Air Liquide and the Swiss-German Linde Kryotechnik.[127] China has now begun to work on their own cryogenic development,[128] and have in fact partnered with Air Liquide to develop their own helium refrigeration capable of cooling to LTS temperatures.[129] Cryogenics are one of the 19 research experiment subjects at China's new CRAFT campus in Hefei, the center of Beijing's fusion R&D program.[130]

Cryogenics Supply Chain Risk Level: Low-Medium. As long as the United States maintains its trade relationships with European allies, cryogenics are an opportunity for our axis of influence to advance.

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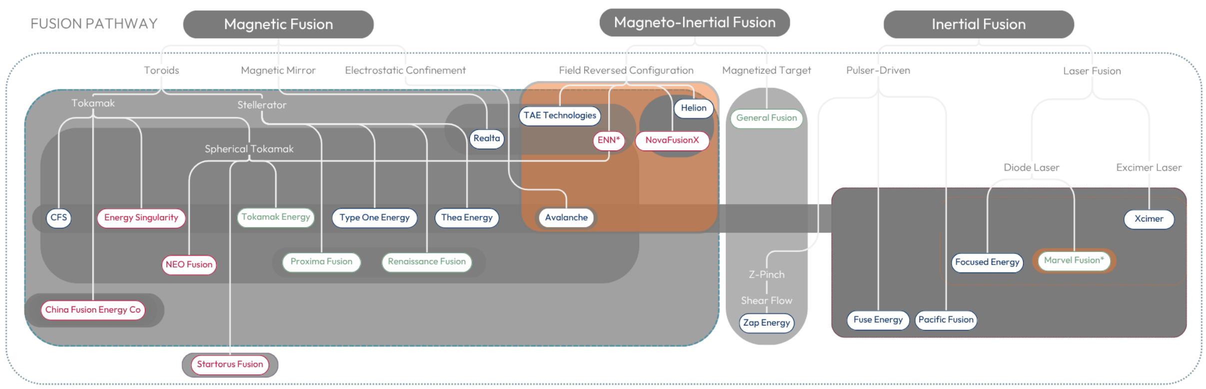
[126] L.R. Baylor, et al., Issues in Formation of Cryogenic Pellets for Fusion Applications, Fusion Science and Technology Vol. 77, Issue 7-8 at 728-737 (2021).
[127] Extreme cryogenics: serving the future, Air Liquide (2021); About Linde Kryotechnik, Linde Kryotechnik AG (last accessed 2025).
[128] Xin Chen, et al., RAMI analysis of the helium refrigeration system of HL-2M tokamak, Fusion Engineering and Design Vol 172 (2021).
[129] Air Liquide JV to develop helium refrigeration in China, Cooling Post (2021).
[130] Yuntao Song, All for Fusion Energy: Overview and Updates of R&D at ASIPP, Fusion Power Associates Meeting (2024).

Alternative Fuels



"Alternative Fuels" refers to non-D-T fusion fuels. The promise of alternative fuels is fusion that generates fewer, lower-energy neutrons, which would require less radiation shielding and material requirements. In addition, these fuels reduce proliferation concerns and eliminate the need for tritium breeding. That promise is paired with problems, however, as it is more difficult to achieve fusion reactions with advanced fuels than with D-T.

Ideal Temperature Estimates for a Fusion Plant Using Different Fuel Types

Deuterium-Tritium (D-T)	150 Million °C
Deuterium-Deuterium (D-D)	400 - 500 Million °C
Deuterium-Helium-3 (D-^{3}He)	500 - 600 Million °C
Proton-Boron-11 (p-^{11}B)	1.5 Billion °C

Deuterium-Deuterium

Deuterium-deuterium fusion combines two deuterium (hydrogen-2) atoms (See "Deuterium-Tritium"). D-D fusion requires temperatures higher than D-T fusion does, in the range of 400-500 million degrees for a suitable power plant. Neutrons in D-D fusion have similar energies to those in a fission reactor,[131] avoiding some materials challenges found in D-T fusion, but at the

[131] D-D neutrons have an energy of 2.46 MeV, compared with the slightly over 2 MeV found in a fission reactor. See David Chichester, et al., Measurement of the Neutron Spectrum of a DD Neutron Generator,

cost of much higher required reaction temperatures. For the first generations of fusion plants, D-D may find its use not as the main fuel cycle, but instead as an initial fuel to breed fuels more economical to use. D-D fusion can also occur as an incidental side reaction for other deuterium-based fuel cycles, particularly the D-^{3}He reaction detail later in this section.

Proton-Boron-11

Proton-Boron-11 (p-^{11}B) fusion is the combination of a single proton (a common hydrogen ion) with a boron atom, turning into three alpha particles (Helium-4). The p-^{11}B reaction itself will not produce neutrons, but various side reactions will, albeit several orders of magnitude fewer than D-T.[132] The process is slightly less energetic[133] than other relevant fusion reactions, but is still more energy-dense than any current form of power production. Unfortunately, the incredible promise is paired with significant challenges. Proton-boron fusion will require temperatures almost ten times higher than D-T fusion.[134] The reduced level of neutrons, while limiting radiation, also means that new methods of energy capture will be required.[135] Still, a number of companies consider the promise of p-^{11}B enough to pursue it as their primary approach.[136]

Looking at the constituent elements of p-^{11}B, hydrogen is the most abundant element in the universe. It can be produced from water, and has been a clean energy target for decades.[137]

21st International Conference on the Application of Accelerators in Research and Industry, Idaho National Lab (2010), and M. M. Islam & H.H. Knitter, The Energy Spectrum of Prompt Neutrons from the Fission of Uranium-235 by 0.40-MeV Neutrons, Nuclear Science and Engineering, Vol 50 at 108–114 (1973).

[132] Several of these side reactions will likely be unavoidable. Some ^{11}B-^{11}B fusion will happen, as will ^{4}He-^{11}B.

[133] 8.7 MeV per p-^{11}B fusion vs 17.6 MeV per D-T fusion.

[134] p-^{11}B ignition temperature is 123 keV, compared to 13.6 keV for D-T fusion. The reaction cross-section, a proxy for the probability of a reaction to occur, is three orders of magnitude lower for proton-boron than D-T.

[135] In conventional fission reactors, power is generated from neutrons depositing their energy in water, heating it up. In the next generation of fission reactors and D-T fusion reactors, the role of water may be taken by other media (like molten salts, helium, or liquid metals), but the core process is the same. An alternatively fueled fusion reactor would likely require a form of direct energy conversion, where charged particles are collected on an anode, or where the magnetic field of the moving charged particles induces a current in a coil. Molten salts or liquid metals are still part of some alternatively fueled fusion machine designs for thermal management. See Direct Energy Conversion, ScienceDirect (last accessed 2025).

[136] Those companies include Blue Laser, Ex-Fusion, China's ENN Energy Research Institute, HB11, LPP Fusion, Marvel Fusion, NearStar Fusion, Princeton Fusion Systems, and TAE Technologies.

[137] When hydrogen is referred to as fuel outside of the fusion context, it is referring to the recombination of hydrogen and oxygen, as in rockets. This chemical process features an inherent inefficiency-one must break the chemical bonds in water to create the pure hydrogen and oxygen, and then harvest the energy by recombining them. This chemical process is therefore much more like charging and discharging a battery than it is like burning a fuel. As such, this hydrogen process is mostly useful for dealing with an imbalance in energy production and demand, if power is produced by uncontrolled variable systems like renewables or baseload systems like conventional nuclear fission. Since fusion takes advantage of nuclear bonds, thousands of times stronger than chemical bonds, fusing hydrogen actually results in a net energy gain, and not just moving energy around.

Pure hydrogen is very cheap, costing about 0.1 cents per gram. The demand for deuterium in other fusion approaches would also inherently create a supply of undeuterated hydrogen. A 1 GW power plant might need 100 kg of fuel or less per year. **Hydrogen Supply Chain Risk Level: None.**

Boron is also not a major supply chain risk. The United States is a top exporter of boron (and China is a top importer[138]). Unlike tritium and deuterium, ^{11}B is the most common natural isotope of boron, comprising about 80% of natural boron. Boron-11 is also cheap, with 99% enriched boron oxide available for about $70 per gram.[139] Finally, since a fusion power plant would not need very much boron-11, boron availability is unlikely to be a problem in the foreseeable future. **Boron-11 Supply Chain Risk Level: None-Low.**

Deuterium-Helium-3

Deuterium-Helium-3 (D-^{3}He) has some advantages and some drawbacks relative to p-^{11}B fusion. As an advantage, D-^{3}He requires a much lower temperature than p-^{11}B[140] and produces over twice as much energy per reaction.[141] As a downside, D-He3 will inherently[142] produce D-D fusions in its process, meaning that D-^{3}He will still be a neutronic approach,[143] although measurably less than D-T. Helion is the only major company attempting to commercialize D-^{3}He fusion.

Helium-3 is the only 'advanced' fusion fuel material that is not naturally abundant on Earth, but it can be bred. While helium-3 is stable, it is a miniscule fraction of natural helium.[144] ^{3}He is also

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[138] A number of Chinese companies, including ENN Energy Research Institute, are pursuing p-^{11}B fusion as their primary approach. This trade imbalance is unlikely to yield a geopolitical trade level for the United States, given the small inventories of boron required.
[139] Boron - 11B Oxide, Sigma Aldrich (last accessed 2025).
[140] D-^{3}He still requires about four times the temperature of D-T, but that is less than half the temperature required for p-^{11}B.
[141] 18.3 MeV released per reaction, which is slightly higher than the 17.7 MeV released in D-T fusion. The most significant difference between the two reactions is not the amount of energy released, but the manner in which it is carried. Most D-T energy goes into the free neutron, much like how the recoverable energy in fission reactors is carried by neutrons. In a D-^{3}He reaction, the energy is carried by the 'fast ions' of a proton (^{1}H) and alpha particle (^{3}He). Similarly, a p-^{11}B reaction puts its energy in the fast ions of three alpha particles. John J. Reinmann and Warren D. Rayle, Deuterium-Helium 3 Fusion Power Balanced Calculations, NASA Lewis Research Center (1971).
[142] With current technology and approaches.
[143] Therefore still creating radiation, but with a smaller volume of lower-energy neutrons than D-T.
[144] This is highly dependent on the source. Helium found in natural gas has a ^{3}He ratio of 70-210 parts per billion, whereas ^{3}He from the lithium ore at the Edison Mine in South Dakota is up to 12 parts per million. Primordial sources of helium have a much higher ratio of ^{3}He to ^{4}He, but this has changed over time, as ^{3}He has escaped through the atmosphere, and ^{4}He has been supplemented by the alpha particles emitted from radioactive decay. See Norman Holden, Helium Isotopic Abundance Variation in Nature, Presentation at 37th IUPAC General Assembly (1993).

the product of tritium decay, so sources of tritium are also inherently sources of ^{3}He with time and processing. The Canadian company OPG (See "Deuterium-Tritium") is the only current civilian seller of ^{3}He through its subsidiary, Laurentis Energy Partners.[145]

The most abundant known source of ^{3}He is in the regolith found on the Moon,[146] and the Department of Energy has made an agreement to purchase lunar-derived ^{3}He for a delivery date by 2029.[147] Helium-3 is similarly expensive to tritium, now costing over $30,000 USD per gram, and a D-^{3}He fusion machine will likely require a similar mass of ^{3}He as a D-T machine would use tritium. Fortunately, since Helium-3 can also be bred from D-D reactions, a company intending to use this fuel cycle could run their machine with D-D fuel until they create startup inventory, and continue to breed some additional fuel during normal operations.[148]

Helium-3 Supply Chain Risk Level: Medium-High. Like tritium, helium-3 is highly scarce, but can be bred from more commonplace elements in regular fusion machine operation.

Possible Mitigations: Any efforts to increase tritium production would also increase production of ^{3}He, if processed. Lunar helium mining would represent a giant leap forward in effort, but may be a natural step as we build our space travel capabilities in advance of a Martian mission.

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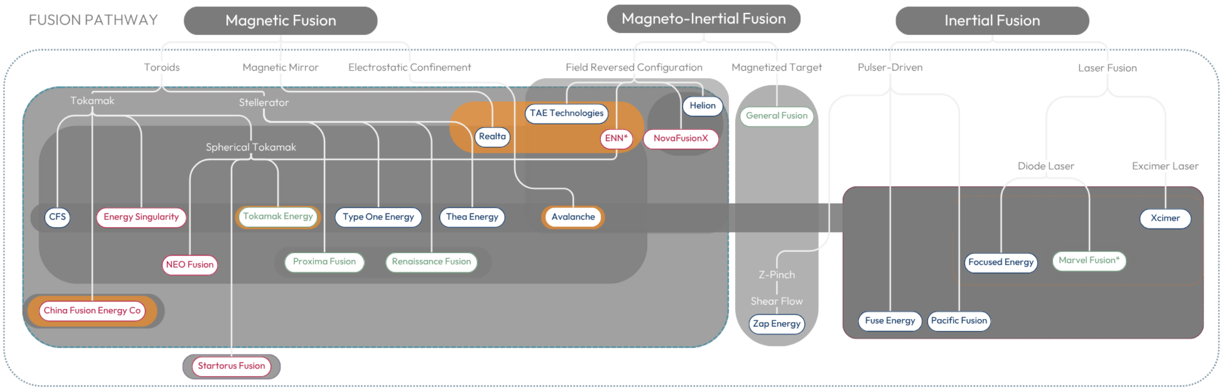
[145] Laurentis Energy Partners launches Helium-3 Production, Laurentis Energy Partners (2021).
[146] See Helium-3 mining on the lunar surface, European Space Agency (last accessed 2025). On the topic of using space travel for fusion, it's also worth noting that fusion would be an excellent fuel for a space mission. Since a rocket needs to take its fuel with it, which adds more weight, which requires more fuel, and so on, energy density is paramount. Fusion, the most energy-dense fuel source, could allow spacecraft to be significantly lighter, faster, and cheaper. See Fusion Spacecraft Propulsion Roadmap, Fusion Industry Association (2025).
[147] U.S. Department of Energy Buys Helium-3 from U.S. Space Resources Company Interlune in Historic Agreement, Interlune (2025).
[148] Helion, the only major fusion company pursuing ^{3}He fuel, holds a patent on a system designed to generate it. See John Slough, et al., US20230041682A1: Advanced fuel systems and reactors using the same, Google Patents (2023) and Lily Hale, How to engineer a renewable deuterium-helium-3 fusion fuel cycle, Helion (last accessed 2025).

Neutral Beam Heating



The primary alternative to RF Heating (see "RF Heating") is Neutral Beam Heating (NBH) / Neutral Beam Injection (NBI), where particle accelerators play a crucial role by injecting fast neutral particles into the plasma. NBH is generally used in magnetic fusion, and is being pursued by companies designing tokamaks, stellarators, magnetic mirrors, and more. Most companies pursuing neutral beam heating as an approach are also considering RF heating as well, though the inverse is not necessarily true. As magnetically confined fusion machines have very strong magnetic fields, a charged particle could not be reliably injected into the medium without being repelled on the way in. To inject neutral beams, a particle accelerator brings high-speed deuterium ions through a deuterium gas (see "Deuterium-Tritium"). Electrons are stripped off from the gas, and pair with the high-energy deuterium atoms. The atom, now electrically neutral, can pass through the magnetic fields into the plasma.[149] Some companies consider NBI a much cheaper method, citing cost savings of up to 50% over RF heating.[150]

The complexity of particle accelerators, their reliance on specialized materials, and intricate existing global supply chains make them vulnerable to supply chain gaps. From a materials perspective, particle accelerators in fusion rely on scarce, high-performance materials. Key components may require high-purity tungsten,[151] of which China provides 80% of the world's supply[152] **(Supply Chain Risk Level: Medium-High)**. High-temperature superconducting (HTS)

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[149] Garry McCracken & Peter Stott, Fusion (2nd Ed.), Elsevier at 91-105 (2013).
[150] See T. Roche, et al., Generation of field-reversed configurations via neutral beam injection, Nature Communications (2025) and TAE shortens device roadmap, prepares for a commercial era, TAE Technologies (2025).
[151] See K. Srinivasan, Radiation shielding properties of tungsten alloy multilead collimator materials in linear accelerator, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms Vol. 563 (2025) and Ali Sundermier, New research on tungsten unlocks potential for improving fusion materials, SLAC National Accelerator Laboratory (2024).
[152] Anthony Milewski, Tungsten supply crisis threatens defense and tech industries, The Oregon Group (2025).

tapes and RF power systems are also used within particle accelerators.[153] With China controlling some aspects of the supply chain for these materials, the U.S. fusion industry faces potential bottlenecks and foreign dependence.

There are a few American companies that could act as suppliers of NBIs. General Atomics[154] and TAE Technologies[155] stand out as two likely vendors currently established in the space. As the space is currently rather niche, neither have the current capacity to provide NBIs for the entire fusion industry, but would be likely to be the foremost beneficiaries of expanded demand.

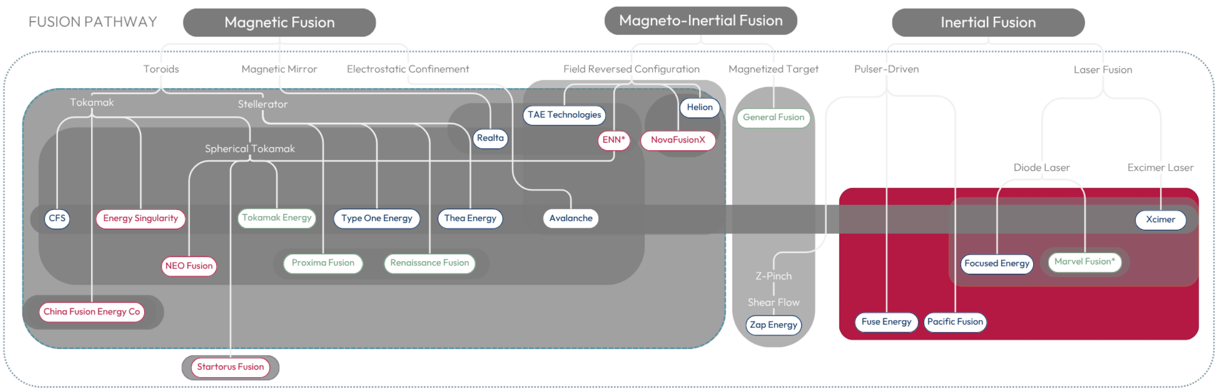
Beyond material scarcity, particle accelerators for fusion rely on a fragmented and highly specialized supply chain. Many critical components, such as RF cavities and vacuum chambers, require precision manufacturing concentrated in Germany, Japan, and China, leading to years-long lead times **(Supply Chain Risk Level: Medium)**. A shortage of accelerator physicists and engineers further strains production. Additionally, cross-sector competition from industries like medical imaging, semiconductor fabrication, and defense could increase costs and limit availability.

Neutral Beam Heating Supply Chain Risk Level: Medium-High. Like many other components on this list, neutral beam injectors are a specialized piece of equipment without the current industrial base to support a full fusion industry. Neutral beams also happen to use a number of somewhat vulnerable components found elsewhere on this list, like high-temperature superconductors, along with tungsten. Those vulnerabilities could compound as the industry scales.

Possible Mitigation(s): Creating a robust neutral beam injector industry in the United States will require workforce training and education, and securing appropriate supplies of critical materials will be necessary. The elevation of fusion to a national security priority would be instrumental in clearing the way for fusion industry access to these devices.

[153] See "RF Heating" and "High-Temperature Superconductors".
[154] Particle Accelerators, General Atomics (last accessed 2025).
[155] Ryohtaroh Satoh, Google-backed fusion group moves to commercialize neutral-beam technology, Financial Times (2025).

Targets



Targets, which consist of the frozen fusion fuel and sometimes a shaped structure around it, are an essential component in multiple fusion approaches, and they take different forms where necessary. Laser fusion can be separated into two approaches: direct drive, where the laser strikes the fuel pellet, and indirect drive, where the laser strikes a hohlraum around the pellet, which emits X-rays that compress the fuel pellet inside. Targets are also used in pulsed inertial or magneto-inertial approaches.[156] In some variations, a liner surrounding the fusion fuel is compressed by strong magnetic fields.

For laser-driven inertial fusion, the most notable difficulty in acquiring targets today is simply cost, as each is a bespoke, ultra-low tolerance part. At the National Ignition Facility, the world's most successful inertial fusion machine, targets can cost upwards of $10,000 apiece.[157] It's virtually guaranteed that fusion target costs will significantly decrease with mass production of any specific target design, but it's yet unclear if targets can reach the ~$1/target threshold many consider to be necessary for economic viability.[158]

For pulsed inertial fusion, the targets can reach substantially lower costs (even much less than a $1/target) but still need to be manufactured in the millions at scale. A system will need to be manufactured in all cases to fill these targets.

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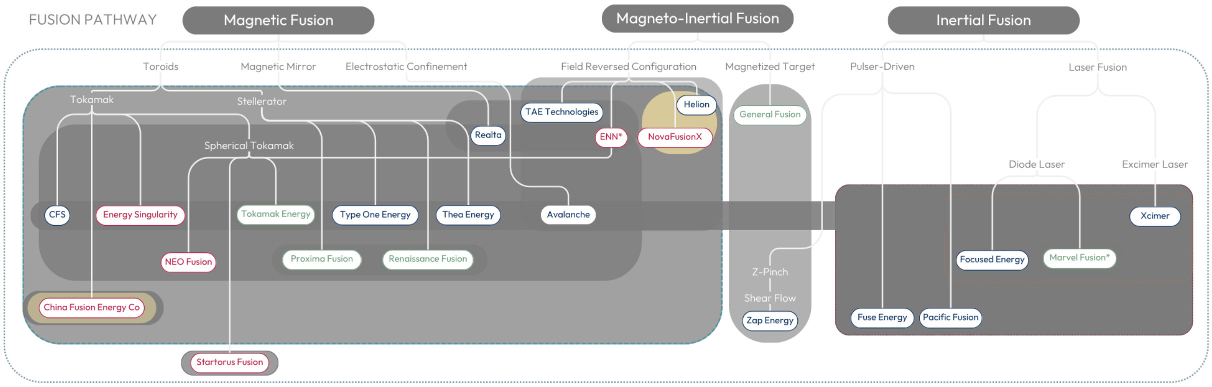
[156] General Fusion also supports a magnetized target approach, but the target is not a manufactured capsule, but instead is magnetized plasma injected into a liquid metal liner, to be collapsed with pistons. While it is a target approach, that target is not a manufactured part worthy of supply chain concern. Maurizio Di Paolo Emilio, General Fusion is Developing a Practical Approach to Magnetized Target Fusion (MTF), Power Electronics News (2021).
Arthur Turrell, "The Star Builders", Scribner (2021) at 145.
[157] David Kramer, NIF success gives laser fusion energy a shot in the arm, Physics Today (2023).
[158] Sourabh K. Saha, Additively manufactured nanoporous foam targets for economically viable inertial fusion energy, Societal Impacts Vol 3 (2024).

The materials in a target are generally not those with major supply chain constraints, but some are expensive or difficult to work with. The hohlraum of an indirect drive laser target will be made of a high-Z[159] material, like gold or depleted uranium, that may be expensive, but will be accessible.

Supply Chain Risk Level: Low-Medium. The question regarding fusion targets is likely not going to be if they can be manufactured using accessible materials, but if they can be made under the strict confines of cost and quality control for a fusion plant's financial viability.

[159] In this context, Z means atomic number, or number of protons. Higher-Z atoms are heavier.

Copper



All fusion companies will likely use copper to some extent, as a component in electronics, wiring, and REBCO superconductors. However, for the purpose of this analysis, only the companies that plan on using copper magnets for plasma control (i.e., not using HTS tape) are counted in this paper's ranking methodology. Those companies have exceptional needs for copper. For example, Helion used over 600 tons of copper for Polaris, their pre-commercial test machine.[160] Copper is also arguably the most threatened constituent material in REBCO high-temperature superconducting tape.

Relative to high-temperature superconductors, copper is weaker and can handle less current,[161] but is more durable, malleable, can function without cryogenics, significantly cheaper, and can turn on much faster. Most importantly, copper wires have been manufactured for decades and don't require significant growth of a new manufacturing industry.

Without counting the demand from fusion, copper needs are generally rising, with an additional 61 mines expected to be needed by 2030.[162] Developing new mines is lengthy and laborious, taking an average of 29 years to complete in the United States.[163] In November 2025, copper was added to the United States' critical minerals list, reflecting its importance not just to the fusion industry, but also to the broader technology sector.[164]

Currently, copper production is predominantly centered in Latin America (but with other significant production in Africa, Asia, and North America), and China is the dominant importer

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[160] SCSP engagement with Helion representatives (2025).
[161] By a factor of 20,000, according to Superconductors: Distribution Class?, Thunder Said Energy (2024).
[162] Bruno Venditti, How Many New Mines Are Needed for the Energy Transition?, Visual Capitalist (2025).
[163] Ernest Scheyder, US mine development timeline second-longest in world, S&P Global says, Reuters (2024).
[164] Hannah Northey, Met coal, copper, and uranium are now 'critical' minerals, E&E News by Politico (2025).

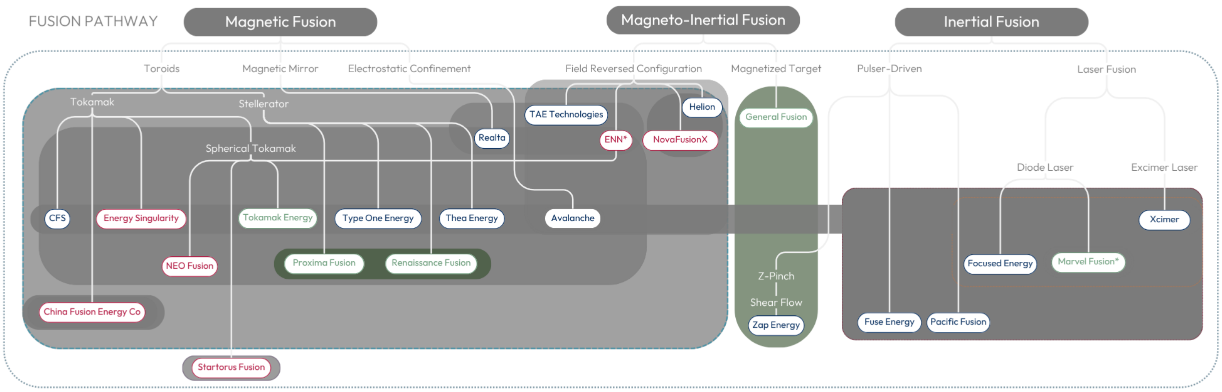
of raw copper and producer of finished copper products.[165] This dominance is a result of over a decade of investment into third-world infrastructure through the Belt and Road initiative's loan programs and direct ownership.[166] In the Democratic Republic of Congo, the second-largest copper producer, Chinese firms own over 80% of copper mines.[167] In recent years, the United States has backed a major railway in Africa to facilitate access to copper, but still lags behind China's influence.[168]

Supply Chain Risk Level: Medium. Copper will be used near-ubiquitously in fusion machines, but only a few companies (those who use magnetic fields but not superconducting magnets) will have truly exceptional volume needs. Copper is in high demand, but there is a robust global supply chain already, and no singular reliance on any competitor state.

Possible Mitigation(s): Additional investments in copper-rich places, like with the Lobito Corridor railway, would serve to increase American access to copper.

[165] A Global View of Production and Trade, International Copper Association (last accessed 2025).
[166] Lea Thome, et al., Chasing copper and cobalt: China's mining operations in Peru and the DRC, AIDDATA (2025).
[167] Emmet Livingstone, D.R. Congo's mining capital is at the heart of Biden's bid to counter China in Africa, NPR (2024).
[168] Ellington Arnold, The Lobito Corridor: Building Africa's Most Important Railway, U.S. Chamber of Commerce (2024).

Liquid Metals



Liquid metal walls have been a proposed solution to the problem of high-energy neutrons from D-T fusion irradiating structural components. The difficulties surrounding liquid metals are not about obtaining metals, but rather the complicated engineering of pumping metal through a system without corrosion, melting structural components, or clogging. Liquid metals are not just limited to fusion machine use, but also appear in designs of next-generation fission reactors.

The purpose of liquid metals in a fusion power plant is similar to the role that molten salts would fill (see the Molten Salts section). Liquid metals would serve as a heat conduit, as a medium for multiplying neutrons and breeding tritium, and as a protective layer for more sensitive equipment. Most fusion companies pursuing this approach plan on using lead-lithium as their liquid metal of choice (see the Enriched Lithium sidenote of “Deuterium-Tritium”). In this formulation, lead takes the role of neutron multiplier, avoiding the limited supply of beryllium that could limit the scaling of the FLiBe molten salt approach.[169] Research into all properties of lead-lithium is still limited, and new experiments are recommended to enable use in fusion machines.[170] Some remaining challenges include liquid metal surface characteristics and the magnetohydrodynamic effect.[171]

Liquid Metals Supply Chain Risk Level: Low-Medium. This segment of the industry is too new to have a fully developed supply chain, but there are unlikely to be any material constraints that significantly limit the ability to scale in the United States. Just like with molten salts, the challenges remaining are mostly related to research and development, and not the current

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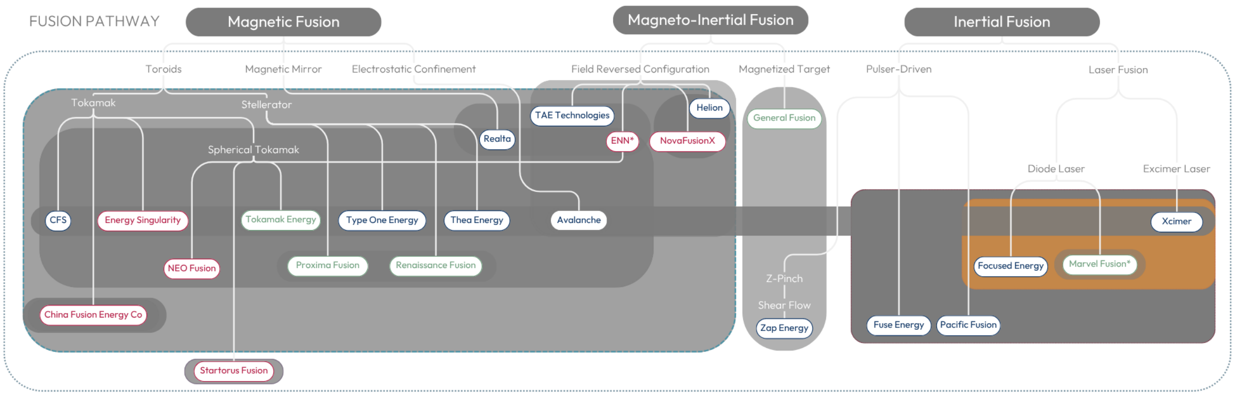
[169] Amit Raj Sharma, et al., Re-investigations of integral neutron multiplication experiments with 14 MeV neutrons in lead, Fusion Engineering and Design Vol 55 (2001).
[170] D. Martelli, et al., Literature review of lead-lithium thermophysical properties, Fusion Engineering and Design Vol 138. (2019).
[171] Lin Zhang, et al., Liquid metals power advanced nuclear energy systems, Innovation (Camb) (2025).

manufacturing and materials landscape. Additional research is required, which creates the opportunity for the United States to lead in production and sale of liquid metal systems.

Laser Diodes[172] and Optics



While not necessary for other approaches, laser diodes are absolutely critical for many laser fusion companies,[173] and are those companies' current greatest bottleneck in the supply chain. One analysis indicates that laser diode emitters would make up 60 percent of the cost of a laser fusion power plant.[174] Even magnetic fusion companies may have some dependence on laser diodes, as excimer lasers are used in the production of Pulsed-Laser Deposition HTS magnets.[175]

For a profitable diode laser power plant, pump diodes will likely need a price point of only a few cents per watt, an order-of-magnitude price reduction.[176] Diodes will also need longer lifetimes, to extend from surviving approximately 2 gigashots to 15-30.[177] China produces the largest volume of laser diode exports of any country,[178] but the highest-quality laser diodes, capable of withstanding a fusion machine's beamline, have been made in the United States, Japan, or

[172] Laser diodes could arguably have been included as a subsection in the above "Electronics" category. They appear here due to the significant gap in the ranking metrics between the utilization of diodes and other electronics, and its natural grouping with optics, both of which are most utilized in laser fusion approaches. One could also argue that the components in this section are under-ranked, as is noted in footnote 9. Ranking by investment in private companies neglects the substantial investments that the United States has put into public laser fusion research at NIF.
[173] Although not all. NIF and the in-process Mianyang laser fusion facility use older flashlamp laser technology, rather than the more modern diode systems. Diodes are ultimately a more efficient technology, as flashlamps emit a wider range of wavelengths of light, which must mostly be discarded. Eric Lerner, Diode arrays boost efficiency of solid-state lasers, Laser Focus World (1998).
[174] Mike Hatcher, LASER 2025: Fusion forum highlights supply-chain challenges, Optics (2025).
[175] Yue Zhao, et al., Commercial compact fusion triggered REBCO tape industry: Pulsed laser deposition technology opportunities and challenges, Superconductivity Vol 15 (2025).
[176] Constantin Haefner, et al., Status and Perspectives of High-Power Pump Diodes for Inertial Fusion Energy Lasers, IFE Science & Technology Community Strategic Planning Workshop 2022 (2022).
[177] See Lucia Koubíková and Lukas Gruber, Pioneering the petawatt regime at ELI-Beamlines, Laser Focus World at 2 (2021) and Jon Zuegel, Diode-pumped, solid-state laser (SSDL) drivers for inertial fusion energy (IFE), Enabling Technologies for Improving Fusion Power Plant Performance and Availability Workshop at 5 (2023).
[178] Laser Diodes to Exports in the United States, Volza (2025).

Europe (with Germany standing out in particular). This is beginning to change, as major laser manufacturer Coherent recently opened an office in Shenzhen.[179] Dilas, a German subsidiary of the American company Coherent, has manufactured in China since 2008, and allegedly has recently had its staff poached by Chinese corporations.[180]

Potential supply chain disruptions could occur not just at the level of manufactured laser diodes, but also regarding a diode's constituent materials. Gallium and germanium are necessary for current laser diode formulations, and China recently banned exports of the two metals before reversing course.[181] China has produced 90 percent of the world's gallium over the last decade. If needed, American companies may still be able to import both metals through third-country trade loopholes, but this could potentially be shut off.[182] Indium is another necessary material for diode production, on which the United States is completely import-dependent, with China as the world's largest producer.[183] Other rare earths, like gadolinium and scandium, can be used in certain diode formulations.[184]

Optics, the mirrors, lenses, and fibers that control the path of a laser beam, will also be a necessity for a laser fusion facility. A laser fusion facility will also have significant constraints in terms of optical purity and robustness. Considering the conditions of a fusion power plant, these optics will likely need to meet optical, mechanical, and thermal specifications that have never before been combined in one optic.[185] Alternative optical constructions, including gas and plasma optics, have been proposed, but do not exist at any commercial scale.[186]

Laser Diodes and Optics Risk Level: Medium-High. While the United States and its allies produce most of the high-quality laser diodes that would be used in a fusion power plant, our production capacity would need to be significantly increased, and the cost of diodes significantly lowered. The raw materials behind laser diode production also have notable Chinese dependencies, and manufactured optics will need to be of a yet-unique quality for production.

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[179] New Office Opens in Shenzhen, Coherent Corporation (2021).
[180] Dilas Opens Fab in China, Photonics Spectra (2008); and SCSP engagement with anonymous representative.
[181] See Sally Cole Johnson, Germanium and gallium supply chain disruption escalates for U.S., Laser Focus World (2025); Keith Bradsher, China Suspends Some Export Controls on Critical Minerals but Retains Others, New York Times (2025). As of November 2025, the announcement of China endorsing a general export license for these metals came not from China, but from the White House following trade talks.
[182] Sarah Godek, China's Germanium and Gallium Export Restrictions: Consequences for the United States, Stimson (2025).
[183] Laura Dair, Indium Mineral Commodity Summaries 2025, U.S. Geological Survey (2025).
[184] V. Lupei, et al., Improved laser efficiency by direct diode laser pumping of the radiation-resistant Nd:gadolinium-scandium-garnet, Laser Physics Vol. 24 (2014).
[185] Sally Cole Johnson, High-precision optics are essential for commercial laser-driven fusion, Laser Focus World (2025).
[186] Matthew Edwards, et al., Gas and Plasma Final Optics for Inertial Fusion Energy Lasers, Lawrence Livermore National Laboratory (2021).

Possible Mitigation(s): Provide tax credits for the manufacture of advanced laser diodes. Secure a supply of relevant rare-earths through the Department of War's stake in MP Materials.

Appendix 1: Supply Chain Risks Chart

Component, Subcomponent, or System	Risk Level
Enriched Lithium	**High**
Helium-3	**Medium-High**
RF Heaters	**Medium-High**
High Power Switches	**Medium-High**
Tungsten	**Medium-High**
Neutral Beam Injectors	**Medium-High**
Laser Diodes and Optics	**Medium-High**
High-Temperature Superconductors	**Medium-High**
Capacitors	**Medium**
Advanced Robotics	**Medium**
Tritium	**Medium**
Semiconductor Chips	**Medium**
Precision Manufacturing	**Medium**
Copper	**Medium**
Molten Salts	**Low-Medium**
Deuterium	**Low-Medium**
Rare Earths / Yttrium	**Low-Medium**
Cryogenics	**Low-Medium**
Targets	**Low-Medium**
Liquid Metals	**Low-Medium**
Beryllium	**Low-Medium**
Raw Lithium	**Low**
Boron-11	**None-Low**

Flouride	**None**
Hydrogen	**None**

Appendix 2: Fusion Supply Chain by Nation

Nation	Fusion Input
Brazil	Beryllium
Canada	Tritium, Helium-3
China	Steel Forgings, High Power Switches, Capacitors, Robotics, Lithium, High-Temperature Superconductors, Rare Earth and related minerals (yttrium, gallium, gadolinium, germanium), Tungsten, Precision Manufacturing, Copper, Laser Diodes, Indium
Democratic Republic of Congo	Copper
France	Cryogenics
Germany	High Power Switches, Cryogenics, Precision Manufacturing, Laser Diodes
Italy	High Power Switches
Japan	Steel Forgings, High Power Switches, Robotics, Gyrotrons, High-Temperature Superconductors, Precision Manufacturing, Laser Diodes
Kazakhstan	Beryllium
Peru	Copper
Russia	Robotics, Gyrotrons, HTS*
South Korea	HTS
Spain	High Power Switches
Switzerland	Cryogenics
Taiwan	Computing Chips
United Kingdom	Steel Forgings, Radiation-resistant Robotics
United States of America	Capacitors, Robotics, Beryllium, HTS Magnet Systems, limited Rare Earths, Neutral Beam Injectors, Laser Diodes

* mostly through ownership of Faraday Factory, rather than local production