A Nickel Short: Rethinking Element Scarcity in Pursuit of a Fusion-Powered World

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ABSTRACT

Fusion energy presents a promising solution for current global decarbonization goals. This thesis presents an adaptable model for evaluating mineral sufficiency in the global deployment of fusion power. Using the ARC Magnetic Confinement (MC) Deuterium-Tritium (D-T) fusion concept as a framework, this research integrates mineral usage estimates from the International Energy Agency (IEA) with MIT Energy Initiative's (MITEI) energy production forecasts by generation technology. Using MITEI's $2,800/kW cost scenario for fusion power generation, the model situates the demand for fusion-critical minerals within the broader context of growing mineral needs driven by the clean energy transition, and offers specific, quantitative insights into mineral sufficiency risks. The study finds that beryllium will face significant shortages solely due to fusion demand, with resource exhaustion projected to occur within 40 years. When accounting for additional demands from Electric Vehicles (EVs), battery storage, and transmission infrastructure, chromium and nickel are projected to exhaust economically extractable reserves within 21 to 35 years at current prices. The research further reveals that for nine of the thirty elements evaluated, over 50% of production is concentrated in a single country, and for half of the minerals China is the largest producer, introducing geopolitical risks. Notably, at just 13 kg per reactor, the demand for Rare Earth Elements (REEs) is not exposed to a significant risk, even without the top producing country. The research also surfaces current reactor designs and strategies which could help mitigate each identified risk.

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Contents

List of Figures

List of Tables

Abbreviations

APS	**Announced Pledges Scenario**
ARC	**Affordable, Robust, Compact**
CAGR	**Compound Annual Growth Rate**
CFS	**Commonwealth Fusion Systems**
D-T	**Deuterium Tritium**
EV	**Electric Vehicle**
FPP	**Fusion Power Plant**
FSI	**Fragile States Index**
HTS	**High Temperature Superconductor**
IAEA	**International Atomic Energy Agency**
ICF	**Inertial Confinement Fusion**
ITER	**International Thermonuclear Experimental Reactor**
MC	**Magnetic Confinement**
MITEI	**Massachusetts Institute of Technology Energy Initiative**
NIF	**Nuclear Ignition Facility**
NRC	**Nuclear Regulatory Commission**
NZE	**Net Zero Emissions by 2050 Scenario**
RAFM	**Reduced Activation Ferritic-Martensitic (Steel)**
REBCO	**Rare Earth Barium Copper Oxide**
REE	**Rare Earth Element**
REO	**Rare Earth Oxide**
RF	**Radio Frequency**
SMR	**Small Modular Reactor**
SPARC	**Smallest Possible ARC**
STEPS	**Stated Policy Scenario**
TBR	**Tritium Breeding Ratio**
USGS	**United States Geological Survey**

Chapter A: Introduction

1. Overview

1.1 Context and Motivation

Anthropogenic climate change is accelerating, and the most consequential metric in mitigating climate change is cumulative, rather than annual, global greenhouse gas emissions. As of 2023, global emissions exceed forty-two gigatons (Gt) of CO_2 per year. With a remaining carbon budget of approximately 360 Gt to retain a 50% likelihood of limiting warming to 1.5°C, humanity has fewer than nine years at current emissions levels before this threshold is exceeded [1]. To remain within this planetary boundary, a complete transition to net-zero emissions is essential. However, the current portfolio of renewable energy technologies is insufficient to meet this challenge on its own. The inherent variability of solar and wind power necessitates either large-scale overbuilding or extensive storage to achieve firm capacity, both of which impose significant economic inefficiencies [2].

To close this reliability gap, the global energy transition requires the deployment of firm, zero-carbon energy sources; technologies that provide dispatchable electricity without the emissions or other risks associated with conventional fossil fuels or nuclear fission. While traditional fission produces long-lived radioactive waste that remains hazardous for over 10,000 - 1,000,000 years depending on isotopic composition and repository design [3], emerging nuclear technologies such as Small Modular Reactors (SMRs) and nuclear fusion offer alternative pathways. Among these, fusion energy is uniquely positioned to transform the global energy system. Its primary fuel, deuterium, is abundantly available in seawater, approximately one atom per 6,500 of hydrogen, providing an effectively inexhaustible supply that could meet human energy needs for millions of years [4]. Furthermore, fusion reactions yield extraordinary energy density: a single gram of deuterium-tritium fuel can release energy equivalent to over 170 tanks of gasoline [5, 4].

However, realizing fusion’s promise requires more than accessible fuel. The construction and maintenance of fusion reactors demand substantial quantities of materials, including lithium, beryllium, and Rare Earth Elements (REEs) [6]. These same materials are essential for renewable energy technologies such as batteries and wind turbines, creating overlapping demand that may exacerbate supply chain constraints [7]. China has already moved aggressively to secure control over critical mineral refining and production infrastructure, processing approximately 60-90% of global lithium, cobalt, and REEs [8]. This strategic positioning gives China disproportionate influence over future clean energy deployment, including fusion.

Meanwhile, recent scientific breakthroughs have accelerated private and public interest in fusion. In December 2022, the National Ignition Facility (NIF) achieved energy breakeven ($Q > 1$), producing 3.15 MJ of fusion energy from 2.05 MJ of laser input, a historic milestone confirming the physical viability of laboratory fusion ignition [9]. This result, while not yet commercially scalable, has catalyzed renewed investment in the sector. Over forty-two privately funded fusion companies now exist worldwide, having collectively raised more than $7 billion in disclosed capital [10]. Despite this momentum, significant uncertainty persists. Suppliers remain hesitant to invest due to the monopsonistic market structure and the broad diversity of technical approaches under development, from magnetic confinement to inertial fusion and alternative reactor designs [11, 10].

This thesis addresses the emerging need for strategic foresight in fusion energy supply chains. Specifically, it identifies potential constraints in resource availability, evaluates where risks are most likely to emerge, and offers pathways by which countries and companies can mitigate those risks, both through domestic development and international cooperation. In the context of high uncertainty regarding which fusion approach will succeed or when commercial deployment will occur, early investment in secure, diversified access to critical inputs is not only prudent but essential.

1.2 Overview of Fusion Power Plants

Fusion Power Plants (FPPs) are a type of electrical power plant which uses a nuclear fusion reaction, the energy source powering our sun, to create electricity. This is achieved through the merging of two light nuclei, such as deuterium and tritium, into a heavier nucleus (typically helium), releasing energy due to mass-to-energy conversion via Einstein's $E=mc^2$ [12].

FPPs are a desirable component of the future power grid for several reasons. The primary fuel can be sourced from water and is far more abundant and globally distributed than other energy fuel, providing a long-term and geopolitically stable energy supply [13]. Furthermore, fusion generates significantly less long-lived radioactive waste compared to fission [13]. Fusion is also safer than traditional fission, as it inherently avoids the risk of runaway reactions. Sustaining nuclear fusion requires the maintenance of extreme plasma temperatures and densities over sufficient confinement times. If the minimum temperature, pressure, or confinement, are not continuously upheld, the reaction ceases instantaneously [14].

1.3 Selection Criteria for D-T MC FPP

Over fifty organizations around the world are pursuing various approaches to developing the world's first FPP. Each has a different mechanism, materials, design elements, and fuel choice but ultimately, these approaches fall into six major design categories and six types of fuels [5].

There is significant uncertainty around which approach will become the most successful as there is yet to be an operational FPP in the market. For this paper, a single fuel mix and reactor design were selected as a basis for the model to allow for a more comprehensive analysis of the supply chain risks and mitigation strategies and to determine total quantities of each relevant mineral required to build and run a reactor. Given the uncertainty in approaches and with the objective of providing insight to the widest possible segment of the fusion industry, this paper will focus on the most pursued approaches and fuels, while incorporating flexibility within the model for analysis of different component types and materials.

The main categories of reactor design are; magnetic confinement, inertial confinement, magneto-inertial confinement, Hybrid, non-traditional, and muon-catalyzed[1].This paper will focus on Magnetic Confinement (MC) Fusion, which is the general approach being pursued by over half (51%) of fusion companies [10].

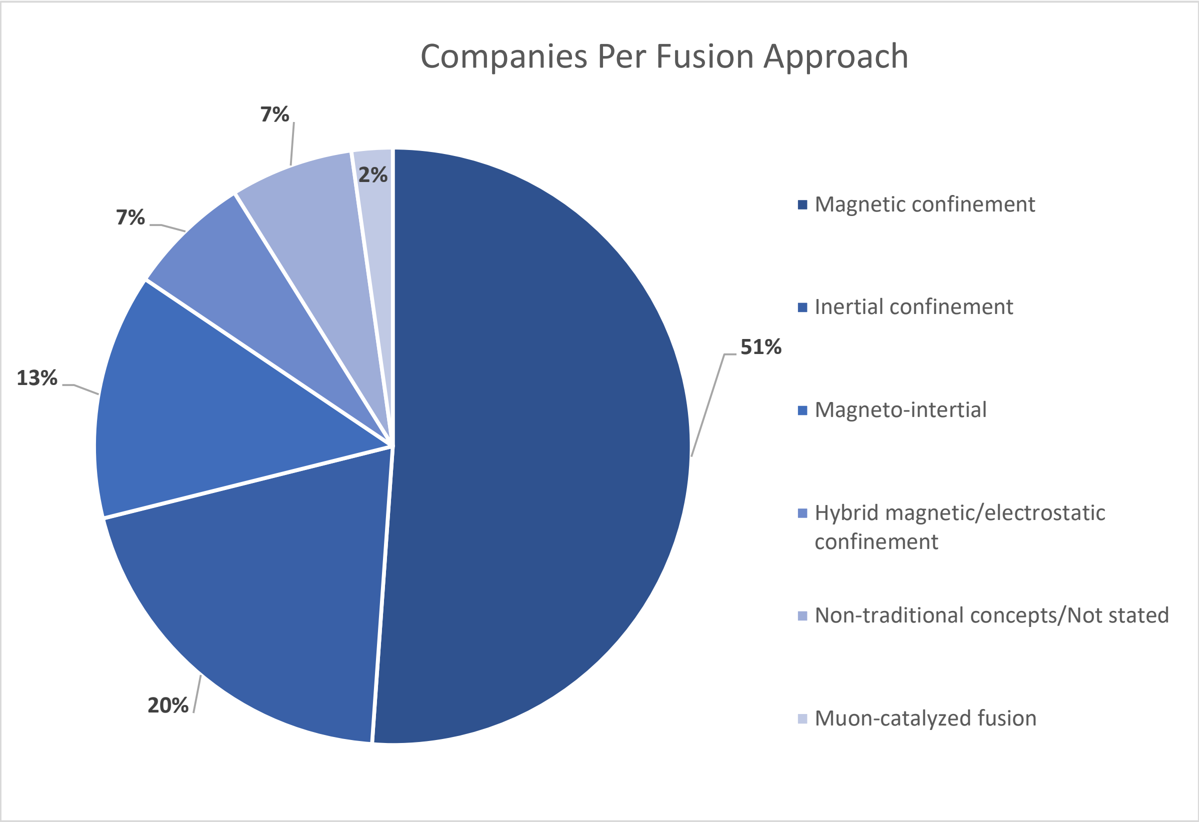


Figure 1: Popularity of different fusion approaches by % of companies pursuing each approach [10]

[1] Muon catalyzed fusion (also known as cold fusion) has been broadly determined infeasible as an approach to fusion, as the energy cost of muon production is about twice the energy released by the muon catalyzed fusion approach [100, 99].

The main fuels being considered are deuterium-tritium, deuterium-deuterium, proton-boron-11, multi-fuel, deuterium-helium3, and lithium. According to the Fusion Industry Association, Deuterium-Tritium (D-T) is the most popular fuel mixture across the industry representing 68% of companies [10]. This is likely due to the comparatively low temperature required to achieve a positive energy return from a D-T reaction at "only" 175 million degrees, as compared to minimum temperatures ranging from 232 million degrees to 1.7 billion degrees for the other mixtures [5].

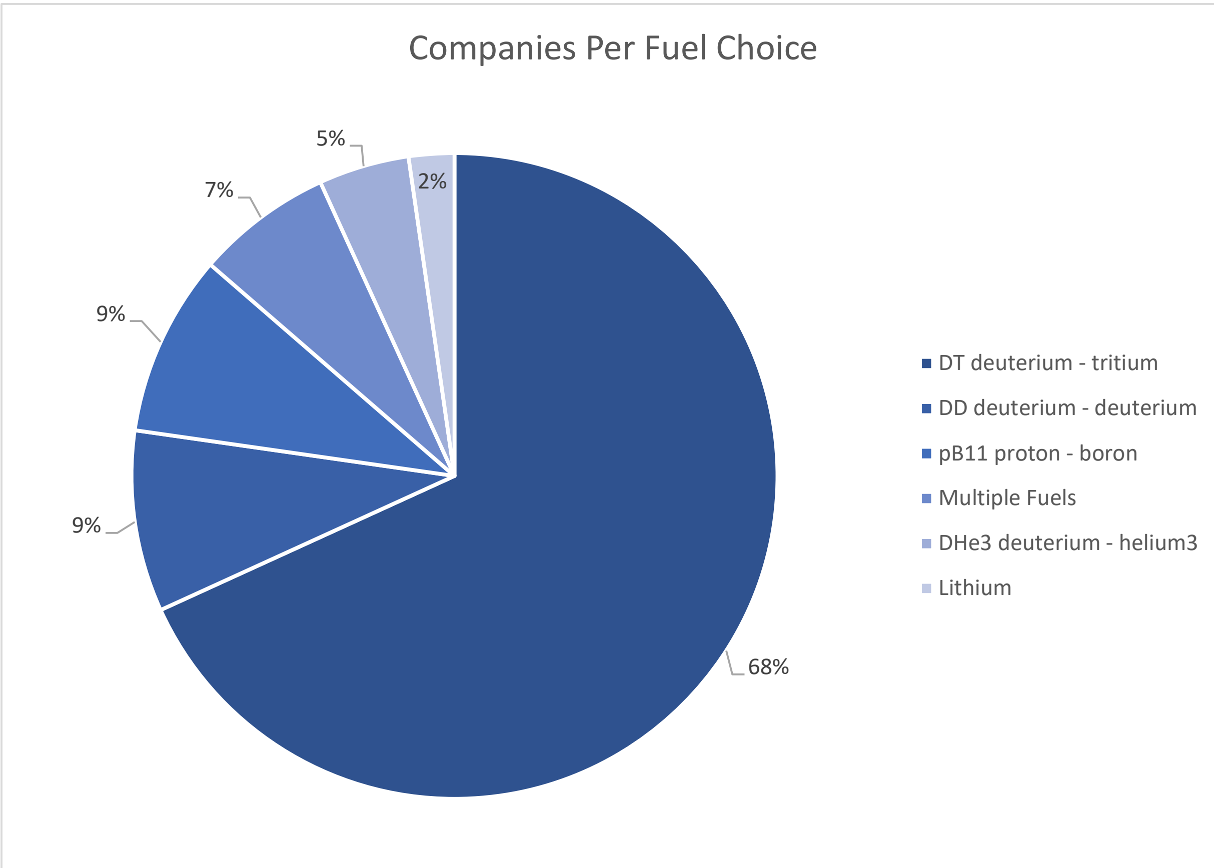
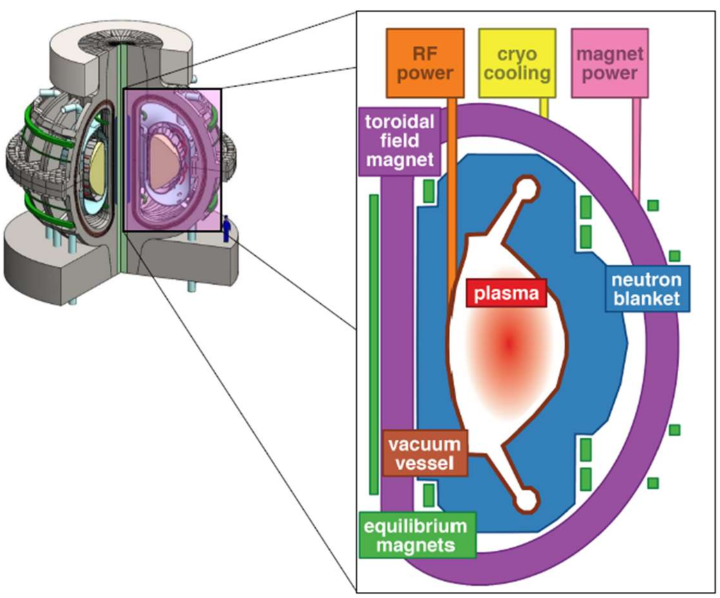


Figure 2: Popularity of different fusion fuel mixtures by % of companies pursuing each fuel mixture [10]

Additionally, through publicly shared data relating to Smallest Possible ARC (SPARC), Affordable, Robust, Compact (ARC), and International Thermonuclear Experimental Reactor (ITER) projects, more data is available to provide insights into the materials required to build D-T MC reactors than any other reactor type. This allows for the development of a meaningful and representative model which can be easily adapted for further insights using confidential data or alternate assumptions.

1.4 Detailed Overview of D-T MC FPP

In simple terms, in D-T MC fusion, power is created by using magnets powered by as much energy as a mid-sized US city, to squeeze a star more than ten times as hot as the sun[2], into a bottle the size of a house[3] [5], all to create heat that spins a turbine[4] and generates electricity. As illustrated in figure 3, in a fusion power plant, the magnets are huge coils of High Temperature Superconductor (HTS) tape formed into electromagnets, and the "bottle" is the vacuum vessel. The "Star" is the plasma created inside this power plant by heating the Deuterium-Tritium fuel with Radio Frequency (RF) power units. Once the power plant is operating, the plasma emits high-energy neutrons. The neutron blanket then captures their kinetic energy and uses it to heat a working fluid into steam to spin the turbine and generate electricity [2].



"Star":

- D-T Plasma
- RF Power

"Bottle":

- Vacuum Vessel

Magnet System:

- Toroidal Field Magnet
- Equilibrium Magnets
- Magnet Power
- Cryo-Cooling

Water Boiler:

- Neutron Blanket

Figure 3: Fusion Reactor Subsystems [15]

The Magnet System is composed of several sets of large superconducting electromagnets, the support structures which hold them in place, and the cooling systems that keep them within the temperature range required to maintain their superconducting properties.

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[2] Sun = 15 million ^{0}C, [95], minimum temperature for D-T fusion = 175 million ^{0}C [5]

[3] Actually many sizes ranging from SMall Aspect Ratio Tokamak (SMART) at roughly the size of a minivan [96] to ITER which is the size of a small office building [97]

[4] This is not true of all fusion approaches. Many, like Helion aim to use induced current rather than turbines to generate electricity [98].

The magnets themselves exert force on the plasma, compressing it to a sufficient density[5] and insulating the walls of the vacuum vessel from its immense heat. The critical component of these magnets is a superconductor referred to as Rare Earth Barium Copper Oxide, or "REBCO" tape, wrapped around large frames which hold them in place and facilitate the conductive cooling required to keep them working.

The vacuum vessel is made up of specialized steel designed to resist extremely high temperatures and be minimally activated by exposure to neutron bombardment from the plasma inside. It protects other components of the reactor from heat and neutron damage and provides a vacuum for the plasma to circulate without losing heat by transferring energy to non-fuel particles [5].

The plasma is made by heating a few grams [16] D-T fuel to a temperature of around 175 million degrees [5]. The external heat used to create this plasma is provided by RF Power Units which inject radio frequency waves into the plasma to increase its temperature and drive its movement within the reactor.

The Water Boiling System is primarily composed of a neutron blanket, which uses specialized composites of beryllium and lithium[6] to provide three key functions within the reactor: extracting heat, protecting other components from neutrons, and breeding Tritium, one of the two components of fusion fuel. In addition to the blanket, the water boiling system also includes a heat exchanger, a mechanism for extracting the Tritium, and a system for replenishing the spent lithium, which is consumed in the process of breeding tritium [17].

One important aspect of the design of neutron blankets that drives their mineral needs is the three-step process by which they breed tritium. The first step in tritium breeding is to slow down or moderate the neutron so it has a chance of interacting with the rest of the blanket. The second is to increase the number of neutrons sent into the rest of the blanket. These functions are provided by a moderator and a neutron multiplier. In the case of this example, beryllium provides both these functions. In the last step, the breeder, in this case lithium, captures the moderated neutrons and produces tritium and helium-4. The three-part nature of this process will create critical opportunities to address lithium supply risks assessed later in the paper.

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[5] For a fusion reaction to achieve energy gain and emit more energy than it consumes, it must reach minimum specific combined levels of temperature, density, and duration based on the fuel being used [101].

[6] Other blanket materials exist and will be discussed in more detail below, but Beryllium and Lithium is one of the most common combinations [37].

1.5 Assumptions

While assumptions specific to particular components of the model will be discussed in their respective sections, several overarching assumptions underpin the overall modeling framework. Foremost among these is the assumption that fusion energy is scientifically achievable. Although this has not yet been conclusively demonstrated, over sixty years of sustained scientific progress have steadily advanced the field toward achieving the levels of energy gain necessary for economically viable fusion power. As demonstrated by Wurzel and Zhu [18], research across the fusion sector continues to make incremental progress toward attaining the energy gain (Q) of 20-40 estimated to be the threshold for economically viable FPPs [19].

With this as an initial assumption, this analysis does not attempt to resolve uncertainties surrounding the economic viability of fusion power but instead assumes minimum economic performance standards must be met in order for fusion to compete with other energy sources and grow to become a meaningful power source in the global power grid.

This paper adopts the model presented in the Massachusetts Institute of Technology Energy Initiative's (MITEI's) report The Role of Fusion Energy in a Decarbonized Electricity System [2], projecting that each FPP will produce 500 MW of electric power over an operational life of approximately 40 years. Because this is the engineered lifespan of existing firm dispatchable power alternatives such as nuclear fission and natural gas generation facilities, competitive forces would limit demand for fusion power if this lifespan and power output could not be achieved [20, 21].

This approach also applies to the assessment of availability of critical materials at current market costs, as these costs directly influence reactor construction expenses which are the basis of the MITEI projected growth rates. To clarify the difference between absolute constraints and constraints given affordable cost levels, the terms *resources* and *reserves* as defined by the McKelvey Box classification system, will be used throughout this study. This system is the most relevant as it is used by the United States Geological Survey (USGS) for the evaluation of mineral availability in the mineral commodity summaries which provided the foundational supply data for this paper. Below are those definitions:

> ***Reserve:*** *That portion of the identified resource from which a usable mineral and energy commodity can be economically and legally extracted at the time of determination. The term ore is used for reserves of some minerals* [22].

> ***Resource:*** *A concentration of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form that economic extraction of a commodity is regarded as feasible, either currently or at some future time* [22].

In other words, while resources represent the absolute limits of a given mineral, the quantity of reserves (i.e., economic limit) also represents a meaningful capacity constraint for the purposes of this study.

Although reserves typically expand over time as demand increases, reserves are defined as resources that are economically extractable at present-day costs. Consequently, accessing additional resources beyond current reserves would require price increases which would undermine the economic assumptions driving the projected scale of fusion energy deployment [22].

While future technological advances could convert additional resources into reserves by lowering extraction or refinement costs, this analysis does not assume the availability of such future reserves. Instead, one of the central aims of this study is to identify where targeted research and investment are needed to enable such cost reductions to increase the affordable supply of critical minerals.

Chapter B: Methodology

2. Scope of Analysis: Inclusions and Exclusions

The purpose of this paper is to examine supply chain risks specific to the deployment of fusion energy technologies. Accordingly, the scope of analysis is deliberately limited to components unique to the fusion reactor system itself. Broader balance-of-plant infrastructure such as steam turbines, electrical systems for power conversion, and transmission interconnects are excluded from this discussion, as these elements are largely comparable across various thermal power generation technologies.

Similarly, the civil engineering and construction requirements associated with FPPs, such as the use of nuclear-grade concrete and neutron-resistant building materials are not addressed in detail here. Specific regulatory standards for fusion plant construction remain undefined and requirements could vary significantly, and it is unclear whether they will align with standards for SMRs [23, 24]. Civil construction is also excluded due to the lack of mineral shortage risk in regard to the required input, concrete [25].

While traditional nuclear fission facilities require extensive management of long-lived radioactive waste, FPPs primarily generate short-lived activation products and inert helium gas during their operational lifetime [26]. Accordingly, the management of activated materials is excluded from the scope of this study. This exclusion is further justified by the paper's primary focus on material inputs, whereas waste management activities are predominantly service-oriented. Moreover, given the expected operational lifespans of approximately 40 years for fusion plants and the deferral of significant waste management activities until decommissioning, the majority of associated impacts fall outside the relevant time horizon considered in this analysis [2, 5].

3. Supply Analysis

A differentiating feature of this analysis is the detailed approach to supply analysis. By incorporating country-level data into the model, geopolitical risks associated with high concentrations of each element in a particular country can also be assessed. Supply is evaluated through three primary metrics: resources, reserves, and production. As defined previously, resources refer to naturally occurring concentrations of minerals with potential for economic extraction, while reserves are subsets of resources that are economically viable for extraction under current conditions [22]. Production encompasses annual outputs from mining, mineral processing, and refinement stages. These metrics provide a comprehensive view of both the current availability and future potential of mineral supplies.

Understanding the geopolitical distribution of mineral supplies is crucial, as reliance on a single country for a significant portion of a mineral's supply can pose risks. This study analyzes country-level data to assess the concentration of annual supplies and long-term inventories, identifying minerals that could become critical if a major supplier were to restrict exports or experience disruptions.

Refinement losses, which vary significantly across different REEs and processing methods, are not included in the current supply estimations. This means additional shortages may exist which will not be identified by this paper. Further research is warranted to assess the impact of refinement efficiencies on supply availability.

This structured approach ensures a comprehensive assessment of mineral supply risks pertinent to fusion energy, incorporating considerations of data completeness, geopolitical factors, and processing efficiencies.

3.1 Mines and Resources

The primary data source for this assessment is the USGS Mineral Commodity Summaries (MCS) 2025, which offers detailed statistics on global mineral production, reserves, and resources. To evaluate data completeness, the number of unavailable or withdrawn data points was divided by the total number of entries for each mineral. This analysis provided insight into the reliability and representativeness of any insights made from USGS supply data. Detailed results are presented in Appendix 1.

Publicly available data often provide either global totals for individual REEs or aggregated country-level data without specific breakdowns, complicating precise assessments [27]. To address this, mine-specific REE distribution patterns ("REE patterns") were applied to total Rare Earth Oxide (REO) quantities, enabling estimation of individual REE contents at the mine level [28]. These estimates were then aggregated to the country level. REO quantities were converted to elemental REE quantities using established stoichiometric conversion factors. For instance, converting lanthanum oxide (La_2O_3) to elemental lanthanum involves a factor of approximately 0.85.

4. Demand Analysis

4.1 Integration of Source Models

One of the key contributions of this paper to the analysis of supply chain risk management for the fusion industry is its comprehensive approach to mineral demand forecasting. In addition to assessing the requirements created by fusion reactors themselves, this analysis situates fusion-related demand within the broader context of expanding mineral needs from the clean energy transition and ongoing baseline demand across other sectors. By incorporating these overlapping demand streams, this paper identifies additional potential risks that may not be fully captured when examining fusion-related demand in isolation.

Several different types of data were collected to support this analysis: (1) projected total and energy-specific demand to 2040 for relevant minerals from the IEA [7], (2) mineral consumption per unit of power output by production type (e.g., coal, fusion, renewables) from the International Energy Agency (IEA) [29], (3) projected electricity supplied to the grid by production type through 2100 from the MITEI report [2], and (4) total current mineral demand and energy specific demand by element from multiple sources, but primarily the United States Geological Survey Mineral Commodity Studies [30].

(1) Fusion Energy Generation: This segment encompasses all mineral requirements for the construction, operation, and fueling of fusion reactors. Mineral input intensities per unit of power output were calculated based on the inputs for each subsystem and component as well as their average lifespans, and future demand was projected by multiplying these intensities by the fusion deployment levels modeled in the MITEI scenario assuming a $2,800/kW overnight capital cost by 2050 [2]. This approach harmonizes fusion-specific mineral demand with broader energy transition mineral projections developed by the IEA, while avoiding double-counting in areas where fusion displaces other generation technologies in the modeled scenario.

(2) Non-Fusion Energy Generation: Non-fusion energy generation includes renewables (e.g., solar, wind) and non-renewables (e.g., coal, gas) modeled in the MITEI report. Mineral requirements per unit of energy output were drawn from IEA data and multiplied by the projected output levels of each technology under the $2,800/kW scenario. This process ensured that the mineral demands associated with displaced energy technologies were appropriately adjusted, maintaining consistency between MITEI fusion modeling and IEA baseline projections for other generation sources [7, 2].

(3) Non-Generation Clean Energy Transition Technologies: This segment includes minerals used in energy storage systems, grid transmission infrastructure, and electric vehicles. Where available, IEA projections to 2040 were used directly. Beyond 2040, demand was conservatively projected to 2100 based on global population growth rates, consistent with United Nations projections [31]. This assumption is conservative given that it excludes growth in affluence, which is expected to further increase demand as developing economies continue to grow [32]. Additionally, continued global warming through at least 2100, as indicated by emissions pathway analyses [33], is likely to sustain strong investment in clean energy technologies.

(4) Non-Energy Related Uses: Minerals critical to fusion energy also serve diverse non-energy markets. For example, in addition to their roles in superconductors and electrical systems, approximately 59% of global copper consumption is in construction, consumer goods, and industrial machinery [30]. Where IEA projections for non-energy mineral demand were available through 2040, these were used directly in the model [29]. Beyond 2040, future non-energy mineral demand was conservatively projected based on population growth trends. For minerals lacking specific demand projections, population growth was similarly used as the basis for extrapolation.

Because not all data sets covered all years and some temporal gaps existed in these data sources, missing values were interpolated using a geometric growth approach. Specifically, the geometric growth rate was calculated between available years, and the implied intermediate values were derived accordingly. The objective was to estimate mineral demand volumes for 2025 and 2040 to allow for like-for-like integration with the IEA projections and to extend projections to 2050 and 2100 to allow for integration with the MITEI projections.

Distinct methodologies were then applied to each major segment of mineral demand: fusion energy generation, non-fusion energy generation, non-generation clean energy transition technologies, and non-energy related uses. With demand thereby projected across the 2025-2100 period, resource sufficiency could be evaluated not only for fusion-specific demand, but for the broader market impacts associated with integrating fusion into the global energy system.

To integrate different demand streams and avoid double-counting, the following method was applied: existing projections of energy-related mineral demand were subtracted from total projected demand for each element, and new fusion-aligned projections based on the MITEI model were added. This adjustment ensures that minerals included in IEA energy generation models are not double counted with newly projected fusion deployment needs. Non-generation clean energy transition demands, already accounted for separately by the IEA, were similarly subtracted from total market demand figures before projecting forward.

Figure 4 illustrates this approach: to prevent overlap in projected demand, existing energy transition-related demand was removed before reintroducing harmonized projections for clean power, including fusion, based on MITEI's internally consistent scenario modeling.

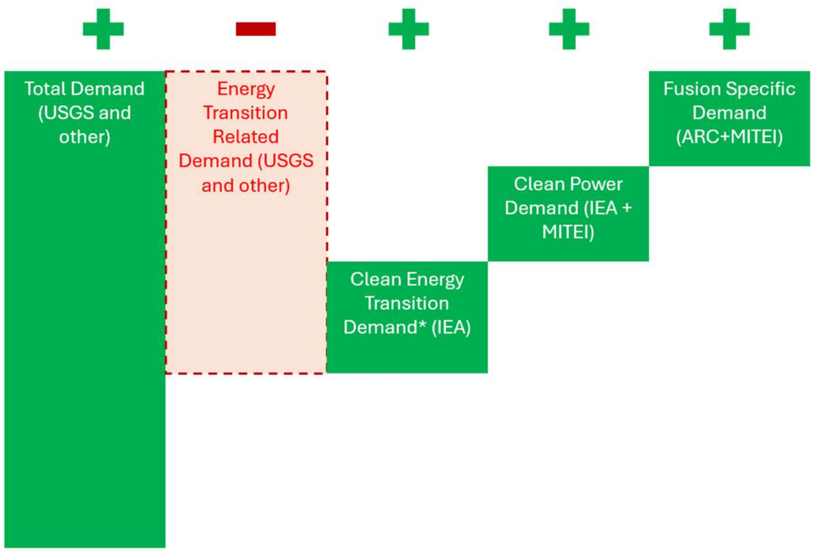

Figure 4: Composition of aggregate demand model.

4.2 Fusion Demand Estimation

4.2.1. Decomposition of FPP Components

To assess the supply chain requirements of grid-scale fusion reactors, this study categorizes material inputs into three primary domains: (1) initial construction materials, (2) fuels and consumables, and (3) components required for maintenance and periodic replacement. The analysis of construction and maintenance inputs is completed by decomposing the parts of the reactor into subsystems, components, and raw material inputs. This structure facilitates a bottom-up quantification of elemental demand and enables comparison against known global supply capacities.

Subsystems are categorized based on data derived from the ARC reactor design from Commonwealth Fuson Systems (CFS). Although the ARC reactor represents only one specific D-T MC FPP design, its architecture is representative of common technological features pursued across multiple fusion concepts. Due to the proprietary nature of detailed design data in the fusion sector, ARC is one of the few publicly documented reference designs that includes the required granularity for bottom-up materials analysis [34].

While acknowledging the limitations of relying on a single design, this paper adopts ARC as a reference model primarily for its illustrative value and data availability. However, in order to ensure relevance and applicability across different fusion approaches, the analytical framework developed here is modular. It is designed to accommodate alternate settings, allowing researchers with diverse approaches to fusion to apply proprietary assumptions about material quantities and compositions in place of ARC's baseline data. This flexibility ensures broader applicability of the framework across different fusion reactor configurations. See Append

Table 1: Construction and maintenance materials and quantities

Component	Material[6]	Quantity	Unit	Replacement / yr (t)[66]
First wall	Tungsten	3.72	tonnes	0.74
Inner VV wall	Inconel 718	16.6	tonnes	11.07
Multiplier	Beryllium	3.82	tonnes	0.00
Outer VV wall	Inconel 718	51.4	tonnes	8.57
VV ribbing	Inconel 718	6.8	tonnes	1.13
VV posts	Inconel 718	4.14	tonnes	0.69
Blanket tank	Inconel 718	97.1	tonnes	19.42
TiH_2 shield	TiH_2	380	tonnes	76.00
Channel FLiBe	FLiBe	8.07	tonnes	0.00
Blanket tank FLiBe	FLiBe	475	tonnes	0.00
Replacement Lithium	Lithium	0.002	tonnes	0.00
Heat exchanger FLiBe	FLiBe	475	tonnes	95.00
Magnet structure	SS316 LN	4350	tonnes	0.00
Magnet top ring	SS316 LN	959	tonnes	0.00
REBCO structure	Copper	358	tonnes	0.00
REBCO tape	REBCO	5730	km	0.00
Cryogen System	Helium	27	tonnes	2.48
Cryogen System	Neon	27	tonnes	2.48

Once component-level material quantities are established using ARC as a baseline, each alloy or composite is decomposed into its elemental constituents to calculate total elemental demand. This was done by applying known mass fractions to the aggregate weight or volume of the component in question. For most alloys, this process involved multiplying the total weight of the material by the mass fraction of each element, derived from published industrial materials datasheets from manufacturers like AZO Materials [35].

In some instances, however, key material quantities were not available by weight. This was especially true for complex materials such as the multi-layered REBCO superconducting tapes, for which ARC provides material specifications in linear units (kilometers) rather than in metric tons [34]. In such cases, a multi-step volumetric approach was employed. First, the physical volume of each tape layer was computed based on its thickness and cross-sectional area (e.g., 1 nm × 4 mm × 1 km = 4 × 10^{-3} cm^3). This volume was then multiplied by the material's density to obtain mass per kilometer, which was further broken down by the relative contribution of each element.

This method is captured by the following general formula:

$$Me = V \times \rho \times fe$$

Where:

- $\mathbf{M_e}$: Mass of element e per unit length
- **V**: Total volume of compound/alloy
- $\boldsymbol{\rho}$: Density of the layer material
- $\boldsymbol{f_e}$: Mass fraction of element e in the layer

When direct data on mass fractions $\boldsymbol{f_e}$ were unavailable, they were derived from molecular composition using standard chemistry formulations as presented in LibreTexts Chem 2A. Specifically, the relative mass contribution of each element in a compound was computed as: [36]

$$f_e = \frac{A_{r,e} \cdot n_e}{\sum_i A_{r,i} \cdot n_i}$$

Where:

- $\boldsymbol{f_e}$: Mass fraction of element e
- $\boldsymbol{A_{r,e}}$: Atomic weight of element e (relative atomic mass)
- $\boldsymbol{n_e}$: Number of atoms of element e in the molecular formula
- $\mathbf{\sum(A_{r,i} \times n_i)}$: Molar mass of the compound (sum over all elements in the compound)

By applying these formulas to each component and summing across all subsystems, this study derives a full elemental breakdown for the reference reactor. From here, a downstream analysis of supply risk related to each element can be conducted.

4.2.2. Material Consumption Rates

In addition to determining the quantity of each material required to build an FPP, there are multiple consumables which are used up or replaced throughout the life of the reactor. These come in the form of fuels, replacement parts, and leakage [5, 37].

Fuels include Deuterium and Tritium. These are both required inputs that make up the D-T plasma. The consumption rate of tritium was directly calculated using the 6.9 Mg / MWh (thermal) and 7.6mg / MWh (thermal) value provided in the MITEI report [2]. Deuterium was excluded from this study due to its abundance in seawater and a broad understanding that it is effectively inexhaustible as a resource [37].

Although the neutron blanket is usually considered a lifetime component, some MC-FPP concepts will require ongoing redox control and replenishment of breeding materials. Redox control for a FLiBe blanket requires metal beryllium at the rate of a few kilograms per year. For blanket designs that are sensitive to Li-6 enrichment, a few kilograms per year of enriched lithium fluoride may be needed to maintain the required tritium breeding performance [2]

4.2.3. Adjustments for Specific Components

Lithium occurs as two stable isotopes: lithium-6 (^{6}Li) and lithium-7 (^{7}Li), which occur in natural lithium in abundances of approximately 7.5% and 92.5%, respectively [38].The primary driver of lithium demand today is the production of lithium-ion batteries, which accounts for approximately 87% of total end-use demand by volume [30].

In battery manufacturing, natural lithium, lithium-7-enriched, and lithium-6-enriched materials are all utilized [39, 40]. Given the lack of a specific isotopic preference in this application, and the dominance of batteries in total lithium consumption, this study follows the approach adopted by the IEA *Global Critical Minerals Outlook* and treats non-fusion lithium demand as a single quantity of demand for lithium in the naturally occurring isotopic blend [29].

By contrast, nuclear fusion applications typically rely exclusively on lithium-6. In fusion systems, maximizing tritium breeding is critical, and ^{6}Li is preferred due to its high neutron cross-section (approximately 940 barns) [40] which facilitates the neutron interaction that produces tritium and helium [5]. To meet this requirement, natural lithium is typically enriched through the COLEX process to increase the concentration of ^{6}Li to the necessary levels [41]. For this reason, the actual fusion related demand must be adjusted to represent the amount of natural lithium required for the ^{6}Li portion alone to meet fusion demand. In this study, the required quantity of ^{6}Li is divided by its proportional abundance to determine the corresponding amount of natural lithium needed, thereby providing a consistent and meaningful basis for comparing demand with available supply.

Aluminum and steel are not included in the IEA's projections for mineral requirements in the clean energy transition, as indicated by their published comparative assessments of material use across energy technologies [42]. Although the IEA does not provide an explicit rationale for this exclusion, it can be inferred that their analysis focuses on minerals that exhibit both high supply risk and strong specific linkage to energy technology innovation, characteristics less associated with these widely available industrial metals at present. Consequently, in this study, where clean energy rollout demand for minerals is projected using IEA data, aluminum and steel requirements will be estimated separately using non-energy-sector demand trajectories.

Nevertheless, future research may warrant closer investigation of aluminum in particular. According to the U.S. Department of Energy, aluminum is classified as "near-critical" between 2025 and 2035, reflecting a combination of high supply risk and moderate energy importance [42]. While not currently categorized among the most critical minerals for energy applications, aluminum's evolving strategic significance suggests that its role in fusion energy infrastructure may merit re-evaluation if supply chain vulnerabilities become more pronounced. [7]

4.3 Non-Fusion Demand Growth

The next phase of the analysis involves projecting non-fusion demand for each of the critical materials. For minerals with significant applications outside the fusion industry, current demand data were obtained from sources such as the USGS, IEA, and select industry reports. In some cases, these sources also specify the proportion of existing demand attributable to the energy or clean technology sectors. However, because non-fusion uses are not the primary focus of this study and given that many raw materials lack publicly available long-term demand forecasts, a standardized methodology was adopted to estimate future demand [43].

Following a population-based growth model described by the Consortium for Mathematics and its Applications [44], demand for materials not predominantly used in clean energy sectors is projected to grow in proportion to global population. This is a standard approach, consistent with methods employed in recent market assessments, such as Industry ARC's analysis of gadolinium [45].

For population projections, this paper adopts the United Nations median scenario, which offers the most authoritative and widely cited estimates available. The UN's projections have demonstrated strong historical accuracy, for example, their 1968 projection for 1990 was off by only 0.06 billion people, and their 2000 projection for 2020 was within 0.2 billion [31, 46]. Accordingly, the UN's median population growth rate was used for all population-based geometric projections in this model, as outlined in earlier sections.

In cases involving energy-related demand, scenario-based forecasts from the IEA are used wherever possible. These include the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 Scenario (NZE), each representing different trajectories of climate policy implementation [29]. For the purposes of this analysis, STEPS was deemed the most probable, as it is grounded solely in currently enacted policies [47]. Although more ambitious scenarios may offer more sustainable outcomes, this study prioritizes the most certain trajectory to enhance the practical applicability of its findings for stakeholders in the fusion energy sector.

4.4 Growth Rate Estimation for Element Demand

Rather than applying a uniform growth rate across all minerals, the model derives a specific Compound Annual Growth Rate (CAGR) for each mineral within each interval. This allows the model to account for the varying roles materials play in reactor systems, some used predominantly in initial construction, others consumed continuously over the reactor lifespan.

For each material and time interval, the annual growth rate r_e is calculated using:

$$r_e = \left(\frac{U_t}{U_0} \right)^{\frac{1}{t}} - 1$$

Where:

- U_t = Annual demand at the end of the interval
- U_0 = Annual demand at the beginning of the interval
- t = Number of years in the interval
- r_e = Estimated annual growth rate

For example, if the demand for a mineral rises from 0.09 to 1.83 thousand tons between 2040 and 2050:

$$r = \left(\frac{1.83}{0.09}\right)^{\frac{1}{10}} - 1 \approx 34.3\%$$

These material-specific growth rates are then used to estimate cumulative demand within each interval using the continuous growth formula below.

5. Resource and Reserve Sufficiency Analysis

To determine how many years of growing demand can be supported by a finite global supply of a given element, the analysis calculates cumulative consumption over each period using a closed-form expression for cumulative use under exponential growth:

$$C = U_0 \times \frac{(1+r)^t - 1}{r}$$

Where:

- C = Cumulative demand over the period
- U_0 = Starting annual demand
- r = Annual growth rate
- t = Number of years in the period

The model applies this formula iteratively across the three periods. After each interval, the cumulative consumption is subtracted from the total known quantity of reserves or resources. The number of years to depletion is back calculated by solving the inverse of the cumulative demand formula:

$$n = \frac{\ln\left(1 + \frac{S}{U_0} \times r\right)}{\ln(1+r)}$$

Where:

- S = Remaining available supply at the start of the interval
- U_0 = Starting annual demand
- r = Annual growth rate for the period
- n = Number of years until exhaustion within the interval

If the value of *n* is less than the length of the interval, this indicates that the mineral is depleted during that period. The final value for years of sufficiency is computed as the sum of the total length of all completed periods plus the partial duration *n* in the final incomplete period.

5.1 Sufficiency Analysis (Supply vs Demand)

This analysis adopts a forward-looking resource sufficiency framework aligned with recent modeling efforts by the IEA [29] and the MIT Energy Initiative [2]. Following the structure of these prior studies on resource sufficiency, the analysis evaluates material adequacy for large-scale deployment of FPPs using four primary indicators:

1. **Sufficiency of total resources and reserves for FPP-related demand**
   Measured in years to depletion, assuming fusion-sector-only consumption.

2. **Sufficiency of total resources and reserves for projected total demand**
   Measured in years to depletion, considering both fusion and non-fusion applications.

3. **Sufficiency of annual production capacity to meet FPP-related demand**
   Measured as fusion-sector demand as a percentage of annual production.

4. **Sufficiency of annual production capacity to meet projected total demand**
   Measured as total demand (fusion + non-fusion) as a percentage of annual production.

This section describes the methodology used to evaluate the first indicator, which calculates the number of years global mineral quantities could support fusion deployment alone. It includes detailed steps on demand growth modeling and resource depletion timing under evolving growth conditions.

5.2 Piecewise Projections For Years of Sufficiency

The IEA and MITEI provide a basis for projections of material demand at select milestone years: 2025, 2040, 2050, and 2100. However, to assess cumulative demand and estimate resource and reserve exhaustion timing, a continuous function representing material demand is required.

To resolve this, demand for each material is modeled as a piecewise exponential function, segmented into three distinct time intervals:

- 2025-2040
- 2040-2050
- 2050-2100

Within each interval, demand is assumed to grow geometrically at a rate estimated individually for each material and time period based on the values provided in the deployment scenario.

This follows the methodology described in the mathematics textbook *For All Practical Purposes* for the measurement of exhaustion of a nonrenewable resource[7] [44].

6. Assessment Factors

With this data collected and combined, it was possible to conduct a quantitative assessment of risks related to total supply, annual supply, and country-specific supply constraints on each of the elements relevant to FPPs, then map them back to their respective components and sub-systems to allow for insights on criticality of shortfalls identified.

Chapter C: Assessment and Results

7. Quantitative Mineral Availability Risks

7.1 Trends and specific minerals

According to long term projections in the Climate Smart “Minerals for Climate Action” report, the clean energy transition will drive consistent growth in demand for most major metals throughout the 21st century [43]. While advancements in energy efficiency and reductions in material intensity across clean technologies may temper the growth in raw material requirements, these effects are unlikely to fully offset rising global consumption [29, 43].

Several scientific and industrial initiatives are actively exploring alternative materials and processes to alleviate some of these constraints. These include efforts from both private companies and national laboratories that aim to substitute, recycle, or redesign material for systems in critical components of clean energy technologies, including fusion systems [10, 8].

This study identifies four distinct categories of risk in the long-term availability of fusion-relevant materials. First, some minerals are effectively unconstrained. These materials exhibit ample availability, with known reserves and existing production rates sufficient to meet fusion-sector needs for well over a century, even under aggressive energy transition scenarios. Second, certain materials appear sufficient for fusion-specific demand but may face limitations when broader clean energy transition requirements are included. In these cases, the fusion sector alone would not strain supply, but fusion must compete with growing demand from batteries, electric vehicles, and other decarbonization technologies. These scenarios may best be addressed through various hedging strategies. Third, a more critical category includes minerals for which the projected demand from fusion alone exceeds economically recoverable

[7] Note here, the word resource is used broadly in the generic sense, not the specific mineralogical sense defined by the McKelvey box

supply or scalable production capacity. These minerals present a structural constraint that must be addressed through substitution, recycling, or significant expansion of extraction and refining capacity. Finally, some materials present sufficient total global supply, but their availability is not certain, due to high geopolitical concentration. In these cases, more than half of global production comes from a single country, creating supply risks in the event of trade disruptions, export restrictions, or geopolitical conflict.

China's role in the supply of critical materials is particularly notable. It currently dominates the production of fourteen of the twenty-eight critical minerals assessed in this study. This concentration introduces a systemic risk, even when geological abundance is not an issue, due to vulnerabilities associated with centralized refining infrastructure and global market leverage.

In terms of risk timing, the model suggests that most materials will remain sufficient throughout the first half of the 21st century. However, the risks intensify around mid-century as fusion deployment accelerates alongside the broader clean energy transition, particularly between 2040 and 2060. A few minerals, most notably beryllium, nickel, and lithium, present earlier constraints that demand short-term strategic attention. These early-stage vulnerabilities are due to a combination of limited reserves, complex production processes, and overlapping demand from other clean energy technologies.

Despite frequent concerns surrounding REEs, their use in HTS REBCO tapes does not appear to pose a major supply risk. The material requirements are minimal due to the microscopic thickness of the superconducting layer at only 1-3 microns [48]. Of this, REEs represent only around 13% by volume. For a 500 MW FPP, this corresponds to an estimated thirteen kilograms of REE material in total. These low absolute volumes mean that even widespread fusion deployment will not materially affect the global REE supply balance under any of the scenarios modeled.

One potential exception is lanthanum, which is sometimes used in the buffer layer of REBCO tapes. The model indicates that lanthanum may become supply-constrained around 2075, though this is largely driven by non-fusion applications. Additionally, many commercially available REBCO designs avoid the use of lanthanum altogether, offering a straightforward mitigation pathway [49, 48, 50]

In summary, while most fusion-relevant materials will remain available through mid-century, a subset of critical elements, especially those with high cross-sectoral demand or geographically concentrated supply chains, pose credible long-term risks that merit proactive mitigation strategies.

7.2 General Opportunities

Where material scarcity presents a constraint, whether due to total physical shortage or the limited availability of economically recoverable reserves, several mitigation pathways are being explored. In cases of absolute scarcity, advances in mineral exploration and geological detection are critical. Artificial intelligence-driven prospecting techniques, such as those developed by KoBold Metals and Earth AI, have shown potential in identifying previously overlooked deposits of copper, cobalt, silver, and gold by training models on national geological archives and other large-scale datasets [51, 52]. These approaches represent a promising frontier for alleviating supply constraints through the discovery of new primary sources.

For minerals constrained not by physical scarcity but by processing limitations, improving the efficiency of refining and extraction technologies offers a viable means to expand economically recoverable reserves [53]. Simultaneously, financial strategies such as the use of futures contracts and the strategic stockpiling of critical materials may offer buffers against price volatility and supply disruptions in the near to medium term [54].

Recycling also presents a substantial opportunity for mitigating future shortages. According to the Climateworks Foundation, accelerated investment in circular economy infrastructure could allow recycled materials to meet between 60% and 80% of total mineral demand by 2050 [55]. Such a transition would significantly reduce dependence on primary extraction, especially for materials with high recycling potential such as aluminum, copper, and nickel.

Technological shifts are also influencing the trajectory of mineral demand. The transition to alternative chemistries in battery design, such as lithium iron phosphate cells, has the potential to reduce reliance on high-risk elements like cobalt. Similarly, aluminum is increasingly being explored as a partial substitute for copper in electrical grid infrastructure, potentially reducing strain on copper supply chains [56].

Together, these dynamics underscore the critical importance of integrating supply-side innovation, demand-side substitution, and strategic risk management in ensuring the long-term sustainability of mineral supply chains essential for the fusion energy transition.

7.3 Fusion Demand Alone may present risks for Select Materials

Table 2: Risks Driven by Fusion Demand Alone

	All Countries		
	Resources (Yrs Till Exhaustion)	Annual Production % of Production (2050)	% of Production (2100)
Element	Fusion Alone	Fusion Alone	Fusion Alone
Beryllium	40	1,052%	28,454%
Tantalum			489%
Lithium			811%
Titanium			223%

Even before integrating demand from other sectors, several critical materials already exhibit signs of strain under projected fusion-driven use alone. Chief among these is beryllium, for which fusion deployment would exhaust all known global resources within 40 years, including deposits not currently considered economically recoverable. This timeline is particularly concerning given that it precedes the expected end-of-life for the first commercial FPP. While total depletion is not imminent for lithium, tantalum, or titanium, the intensity of fusion-specific demand is similarly striking. By 2100, demand for these elements from fusion alone is projected to exceed current global annual production by factors of 8 (lithium), 5 (tantalum), and 2 (titanium), respectively with much larger supply gaps projected including non-fusion demand as well. Even in the nearer term, lithium demand from fusion could account for nearly 30% of global supply by 2050 (197% when including non-fusion demand). These figures suggest that even absent broader industrial growth, fusion presents a significant source of supply pressure for select inputs.

A closer examination of beryllium provides additional insight into potential strategies for alleviating this constraint. Beryllium plays an essential dual role in the breeding blankets of D-T fusion reactors: it enhances neutron multiplication and aids in neutron moderation by slowing fast neutrons to energies suitable for tritium breeding in lithium blankets [37, 57, 34]. These functions are crucial for achieving a Tritium Breeding Ratio (TBR) greater than one, enabling the reactor to maintain its own tritium fuel supply, which is a requirement of commercial fusion.

However, despite its strategic role in FPPs, beryllium is not yet being used in experimental and demonstration reactors. For example, ITER will test several small-scale breeding modules but will not require full-scale deployment of beryllium-based systems [58]. This lag offers valuable time to find a solution before beryllium supply becomes a constraint on fusion's growth.

While beryllium is still a dominant blanket approach, concepts such as lead-based multipliers or liquid metal blankets are already under development by entities like General Fusion and the EUROfusion DEMO team. These solutions could reduce reliance on beryllium for neutron multiplication altogether [59, 60]. Given fusion's dominance as a future demand driver for beryllium, vertical integration may also become necessary for securing sufficient beryllium at scale. This approach has already been successfully deployed by CFS to ensure sufficient production of superconducting magnets [61].

The status of lithium is more complex due to its widespread use in batteries, electric vehicles, and industrial processes [54]. As such, the total global demand for lithium needs to be considered, rather than just demand related to fusion. Since FPP designs rely exclusively on the ^{6}Li isotope of lithium, the effective demand for lithium from fusion has to reflect the quantity of lithium required to produce the required amount of ^{6}Li. This adjustment is required because of the uneven distribution of ^{6}Li and ^{7}Li in natural lithium, with ^{6}Li representing only 7.5% of its composition [40]. After this adjustment was made, the known economically recoverable reserves were projected to be depleted within 53 years.

The reason ^{6}Li is preferred to ^{7}Li for fusion breeding blankets is because of its large cross section, a term used to describe its probability of interacting with neutrons to breed tritium. However, research suggests that ^{7}Li, the more abundant isotope, may may be able to be mixed with ^{6}Li or replace it all together due to its other properties [62]. Though not as effective for direct tritium breeding, ^{7}Li can act as a neutron multiplier and interact with high-energy neutrons in energy bands where ^{6}Li is less effective [37, 63].

This broader view reveals important opportunities to reduce ^{6}Li-specific demand through engineering. Since the Tritium Breeding Ratio is determined by the combination of neutron multiplication and neutron capture efficiencies, improvements to either stage can raise the TBR above one. In other words, using ^{7}Li as a neutron multiplier to enhance the number of neutrons, as a moderator to increase the likelihood of neutrons interacting with 6Li, or as a high-energy breeder to capture neutrons outside the optimal energy range for 6Li, can all similarly impact the TBR [57]. These design strategies would not only alleviate material pressure but may also offer secondary benefits, such as potential for better integration with diverse reactor types and cooling systems.

Beyond technical considerations, ^{6}Li also presents regulatory and proliferation risks. The enrichment technologies used to isolate ^{6}Li can be adapted to produce weapons-grade materials, as the only difference between these ^{6}Li applications lies in the scale of production. Because of this, ^{6}Li is controlled in the US, and access for fusion applications may face geopolitical or security-related constraints [41, 64]. While these issues are not insurmountable, they add another layer of complexity to long-term lithium provisioning for fusion energy and will likely require active involvement in policy creation.

The next two elements, tantalum and titanium, face demand pressure impacting their roles in structural and shielding components. Both are alloying inputs in Inconel 718, a high-performance nickel-based superalloy used in vacuum vessel and blanket tank structures. Inconel 718 offers superior performance in high-radiation, high-temperature environments, maintaining mechanical integrity above 750°C and exhibiting strong resistance to neutron-induced embrittlement, a common failure mode in high radiation environments [65, 6, 66]. Its compatibility with tungsten and suitability for additive manufacturing further enhance its appeal in reactor component design [67].

While Tantalum and Titanium are not replaceable as inputs into Inconel 718, there are many other super-alloys which can provide the same function for fusion and may even have additional benefits beyond alleviating supply constraints. Vanadium alloys are under active development by companies like Toakamak Energy due to their low activation profiles and high compatibility with lithium-based blankets [68]. Similarly, Reduced Activation Ferritic-Martensitic (RAFM) steels, including Eurofer 97 which are becoming popular in reactor designs across the EU and UK, offer pathways to reduce reliance on high-cost or scarce alloying elements while maintaining performance [69].

Beyond Inconel 718, Titanium serves an equally critical function in the form of TiH_2, a neutron-shielding material placed between the breeding blanket and other reactor subsystems. This protects the rest of the reactor, including the magnets, and even the operators from severe radiation exposure [70]. Due to space constraints within tokamak and stellarator structural designs, shielding must be both thin and highly effective. TiH_2's high hydrogen content enables it to absorb neutron bombardment at significantly reduced thickness compared to stainless steel alternatives like SS316L, offering up to 20% space savings. While alternatives such as ZrH_2 and $Mg(BH_4)_2$ are under investigation, titanium remains the current material of choice for this application [71].

Tantalum faces constraints not due to absolute scarcity but due to limited production volumes driven by its highly specialized end uses such as aerospace, pressure vessels, and cryogenic tanks [72]. Projections suggest that total tantalum demand will outpace supply by 54% by 2040 and nearly sevenfold by 2100. While titanium demand from fusion alone may exceed market supply, its relatively low concentration in Inconel 718 (1%) suggests that the total titanium requirements for fusion applications may not be as large as initially anticipated. Additionally, a cost sensitivity analysis could reveal enough flexibility in the willingness to pay among fusion companies, potentially incentivizing sufficient titanium supply to enter the market through market-driven forces [73].

Across these constrained elements, different mitigation strategies are appropriate. For beryllium, total supply constraints suggest that material substitution through lead or liquid metal blanket concepts is likely the most effective path. For lithium, particularly where fusion is not the dominant demand driver, hedging strategies such as futures contracts or physical stockpiling are plausible. For example, securing a full 40-year lithium supply for a fusion reactor at current prices would cost less than $2 million and require less than one shipping container of space for physical storage[1]. This strategy could provide a simple and scalable approach to insulating reactor construction from market fluctuations, provided issues of storage security and cost are addressed.

[1] Estimated lithium consumption: 13 metric tons per year × 40 years = 520 metric tons. At a lithium density of 8.96 t/m^3, this equates to ~59 m^3—below the 63 m^3 capacity of a standard

40-foot container [74]. Total cost (TC) = 520 t × $5,900/t = $3.068 million. Accounting for the time value of money at 5% annual interest:

$$\mathrm{TC} - (\mathrm{TC}/40) \times 1 - (1 + 0.05) - 400.05\,\frac{1 - (1 + 0.05)^{-40}}{0.05}\,0.051 - (1 + 0.05) - 40$$

≈500,000 in net present value savings from deferring purchase [75].

7.4 Integration with Existing Demand Accelerates Exhaustion

Table 3: Additional Risks Driven by Addition of Existing, Non-Fusion Demand

	All Countries				
	Resources (Yrs Till Exhaustion)	Reserves (Yrs Till Exhaustion)	Annual Production % of Production (2040)	% of Production (2050)	% of Production (2100)
Element	Existing + Fusion	Existing + Fusion	Existing + Fusion	Existing + Fusion	Existing + Fusion
Chromium		21			
Cobalt	74				
Copper		47			
Lanthanum	50				
Molybdenum	57	44			
Nickel		35			
Niobium	8				
Silver		16			
Tungsten			166%	175%	193%
Vanadium			257%	271%	286%

Beyond the elements constrained by fusion demand alone, several key reactor inputs face potential exhaustion within the next several decades due to rapid consumption in non-fusion industries. The metals highlighted here, Chromium, Cobalt, Copper, Molybdenum, and Nickel all show signs of strain under the combined demand scenario, with reserves at risk of economic exhaustion within the 21st century. For these scenarios, fusion demand alone is often modest, but when layered onto sectors like EV batteries, infrastructure, and clean energy expansion, these elements are pushed into supply constraint scenarios. In addition to the alloys discussed earlier like Inconel 718, fusion reactors rely on several other alloys materials, for which the unique composition must be considered.

One such material is SS316LN, an austenitic stainless steel used in the magnet structure and top ring components due to its non-magnetic properties, weldability, and resistance to stress [11, 76]. The last of these qualities is critically important, as stress simulations in the TF coils showed stresses as high as 95,000 pounds per square inch[8] in the SS316LN structure [6]. SS316LN consists primarily of Iron and Chromium, with significant additions of Nickel and Molybdenum, and trace nitrogen to increase strength [76]. Each fusion plant uses over 5,000 tons of this alloy [6].

[8] 660 MPa in source paper, converted at 145.038 psi / MPa [102]

Hastelloy C276 is another high-performance alloy used in fusion, specifically in REBCO tape structures, due to its strength and ductility at low temperatures [77]. REBCO tapes, which must be kept near 20 K to maintain superconductivity, also need to be wound into coils and resist a costly material failure called "quench" [2, 78, 6]. Hastelloy C276's properties make it ideal for these demands. Hastelloy 276 consists of ~57% Nickel, 15-17% Molybdenum, ~16% Chromium, and small additions of Cobalt and Iron [35]. While an FPP contains only about 8 tons of Hastelloy C276 [6] compared to 176 tons of Inconel 718, the model suggests that some of its constituent elements will still experience supply shortages due to growing global demand in unrelated industries.

The following sections will examine the potential shortages and mitigation strategies for each element present in SS316LN and Hastelloy C276.

Chromium is used across Inconel, SS316LN, and Hastelloy C276. Economically accessible reserves of chromium are projected to reach exhaustion in just 21 years when accounting for demand across all markets. While fusion-specific uses are not projected to exceed 1% of global demand within the timeframe of the model, growing consumption for use in stainless steel more broadly is expected to drive shortages of chromium.

With respect to potential mitigation strategies, there are no substitutes for chromium in stainless steel, as the same oxide-forming behavior that makes chromium essential to corrosion resistance is what makes it irreplaceable in fusion alloys [30, 79] . Hedging may be a feasible solution, however, as chromium is traded on the London Metal Exchange and since the direct demand for fusion is comparatively small. The financing cost of this hedge was estimated at ~$3m using the same methodology described earlier for lithium, but further cost analysis with current and projected market interest rates would be needed to determine if this is the right approach. This approach should be considered in comparison with the cost of directly absorbing the rising market price[9] starting from 2040, by which time demand is projected to have exceeded supply by 27%.

Cobalt is primarily used in fusion reactors as a minor component in superalloys, such as Inconel 718 and Hastelloy C276 [35, 73]. However, its broader supply risk arises from its significant role in the production of Electric Vehicle (EV) battery cathodes, which now account for nearly 60% of global cobalt demand [80]. If current trends continue, economically recoverable cobalt reserves could be depleted within 35 years, and total cobalt reserves may be exhausted in 73[10]

[9] Shortages of reserves tend to drive up market prices, making formerly sub-economic resources economical to extract and increasing supply [103].

[10] Note: cobalt resource data from 7% of producing countries is marked as unavailable in the USGS, introducing potential uncertainty into this figure [30]

years, considering both fusion and non-fusion applications. This risk is heightened by the concentration of 78% of global cobalt production in the Democratic Republic of Congo (DRC), a country ranked fourth in the Fund for Peace's Fragile States Index [81].

Despite these challenges, cobalt does not degrade during recycling and with just 25% of US demand offset by scrap recovery [30] there is likely opportunity to invest in enhanced recycling or waste recapture programs. Importantly, these solutions would align supply resource availability more with the locations of consumer markets than the locations of natural resources, expanding access and reducing dependence on the DRC. Since a large, non-fusion market exists for cobalt, long-term contracts, stockpiling, or futures may also be viable risk mitigation strategies.

Copper is among the most essential metals in fusion reactors, appearing as a component in the REBCO superconductor itself, as a structural material in the REBCO tape, as a structural material binding tapes together into cables, and as a component of Inconel 718 used in the vacuum vessel and blanket tank [6, 77]. Copper's high conductivity, compatibility with cryogenic systems, and partial radiation resistance make it irreplaceable in plasma confinement technologies [82, 66].

Despite its many uses un fusion, demand for copper from clean energy transitions is growing even faster. Offshore wind, grid electrification, and electric vehicles are projected by the model to drive global copper demand to more than 70% over capacity by 2050 [83]. This growth trajectory places copper on a path to economic exhaustion in 34 years when fusion demand is added.

Fortunately, there are many potential mitigation strategies for copper. Markets are mature, and recycling currently meets about 35% of demand in the US [30], with significant potential for growth [84]. Copper can also be replaced by aluminum for many electrical applications [85], and given its high radiation resistance, further scientific investigation of its potential within fusion may be justified [86]. Finally, copper is heavily traded on global commodity exchanges, and the hedging cost was calculated to be less than $20k per reactor using the methodology described previously.

Molybdenum, present in Inconel 718, SS316LN, and Hastelloy C276, provides elevated strength and corrosion resistance at high temperatures [87]. Fusion reactors use it for structural metal components including the vacuum vessel, blanket tank, and magnet supports [6]. While important functionally, the volume of molybdenum required for fusion is relatively small at ~130 tons per reactor. While there are several potential substitutes for molybdenum in alloy steels such as boron, chromium, niobium, and vanadium [30], all but vanadium are either already projected to experience risks or would quickly experience constraints if substituted for molybdenum.

Outside of fusion, Molybdenum is mostly used in steelmaking and chemical making [30]. Total demand including fusion and non-fusion is projected to exhaust economically recoverable reserves in ~44 years and total resources in ~60 years. There is also little futures market activity for molybdenum, so the best strategies here are likely to be advanced procurement or accelerated recycling. In fact, 30% of US molybdenum already comes from recycled scrap and beyond recycling molybdenum individually, Inconel 718 and SS316LN can be remelted and reused in their alloy form [88, 89].

Nickel, found in all major fusion alloys including Inconel 718, Hastelloy C276, and SS316LN, is one of the most critical metals in fusion construction. Nickel demand is surging not only from the traditional stainless-steel sector but demand from EV battery production is growing rapidly and expected to surpass steel demand by the late 2030s [90]. This is concerning as FPPs will consume almost 1,600 tons of nickel each over their lifetimes, and our model shows that current reserves would be exhausted in ~35 years if fusion demand scales in alignment with the MITEI Projections.

While nickel cannot be directly replaced in the aforementioned superalloys, many alternates to these alloys with lower nickel content are already being explored in various fusion approaches. Options being discussed include vanadium alloys [11], and high-strength alloys such as CuCrZr [2], as well as RAFM steels like EUROFER [66].

In fact, a recommendation of this paper is a further analysis of alternatives to Inconel 718, as it has already been determined not to be the best long-term choice for FPPs [11]. For this reason and due to the many strong alternative options, replacement with another alloy is likely the best approach for applications related to Inconel 718. Since SS316LN is less replaceable [10] remelting scrap to reduce need for new nickel may be a good approach as stainless steels, including this one are 95% to 100% recyclable from scrap [91]. Given the broad application of nickel across nearly all steel-strengthened fusion components, this shortfall poses an important long-term risk and merits early planning and additional research.

While these elements do not face immediate exhaustion from fusion demand alone, their integration into critical alloys and the rapid expansion of demand in adjacent sectors such as batteries, wind energy, EVs, and infrastructure poses a significant risk to their long-term availability.

Where applicable, commodity futures provide hedging opportunities, which could be a prudent strategy for firms planning multiple reactors. However, in cases such as molybdenum and chromium, where market liquidity is limited, physical stockpiling may be the only economical approach. However, early action is essential to secure and advantageous pricing and further analysis is needed to determine if physical storage requirements are feasible and cost-effective. Other suggested strategies for risk mitigation included substitution, recycling, verticalization, and use of alternative reactor designs with fewer mineral requirements.

In addition to these minerals, the model showed demand for several other elements exceeding current supply by 2040 but required industry growth rates only 1%-2% per year higher than population growth to meet demand. These were determined to be of minimal risk but should be monitored going forward.

7.5 Top-Country Dependence Dramatically Increases Supply Risk

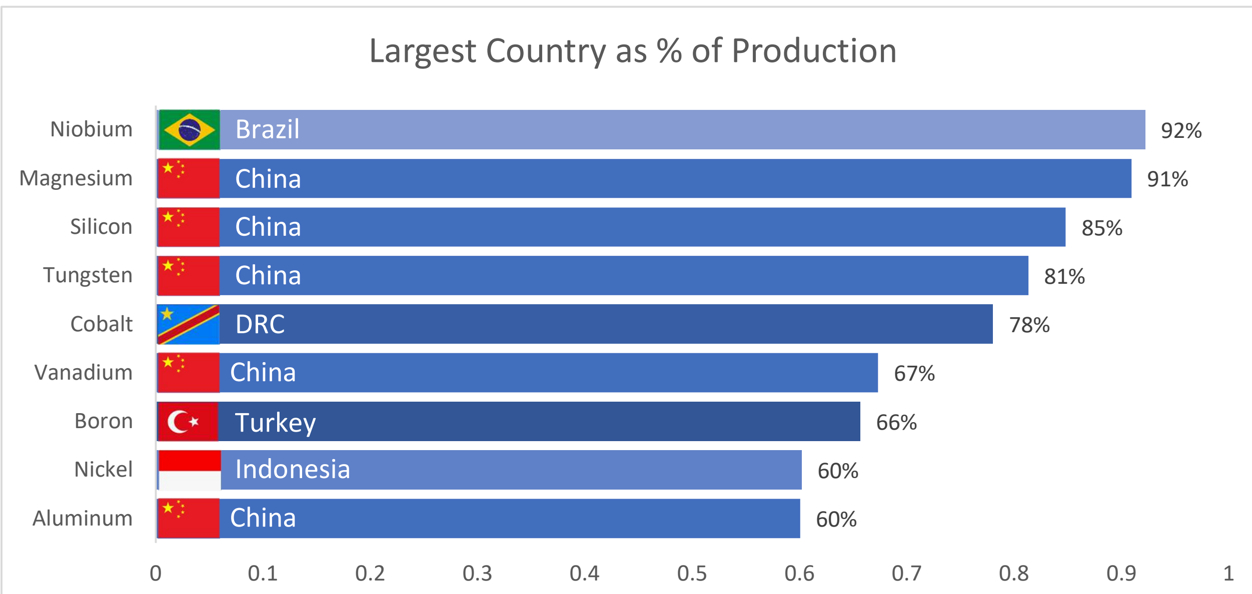

Figure 5: Largest Countries as % of Production by Mineral

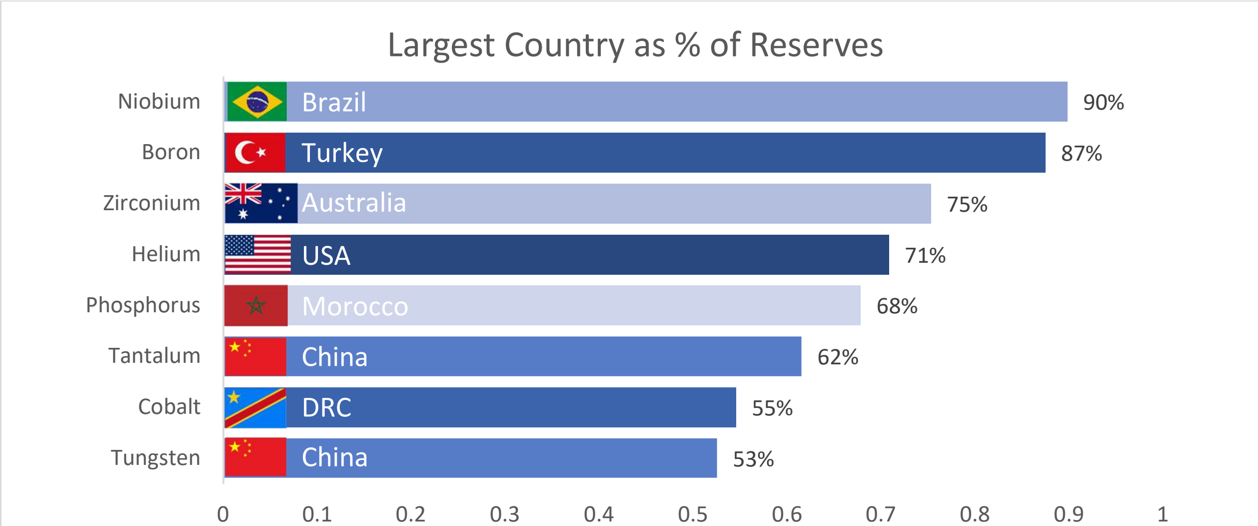

Figure 6: Largest countries by % of reserves per mineral.

In addition to the timeline risks associated with economically recoverable supply exhaustion and permanent resource exhaustion, fusion supply chains must plan for geopolitical vulnerabilities. The IEA highlights supply concentration as a proxy for geopolitical risk in its mineral security framework [29]. To further contextualize insights and recommendations, this study also incorporated the Fund for Peace Fragile States Index (FSI), which ranks countries by stability and conflict risk. The result is an informative layer of supply chain fragility that contextualizes the significance of the concentration metric.

Overall, if the top producing country for each element were removed from the market due to sanctions, conflict, or trade restrictions, projected demand by 2040 would exceed global capacity by as much as 1,500% (niobium), 900% (tungsten), 800% (vanadium), 700% (magnesium), or 500% (cobalt).

The most significant geopolitical risk likely comes from cobalt, with 78% of current production and 55% of reserves located in the Democratic Republic of Congo, which is ranked as the fourth most fragile country by the FSI. The ongoing conflict in 2025 over strategic regions like Goma and Bukavu also suggests supplies may be uncertain in coming years [92].

Other key minerals such as magnesium (91% from China), vanadium (67% from China), and niobium (92% from Brazil) show similar exposure to a single nation, with China notably appearing multiple times. Despite its low fragility index ranking of 102, the level of concentration across multiple minerals suggests further study on resource risks in China is merited.

In light of these risks, fusion developers and policy stakeholders can look to proactive foreign engagement and supply chain diplomacy as potential strategies to reduce risk. The IEA suggests several strategies for this approach, including targeted foreign investment, long-term commercial partnerships, and increased investment in materials R&D [54]

Together, these approaches can reduce the exposure of the fusion sector to politically or logistically fragile regions and help ensure a steady, scalable supply base as reactor construction ramps up.

7.6 Data with High Uncertainty

Beyond the clearly identified risks already mentioned, there are several elements for which a lack of data prevents definitive risk assessment, yet preliminary indicators suggest these may warrant closer attention. For instance, niobium and tantalum suffer from especially severe data gaps, with only 50% and 8% of countries, respectively, reporting resource figures. In the case of tantalum, even reserves are only reported for 25% of producing countries, leaving considerable uncertainty around global sufficiency.

Other elements including barium, fluorine, manganese, silver, and tungsten appear to have relatively short supply horizons (ranging from 16 to 61 years of reserves), but these figures are based on incomplete coverage, with between 13% and 54% of countries unaccounted for. Given their use in various fusion-relevant alloys, structural materials, and shielding compounds, these gaps represent a blind spot in strategic planning. Further investigation is needed to determine whether these materials pose latent risks to long-term fusion scalability, particularly as reactor demand intersects with demand growth from adjacent clean energy sectors. Full data in Table 1.

Table 4: Data with high uncertainty

	Years to Exhaustion	% of Data Missing
Resources with missing data		
Niobium	8	50%
Tantalum	18	92%
Reserves with Missing data		
Silver	16	13%
Tungsten	34	0%
Cobalt	35	7%
Barium	43	54%
Fluorine	43	25%
Manganese	61	18%
Tantalum	70	75%

8. Conclusion

This thesis examines the critical supply chain risks associated with deploying FPPs, focusing on the availability of essential minerals such as chromium, lithium, beryllium, nickel, and REEs. While many of these materials are abundant relative to fusion demand, the rapid expansion of other clean energy technologies could strain global supplies in the coming decades. The research highlights the need for strategic foresight in managing these resources, as certain materials face near-term shortages due to both fusion demand and competition from sectors like EVs and renewable energy technologies.

The study finds that, without proactive measures, simultaneous demand from these industries could lead to supply exhaustion, particularly for beryllium, where known resources may be depleted within forty years due to fusion demand alone. Furthermore, for nine of the thirty elements evaluated, over 50% of global production comes from a single country, with China being the largest producer for five of these minerals, presenting significant geopolitical risks. For Niobium, Tungsten, and Vanadium, the loss of the largest producing country from the market would push demand to between 700% and 1,500% of supply.

To mitigate these challenges, strategies such as market hedging, strategic stockpiling, and long-term contracts offer cost-effective risk management. Additionally, the fusion industry is exploring alternative designs and material options to address scenarios where absolute material availability may become a concern. The findings also underscore the importance of international cooperation and supply chain diversification, urging countries with critical mineral reserves to adopt proactive policies balancing domestic resource development with global collaboration to secure long-term fusion energy infrastructure stability.

While this research provides a comprehensive analysis, several avenues remain for future exploration. Proportions of wind and solar energy among the “other renewables” section of the MITEI model, are sensitive variables, and improved certainty is essential to better understand material supply constraints. Further mapping of materials used in different fusion reactor designs and the evolution of material costs over time is also needed, as prices may fluctuate due to supply chain disruptions or technological advancements. Moreover, exploring the feasibility of mitigation strategies, such as material recycling and substitution, is critical for ensuring the sustainability of fusion power plants.

In conclusion, while the transition to fusion energy offers exciting opportunities, it also presents substantial challenges. A proactive and holistic approach to supply chain management, underpinned by detailed modeling and strategic investments in material security, will be crucial to unlocking fusion’s full potential as a cornerstone of the clean energy future.

Appendix 1 - Data Completeness and Confidence

Table 5: Supply Data Completeness Summary

Supply Data Completeness Summary (%NA)

	Mine Production	Processing	Reserves	Resources
Aluminum	5%			
Boron	20%		40%	
Cobalt			8%	
Manganese			18%	
Molybdenum			6%	
Niobium			50%	
Silicon	5%			
Silver	7%	93%	13%	
Tantalum			75%	92%
Titanium		7%	20%	
Tungsten			23%	
Zirconium			8%	
Gold			5%	
Cadmium	100%		100%	
Helium			60%	
Lithium	8%			
Selenium		11%	27%	
Iron			16%	
Barium	8%		54%	
Fluorine	8%		25%	

Review of data competenes for relevant mineral data from USGS Mineral Commodity Study (MCS)

Minerals not shown here are complete for all data sets.

Appendix 2 - Minerals Data

Table 6: Non-Fusion Mineral Demand Data

Model	Category	Year	Kg/Mw (Built)	Source		Aluminum	Barium	Beryllium	Beryllium Floride	Boron	Cobalt	Chromium	Copper	Carbon	Fluorine	Helium	Hydrogen	Iron	Lanthanum	Lithium	Lithium Fluoride	Magnesium	Manganese	Molybdenum	Nickel	Niobium	Nitrogen	Phosphorus	Rare earths	Silver	Silicon	Sulfur	Tantalum	Titanium	Tungsten	Vanadium	Yttrium	Zinc	Zirconium
Resource Intensity from IEA																																							
	Generation		Offshore wind	IEA		0	0	0	0	0	0	525	8,000		0	0	0	0	0	0	0	0	790	109	240	0	0	0	239	0	0	0	0	0	0	0	0	5,500	0
	Generation		Onshore wind	IEA		0	0	0	0	0	0	470	2,900		0	0	0	0	0	0	0	0	780	99	404	0	0	0	14	0	0	0	0	0	0	0	0	5,500	0
	Generation		Solar PV	IEA		0	0	0	0	0	0	0	2,822		0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3,948	0	0	0	0	0	0	30	0
	Generation		Nuclear	IEA		0	0	0	0	0	0	2,190	1,473		0	0	0	0	0	0	0	0	148	71	1,297	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	Generation		Coal	IEA		0	0	0	0	0	201	308	1,150		0	0	0	0	0	0	0	0	5	66	721	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Generation		Natural gas	IEA		0	0	0	0	0	2	48	1,100		0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Converted to t / GWh						5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Model	**Type**	**Year**	**t/GWh (Deliver**	**Source**		**Aluminum**	**Barium**	**Beryllium**	**Beryllium Floride**	**Boron**	**Cobalt**	**Chromium**	**Copper**	**Carbon**	**Fluorine**	**Helium**	**Hydrogen**	**Iron**	**Lanthanum**	**Lithium**	**Lithium Fluoride**	**Magnesium**	**Manganese**	**Molybdenum**	**Nickel**	**Niobium**	**Nitrogen**	**Phosphorus**	**Rare earths**	**Silver**	**Silicon**	**Sulfur**	**Tantalum**	**Titanium**	**Tungsten**	**Vanadium**	**Yttrium**	**Zinc**	**Zirconium**
	Generation		Offshore wind		1	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Generation		Onshore wind		2	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Generation		Solar PV		3	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Generation		Nuclear		4	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Generation		Coal		5	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Generation		Natural gas		6	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Projections from MITEI applied (t/yr)																																							
Model	**Type**	**Year**	**t/yr to meet de**	**Source**		**Aluminum**	**Barium**	**Beryllium**	**Beryllium Floride**	**Boron**	**Cobalt**	**Chromium**	**Copper**	**Carbon**	**Fluorine**	**Helium**	**Hydrogen**	**Iron**	**Lanthanum**	**Lithium**	**Lithium Fluoride**	**Magnesium**	**Manganese**	**Molybdenum**	**Nickel**	**Niobium**	**Nitrogen**	**Phosphorus**	**Rare earths**	**Silver**	**Silicon**	**Sulfur**	**Tantalum**	**Titanium**	**Tungsten**	**Vanadium**	**Yttrium**	**Zinc**	**Zirconium**
MITEI Projections	Generation	2020	Offshore wind	MITEI, IEA		0	0	0	0	0	0	0	832	12,684	0	0	0	0	0	0	0	0	0	1,253	173	381	0	0	0	379	0	0	0	0	0	0	0	0	6,720
MITEI Projections	Generation	2020	Onshore wind	MITEI, IEA		0	0	0	0	0	0	0	771	4,756	0	0	0	0	0	0	0	0	0	1,279	162	662	0	0	0	23	0	0	0	0	0	0	0	0	9,021
MITEI Projections	Generation	2020	Solar PV	MITEI, IEA		0	0	0	0	0	0	0	0	29,901	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	41,834	0	0	0	0	0	0	318
MITEI Projections	Generation	2020	Nuclear	MITEI, IEA		0	0	0	0	0	0	0	23,006	15,474	0	0	0	0	0	0	0	0	0	1,551	744	13,629	0	0	0	5	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2020	Coal	MITEI, IEA		0	0	0	0	0	0	9,763	14,902	55,731	0	0	0	0	0	0	0	0	0	224	3,211	34,943	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2020	Natural gas	MITEI, IEA		0	0	0	0	0	0	48	1,296	29,490	0	0	0	0	0	0	0	0	0	0	0	422	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2025	Offshore wind	MITEI, IEA		0	0	0	0	0	0	0	1,465	22,324	0	0	0	0	0	0	0	0	0	2,204	304	670	0	0	0	667	0	0	0	0	0	0	0	0	15,348
MITEI Projections	Generation	2025	Onshore wind	MITEI, IEA		0	0	0	0	0	0	0	1,357	8,371	0	0	0	0	0	0	0	0	0	2,252	286	1,165	0	0	0	40	0	0	0	0	0	0	0	0	15,877
MITEI Projections	Generation	2025	Solar PV	MITEI, IEA		0	0	0	0	0	0	0	0	52,627	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	73,628	0	0	0	0	0	0	559
MITEI Projections	Generation	2025	Nuclear	MITEI, IEA		0	0	0	0	0	0	0	23,006	15,474	0	0	0	0	0	0	0	0	0	1,551	744	13,629	0	0	0	5	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2025	Coal	MITEI, IEA		0	0	0	0	0	0	17,791	27,155	101,555	0	0	0	0	0	0	0	0	0	409	5,850	63,674	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2025	Natural gas	MITEI, IEA		0	0	0	0	0	0	58	1,568	35,674	0	0	0	0	0	0	0	0	0	0	0	511	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2030	Offshore wind	MITEI, IEA		0	0	0	0	0	0	0	2,963	45,155	0	0	0	0	0	0	0	0	0	4,459	615	1,355	0	0	0	1,349	0	0	0	0	0	0	0	0	31,044
MITEI Projections	Generation	2030	Onshore wind	MITEI, IEA		0	0	0	0	0	0	0	2,744	16,933	0	0	0	0	0	0	0	0	0	4,554	578	2,356	0	0	0	82	0	0	0	0	0	0	0	0	32,114
MITEI Projections	Generation	2030	Solar PV	MITEI, IEA		0	0	0	0	0	0	0	0	106,449	0	0	0	0	0	0	0	0	0	0	0	49	0	0	0	0	0	148,929	0	0	0	0	0	0	1,131
MITEI Projections	Generation	2030	Nuclear	MITEI, IEA		0	0	0	0	0	0	0	25,307	17,021	0	0	0	0	0	0	0	0	0	1,707	818	14,992	0	0	0	6	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2030	Coal	MITEI, IEA		0	0	0	0	0	0	6,509	9,935	37,154	0	0	0	0	0	0	0	0	0	150	2,140	23,295	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2030	Natural gas	MITEI, IEA		0	0	0	0	0	0	66	1,777	40,430	0	0	0	0	0	0	0	0	0	0	0	579	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2040	Offshore wind	MITEI, IEA		0	0	0	0	0	0	0	6,659	101,471	0	0	0	0	0	0	0	0	0	10,020	1,383	3,044	0	0	0	3,031	0	0	0	0	0	0	0	0	69,762
MITEI Projections	Generation	2040	Onshore wind	MITEI, IEA		0	0	0	0	0	0	0	6,167	38,052	0	0	0	0	0	0	0	0	0	10,235	1,299	5,294	0	0	0	184	0	0	0	0	0	0	0	0	72,167
MITEI Projections	Generation	2040	Solar PV	MITEI, IEA		0	0	0	0	0	0	0	0	239,212	0	0	0	0	0	0	0	0	0	0	0	110	0	0	0	0	0	334,672	0	0	0	0	0	0	2,542
MITEI Projections	Generation	2040	Nuclear	MITEI, IEA		0	0	0	0	0	0	0	37,577	25,274	0	0	0	0	0	0	0	0	0	2,534	1,215	22,261	0	0	0	9	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2040	Coal	MITEI, IEA		0	0	0	0	0	0	2,712	4,139	15,481	0	0	0	0	0	0	0	0	0	62	892	9,706	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2040	Natural gas	MITEI, IEA		0	0	0	0	0	0	62	1,672	38,052	0	0	0	0	0	0	0	0	0	0	0	545	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2050	Offshore wind	MITEI, IEA		0	0	0	0	0	0	0	10,821	164,891	0	0	0	0	0	0	0	0	0	16,283	2,247	4,947	0	0	0	4,926	0	0	0	0	0	0	0	0	113,363
MITEI Projections	Generation	2050	Onshore wind	MITEI, IEA		0	0	0	0	0	0	0	10,021	61,834	0	0	0	0	0	0	0	0	0	16,631	2,111	8,603	0	0	0	299	0	0	0	0	0	0	0	0	117,272
MITEI Projections	Generation	2050	Solar PV	MITEI, IEA		0	0	0	0	0	0	0	0	388,719	0	0	0	0	0	0	0	0	0	0	0	179	0	0	0	0	0	543,843	0	0	0	0	0	0	4,131
MITEI Projections	Generation	2050	Nuclear	MITEI, IEA		0	0	0	0	0	0	0	49,847	33,527	0	0	0	0	0	0	0	0	0	3,362	1,611	29,530	0	0	0	11	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2050	Coal	MITEI, IEA		0	0	0	0	0	0	2,170	3,312	12,385	0	0	0	0	0	0	0	0	0	50	713	7,765	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2050	Natural gas	MITEI, IEA		0	0	0	0	0	0	29	773	17,599	0	0	0	0	0	0	0	0	0	0	0	252	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2100	Offshore wind	MITEI, IEA		0	0	0	0	0	0	0	12,486	190,259	0	0	0	0	0	0	0	0	0	18,788	2,592	5,708	0	0	0	5,684	0	0	0	0	0	0	0	0	130,803
MITEI Projections	Generation	2100	Onshore wind	MITEI, IEA		0	0	0	0	0	0	0	11,563	71,347	0	0	0	0	0	0	0	0	0	19,190	2,436	9,927	0	0	0	344	0	0	0	0	0	0	0	0	135,313
MITEI Projections	Generation	2100	Solar PV	MITEI, IEA		0	0	0	0	0	0	0	0	448,522	0	0	0	0	0	0	0	0	0	0	0	207	0	0	0	0	0	627,511	0	0	0	0	0	0	4,766
MITEI Projections	Generation	2100	Nuclear	MITEI, IEA		0	0	0	0	0	0	0	7,669	5,158	0	0	0	0	0	0	0	0	0	517	248	4,543	0	0	0	2	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2100	Coal	MITEI, IEA		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MITEI Projections	Generation	2100	Natural gas	MITEI, IEA		0	0	0	0	0	0	12	314	7,135	0	0	0	0	0	0	0	0	0	0	0	102	0	0	0	0	0	0	0	0	0	0	0	0	0
IEA Projections	Batteries	2020	Current	IEA		0	0	0	0	0	0	0	8,000	15,000	0	0	0	0	0	2,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IEA Projections	Batteries	2030	Low	IEA		0	0	0	0	0	3,000	0	55,000	86,000	0	0	0	0	0	12,000	0	0	4,000	0	10,000	0	0	0	0	0	1,000	0	0	0	0	11,000	0	0	0
IEA Projections	Batteries	2030	High	IEA		0	0	0	0	0	6,000	0	90,000	142,000	0	0	0	0	0	20,000	0	0	7,000	0	17,000	0	0	0	0	0	1,000	0	0	0	0	19,000	0	0	0
IEA Projections	Batteries	2040	Low	IEA		0	0	0	0	0	9,000	0	133,000	177,000	0	0	0	0	0	28,000	0	0	9,000	0	36,000	0	0	0	0	0	4,000	0	0	0	0	139,000	0	0	0
IEA Projections	Batteries	2040	High	IEA		0	0	0	0	0	14,000	0	211,000	280,000	0	0	0	0	0	45,000	0	0	14,000	0	57,000	0	0	0	0	0	7,000	0	0	0	0	219,000	0	0	0
IEA Projections	EVs	2020	Current	IEA		0	0	0	0	0	21,000	0	110,000	141,000	0	0	0	0	0	20,000	0	0	25,000	0	80,000	0	0	0	2,000	0	0	0	0	0	0	0	0	0	0
IEA Projections	EVs	2030	Low	IEA		0	0	0	0	0	106,000	0	717,000	1,065,000	0	0	0	0	0	152,000	0	0	102,000	0	647,000	0	0	0	11,000	0	8,000	0	0	0	0	0	0	0	0
IEA Projections	EVs	2040	Low	IEA		0	0	0	0	0	127,000	0	951,000	1,027,000	0	0	0	0	0	248,000	0	0	117,000	0	950,000	0	0	0	14,000	0	26,000	0	0	0	0	0	0	0	0
IEA Projections	EVs	2030	High	IEA		0	0	0	0	0	257,000	0	1,633,000	2,499,000	0	0	0	0	0	358,000	0	0	246,000	0	1,567,000	0	0	0	23,000	0	20,000	0	0	0	0	0	0	0	0
IEA Projections	EVs	2040	High	IEA		0	0	0	0	0	441,000	0	3,119,000	3,569,000	0	0	0	0	0	859,000	0	0	404,000	0	3,287,000	0	0	0	35,000	0	90,000	0	0	0	0	0	0	0	0
IEA Projections	Transmissior	2020	Current	IEA		9,110,000	0	0	0	0			4,970,000		0	0	0	0			0	0				0	0	0		0		0	0	0	0				
IEA Projections	Transmissior	2030	Low	IEA		10,800,000	0	0	0	0			6,230,000		0	0	0	0			0	0				0	0	0		0		0	0	0	0				
IEA Projections	Transmissior	2040	Low	IEA		12,870,000	0	0	0	0			7,610,000		0	0	0	0			0	0				0	0	0		0		0	0	0	0				
IEA Projections	Transmissior	2030	High	IEA		12,070,000	0	0	0	0			7,310,000		0	0	0	0			0	0				0	0	0		0		0	0	0	0				
IEA Projections	Transmissior	2040	High	IEA		16,320,000	0	0	0	0			10,010,000		0	0	0	0			0	0				0	0	0		0		0	0	0	0				
IEA Projections	Other	2021	Current	IEA							145,000		19,548,000	3,388,000						63,000					2,519,000				67,000										
IEA Projections	Other	2023	Null	IEA							151,000		19,574,000	3,340,000						73,000					2,626,000				77,000										
IEA Projections	Other	2030	Null	IEA							167,000		19,127,000	4,406,000						89,000					2,801,000				88,000										
IEA Projections	Other	2040	Null	IEA							194,000		20,036,000	6,184,000						123,000					2,857,000				105,000										
Population-Based Gro	Total	2025	Null	IEA		0	0	0	0	0	0	0	0	0	6,400,000	0	0	0	0	0	0	0	24,140,000	0	0	117,450	0	0	0	0	0	0	0	0	0	0	0	0	0
Population-Based Gro	Total	2020	Null	IEA		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6,450,000	0	0	0	0	0
Population-Based Gro	Total	2022	Null	IEA		0	0	0	0	0	0	0	0	0	0	6,000,000	0	0	0	0	93,000	0	0	0	0	0	43,000,000	0	0	0	0	67,000,000	0	0	119,200	112,190	0	0	1,200,000
Population-Based Gro	Total	2023	Null	IEA		0	7,900,000	0	0	3,400,000	214,000	0	25,854,000	4,632,000	0	0	97,000,000	2,050,000,000	31,120	165,000	0	0	0	0	3,105,000	0	0	45,700,000	92,000	36,000	3,500,000	0	2,800	0	0	0	0	13,830,000	0
Population-Based Gro	Total	2024	Null	IEA		77,000,000	0	456	0	0	0	53,000,000	0	0	0	0	0	0	0	0	0	550,000	0	294,109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Population-Based Gro	Total	2025	Null	IEA		0																																	
Population-Based Gro	Energy	2022	Null	IEA		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	962,500	0	0	0	0	0	0	0	0
Population-Based Gro	Energy	2023	Null	IEA		0	0	0	0	0	64,000	0	6,311,000	1,292,000	0	0	0	0	0	92,000	0	0	0	0	478,000	0	0	0	16,000	0	0	0	0	0	0	0	0	0	0
Population-Based Gro	Energy	2024	Null	IEA		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Population-Based Gro	Energy	2025	Null	IEA		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apply As Percent	Recycling	2025	Null	IEA		65,818,884	0	106	0	0	39,131	18,759,092	4,814,670	468,107	0	0	0	744,936,659	0	8,180	1,025	25,089	0	90,880	60,125	25,820	0	0	27,144	31,303	0	0	32	65,056	49,318	5,410	0	4,636,922	43,134

Appendix 3 - Complete Insights Data

Table 7: Complete findings with and without largest country

>0% data missing	> 25% data missing	> 50% data missing

Sufficiency Including Supply from All Countries

	Total Supply Exhaustion	
Demand Group	Fusion Alone	Existing + Fusion
Element	Resource Years	Resource Years
Aluminum	261	165
Barium	439	196
Beryllium	40	37
Beryllium Floride	0	0
Boron	0	0
Carbon	0	0
Chromium	0	0
Cobalt	162	74
Copper	256	216
Fluorine	207	1,190
Helium	0	0
Hydrogen	0	0
Iron	310	287
Lanthanum	345	50
Lithium	97	96
Magnesium	0	0
Manganese	0	0
Molybdenum	142	57
Nickel	147	84
Niobium	103	8
Nitrogen	0	0
Phosphorus	0	0
Silicon	0	0
Silver	0	0
Sulfur	0	0
Tantalum	63	18
Titanium	151	203
Tungsten	0	0
Vanadium	370	210
Yttrium	182	182

	Economic Supply Exhaustion	
	Fusion Alone	Existing + Fusion
	Reserve Years	Reserve Years
Aluminum	249	78
Barium	403	43
Beryllium	0	0
Beryllium Floride	0	0
Boron	288	241
Carbon	0	0
Chromium	186	21
Cobalt	150	35
Copper	220	47
Fluorine	125	43
Helium	232	944
Hydrogen	0	0
Iron	280	82
Lanthanum	0	0
Lithium	76	68
Magnesium	0	0
Manganese	255	62
Molybdenum	136	44
Nickel	130	35
Niobium	143	119
Nitrogen	0	0
Phosphorus	412	844
Silicon	0	0
Silver	196	16
Sulfur	0	0
Tantalum	90	70
Titanium	133	70
Tungsten	129	34
Vanadium	342	69
Yttrium	0	0

	% of Annual Supply					
	Fusion Alone			Existing + Fusion		
	% of Production (2040)	% of Production (2050)	% of Production (2100)	% of Production (2040)	% of Production (2050)	% of Production (2100)
Aluminum	0%	0%	0%	124%	130%	138%
Barium	0%	0%	0%	109%	115%	122%
Beryllium	90%	1,052%	28,454%	246%	1,216%	28,628%
Beryllium Floride	0%	0%	0%	0%	0%	0%
Boron	0%	0%	0%	84%	89%	94%
Carbon	0%	0%	0%	0%	0%	0%
Chromium	0%	0%	0%	127%	134%	142%
Cobalt	0%	0%	1%	118%	124%	132%
Copper	0%	0%	0%	89%	93%	99%
Fluorine	0%	0%	8%	75%	80%	92%
Helium	0%	0%	0%	4%	4%	4%
Hydrogen	0%	0%	0%	0%	0%	0%
Iron	0%	0%	0%	149%	157%	166%
Lanthanum	0%	0%	0%	0%	0%	0%
Lithium	3%	30%	811%	55%	85%	869%
Magnesium	0%	0%	0%	59%	62%	66%
Manganese	0%	0%	0%	136%	143%	151%
Molybdenum	0%	1%	14%	126%	133%	153%
Nickel	0%	0%	9%	106%	113%	126%
Niobium	0%	0%	9%	121%	128%	144%
Nitrogen	0%	0%	0%	32%	34%	36%
Phosphorus	0%	0%	0%	22%	23%	24%
Silicon	0%	0%	0%	93%	102%	109%
Silver	0%	0%	1%	177%	187%	198%
Sulfur	0%	0%	0%	91%	96%	101%
Tantalum	1%	14%	489%	154%	175%	659%
Titanium	1%	7%	223%	2,318%	2,450%	2,803%
Tungsten	0%	0%	9%	166%	175%	193%
Vanadium	0%	0%	0%	257%	271%	286%
Yttrium	0%	0%	0%	0%	0%	0%

Sufficiency Excluding Supply From Largest Country

	Total Supply Exhaustion			Economic Supply Exhaustion	
	Fusion Alone	Existing + Fusion		Fusion Alone	Existing + Fusion
Element	Resource Years	Resource Years		Reserve Years	Reserve Years
Aluminum			Aluminum		
Barium			Barium		
Beryllium			Beryllium		
Beryllium Floride			Beryllium Floride		
Boron			Boron		
Carbon			Carbon		
Chromium			Chromium		
Cobalt			Cobalt		
Copper			Copper		
Fluorine			Fluorine		
Helium			Helium		
Hydrogen			Hydrogen		
Iron			Iron		
Lanthanum			Lanthanum		
Lithium			Lithium		
Magnesium			Magnesium		
Manganese			Manganese		
Molybdenum			Molybdenum		
Nickel			Nickel		
Niobium			Niobium		
Nitrogen			Nitrogen		
Phosphorus			Phosphorus		
Silicon			Silicon		
Silver			Silver		
Sulfur			Sulfur		
Tantalum			Tantalum		
Titanium			Titanium		
Tungsten			Tungsten		
Vanadium			Vanadium		
Yttrium			Yttrium		

	% of Annual Supply					
	Fusion Alone			Existing + Fusion		
	% of Production (2040)	% of Production (2050)	% of Production (2100)	% of Production (2040)	% of Production (2050)	% of Production (2100)
Aluminum	0%	0%	0%	309%	326%	344%
Barium	0%	0%	0%	160%	169%	178%
Beryllium	90%	1,052%	28,454%	246%	1,216%	28,628%
Beryllium Floride	0%	0%	0%	0%	0%	0%
Boron	0%	0%	0%	246%	259%	274%
Carbon	0%	0%	0%	0%	0%	0%
Chromium	0%	0%	1%	229%	242%	256%
Cobalt	0%	0%	6%	537%	565%	599%
Copper	0%	0%	0%	116%	122%	129%
Fluorine	0%	0%	0%	0%	0%	0%
Helium	0%	0%	0%	7%	7%	7%
Hydrogen	0%	0%	0%	0%	0%	0%
Iron	0%	0%	0%	238%	251%	265%
Lanthanum	0%	0%	0%	0%	0%	0%
Lithium	4%	47%	1,295%	88%	135%	1,388%
Magnesium	0%	0%	0%	652%	687%	726%
Manganese	0%	0%	0%	216%	228%	241%
Molybdenum	0%	2%	23%	216%	229%	263%
Nickel	0%	1%	22%	267%	283%	318%
Niobium	0%	4%	120%	1,548%	1,635%	1,844%
Nitrogen	0%	0%	0%	46%	49%	52%
Phosphorus	0%	0%	0%	40%	42%	45%
Silicon	0%	0%	2%	608%	669%	715%
Silver	0%	0%	1%	243%	257%	272%
Sulfur	0%	0%	0%	117%	124%	130%
Tantalum	2%	25%	846%	266%	303%	1,139%
Titanium	2%	21%	693%	7,208%	7,617%	8,716%
Tungsten	0%	1%	48%	887%	936%	1,035%
Vanadium	0%	0%	0%	787%	829%	876%
Yttrium	0%	0%	0%	0%	0%	0%

Appendix 4 – Mineral applications in ARC reactor

Table 8: Minerals Composition Per Component and Alloy

Component	Material / Compound	Aluminum	Barium	Beryllium	Beryllium Floride	Boron	Carbon	Chromium	Cobalt	Copper	Fluorine	Helium	Hydrogen	Iron	Lanthanum	Lithium	Lithium Floride	Magnesium	Manganese	Molybdenum	Nickel	Niobium	Nitrogen	Oxygen	Phosphorus	Silicon	Silver	Sulfur	Tantalum	Titanium	Tungsten	Vanadium	Yttrium
Blanket tank	Inconel 718	■				■	■	■	■	■				■					■	■	■	■			■	■		■	■	■			
Blanket tank FLiBe	FLiBe			■	■						■					■	■																
Channel FLiBe	FLiBe			■	■						■					■	■																
Cryogen System	Helium											■																					
First wall	Tungsten																														■		
Heat exchanger FLiBe	FLiBe			■	■						■					■																	
Inner VV wall	Inconel 718	■				■	■	■	■	■				■					■	■	■	■			■	■		■	■	■			
Magnet structure	SS316 LN						■	■						■					■	■	■		■		■	■		■					
Magnet top ring	SS316 LN						■	■						■					■	■	■		■		■	■		■					
Multiplier	Beryllium			■																													
Outer VV wall	Inconel 718	■				■	■	■	■	■				■					■	■	■	■			■	■		■	■	■			
REBCO structure	Copper									■																							
REBCO tape	Al2O3	■																						■									
REBCO tape	Copper									■																							
REBCO tape	Hastelloy C276						■	■	■					■					■	■	■				■	■		■			■	■	
REBCO tape	LaMnO3														■				■					■									
REBCO tape	MgO																	■						■									
REBCO tape	Silver																										■						
REBCO tape	Y2O3																							■									■
REBCO tape	YBaCuO		■							■														■									■
Replacement Beryllium	Beryllium			■																													
Replacement Lithium	Li7F										■					■																	
TiH_2 shield	TiH_2												■																	■			
VV posts	Inconel 718	■				■	■	■	■	■				■					■	■	■	■			■	■		■	■	■			
VV ribbing	Inconel 718	■				■	■	■	■	■				■					■	■	■	■			■	■		■	■	■			

Sources: [35, 48, 6]

Appendix 4 – Risks Summary Table

Element	All Countries – Resources (Yrs Till Exhaustion) – Fusion Alone	All Countries – Resources (Yrs Till Exhaustion) – Existing + Fusion	All Countries – Reserves (Yrs Till Exhaustion) – Existing + Fusion	All Countries – Annual Production – % of Production (2050) – Fusion Alone	All Countries – Annual Production – % of Production (2100) – Fusion Alone	All Countries – Annual Production – % of Production (2040) – Existing + Fusion	All Countries – Annual Production – % of Production (2050) – Existing + Fusion	All Countries – Annual Production – % of Production (2100) – Existing + Fusion	Less Largest Country – Annual Production – % of Production (2050) – Fusion Alone	Less Largest Country – Annual Production – % of Production (2100) – Fusion Alone	Less Largest Country – Annual Production – % of Production (2040) – Existing + Fusion	Less Largest Country – Annual Production – % of Production (2050) – Existing + Fusion	Less Largest Country – Annual Production – % of Production (2100) – Existing + Fusion
Aluminum											309%	326%	344%
Beryllium	40	37		1,052%	28,454%	246%	1,216%	28,628%	1,052%	28,454%	246%	1,216%	28,628%
Chromium			21										
Cobalt		74									537%	565%	599%
Copper			47										
Lanthanum		50											
Lithium			68		811%			869%					
Magnesium											652%	687%	726%
Molybdenum		57	44										
Nickel			35										
Niobium		8								120%	1,548%	1,635%	1,844%
Silicon											608%	669%	715%
Silver			16										
Tantalum		18			489%	154%	175%	659%		846%	266%	303%	1,139%
Titanium					223%	2,318%	2,450%	2,803%		693%	7,208%	7,617%	8,716%
Tungsten						166%	175%	193%		48%	887%	936%	1,035%
Vanadium						257%	271%	286%			787%	829%	876%

Not Included
Helium
Neon
Yttrium

Bibliography

[1] V. P. Z. H.-O. P. D. R. J. S. P. S. A. P. W. M.-O. C. P. R. P. S. C. J. M. Y. C. X. Z. M. G. E. L. T. M. M. T. a. T. W. (. Masson-Delmotte, "An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change sustainable development,," IPCC, Cambridge, UK, 2018.

[2] MITEI, "MITEI Fusion Report," MIT, Cambridge, 2024.

[3] J. T. Larkins and R. P. Savio, "Technical Bases for Yucca Mountain Standards," in *News Conference to Release the National Research Council Report*, Washington, DC, 1995.

[4] US Department of Energy, "DOE Explains...Deuterium-Tritium Fusion Fuel," US Department of Energy, [Online]. Available: https://www.energy.gov/science/doe-explainsdeuterium-tritium-fusion-fuel. [Accessed 25 02 2025].

[5] P. Z. Hartwig, *Lecture 1.1 Nuclear notation and Fundamentals,* Cambridge, MA: MIT, 2025.

[6] J. B. T. P. F. M. J. S. P. B. C. K. D. S. H. B. C. H. J. G. C. S. a. D. W. B.N. Sorbom, "ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets," Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA, 2015.

[7] IEA, "Minerals used in clean energy technologies compared to other power generation sources," IEA, 2021.

[8] IEA, "Energy Technology Perspectives," International Energy Agency, https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf, 2023.

[9] D. Clery, "Laser-fusion experiment squeezes out even more energy," *Science,* no. https://www.science.org/content/article/laser-fusion-experiment-squeezes-out-even-more-energy#:~:text=That%20shot%20released%203.15%20megajoules,target%20than%20went%20into%20it., pp. https://www.science.org/content/article/laser-fusion-experiment-squeezes-out-even-more-energy#:~:text=That%20shot%20released%203.15%20megajoules,target%20than%20went%20into%20it., 2 Oct 2023.

[10] FIA, "The global fusion industry in 2024 Fusion Companies Survey by the Fusion Industry Association," Fusion Industry Association, Washington, D.C., 2024.

[11] L. Araiinejad, "Techno-economic Analysis of Deuterium-Tritium Magnetic Confinement Fusion Power Plants," Massachusetts Institute of Technology, Cambridge, MA, 2024.

[12] W. M. Stacey, Fusion: An Introduction to the Physics and Technology of Magnetic Confinement Fusion, 2nd Edition, Wiley, 2010.

[13] "Advantages of fusion," ITER, 2025. [Online]. Available: https://www.iter.org/fusion-energy/advantages-fusion. [Accessed 24 03 2025].

[14] N. F. G. Loureiro, Z. H. PhD and P. Sara Ferry, Composers, *Energy for Tomorrow—MIT's Plasma Science and Fusion Center.* [Sound Recording]. MIT Plasma Science and Fusion Center. 2024.

[15] D. Brunner, "Introduction to Fusion Energy (Part 2): Systems," MIT PSFC, Cambridge, MA, 2025.

[16] ITER, "Fuelling," 2025. [Online]. Available: https://www.iter.org/machine/supporting-systems/fuelling.

[17] Kyoto Fusioneering, "THE FUSION ERA – The Breeding Blanket's Essential Role in Fusion Innovation," 2025. [Online]. Available: https://kyotofusioneering.com/en/news/2024/04/18/2271#:~:text=Finally%2C%20the%20blanket%2C%20together%20with,Fuel%20Cycle%20and%20Thermal%20Cycle..

[18] S. E. Wurzel and S. C. Zhu, "Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," *Phys. Plasmas,* p. 29, 2022.

[19] F. a. a. F. P. S. R. A. a. P. Prospects, "T. Hamacher, A.M.Bradshaw," *Proceedings of the 18th World Energy Congress.,* p. 2, 2001.

[20] B. Rose, "What is the typical lifespan of a gas-fired power plant and how is maintenance and replacement managed?," *Medium,* pp. https://medium.com/@Breadarose/what-is-the-typical-lifespan-of-a-gas-fired-power-plant-and-how-is-maintenance-and-replacement-24aec33dad14#:~:text=The%20typical%20lifespan%20of%20a%20gas%2Dfired%20power%20plant%20can,to%2040%20years%20or%20more., 2023.

[21] Seacoast Anti-Pollution League, "The True Lifespan of Nuclear Power Plants," 2023. [Online]. Available: https://saplnh.org/about-nuclear/nuclear-plant-lifespans/. [Accessed 24 03 2025].

[22] V.E. McKelvey; Thomas S. Kleppe, "Principles of the Mineral Resource Classification System of the U.S. Bureau of Mines and U.S. Geological Survey," US Bureau of Mines and US Geological Survey, Washington, DC, 1976.

[23] IAEA, "Fusion - Frequently asked questions," 2025. [Online]. Available: https://www.iaea.org/topics/energy/fusion/faqs. [Accessed 12 04 2025].

[24] C. Safford, "Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," Nuclear Regulatory Commission, 2024.

[25] C. Crownhart, "Yes, we have enough materials to power the world with renewable energy," 31 Jan 2023. [Online]. Available: https://www.technologyreview.com/2023/01/31/1067444/we-have-enough-materials-to-power-world-with-renewables/. [Accessed 20 04 2025].

[26] US Government Accountability Office, "Nuclear Waste Disposal," 2020. [Online]. Available: https://www.gao.gov/nuclear-waste-disposal. [Accessed 18 04 2025].

[27] M. D. Firestone and E. and Jada Garofalo, "An Analysis of the Current Global Market For Rare Earths," University of Wyoming School of Energy Resources, Laramie, 2022.

[28] S.-L. Liu, H.-R. Fan, X. Liu, J. Meng, A. R. Butcher, L. Yann, K.-F. Yang and X.-C. Li, "Global rare earth elements projects: New developments and supply chains," *Ore Geology Reviews,* p. 157, 2023.

[29] IEA, "Global Critical Minerals Outlook 2024," IEA Publications, 2024.

[30] USGS, "Mineral commodity summaries 2025: U.S. Geological Survey," U.S. Geological Survey, 2025.

[31] United Nations Department of Economic and Social Affairs, "World Population Prospects 2024," United Nations, 2024.

[32] N. M. a. J. Kent, "New consumers: The influence of affluence on the environment," *PNAS,* p. 100, 02 04 2003.

[33] Climate Action Tracker, "2100 Warming Projections: Emissions and expected warming based on pledges and current policies," Nov 2024. [Online]. Available: https://climateactiontracker.org/global/temperatures/. [Accessed 12 03 2025].

[34] B. Sorbom, J. Ball, T. Palmer, F. Mangiarotti, J. Sierchio, P. Bonoli, C. Kasten, D. Sutherland, H. Barnard, C. Haakonsen, J. Goh, C. Sung and D. Whyte, "ARC: A compact,

high-field, fusion nuclear science facility and demonstration power plant with demountable magnets," *Fusion Engineering and Design,* pp. 378-405, 2015.

[35] AZO Materials, "Super Alloy HASTELLOY(r) C276 (UNS N10276)," 23 Nov 2012. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=7804. [Accessed 28 Apr 2025].

[36] LibreTexts, General Chemistry I., https://chem.libretexts.org/@go/page/10771, 2020.

[37] R. J. Pearson, "Towards Commercial Fusion: Innovation, Technology Roadmapping for Start-ups, and Critical Natural Resource Availability," The Open University, 2020.

[38] M. S. Choi, J.-S. Ryu, H. Y. Park, K.-S. Lee, Y. Kil and H. S. Shin, "Precise determination of the lithium isotope ratio in geological samples using MC-ICP-MS with cool plasma," *Journal of Analytical Atomic Spectrometry,* p. Issue 4, 2013.

[39] H. M. Díaz-Alejo, V. López-Rodas, C. García-Balboa, F. Tarín, A. I. Barrado, E. Conde and E. Costas, "The Upcoming 6Li Isotope Requirements Might Be Supplied by a Microalgal Enrichment Process," *Microorganisms,* p. 9, 17 Aug 2021.

[40] World Nuclear Association, "Current and Future Generation - Lithium," 23 Aug 2024. [Online]. Available: https://world-nuclear.org/information-library/current-and-future-generation/lithium. [Accessed 16 04 2025].

[41] S. B. Krivit, "Lithium, Lithium, Everywhere, and None to Use for Fusion Reactors," *Energy Times,* pp. https://news.newenergytimes.net/2022/01/08/lithium-lithium-everywhere-and-none-to-use-for-fusion-reactors/#:~:text=But%20when%20lithium%20is%20used,quantities%20needed%20for%20fusion%20reactors., 8 Jan 2022.

[42] US Department of Energy, "What Are Critical Materials and Critical Minerals?," 2020. [Online]. Available: https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals#:~:text=Critical%20minerals:%20The%20Secretary%20of,%2C%20dysprosium%2C%20erbium%2C%20europium%2C. [Accessed 2025].

[43] K. Hund, D. La Porta, T. P. Fabregas, T. Laing and J. Drexhage, "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition," World Bank Publications, Washington DC, 2020.

[44] The Consortium for Mathematics and its Applications, "The Economics of Resources," in *For All Practical Purposes 7th edition*, W. H. Freeman, 2005, pp. 507-511.

[45] Industry ARC, "Gadolinium Market - Forecast(2025 - 2031)," 2025. [Online]. Available: https://www.industryarc.com/Report/15867/gadolinium-market.html. [Accessed 02 04 2025].

[46] Population Matters, "The World of Population Projections," 04 Apr 2024. [Online]. Available: https://populationmatters.org/news/2024/04/the-world-of-population-projections/. [Accessed 02 04 2025].

[47] M. Wolf, "Time is running out for the world to meet climate targets," *Financial Times,* pp. https://www.ft.com/content/aed9fbdb-0e07-423b-8028-15b40d6b1a5a?utm_source=chatgpt.com, 11 Nov 2024.

[48] A. Molodyk, S. Samoilenkov, A. Markelov, P. Degtyarenko, S. Lee, V. Petrykin, M. Gaifullin, A. Mankevich, A. Vavilov, B. Sorbom, J. Cheng, S. Garberg, L. Kesler, Z. Hartwig, S. Gavrilkin, A. Tsvetkov, T. Okada, S. Awaji, D. Abraimov and Fr, "Development and large volume production of extremely high current density YBa2Cu3O7 superconducting wires for fusion," *Nature,* pp. https://www.nature.com/articles/s41598-021-81559-z, 01 Jan 2021.

[49] SuperPower Inc, "Our Technology," SuperPower Inc, 2000. [Online]. Available: https://www.superpower-inc.com/Technology.aspx. [Accessed 28 Dec 2024].

[50] V. Selvamanickam, "Department of Mechanical Engineering Texas Center for Superconductivity," https://indico.cern.ch/event/441807/attachments/1154774/1659387/Selvamanickam_CERN_presentation_09-15_v2.pdf, Meyrin, SW, 2015.

[51] T. De Chant, "Earth AI's algorithms found critical minerals in places everyone else ignored," *Tech Crunch,* pp. https://techcrunch.com/2025/03/25/earth-ais-algorithms-found-critical-minerals-in-places-everyone-else-ignored/, 25 Mar 2025.

[52] T. De Chant, "KoBold Metals and Earth AI to help find critical minerals for the energy transition, raises $491M," *Tech Crunch,* pp. https://techcrunch.com/2024/10/07/ai-powered-critical-mineral-startup-kobold-metals-has-raised-491m-filings-reveal/, 07 Oct 2024.

[53] D. Cohen-Tangui, "Enabling Commercial Fusion," Massachusetts Institute of Technology, Cambridge, MA, 2024.

[54] IEA, "The Role of Critical Minerals in Clean Energy Transitions," International Energy Agency, 2022.

[55] Climateworks Foundation, "Minerals for the Energy Transition," Climateworks Foundation, 2025. [Online]. Available: https://www.climateworks.org/programs/transportation/road-transportation/minerals-for-the-energy-transition/. [Accessed 10 Apr 2025].

[56] A. Mukhopadhyay, "A Greening Economy Will Drive Critical Minerals Demand, Supply," *The Secretariat,* pp. https://thesecretariat.in/article/a-greening-economy-will-drive-critical-minerals-demand-supply, 27 Nov 2024.

[57] Climate and Hope, "Breeder Blanket," Climate and Hope, 2025. [Online]. Available: https://www.climate-and-hope.net/electricity-technologies/breeder-blanket. [Accessed 02 May 2025].

[58] ITER, "Tritium breeding," ITER, [Online]. Available: https://www.iter.org/machine/supporting-systems/tritium-breeding. [Accessed 12 Apr 2025].

[59] General Fusion, "Core Technologies," General Fusion, 2025. [Online]. Available: https://generalfusion.com/fusion-demo-plant/core-fusion-technologies/. [Accessed 07 Apr 2025].

[60] P. Arena, A. Del Nevo, F. Moro, S. Noce, R. Mozzillo, V. Imbriani, F. Giannetti, F. Edemetti, A. Froio, L. Savoldi, S. Siriano, A. Tassone, F. Roca Urgorri and P. A. Di Maio, "The DEMO Water-Cooled Lead–Lithium Breeding Blanket: Design Status at the End of the Pre-Conceptual Design Phase," *Science,* vol. 24, no. https://www.mdpi.com/2076-3417/11/24/11592, p. 11, 11 2021.

[61] Commonwealth Fusion Systems, "Commonwealth Fusion Systems Magnet Success Propels Fusion Energy Toward the Grid," 18 Nov 2024. [Online]. Available: https://cfs.energy/news-and-media/commonwealth-fusion-systems-magnet-success-propels-fusion-energy-toward-the-grid. [Accessed 15 Mar 2025].

[62] Z. Hartwig, Writer, *Fusion Engineering, MIT.* [Performance]. April 30 - Breeding Blankets, 2025.

[63] R. Yoshioka, M. Kinoshita and I. Scott, "7 - Materials," in *Molten Salt Reactors and Thorium Energy*, Woodhead Publishing, 2017, pp. 189-207.

[64] W. Fuß, "Laser isotope separation and proliferation risks," Max-Planck-Institut für Quantenoptik, Garching, 2015.

[65] R. Beaufait and L. Fischer, "Blanket Cooling of a Fusion Reactor," *Energies,* vol. 4, no. https://www.mdpi.com/1996-1073/16/4/1890, p. 16, 2023.

[66] G. Dose, "The lifetime of components in a fusion reactor," *Europhysics News,* vol. 52, no. 5, pp. 24-27, 2021.

[67] S. Jones, "Advanced manufacturing applied to nuclear fusion—challenges and solutions," *Journal of Physics: Energy,* vol. 5, no. 4, 2023.

[68] D. Y. Li, "Tokamak Energy Advances Development of Vanadium Alloys for Fusion Breeder Blankets," Vanitek, 18 Aug 2024. [Online]. Available: https://vanitec.org/latest-from-vanitec/article/tokamak-energy-advances-development-of-vanadium-alloys-for-fusion-breeder-blankets. [Accessed 01 Apr 2025].

[69] H. Tanigawa, E. Gaganidze, T. Hirose, M. Ando, S. Zinkle, R. Lindau and E. Diegele, "Development of benchmark reduced activation ferritic/martensitic steels for fusion energy applications," *Nuclear Fusion,* vol. 57, no. 9, 2017.

[70] K. P. Griffin, M. T. Walsh, S. Cohen, R. Feder, J. Klabacha and Q. Zhou, "Effects of Neutron Radiation and Shielding Recommendations for the PFRC4," [Online]. Available: https://w3.pppl.gov/ppst/docs/walsh.pd. [Accessed 28 Apr 2025].

[71] T. e. a. Hayashi, "Neutronics Assessment of Advanced Shield Materials using Metal Hydride and Borohydride for Fusion Reactors,," *Fusion Engineering and,* vol. 81, pp. 1285-1290., 2006.

[72] Langley Alloys, "What are the applications for Inconel 718?," Netbiz Group, 2025. [Online]. Available: https://www.langleyalloys.com/knowledge-advice/what-are-the-applications-for-inconel-718/. [Accessed 04 Mar 2025].

[73] AZO Materials, "Nickel Alloy Inconel 718 - Properties and Applications by United Performance Metals," 14 Nov 2008. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=4459. [Accessed 20 Apr 2025].

[74] T. Mumtaz, "How many CBM in a 40 feet container?," 11 Apr 2017. [Online]. Available: https://www.cbmcalculator.com/blog/how-many-cbm-is-a-40-feet-container/. [Accessed 02 May 2025].

[75] YCharts, "20 Year Treasury Rate (I:20YTCMR)," 04 May 2025. [Online]. Available: https://ycharts.com/indicators/20_year_treasury_rate. [Accessed 04 May 2025].

[76] AZO Materials, "Stainless Steel - Grade 316 (UNS S31600)," 13 Sep 2001. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=863. [Accessed 7 Apr 2025].

[77] Fujikura Ltd., *Introduction of Fujikura RE-based High Temperature Superconductor,* Tokyo: Superconductor Business Development Division, 2024.

[78] Z. Hartwig, Writer, *Fusion Engineering, MIT, Apr 7 - Superconductors and Quench.* [Performance]. MIT, 2025.

[79] USGS, "Chromium--Makes Stainless Steel Stainless," Sep 2010. [Online]. Available: https://pubs.usgs.gov/fs/2010/3089/pdf/fs2010-3089.pdf. [Accessed 25 Mar 2025].

[80] Deloitte China, "Fueling the Future of Mobility," Deloitte, Beijing, 2020.

[81] The Fund For Peace, "Fragile States Index - Global Data," 2024. [Online]. Available: https://fragilestatesindex.org/. [Accessed 17 Apr 2025].

[82] Luvata, "Fusion energy," 2025. [Online]. Available: https://www.luvata.com/industries/fusion-energy. [Accessed 06 Apr 2025].

[83] S. Farrell and L. Whitton, "BHP Insights: how copper will shape our future," BHP, https://www.bhp.com/news/bhp-insights/2024/09/how-copper-will-shape-our-future, 2024.

[84] International Copper Association, "Copper Recycling," 10 Feb 2022. [Online]. Available: https://internationalcopper.org/resource/copper-recycling/. [Accessed 28 Mar 2025].

[85] A. Hoekstra, "How we can substitute aluminium for copper in the green transition," *Shapes,* 19 Jul 2023.

[86] IMS Team, Metal University, "Aluminum Radiation Shielding in 3D Imaging," Industrial Metal Service, 2025. [Online]. Available: https://industrialmetalservice.com/metal-university/aluminum-radiation-shielding-in-3d-imaging/. [Accessed 4 Apr 2025].

[87] AETHEER, "learly Understand the Important Roles of Molybdenum in Nickel Alloys," [Online]. Available: https://www.aeether.com/AEETHER/media/media-13/media.html. [Accessed 22 Apr 2025].

[88] IMS Team, Metal University, "The Advantages and Disadvantages of Stainless Steel Recycling and Reuse," Industrial Metal Service, 2025. [Online]. Available: https://industrialmetalservice.com/metal-university/the-advantages-and-disadvantages-of-stainless-steel-recycling-and-reuse/. [Accessed 01 May 2025].

[89] P. Nandwana, W. Peter, R. Dehoff, L. Lowe, M. . Kirka, F. Medina and B. S.S., "Recyclability study on Inconel 718 and Ti-6Al-4V powders for use in electron beam melting," *Metallurgical and Materials Transactions B,* vol. 47, no. https://link.springer.com/article/10.1007/s11663-015-0477-9, pp. 754-762, 2015.

[90] Benchmark Source, "Nickel demand for batteries to overtake stainless steel in late 2030s," 11 Jul 2023. [Online]. Available:

https://source.benchmarkminerals.com/article/nickel-demand-for-batteries-to-overtake-stainless-steel-in-late-2030s. [Accessed 17 Apr 2025].

[91] World Stainless, "ecycled for lasting value," 19 Apr 2024. [Online]. Available: https://worldstainless.org/about-stainless/environment/recycling/. [Accessed 30 Apr 2025].

[92] C. Hayes, "Congo's Evolving Crisis: Geopolitical Risks and Investment Implications in the Mineral-Rich DRC," *AInvest,* pp. https://www.ainvest.com/news/congo-evolving-crisis-geopolitical-risks-investment-implications-mineral-rich-drc-2504/, 30 Apr 2025.

[93] *Barker Engineering Library.* [Art]. MIT.

[94] Fusion Energy Base, "Organizations," [Online]. Available: https://www.fusionenergybase.com/organizations. [Accessed 04 25 2025].

[95] A. Barnett, "Temperatures Across Our Solar System," 16 Nov 2023. [Online]. Available: https://science.nasa.gov/solar-system/temperatures-across-our-solar-system/#:~:text=The%20hottest%20part%20of%20the,F%20(5%2C500%C2%B0C). [Accessed 19 04 2025].

[96] M. Banks, "SMART spherical tokamak produces its first plasma," 21 01 2025. [Online]. Available: https://physicsworld.com/a/smart-spherical-tokamak-produces-its-first-plasma/#:~:text=SMART%20has%20been%20constructed%20by,used%20to%20shape%20the%20plasma.. [Accessed 19 04 2025].

[97] ITER, "The ITER Device," [Online]. Available: https://fusionforenergy.europa.eu/the-device/. [Accessed 19 04 2025].

[98] Helion, "Helion's Fusion Technology," 2025. [Online]. Available: https://www.helionenergy.com/technology/. [Accessed 15 01 2025].

[99] Minutephysics, Composer, *Legitimate Cold Fusion Exists | Muon-Catalyzed Fusion.* [Sound Recording]. https://www.youtube.com/watch?v=aDfB3gnxRhc. 2018.

[100] C. Seife, Sun In a Bottle, London, UK: Penguin, 2008.

[101] ITER, "The Tao of Q," 2025. [Online]. Available: https://www.iter.org/node/20687/tao-q.

[102] UnitConverters.net, "Convert Megapascal to Pound-force/square Inch," 2025. [Online]. Available: https://www.unitconverters.net/pressure/megapascal-to-pound-force-square-inch.htm. [Accessed 26 04 2025].

[103] J. Timperley, "Explainer: These six metals are key to a low-carbon future," Carbon Brief, 04 Dec 2018. [Online]. Available: https://www.carbonbrief.org/explainer-these-six-metals-are-key-to-a-low-carbon-future/. [Accessed 18 Apr 2025].

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