

Inflows and Outflows of Nuclear Fusion

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Abstract

Nuclear fusion is regarded as a promising source of clean energy in the future. However, if nuclear fusion is scaled up by 2050, certain materials will be required as inputs and certain materials will be generated as outputs. If we assume that future researchers will be able to develop fusion reactors so that it is globally scaled up, it is important to know how much fuel and by-products will be needed and generated since this would enable future policy makers, entrepreneurs and researchers to analyse the supply chain issues that may be associated with the technology. This paper creates relevant formulas to calculate an estimate of the amount of Lithium needed to be mined and the amount of Helium that would be generated if D-T fusion is scaled up to supply particular percentages of the global energy required in 2050. It also summarizes the major fusion reactions and technologies. The results aim to support future policy decisions, resource planning, and environmental assessments by identifying potential bottlenecks in the supply chain and evaluating the long-term sustainability of fusion power.

Keywords: Inputs, Outputs, Nuclear fusion, D-T, Lithium, Helium, Clean energy

1. Introduction

1.1 What is Nuclear Fusion?

Nuclear fusion is the process where two nuclei combine together to form a much larger nucleus. To understand how this happens, we need to consider some principle theories in quantum mechanics. In order for fusion to occur, we need to overcome the large energetic barrier of Coulombic repulsion caused by the positive charge of the nucleus. This can be done by allowing the nuclei's strong force to become relevant.

The strong force is one of the four fundamental forces in the universe. Being the strongest force of all, it can only be attractive and act at a range of around 10^{-15} m - a range that is astronomically lower than that of the electromagnetic force. If the electromagnetic force has a relative strength of 1, the strong nuclear force, according to T. Gibbons, has a relative strength of 137 (1). The strong force is formed due to the exchange of mesons between the baryons. The exchange of mesons takes place due to the principles of quantum chromodynamics (2).

When two nuclei merge together, it causes a loss of mass and, according to Einstein's formula $E = mc^2$, a huge amount of energy is released that results in a bigger nucleus and usually a neutron with a huge amount of kinetic energy. If the kinetic energy of the neutrons can be captured in an effective manner, electrical energy can be generated (3).

1.2 Why do we care about Nuclear fusion?

Nuclear fusion has a high energy density. This means, unlike other renewable energy sources, a small amount of nuclear fuel can lead to a huge amount of energy given that the system is engineered well enough (3). The amount of energy released during nuclear fusion can, according to researchers, be up to four times greater than nuclear fission and up to roughly four million times higher than gaining energy from oil or coal (4)(5). Nuclear fusion may also be a very cost-effective energy source in the future (6)(7).

In addition to being energetically efficient, nuclear fusion has the added benefit of being significantly cleaner than other energy generation methods. Nuclear fusion does not release carbon dioxide directly into the atmosphere. While the manufacturing and transportation of reactor components and fuel may involve energy generated from carbon emissions, it is still closer to being carbon neutral compared to fossil fuels (3). As opposed to nuclear fission, nuclear fusion does not require Uranium, a non-renewable resource that is radioactive.

However, there are certain challenges regarding nuclear fusion. Most importantly, the technology is still in the research phase as of 2024 (8). According to researchers, Deuterium-Tritium Fusion (D-T Fusion) is regarded as the most commercially viable option (9). In Deuterium-Tritium fusion, a Deuterium atom and a Tritium atom fuse together to form a Helium-4 atom and a neutron with high kinetic energy. Assuming that the neutrons are captured by reactor walls, it may be safe to say that the only by-product in D-T fusion is Helium (10)(11).

Nuclear fusion is more reliable than other green energy sources because it is independent of climate and weather. As a result, a fusion power plant can be installed at any designated area in any type of climate in the world.

To compare fusion with other energy methods, it is best to calculate the energy output per meter squared of land used. This should be done because both the amount of land used and the amount of energy generated should be taken into account while comparing the efficiency of different energy sources. Table 1 demonstrates this (12).

Table 1: The energy output per meter squared of land used

Property	Fusion	Fission	Wind	Solar	Geothermal	Hydropower
Dependency On weather and climate	No	No	Yes	Yes	Yes	Yes
Installation required at selective locations	No	Yes, since fission is radioactive	No	No	Yes	Yes
Death rate per unit electricity production	N/A	0.03	0.04	0.02	Unknown	1.3
Renewable	Yes	No	Yes	Yes	Yes	Yes

Below is a figure that shows land use intensity, in ha/TWh/y, for different electricity sources. It is very important to know that the y-axis over here is at a logarithmic scale. Hence the Land use intensities of Hydropower, solar power (CSP and PV) and wind energies are therefore much higher compared to nuclear fission (Note that “Nuclear” only includes nuclear fission) (13).

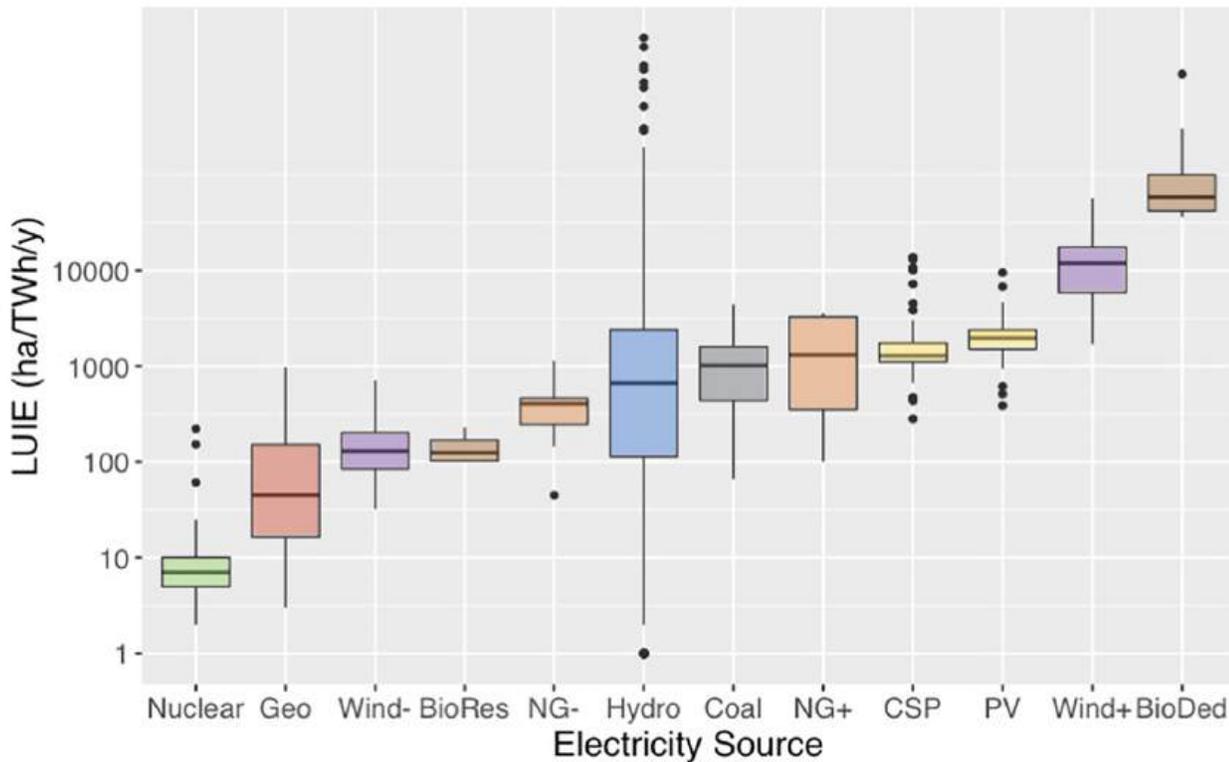


Figure 1

Lovering J, Swain M, Blomqvist L, Hernandez RR (2022) Land-use intensity of electricity production and tomorrow's energy landscape. PLoS ONE 17(7): e0270155. <https://doi.org/10.1371/journal.pone.0270155>

Due to the additional instrumentation needed for nuclear fusion, fusion may need a higher amount of operational space but at the same time produce a higher amount of energy per unit time (14). As a result, it may be safe to assume that in future research, the Land Use Intensity of nuclear fusion may be anywhere between 1 to 100. This makes fusion and geothermal energy the two renewable energy sources with the lowest land use intensity. However, an important factor to consider is that fusion is independent of location while geothermal is not. The independence of location makes fusion energy scalable. Future research may also prove nuclear fusion to have a lower land use intensity compared to geothermal energy.

1.3 Requirements for nuclear fusion

The nuclei must be heated to temperatures of 100 million to around 1 billion degrees Celsius, making them reach the plasma state. This is to ensure that the nuclei can have enough kinetic energy and overcome the coulombic forces that cause them to repel each other. The nuclei must be packed together at extremely high densities. When the particles are close together, they are more likely to collide. As a result, with increased density, fusion yield is higher.

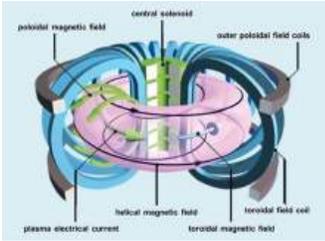
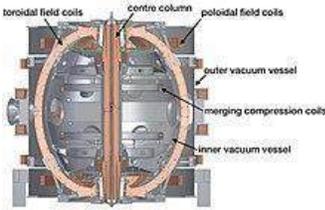
The hot and dense plasma must be confined so that it floats in a vacuum. This is done to stop heat loss to the surroundings by convection and conduction. Also, if the plasma gets into contact with the reactor walls, the walls would get damaged due to the extremely high temperatures (9).

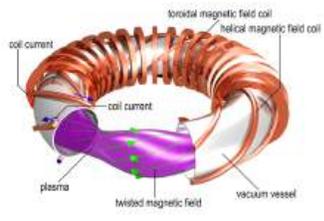
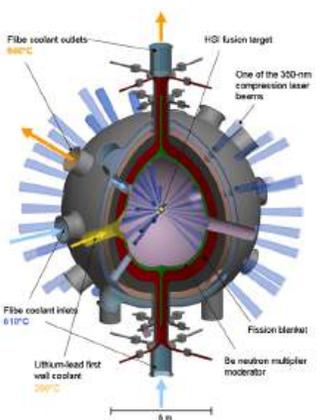
1.4 Different confinement techniques

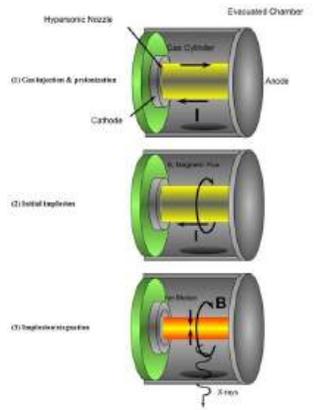
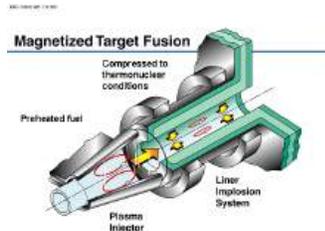
There are various confinement techniques and reactors that are used by organizations interested in fusion energy research.

Tokamaks are donut shaped reactors (toruses) where the plasma is confined by the use of magnetic coils. This method takes advantage of electromagnetism to confine the charged particles. Tokamaks are an example of magnetic confinement techniques. Table 2 compares other confinement techniques to traditional toroidal tokamaks in terms of their shape, size, cost and plasma stability (15)(18-37).

Table 2: Confinement techniques and their properties

Name of technique	Type of confinement	Shape	Size and cost	Plasma stability	Picture
Tokamaks	Uses a combination of toroidal and poloidal magnetic fields to confine the plasma.	Toroidal shape	Larger and more expensive to build compared to spherical tokamaks.	Traditional tokamaks achieve lower plasma stability than spherical tokamaks.	 <p>Figure 2</p>
Spherical tokamaks	Similar to that of traditional tokamaks but with a smaller central column, allowing for higher plasma stability	Spherical tokamaks have a more compact, nearly spherical shape, often compared to a cored apple.	Smaller and cheaper to build compared to traditional tokamaks which allows for quicker construction and experimentation.	Can achieve better plasma stability due to their compact design.	 <p>Figure 3</p>

	and better confinement.				
Stellarators	Uses magnetic confinement	Have a toroidal shape with a complex and twisted magnetic field.	Have a more complex design compared to spherical tokamaks, making them harder to maintain and manufacture.	Does not rely on a strong plasma current, which reduces the risk of instabilities and disruptions	 <p>Figure 4</p>
Inertial Confinement	A technique where small pellets of nuclear fuel are fired at high speeds and heated up using lasers and/or particle beams.	Usually has a spherical shape	Have a smaller size compared to tokamaks. Comparing the cost with tokamaks, Inertial Confinement Techniques require higher initial investments but have lower operational/experimental costs.	Inertial confinement fusion relies on the inertia of imploding fuel pellets to achieve the necessary conditions for fusion. This generally avoids long-term stability issues.	 <p>Figure 5</p>

<p>Z-pinch</p>	<p>A method that compresses the plasma to extremely high densities using strong electric current. The magnetic field created due to the electric field exerts a force on the plasma. This phenomenon is known as the pinch effect.</p>	<p>Cylindrical shape</p>	<p>Smaller and less expensive compared to traditional tokamaks</p>	<p>Made recent advancements in stability but still face significant challenges</p>	 <p>Figure 6</p>
<p>Magnetized target fusion (MTF)</p>	<p>A method that combines Inertial Confinement and Magnetic</p>	<p>Spherical or cylindrical shape</p>	<p>Generally less expensive than tokamaks. Overall size and complexity is also lower.</p>	<p>Can achieve higher plasma stability compared to traditional tokamaks</p>	 <p>Figure 7</p>

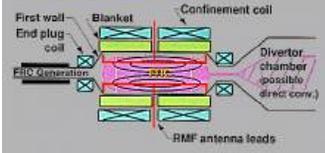
	Confinement.				
Field Reverse Configuration	Compresses the plasma into a super dense formation without having a central penetration.	Toroidal shape	Generally less expensive compared to Tokamaks and Stellarators. Very compact and can be used as a portable power plant.	High Beta values, which means that the plasma is pushing harder than the magnetic fields. It faces challenges on tilt modes and bearing modes. Hence, stability is a concern	 <p>AN FRC POWER PLANT</p> <p>Figure 8</p>

Figure 2: Review on Nanotechnology Applications in Nuclear Energy - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Magnetic-Fields-which-confine-plasma-in-a-torus-shape_fig6_366569783 [accessed 4 Apr 2025]

Figure 3: Gryaznevich, M. P., and A. Sykes. "Merging-compression formation of high temperature tokamak plasma." Nuclear Fusion 57, no. 7 (2017): 072003.

Figure 4: Hydrodynamic modelling of the shock ignition scheme for inertial confinement fusion - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Stellarator-device-scheme-Scheme-by-AbteilungOffentlichkeitsarbeitAbteilung_fig4_290180304 [accessed 4 Apr 2025]

Figure 5: Manheimer, W. (2024) Fusion: It's Time to Color outside the Lines. Open Journal of Applied Sciences, 14, 740-800. doi: 10.4236/ojapps.2024.143052.

Figure 6: Design of Z-pinch and Dense Plasma Focus Powered Vehicles - Scientific Figure on ResearchGate. Available from:

https://www.researchgate.net/figure/Stages-of-Z-Pinch-Formation_fig2_265490651 [accessed 4 Apr 2025]

Figure 7: Siemon, Richard E., Peter J. Turchi, Daniel C. Barnes, James HI Degnan, Paul Parks, D. Ryutov, and Y. C. F. Thio. "Magnetized target fusion: Prospects for low-cost fusion energy." ITC-12. Toki, Japan (2001).

Figure 8: Web Page:

https://www.iterru.ru/FusionCentre/FCMain/FCHistory/alternate_paths/sfrc.htm

1.5 Drawbacks of fusion

The two major reactions used in nuclear fusion research are Deuterium-Deuterium fusion and Deuterium-Tritium fusion. The latter being the more profitable option according to most thinkers, both Deuterium and Tritium can be extracted from natural resources, but faces challenges such as Tritium breeding (discussed below).

Since nuclear fusion requires a huge amount of energy, it is an engineering challenge to build a commercially viable fusion reactor. This is partly due to the fact that a lot of the energy is actually lost through a phenomenon known as microturbulence. Also, the intense heat, mainly through radiation, that comes from the plasma causes serious damages to the reactor walls - especially at the molecular level.

D-T fusion may produce tritiated water and other waste products containing Tritium. Although unreacted Tritium can be collected and reused, tiny amounts would be scattered across reactor components, making them subject to radiation if the reactor components are discarded after prolonged use. This would make D-T fusion environmentally hazardous unless cutting-edge detritiation technologies are developed (9)(16)(17).

1.6 Tritium Breeding

Tritium Breeding is the process where, in D-T fusion, fast-moving neutrons that collide on the blanket (the outermost layer of the reactor wall) undergo a nuclear reaction with Lithium to form Tritium. The Tritium can then be collected and used as a fuel for the next operation in the plant. According to experts the most efficient isotope for Tritium Breeding is ${}^6\text{Li}$, because it generates heat during Tritium Breeding which can be collected (38). Also, Li-6 is responsible for the majority of Tritium Production (10)(39).

For D-T fusion, the best candidate for Tritium breeding is a substance known as FLiBe. FLiBe is a 2:1 mixture of LiF and BeF_2 where the ${}^6\text{Li}$ reacts with neutrons to form Tritium. It also acts as a medium for heat exchange since it converts radiation into heat. Other reactor designs, such as the HCPB (proposed for the Eurofusion project) makes use of Lithium Ceramics (9)(38).

Regardless, it can be safe to assume that the best proposals for D-T fusion relies on a rich supply of Lithium (particularly ${}^6\text{Li}$) for regular operation.

A recent study indicates that in the best-case scenario, D-T fusion plants may be able to generate a 15% surplus of Tritium through Tritium breeding (40). However, the release of radioactive waste products such as tritiated water would remain an environmental concern.

1.7 The scope of this paper

Since D-T fusion is regarded as the most commercially viable fusion reaction, this paper calculates the mass of lithium that has to be mined if D-T fusion generates a particular percentage of the world's energy in 2050. It will also calculate the mass of ${}^4\text{He}$ that would be generated as a by-product when D-T fusion is scaled up in the future.

The materials needed for nuclear fusion to take place can be broken down into two types based on their operational nature: fuels (materials that get used up) and fixtures (materials that do not have to be replaced). The fixtures include all precious and semi-precious metals, materials in the reactors, electric devices and other components of peripheral systems and subsystems.

In this paper, fuels will not strictly refer to the isotopes that react in the fusion reaction. It will refer to the input materials of the nuclear fusion power plant as a whole. For instance, if Tritium Breeding is carried out in D-T fusion, Tritium will be considered as a fixture rather than a fuel since the plant will only need a starting supply of Tritium in order to continue its operation. On the other hand, Lithium-6 has to be considered as a fuel for the power plant since it is a material that has to be replaced after subsequent phases of operation. Consequently, this paper would focus on the final outputs other than energy (or outflows other than energy) and the fuels (inflows) since the goal of this research is to analyze the inflows and outflows of nuclear fusion power plants.

1.8 Assumptions that are to be made

1.81 Assumptions on infrastructure

We will assume that all the fixtures (including machineries, reactor materials, etc.) are present and that the nuclear fusion power plants are fully built and operational. We will also ignore smaller or unimportant inflows such as cooling water and other miscellaneous materials that are used up in the power plants (41).

1.82 Assumptions on research, development and investments

We will assume that by the year of 2050, there would be a substantial investment in nuclear fusion power plants and that researchers would make the power plants commercially-viable by solving the current challenges associated with it.

We would also assume that, in the future, quantum computers would substantially escalate the research, development and operation of all types of nuclear fusion reactors (42).

1.83 Assumptions on the supply of Deuterium

Deuterium is a common isotope abundant in the earth. Although it needs to be refined, we will assume that by 2050, sufficient supply of Deuterium will be provided in order to feed the scaled-up fusion industry. Hence, this paper will focus on fuels other than Deuterium. Specifically, it will calculate an estimate for the amount of lithium that needs to be mined if D-T fusion is scaled up to meet a particular percentage of the world's energy in 2050.

2. Body

2.1 Fuel combinations

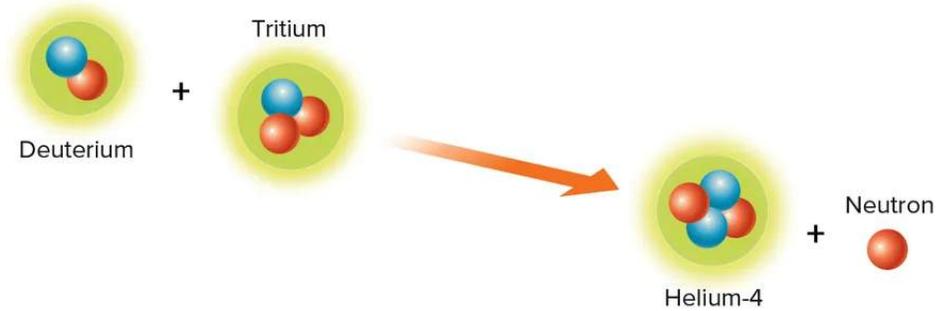
The most commercially viable fuel combination is Deuterium-Tritium (D-T) (9)(41). However, when multiple companies and plants all across the globe would scale fusion up with different types of confinement techniques and different sizes of reactors, it is a clear prediction that many of the plants may prefer other fuel combinations that may seem more profitable to them because of the individual circumstances involved. The choice of other fuel combinations may also be the result of supply chain issues and numerous other factors.

The following diagram illustrates all the potential fuel combinations that can be used in nuclear fusion: (43)

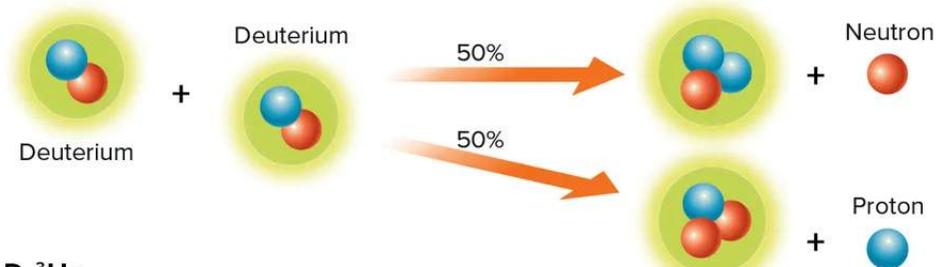


Fusion fuel types

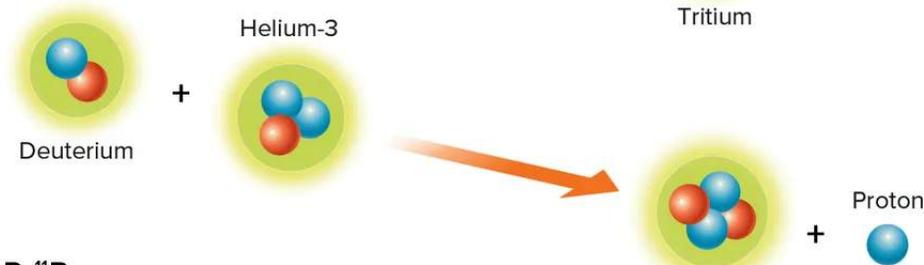
D-T



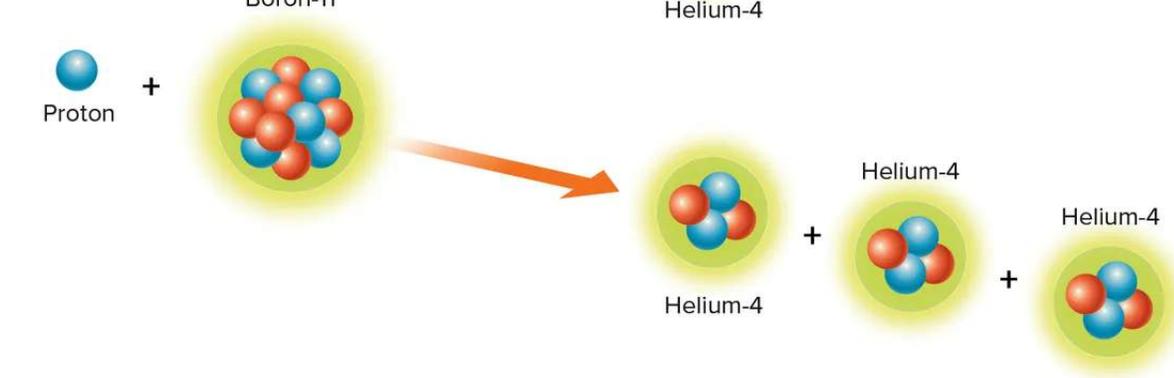
D-D



D-³He



P-¹¹B



SOURCE: REPORTING BY M. MITCHELL WALDROP

5W INFOGRAPHIC / KNOWABLE

Figure 9: Web Page:

<https://knowablemagazine.org/content/article/physical-world/2023/the-challenge-of-fusion-power>

2.2 The respective products of different combinations

As seen from above, fusion does produce by-products. The amount of by-products of the respective fuel combinations are an important factor in scalability. They may be recycled as fuel for another type of fusion reaction that may be carried on simultaneously or later on in the reactor (as in the case with Tritium from D-D fusion). Alternatively, the products may be collected and sold off to other industries (as in the case of He-4). As a result, for entrepreneurs and policy makers, it is very important to consider the amount of products released per unit fuel used for a particular fuel combination.

As seen from the figure above, the molar ratio between the reactants and the products are 1:1, with the exception of Deuterium-Deuterium (D-D) Fusion, where 50% of the reactants get converted into He-3 and neutron and the other 50% gets converted to Tritium and proton. Table 3 calculates the amount of each product, in moles, generated when one mole of each of the fuels react to produce energy:

[Note that 'p' means proton, and not Phosphorus]

Table 3: Amount of product (other than energy) formed when 1 mol of each fuel takes part in the respective fusion reactions

Type of fusion	Amount of product (other than energy) formed when 1 mol of each fuel takes part in the reaction /mol				
	⁴ He	³ He	Tritium (³ H)	Proton (¹ p)	Neutron (¹ n)
D-T	1	0	0	0	1
D-D	0	0.5	0.5	0.5	0.5
D- ³ He	1	0	0	1	0
p- ¹¹ B	3	0	0	0	0

Using the equation

Number of moles = (mass) / (molar mass), we can calculate the amount of each product released when 1 kg of Deuterium is used for D-T, D-D and D-³He fusion and the amount of He-4 released when 1 kg of Boron-11 is used for p-¹¹B fusion.

Assuming that the molar mass of Deuterium is 2.014amu to 3 decimal places (44), 1 kg of Deuterium contains (1000)/2.014 mol

= 496.524 mol to 3 d.p.

Table 4 lists the masses, in amu to 3 d.p., of He-4, He-3, Tritium, Proton, and neutron (44)(45):

Table 4: Isotope masses of the reactants involved

Species	Isotope mass (amu)
⁴ He	4.003
³ He	3.016
Tritium (³ H)	3.016
Proton (¹ p)	1.007
Neutron (¹ n)	1.009
¹¹ B	11.009

Table 5 calculates the amount of the products and reactants involved, in moles and in kg, when 1 kg of Deuterium is used as a fuel. The above values of isotope mass are used to calculate the amount in kg.

Table 5: Amount of products and reactants involved when 1kg of Deuterium is used as a fuel

Type of fusion	Amount of product or reactant (other than energy) formed or needed when 1 kg (496.524 mol) of Deuterium takes part in the reaction /mol					Amount of product or reactant (other than energy) formed or needed when 1 kg (496.5243297 mol) of Deuterium takes part in the reaction /kg				
	⁴ He	³ He	Tritium (³ H)	Proton (¹ p)	Neutron (¹ n)	⁴ He	³ He	Tritium (³ H)	Proton (¹ p)	Neutron (¹ n)
D-T	496	0	496	0	496	1.988	0	1.498	0	0.501
D-D	0	248	248	248	248	0	0.749	0.749	0.250	0.250
D- ³ He	496	496	0	496	0	1.988	1.498	0	0.500	0

In 1 kg of protons, the amount in moles would be (1000)/(1.007) mol

= 993.049 mol to 3 d.p.

Table 6 demonstrates the amount, in moles and kg, of Boron needed and Helium-4 generated when 1 kg of proton is used up in p-¹¹B fusion:

Table 6: Amount of Boron needed and amount of Helium-4 generated when 1kg of proton is used up in p-¹¹B fusion

Species	Amount in moles needed or generated when 1 kg of proton is used /mol	Mass needed or generated when 1 kg of proton is used /kg
¹¹ B	993.049	10.932
⁴ He	2979.147	11.926

2.3 The problems associated with Tritium

Tritium is a radioactive isotope of Hydrogen. It has a half-life of about 12.3 years and is not naturally abundant. As a result, it needs to be produced artificially by Tritium breeding techniques and/or fuel recycle technologies.

On the other hand, some Field Reverse Configuration (FRC) techniques do not require Tritium for operation. For example, the Princeton Field Reverse Configuration (PFRC) reactor uses Deuterium and Helium-3 as fuel. Here, only a relatively-thin (200cm-thick) blanket made of Boron Ceramic is needed which makes the production of PFRC easier and the cost lower compared to D-T fusion. However, Helium-3 is a scarce resource and, as of 2024, can only be produced in Deuterium-fueled Breeder reactors (9-11).

2.4 Predicting the amount of Lithium required for D-T fusion in 2050

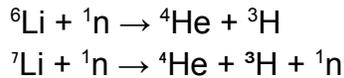
2.41 Predicting the amount of energy required in 2050

Predicting the amount of energy required in 2050 is a big challenge and involves a variety of factors. However, a report from McKinsey and Company states that the global energy demand is expected to be from 52000 TWh to 71000 TWh (46).

So, in the year of 2050, we will assume that the global annual energy demand would be from 5.2×10^{13} kWh to 7.1×10^{13} kWh.

2.42 Creating an equation for the mass of Lithium used up in D-T fusion

In Tritium Breeding, the following reactions occur (40)(47):



The amount of Tritium produced depends on the Tritium Breeding Ratio (TBR) which is the ratio between the number of tritium ions produced and the number of fusion neutrons coming from the plasma. In the most feasible proposed D-T reactors, the TBR is greater than one firstly because of the reaction with ${}^7\text{Li}$ and secondly because of neutron breeding, a process where substances such as Beryllium are used to increase the number of neutrons involved (40). However, regardless of the TBR, the molar ratio of Lithium used up and the Tritium produced will always be equal to 1 since reactions involved in neutron multiplication do not use up lithium or create tritium.

Using the formula

$\text{TBR} = (\text{number of tritium ions produced per second})/(\text{number of fusion neutrons per second})$,

(1) we can come to the following conclusion based on our calculation in section 2.2:

When 1 kg of Deuterium is used up in D-T fusion,

Amount of Tritium produced = $\text{TBR} \times 496.524 \text{ mol}$

So, Amount of Lithium used up = $\text{TBR} \times 496.524 \text{ mol}$

The Relative Formula Mass (RFM) of Lithium used in the FLiBe, Lithium ceramics or equivalent Tritium Breeding medium would depend on the proportion of ${}^6\text{Li}$ in the Lithium. Let the required relative abundance of ${}^6\text{Li}$ be $\rho\%$. Then,

$$\text{RFM of Lithium} = (6\rho + 7(100 - \rho))/100$$

$$\text{RFM of Lithium} = (700 - \rho)/100 \tag{2}$$

Hence,

Mass of refined Lithium needed, M_{Ref} when 1 kg of Deuterium is burnt in D-T fusion would be:

$$M_{\text{Ref}} = \text{TBR} \times 4.965 \times (700 - \rho) \tag{3}$$

However, since the enriched lithium contains a proportion of ${}^6\text{Li}$ that is much higher than that in naturally-abundant lithium, it means that a significantly larger proportion of Lithium would have to be mined in order to achieve the refined mass M_{Ref} that has the desired proportion of ${}^6\text{Li}$.

Let us assume that the natural abundance of ${}^6\text{Li}$ in a naturally-occurring Lithium sample is 7.4% (10).

$$\text{Mass of } {}^6\text{Li in the refined sample} = \rho/100 \times M_{\text{Ref}} \quad (4)$$

Let the mass required for mining lithium be M_{Raw} . Then,

$$7.4\% \text{ of } M_{\text{Raw}} = \rho/100 \times M_{\text{Ref}}$$

$$M_{\text{Raw}} = \rho/7.4 \times M_{\text{Ref}}$$

As a result, we get

$$M_{\text{Raw}} = 4.965\rho(700-\rho)/7.4 \times \text{TBR} \quad (5)$$

This equation will give the total naturally-abundant lithium that needs to be mined, in kg, for every 1 kg of Deuterium that would be used up for D-T fusion for a particular TBD and a particular used percentage abundance of ${}^6\text{Li}$, ρ . It is important to note that a significant portion of the ${}^7\text{Li}$ would be used in other industries such as electric vehicles, electronics, lithium-ion batteries, etc. after the lithium is refined for fusion.

For any mass m kg of Deuterium used, the mass M_{Raw} would be:

$$M_{\text{Raw}} = 4.965m\rho(700-\rho)/7.4 \times \text{TBR} \quad (6)$$

Rearranging the equation gives

$$m = (7.4)/(TBR \times 4.965\rho(700-\rho)) \times M_{\text{Raw}} \quad (7)$$

2.43 Creating an equation for the energy generated in D-T fusion

When one atom of Deuterium reacts with one molecule of Tritium, the total gain in energy is 17.6 MeV or about $2.8198 \times 10^{-12}\text{J}$ of energy (48).

1 kg of Deuterium contains 496.524 mol. Taking Avogadro constant as 6.022×10^{23} , 1kg of Deuterium would contain 2.99×10^{26} particles.

$$\begin{aligned} \text{So, energy produced by fusion reaction when 1 kg of Deuterium is used up} &= 2.99 \times 10^{26} \\ &\times 2.8198 \times 10^{-12}\text{J} \\ &= 8.431 \times 10^{14}\text{J} \end{aligned}$$

Let the proportion of fusion energy converted into electricity be P_E where $0 < P_E < 1$. The value of P_E would dramatically differ in the upcoming years due to the research and development of fusion reactors, peripheral components, plasma modelling, first blanket, etc. However, in most reactors the current value of P_E is very close to 0. As a result, in our calculations it is best to keep this factor as a variable so that we can analyse the different levels of masses as P_E varies.

$$\text{Hence, amount of energy generated when 1 kg Deuterium for D-T fusion is used up} = P_E \times 8.431 \times 10^{14}\text{J}$$

The amount of energy generated when m kg of Deuterium for D-T fusion is used up,

$$E_{\text{DT}} = mP_E \times 8.431 \times 10^{14}\text{J} \quad (8)$$

2.44 Creating a mathematical model for the amount of Lithium required to be mined

From the final equations of sections 2.41 and 2.42, we can conclude that if m kg of Deuterium is used up,

$$E_{DT} = P_E \times 8.431 \times 10^{14} \times (7.4)/(TBR \times 4.965\rho(700-\rho)) \times M_{Raw}$$

$$E_{DT} = 1.257 \times 10^{15} \times 1/(TBR \times \rho(700-\rho)) \times P_E \times M_{Raw}$$

Also, $1 \text{ J} = 2.778 \times 10^{-7} \text{ kWh}$. So, if E_{DT} is to be given in kilowatt-hour, then

$$E_{DT} = 1.257 \times 10^{15} \times 1/(TBR \times \rho(700-\rho)) \times P_E \times M_{Raw} \times 2.778 \times 10^{-7}$$

Hence,

$$E_{DT} = 349194600/(TBR \times \rho(700-\rho)) \times P_E \times M_{Raw}, \text{ where } E_{DT} \text{ is in kWh.} \quad (9)$$

Rearranging this would give:

$$M_{Raw} = 1/P_E \times (TBR \times \rho(700-\rho))/349194600 \times E_{DT} \quad (10)$$

Now, using graphical analysis, we can predict the amount of lithium needed, in kg, for a certain amount of energy to be generated, in kWh, for particular values of P_E , TBR and ρ where, $0 < P_E < 1$.

However, we will assume that for a commercially-viable fusion reactor in the future, the proportion of energy generated by fusion that is converted to electrical energy (P_E) is at least 0.1. We will also assume that the value of P_E will not exceed 0.95.

So, $0.1 < P_E < 0.95$

$1 < TBR < 1.5$ (assuming that some future reactors may reach higher TBR)

The lithium requirements would be very different depending on the type of tritium breeding used. The tritium breeding technologies are classified into two types - solid breeders (eg. Lithium Ceramics) and Liquid Breeders (eg. FLiBe). For solid breeders, ρ would need to be from 30 to 60 while for liquid breeders, ρ would typically need to be around 90 (39).

2.45 Predicting the amount of Lithium needed to be mined for D-T fusion using solid breeders

The following model can be used to determine the amount of Lithium needed to be mined for D-T fusion using solid breeders:

$$M_{Raw} = 1/P_E \times (TBR \times \rho(700-\rho))/349194600 \times E_{DT} \quad (10)$$

Where,

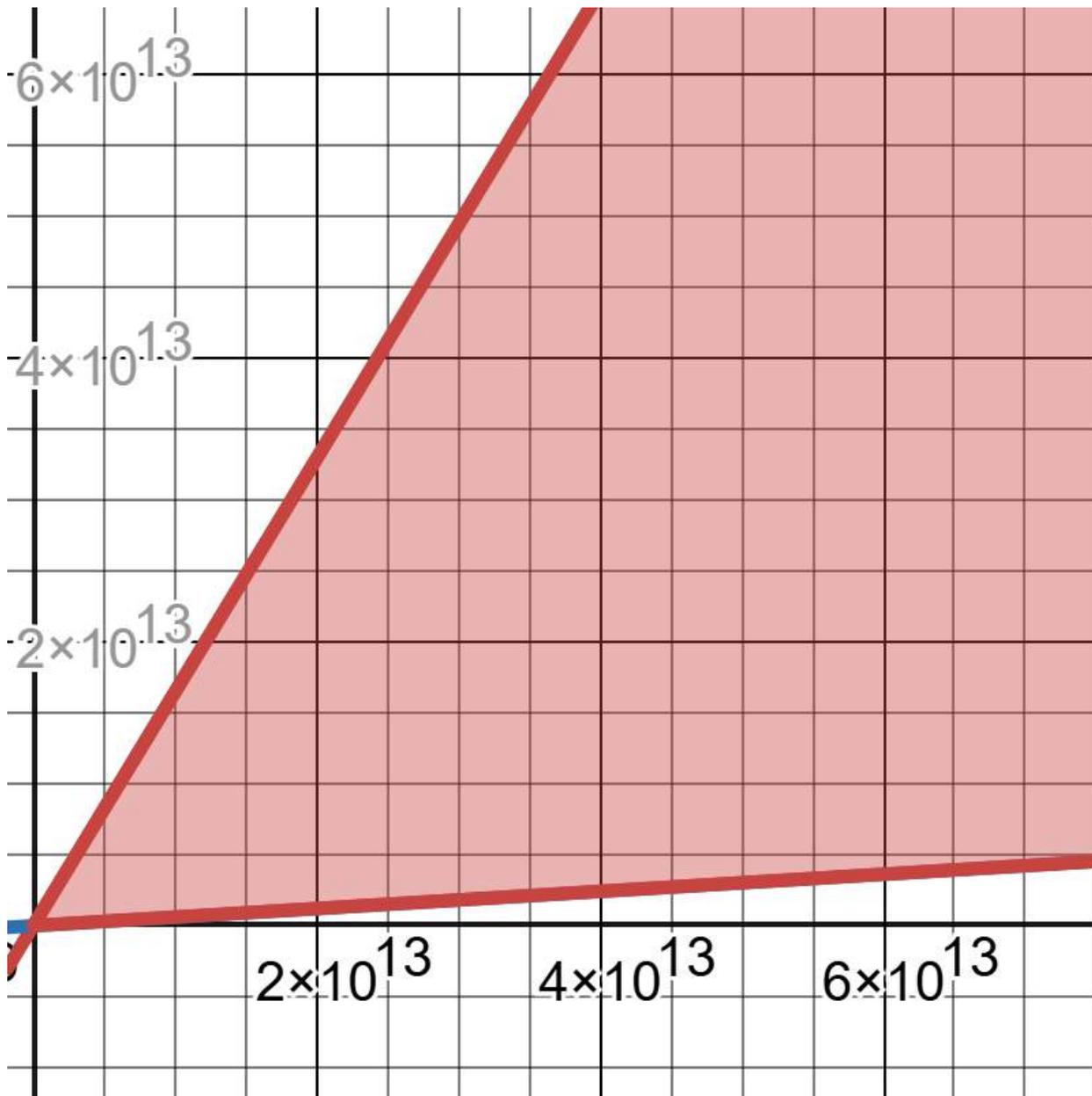
$$0.1 < P_E < 0.95,$$

$$1 < TBR < 1.5,$$

$$30 < \rho < 60$$

2.451 Predicting by using absolute best- and worst-case scenarios

The following shows a graph of $1000M_{Raw}$ against E_{DT} . The value of M_{Raw} is multiplied by 1000 since the line would be flat and difficult to analyze otherwise.



As seen from above, we can now use the graph to estimate the amount of lithium required for generating a particular percentage of the global energy demand in 2050, for the highest requirement (steepest possible line) and the lowest requirement (flattest possible line). Here, the highest possible requirement has $P_E = 0.1$, TBR = 1.5 and $\rho = 60$ while the lowest possible requirement has $P_E = 0.95$, TBR = 1.0 and $\rho = 30$. Table 7 shows the results.

Table 7: Amount of lithium required to be mined for fulfilling particular percentages of the global energy demand in 2050 for the above-mentioned variable ranges

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest requirement	Lowest requirement	Highest requirement	Lowest requirement
10	8.57745×10^9	3.15071×10^8	1.17115×10^{10}	4.30193×10^8
20	1.71549×10^{10}	6.30142×10^8	2.3423×10^{10}	8.60386×10^8
30	2.57324×10^{10}	9.45213×10^8	3.51346×10^{10}	1.29058×10^9
40	3.43098×10^{10}	1.26028×10^9	4.68461×10^{10}	1.72077×10^9
50	4.28873×10^{10}	1.57535×10^9	5.85576×10^{10}	2.15096×10^9
60	5.14647×10^{10}	1.89043×10^9	7.02691×10^{10}	2.58116×10^9

However, it may be very impractical to assume that the P_E would be as high as 0.95. Hence, it is best to calculate lithium requirements for two different possibilities - one where the efficiency is high (where $0.5 < P_E < 0.7$) and one where the efficiency is low (where $0.2 < P_E < 0.4$).

2.452 Lithium requirements for a high range of P_E

We will use the same mathematical model and the same graph ($1000M_{Raw}$ against E_{DT}) but with the following ranges:

$$0.5 < P_E < 0.7,$$

$$1 < TBR < 1.5,$$

$$30 < \rho < 60$$

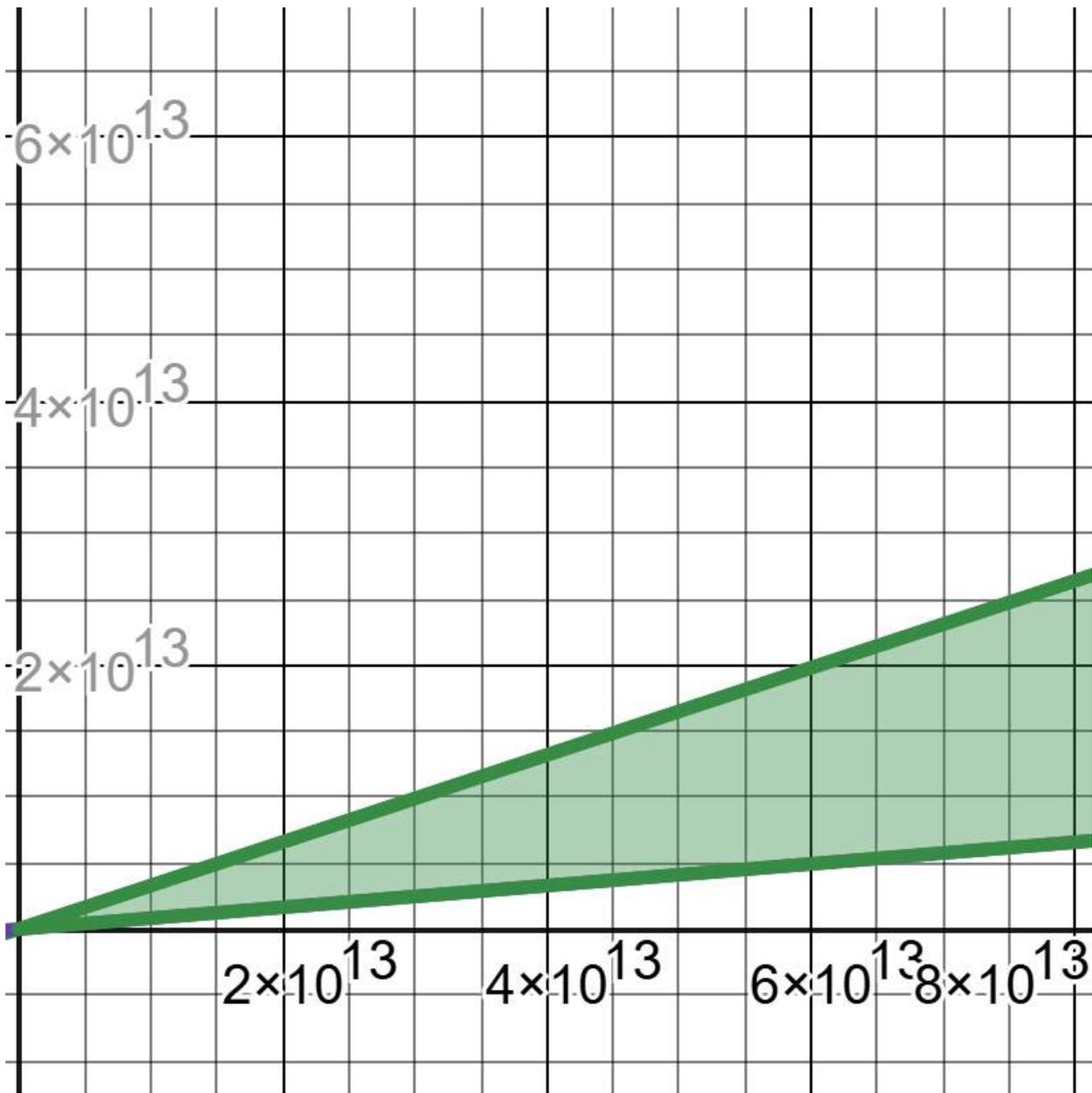


Table 8 shows the results.

Table 8: Amount of lithium required to be mined for fulfilling particular percentages of the global energy demand in 2050 for the above-mentioned variable ranges

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest requirement	Lowest requirement	Highest requirement	Lowest requirement
10	1.71549×10^9	4.27596×10^8	2.3423×10^9	5.83833×10^8
20	3.43098×10^9	8.55192×10^8	4.68461×10^9	1.16767×10^9
30	5.14647×10^9	1.28279×10^9	7.02691×10^9	1.7515×10^9
40	6.86196×10^9	1.71038×10^9	9.36922×10^9	2.33533×10^9
50	8.57745×10^9	2.13798×10^9	1.17115×10^{10}	2.91917×10^9
60	1.02929×10^{10}	2.56558×10^9	1.40538×10^{10}	3.503×10^9

2.453 Lithium requirements for a low range of P_E

We will use the same mathematical model and graph but with the following ranges:

$$0.2 < P_E < 0.4,$$

$$1 < TBR < 1.5,$$

$$30 < \rho < 60$$

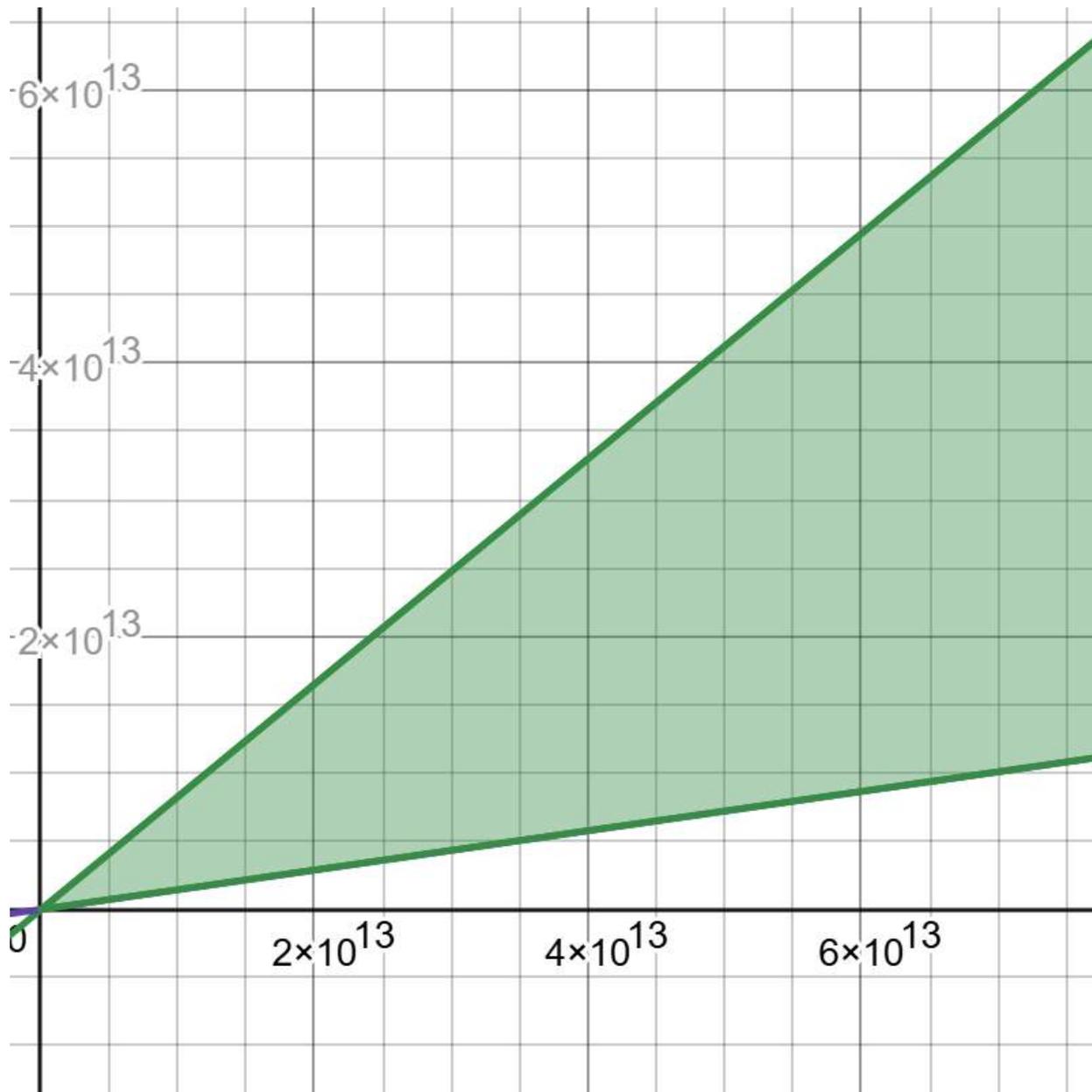


Table 9 demonstrates the lithium requirements for fulfilling particular percentages of the global energy demand in 2050.

Table 9: Amount of lithium required to be mined for fulfilling particular percentages of the global energy demand in 2050 for the above-mentioned variable ranges

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest requirement	Lowest requirement	Highest requirement	Lowest requirement
10	4.28873×10^9	7.48293×10^8	5.85576×10^9	1.02171×10^9
20	8.57745×10^9	1.49659×10^9	1.17115×10^{10}	2.04342×10^9
30	1.28662×10^9	2.24488×10^9	1.75673×10^{10}	3.06512×10^9
40	1.71549×10^{10}	2.99317×10^9	2.3423×10^{10}	4.08683×10^9
50	2.14436×10^{10}	3.74147×10^9	2.92788×10^{10}	5.10854×10^9
60	2.573236×10^{10}	4.48976×10^9	3.513456×10^{10}	6.13025×10^9

2.46 Predicting the amount of Lithium needed to be mined for D-T fusion using liquid breeders

The following model can be used to determine the amount of Lithium needed to be mined for D-T fusion using solid breeders. Current reports show that the proportion of ${}^6\text{Li}$ (ρ) would be approximately 90 (39). Since it is an approximation, we will take $\rho = 90 \pm 5$. It is also important to note that this value would be commonly adjusted by engineers to maximise energy yield based on the specific tritium breeding techniques used and the specific type of reactors used.

$$M_{\text{Raw}} = 1/P_E \times \text{TBR} \times \rho(700-\rho)/349194600 \times E_{\text{DT}} \quad (10)$$

Where,

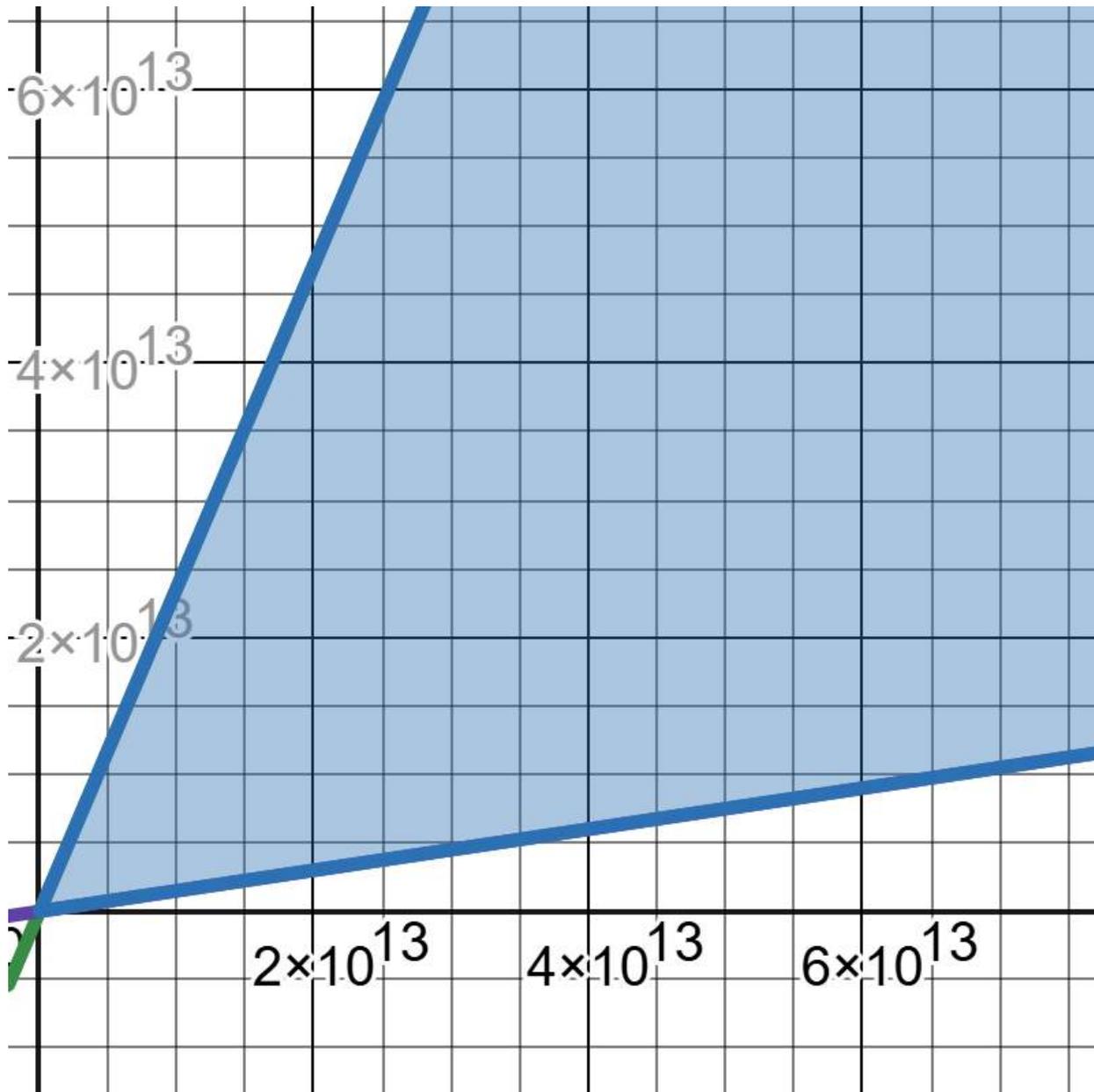
$$0.1 < P_E < 0.95,$$

$$1 < \text{TBR} < 1.5,$$

$$85 < \rho < 95$$

2.461 Predicting by using absolute best- and worst-case scenarios

The following shows a graph of $1000M_{Raw}$ against E_{DT} . The value of M_{Raw} is multiplied by 1000 since the line would be flat and difficult to analyze otherwise.



Just like we have done for solid breeders, the highest possible requirement has $P_E = 0.1$, TBR = 1.5 and $\rho = 60$ while the lowest possible requirement has $P_E = 0.95$, TBR = 1.0 and $\rho = 85$. Table 10 demonstrates the lithium requirements for fulfilling particular percentages of the global energy demand in 2050.

Table 10: Amount of lithium required to be mined for fulfilling particular percentages of the global energy demand in 2050 for the above-mentioned variable ranges

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest requirement	Lowest requirement	Highest requirement	Lowest requirement
10	1.22631×10^{10}	7.78448×10^8	1.67438×10^{10}	1.06288×10^9
20	2.452615×10^{10}	1.5569×10^9	3.34876×10^{10}	2.12576×10^9
30	3.678923×10^{10}	2.33535×10^9	5.023145×10^{10}	3.18864×10^9
40	4.90523×10^{10}	3.11379×10^9	6.697526×10^{10}	4.25153×10^9
50	6.131538×10^{10}	3.89224×10^9	8.371908×10^{10}	5.31441×10^9
60	7.357846×10^{10}	4.67069×10^9	1.004629×10^{11}	6.37729×10^9

Similar to the case for solid breeders, it may be very impractical to assume that the P_E would be as high as 0.95. Hence, it is best to calculate lithium requirements for two different possibilities - one where the efficiency is high (where $0.5 < P_E < 0.7$) and one where the efficiency is low (where $0.2 < P_E < 0.4$).

2.462 Lithium requirements for a high range of P_E

We will use the same mathematical model and graph ($1000M_{Raw}$ against E_{DT}) but with the following ranges:

$$0.5 < P_E < 0.7,$$

$$1 < TBR < 1.5,$$

$$85 < \rho < 95$$

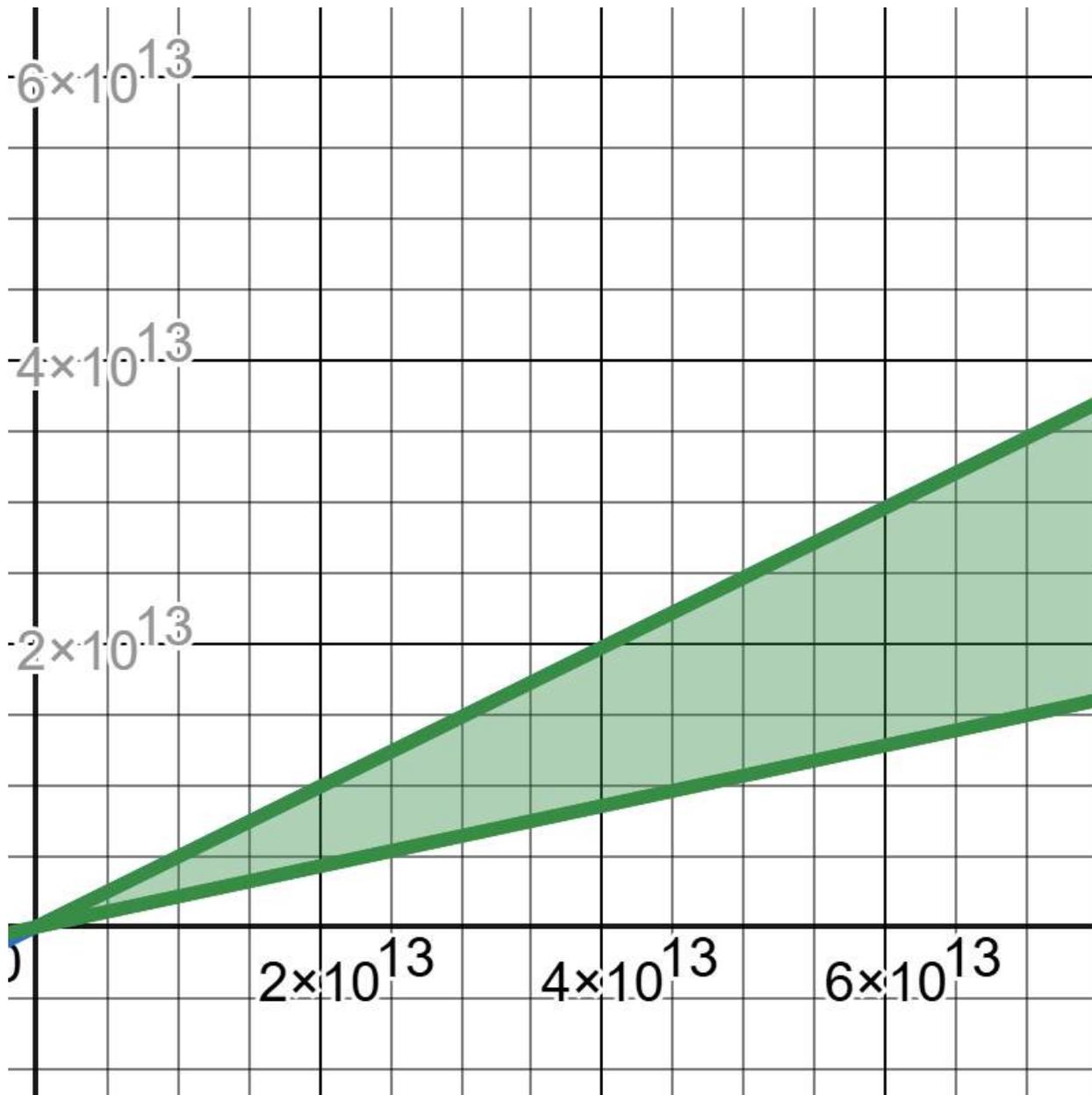


Table 11 demonstrates the lithium requirements for fulfilling particular percentages of the global energy demand in 2050.

Table 11: Amount of lithium required to be mined for fulfilling particular percentages of the global energy demand in 2050 for the above-mentioned variable ranges

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest requirement	Lowest requirement	Highest requirement	Lowest requirement
10	2.567651×10^9	1.11207×10^9	3.50583×10^9	1.5184×10^9
20	5.1353×10^9	2.22414×10^9	7.01166×10^9	3.0368×10^9
30	7.70295×10^9	3.33621×10^9	1.05175×10^{10}	4.55521×10^9
40	1.02706×10^{10}	4.44828×10^9	1.40233×10^{10}	6.07361×10^9
50	1.28383×10^{10}	5.56035×10^9	1.75292×10^{10}	7.59201×10^9
60	1.54059×10^{10}	6.67242×10^9	2.1035×10^{10}	9.11041×10^9

2.463 Lithium requirements for a low range of P_E

We will use the same mathematical model and graph but with the following ranges:

$0.2 < P_E < 0.4,$

$1 < TBR < 1.5,$

$85 < \rho < 95$

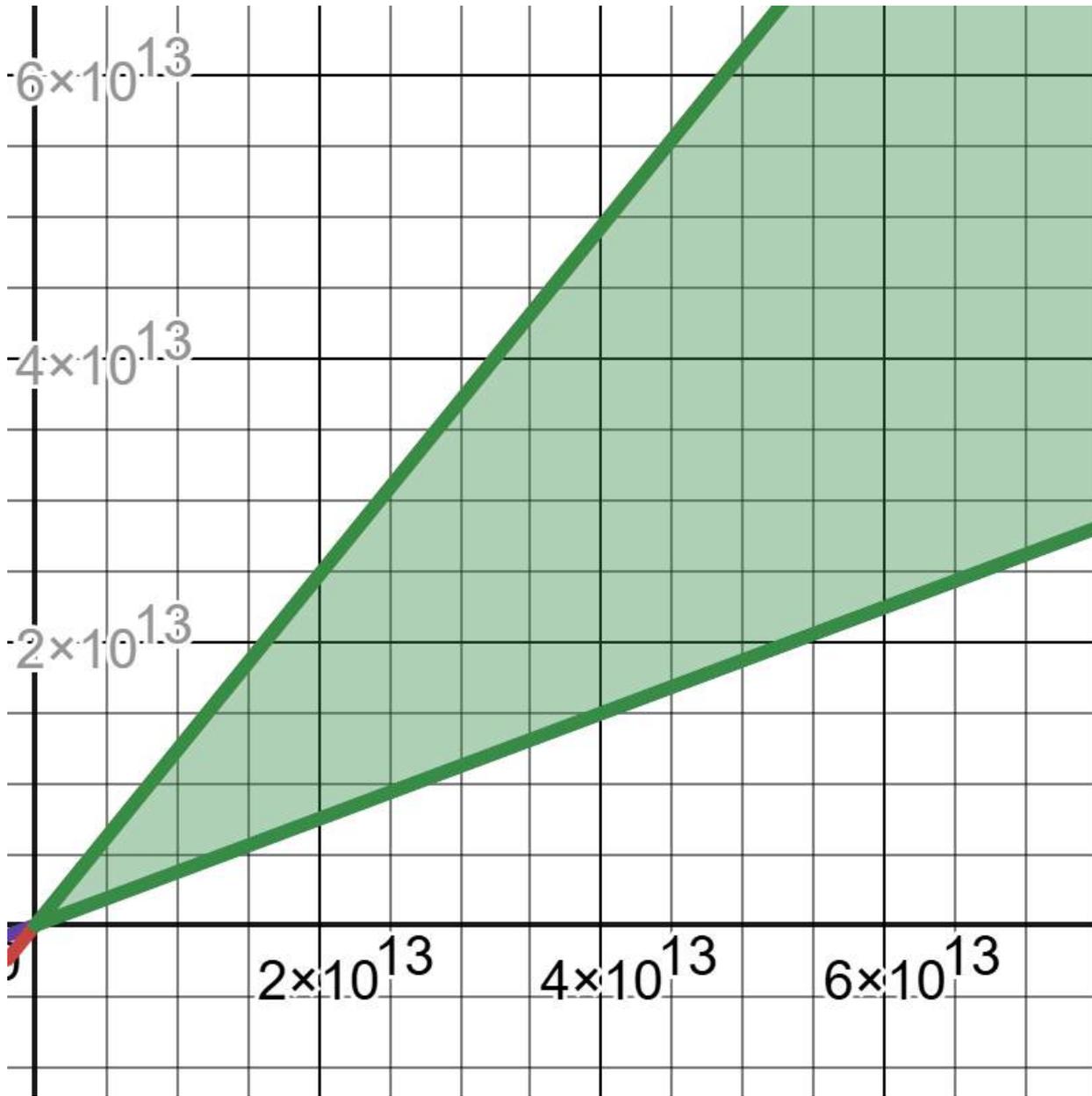


Table 12 demonstrates the numbers.

Table 12: Amount of lithium required to be mined for fulfilling particular percentages of the global energy demand in 2050 for the above-mentioned variable ranges

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest requirement	Lowest requirement	Highest requirement	Lowest requirement
10	6.41913×10^9	1.94612×10^9	8.76458×10^9	2.6572×10^9
20	1.28383×10^{10}	3.89224×10^9	1.75292×10^{10}	5.31441×10^9
30	1.92574×10^{10}	5.83836×10^9	2.629374×10^{10}	7.97161×10^9
40	2.567651×10^{10}	7.78448×10^9	3.505832×10^{10}	1.06288×10^{10}
50	3.209564×10^{10}	9.73061×10^9	4.38229×10^{10}	1.3286×10^{10}
60	3.851477×10^{10}	1.16767×10^{10}	5.258748×10^{10}	1.59432×10^{10}

2.5 Predicting the amount of Helium generated by D-T fusion in 2050

2.51 Creating a mathematical model to predict the amount of Helium generated in 2050

The amount of ^4He that would be generated by D-T fusion for generating a certain percentage of the world's electricity demand in 2050 would depend mostly on the Tritium-Breeding Ratio (TBR) and the proportion of fusion energy converted to electricity (P_E). We can divide the amount of ^4He generated into two categories:

1. The mass generated directly by D-T reactions. Let this amount be H_R .
2. The mass generated due to the tritium breeding. Let this amount be H_T .

In 1 kg of ^4He , $n(^4\text{He}) = 249.813$ mol

= 1.504×10^{26} particles

Since 1 particle of ^4He would produce 2.8198×10^{-12} J of energy,

1 kg of ^4He would produce $1.504 \times 10^{26} \times 2.8198 \times 10^{-12}$ J

= 4.241×10^{14} J

= 117805649.8 kWh

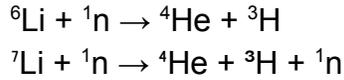
For a given mass of ^4He that takes part in the D-T fusion reaction, the following equation can be used to determine the amount of energy, E_{DT} that is generated.

$$E_{DT} = 117805649.8 \times H_R \times P_E \quad (11)$$

Rearranging this would give:

$$H_R = E_{DT} / (117805649.8 \times P_E) \quad (12)$$

In Tritium breeding, the molar ratio between the overall amount of fusion neutrons generated and the overall amount of ^4He generated is 1:1. Hence, we can say that the amount, in moles, of ^4He produced is equal to the amount, in moles, of fusion neutrons produced by the D-T reactions:



Since 1 fusion neutron creates $2.8198 \times 10^{-12} \text{ J}$ of energy, 1 mol of fusion neutrons would produce $2.8198 \times 10^{-12} \text{ J} \times 6.022 \times 10^{23}$
 $= 1.698 \times 10^{12} \text{ J}$ of energy

Thus, we can say that $1.698 \times 10^{12} \text{ J}$ (or 471670.44 kWh) of energy is released through the D-T fusion reactions for every 1 mol of neutrons coming to the blanket. However, the neutrons represented in the equations above may not always be fusion neutrons due neutron multiplication. So, we can derive the following model by taking into account that $n(\text{neutron}) = n(^4\text{He})/\text{TBR}$ and by saying that the molar ratio between ^4He and ^3H is 1:1 regardless of the TBR:

$$\begin{aligned} E_{\text{DT}} &= n(\text{neutron}) \times P_E \times 471670.44 \\ E_{\text{DT}} &= \text{TBR} \times n(^3\text{H}) \times P_E \times 471670.44 \\ E_{\text{DT}} &= \text{TBR} \times n(^4\text{He}) \times P_E \times 471670.44 \\ E_{\text{DT}} &= \text{TBR} \times H_T \times P_E \times 471670.44 / 4.003 \\ E_{\text{DT}} &= \text{TBR} \times H_T \times P_E \times 117829.2381 \\ H_T &= E_{\text{DT}} / (\text{TBR} \times P_E \times 117829.24) \end{aligned} \tag{13}$$

Let the total mass of ^4He required be M_{He} . Then,

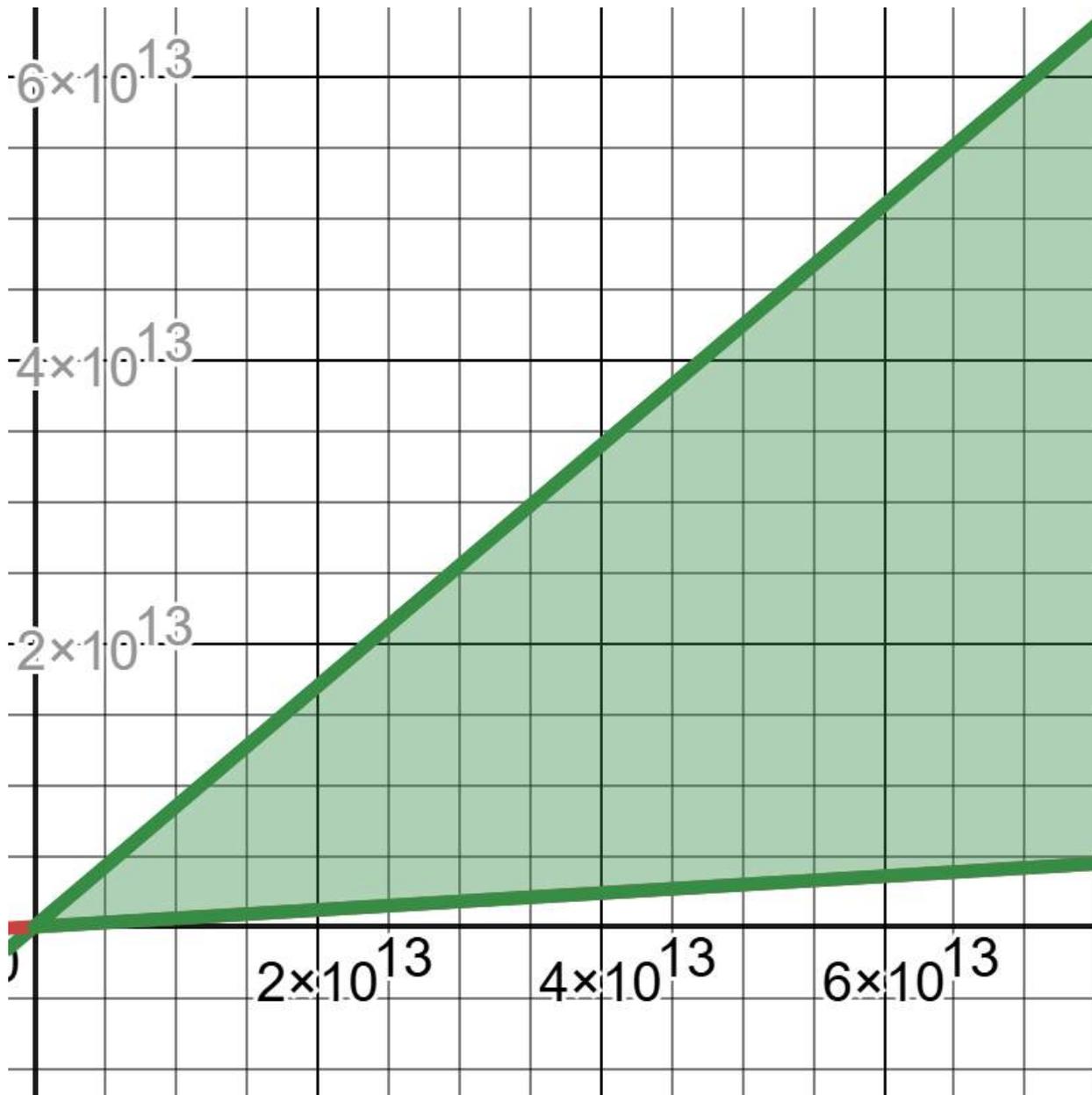
$$\begin{aligned} M_{\text{He}} &= H_T + H_R \\ M_{\text{He}} &= E_{\text{DT}} / (\text{TBR} \times P_E \times 117829.24) + E_{\text{DT}} / (117805649.8 \times P_E) \end{aligned} \tag{14}$$

Where,

$$\begin{aligned} 0.1 &< P_E < 0.95 \\ 1.0 &< \text{TBR} < 1.5 \end{aligned}$$

2.52 Predicting by using absolute maximum and minimum values of P_E

We will use a graph of $10000M_{\text{He}}$ against E_{DT} to analyse the information since the function would normally produce a line that is too flat:



Here, the flattest-possible line has $P_E = 0.95$ and $TBR = 1.5$ while the steepest-possible line has $P_E = 0.1$ and $TBR = 1$. Table 13 demonstrated the Helium outflows for particular percentages of global energy demand met in 2050, assuming the above-mentioned variable ranges.

Table 13: Helium outflows for the above-mentioned variable ranges for particular percentages of global energy demand met in 2050

Percentage of global energy demand met in 2050 (%)	Amount of Helium generated (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest outflow	Lowest outflow	Highest outflow	Lowest outflow
10	4.41758×10^8	3.10160×10^7	6.03169×10^8	4.23488×10^7
20	8.83516×10^8	6.20321×10^7	1.20634×10^9	8.46977×10^7
30	1.32527×10^9	9.30481×10^7	1.80951×10^9	1.27047×10^8
40	1.76703×10^9	1.24064×10^8	2.41268×10^9	1.69395×10^8
50	2.20879×10^9	1.55080×10^8	3.01585×10^9	2.11744×10^8
60	2.65055×10^9	1.86096×10^8	3.61902×10^9	2.54093×10^8

Similar to the case for the calculation for Lithium, it may be very impractical to assume that the P_E would be as high as 0.95. Hence, it is best to calculate lithium requirements for two different possibilities - one where the efficiency is high (where $0.5 < P_E < 0.7$) and one where the efficiency is low (where $0.2 < P_E < 0.4$).

2.53 Helium generated for a high range of P_E

We will use the same mathematical model and graph ($1000M_{Raw}$ against E_{DT}) but with the following ranges:

$$0.5 < P_E < 0.7,$$

$$1 < TBR < 1.5,$$

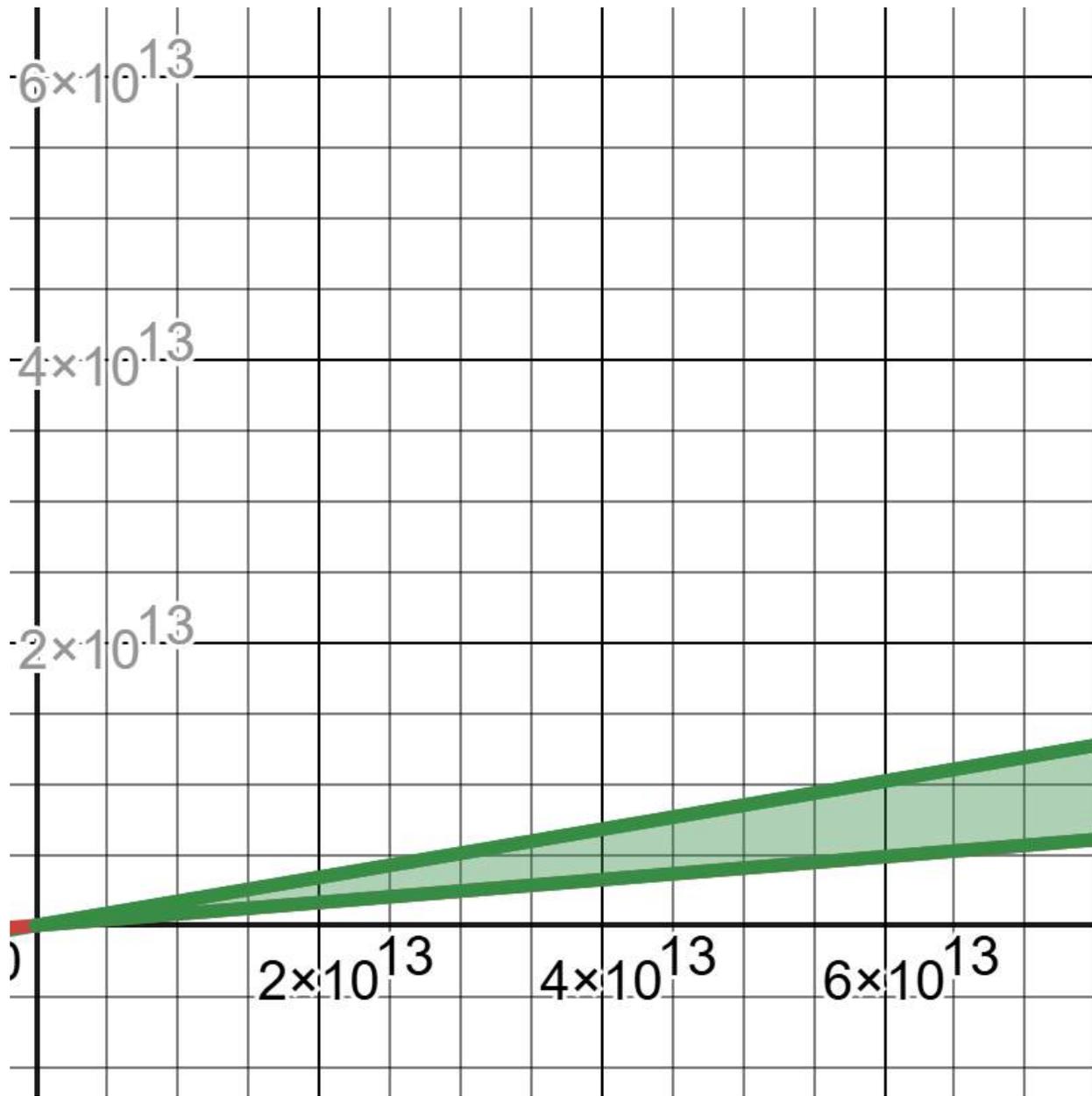


Table 14 demonstrates the helium outflows for particular percentages of global energy demand met by D-T fusion in 2050.

Table 14: Helium outflows for the above-mentioned variable ranges for particular percentages of global energy demand met in 2050

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest outflow	Lowest outflow	Highest outflow	Lowest outflow
10	8.83516×10^7	4.20932×10^7	1.20634×10^8	5.74734×10^7
20	1.76703×10^8	8.41864×10^7	2.41268×10^8	1.14947×10^8
30	2.65055×10^8	1.26280×10^8	3.61902×10^8	1.72420×10^8
40	3.53406×10^8	1.68373×10^8	4.82536×10^8	2.29894×10^8
50	4.41758×10^8	2.10466×10^8	6.03170×10^8	2.87367×10^8
60	5.30110×10^8	2.52559×10^8	7.23804×10^8	3.44841×10^8

2.54 Helium generated for a low range of P_E

We will use the same mathematical model and graph ($1000M_{Raw}$ against E_{DT}) but with the following ranges:

$$0.2 < P_E < 0.4,$$

$$1 < TBR < 1.5,$$

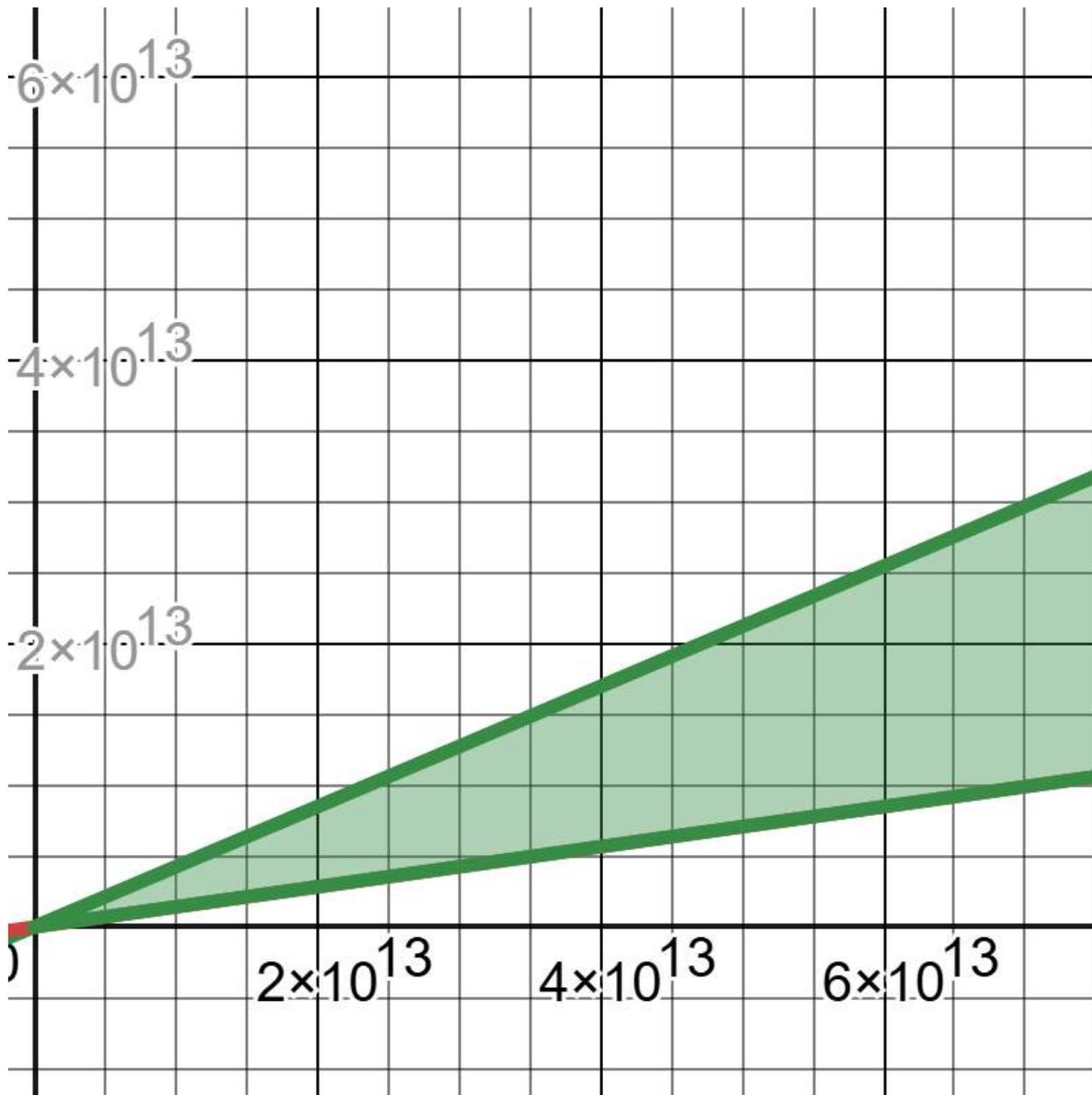


Table 15 demonstrates the helium outflows for particular percentages of global energy demand met by D-T fusion in 2050.

Table 15: Helium outflows for the above-mentioned variable ranges for particular percentages of global energy demand met in 2050

Percentage of global energy demand met in 2050 (%)	Amount of Lithium needed to be mined (kg)			
	Global energy demand = 5.2×10^{13} kWh		Global energy demand = 7.1×10^{13} kWh	
	Highest outflow	Lowest outflow	Highest outflow	Lowest outflow
10	2.20879×10^8	7.36631×10^7	3.01585×10^8	1.00578×10^8
20	4.41758×10^8	1.47326×10^8	6.03170×10^8	2.01157×10^8
30	6.62637×10^8	2.20989×10^8	9.04754×10^8	3.01735×10^8
40	8.83516×10^8	2.94652×10^8	1.20634×10^9	4.02314×10^8
50	1.10440×10^9	3.68316×10^8	1.50792×10^9	5.02892×10^8
60	1.32527×10^9	4.41979×10^8	1.80951×10^9	6.03471×10^8

2.6 Analysis of the inflows and outflows of D-T fusion

2.6.1 Analysis on the amount of Lithium required to be mined for D-T fusion

The amount of Lithium that needs to be mined depends mostly on the proportion of the amount of energy generated by fusion to the amount of energy that is successfully converted to electricity. This, along with the exact enrichment level of Lithium, seems difficult to predict, leading to a huge variation in the amount of Lithium required to be mined. It is important to note that the proportion of energy (P_E) that is used in all the above calculations does not take into account the amount of energy that is generated by the exothermic reaction of tritium breeding. Furthermore, it is important to note that a huge portion of the calculated mass of lithium would be used in other industries once the required percentage of ^6Li is achieved.

If P_E is between 0.1 and 0.95, solid breeders need about 300,000 tonnes to 10 million tonnes to overcome 10% of the global energy demand and need 2 million to 70 million tonnes to accommodate 60% of the energy demand.

If P_E is between 0.2 and 0.4, solid breeders need about 750,000 tonnes to 6 million tonnes to overcome 10% of the global energy demand and need 4.5 million to 35 million tonnes to accommodate 60% of the energy demand.

On the other hand, if P_E is successfully engineered to be between 0.5 and 0.7, solid breeders need about 400,000 tonnes to 2.3 million tonnes to overcome 10% of the global energy demand and need 1.4 million to 14 million tonnes to accommodate 60% of the energy demand.

For liquid breeders, the figures are much higher due to the higher enrichment level of lithium that is required. Assuming P_E is between 0.1 to 0.95, if 10% of global energy is generated in 2050, liquid breeders need about 6 million tonnes to 17 million tonnes and to overcome 60% of energy demand, they would need from about 4.7 million tonnes to a staggering 100 million tonnes.

If P_E is between 0.2 to 0.4, liquid breeders would require 1.9 million tonnes to 8.8 million tonnes to supply 10% of global energy and 12 million to 52 million to supply 60% of the energy.

However, if reactors of liquid breeders are successfully engineered to have a high efficiency ($0.5 < P_E < 0.7$), only 1.1 million to 3.5 million tonnes of lithium would have to be mined to supply 10% of energy while 6.6 million to 21 million tonnes have to be mined to supply 60% of global energy.

2.62 Analysis on the amount of Helium that would be generated due to D-T fusion

Just like the mass of lithium required, the mass of ^4He that would be generated also strongly depends on the P_E . If P_E is between 0.1 to 0.95, the mass of helium generated ranges from 31,000 tonnes to 600,000 tonnes if 10% of global energy is supplied through D-T fusion. If 60% of global energy is generated, the figure stands at 180,000 tonnes to 3.6 million tonnes.

For a low range of P_E (0.2 - 0.4), 10% energy generation would mean that 74,000 tonnes to 300,000 tonnes of ^4He is generated and 60% energy generation would mean that 44,000 to 1.8 million tonnes are generated.

On the contrary, for a high range of P_E (0.5 - 0.7), 10% energy global generation would generate 42,000 tonnes to 120,000 tonnes of helium while 60% energy generation would produce 250,000 tonnes to 720,000 tonnes.

These figures are important since it would help future entrepreneurs and policy makers to analyse the side effects (or additional opportunities) that are associated with D-T fusion. It raises the question of whether or not there would be a surplus of Helium in the future, assuming that D-T fusion truly is scaled up - or whether other industries are going to consume just the amount of Helium that is produced through D-T fusion.

2.7 Other fusion reactions

There are two other fusion reactions that are significantly discussed in current research papers and websites: D-D fusion and D- ^3He fusion. Although D- ^3He fusion requires a rare isotope of Helium, it can be safe to say that most (or all) of the ^3He that would be used in D- ^3He reactions are going to be generated through D-D fusion. This is because, as seen in section 2.2, ^3He is formed in 50% of the D-D fusion reactions. Since Deuterium is naturally abundant in the earth, we will assume that no additional fuel would be required for these two reactions. It is also important to note that D-D fusion produces tritium as well and an increase in the number of power plants that undergo D-D fusion would therefore significantly reduce the mass of lithium that is needed to be mined in order to generate a certain percentage of the global energy.

Another type of fusion reaction is proton- ^{11}B reaction. This would require a significant amount of ^{11}B and would generate a significant amount of helium nuclei (alpha particles).

Regardless, since D-T fusion is considered to be the most commercially-viable option, the data calculated in this research paper would be of considerable importance.

2.8 The Fuel Cycle for ITER

Unlike most other proposed nuclear fusion power plants, ITER has a rather complex fuel cycle (41). It has numerous peripheral systems and releases protium. This means that other fusion reactions are involved and an analysis of the inflows and outflows (outflows other than energy) would require a greater level of scrutiny towards the design and flow system of ITER. This may be an opportunity for future researchers.

3. Conclusion

3.1 Limitations of the study

This study creates a very rough estimate for the mass of lithium required and the mass of ^4He that would be generated. It is based on numerous assumptions associated with the development of fusion technology in the future. However, it is important for policy makers and researchers to consider the outcome of a certain technology and whether or not the world can create a supply chain that would supply the required mass of mined lithium. It is also important since we need to figure out whether or not other industries would consume the amount of Helium (particularly ^4He) that is generated.

The study may fail to capture other inflows that are smaller in amount, such as the Beryllium needed for neutron multiplication. It is also limited in the sense that it fails to address more complex power plants such as ITER. Furthermore, future power plants may also come up with multi-step fusion power plants that convert the fusion products to other materials in order to maximize efficiency in the individual circumstances involved.

3.2 Conclusion

In 2023, the global production of lithium was estimated to be 180,000 metric tonnes (49). Even if we assume that all of the mined lithium would be refined before being sent to other industries (such as batteries, electric vehicles, etc.), this figure would not be enough if a significant portion of the global energy supply has to be covered by D-T fusion. This means that, in addition to the requirement for a substantial increase in the amount of lithium that is needed to be mined, we would have to also think about changing certain parts of the technology. For instance, more research can be done in the search of alternative salt blankets or alternative tritium breeding methods. Furthermore, this paper may provide strong evidence that D-T fusion, although regarded as the most commercially-viable fusion reaction (9), may not be the sole viable option for powering the grids in 2050. It may be economically challenging to supply this amount of lithium.

A solution to this vast requirement for lithium mining may be D-D fusion - if D-D fusion is sufficiently scaled up alongside D-T fusion, there may be a high proportion of Tritium that would be transferred to D-T fusion reactors. This would significantly reduce the amount of lithium that the world needs to mine.

Nevertheless, the future of nuclear fusion would still heavily depend on further research into nuclear fusion, engineering reactors to improve efficiency and the development of specialized quantum computing software algorithms. This provides an opportunity to not only researchers and entrepreneurs in the future but also to current high school, undergraduate and graduate students who are interested in physics, nuclear engineering and quantum computing.

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