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Nuclear Fusion Energy: The State of the Industry

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Abstract

The usage of fossil fuels results in the destruction of our environment through greenhouse gas emissions. A way to combat this problem is to take advantage of renewable energy sources, one such possible contender is nuclear fusion energy. Nuclear fusion energy has the potential to become a replacement for fossil fuel energy due to the massive amounts of clean energy this form of energy provides in such a short time. This form of energy has been explored since the 1920s when nuclear fusion was first understood. Currently, there are many challenges that fusion faces that prevent it from being commercialized, with new advances seeking to solve many of fusion's problems. While fusion still requires significant development before it can become a sustainable energy source, the possibility of harnessing fusion energy is an exciting prospect. In all, this research paper provides a comprehensive overview of what fusion energy is with its advantages and challenges, its usefulness compared to common forms of energy used today like coal, solar, and fission, and state and advancements of fusion.

1 Introduction

With the massive quantities of greenhouse gasses emitted by common energy sources like fossil fuels, the energy humans generate is also destroying the environment. A possible solution to this problem is to replace conventional energy sources with renewable, clean energy. One hypothetical option is nuclear fusion energy, which offers several advantages over its more well-known counterpart: nuclear fission. The reason why fusion isn't widely used throughout the world is due to the challenges associated with it. Some examples of the challenges that fusion faces today are the difficult temperature and pressure requirements related to fusion, the damage that plasma inflicts on surrounding materials during the fusion process, and the high cost needed to build a fusion reactor. Because of these challenges, achieving viable fusion energy is expected to take a long time, with many experts forecasting that it could become feasible only by 2050 (1). The questions that will be answered in this literary review are: How does fusion energy work, and how does it compare to other energy sources like coal, solar, and nuclear fission? What is the current state of fusion technology, and how are recent advancements contributing to its commercialization?

1.1 History

One of the first documented discussions of fusion was by Arthur Eddington, a British astrophysicist, in 1926. He hypothesized that stars produce energy by the fusion of hydrogen atoms into helium, which would later be proven true (2). In 1938, a scientist named Hans Bethe published a paper that correctly explained the fusion in the sun, known as proton-proton fusion. (3). In 1940, researchers began exploring how to use the science of fusion to generate power on Earth. The major problem is that fusion requires extremely high temperatures and a device that can contain the fusion fuel. This led to the development of magnetic confinement, which uses various magnetic fields to control the fusion fuel during the required high-temperature state, in around 1950 (4). One of the first successes of a fusion device was in Russia in 1958 with the tokamak, which used magnetic confinement (5). In 1960, the method of inertial confinement was conceived, which uses lasers pointed at a “pebble” of fusion fuel to achieve the conditions needed for fusion (3). In 1985, the International Thermonuclear Experimental Reactor (ITER) was created, and it does significant fusion research to this day. Another prominent research facility was the Joint European Torus, a prominent fusion research facility in England that is still operating today, which was created by the European Countries in 1973. JET created its first tokamak in 1983, which would later contribute to many world records (4). In 1997, the JET tokamak set the then-world record by using 24 MW of input power to generate 16 MW using fusion. In 2021, the JET tokamak achieved a new record of 59 MJ in 5 seconds (4). This record was eclipsed on October 3, 2023, when the JET tokamak generated 69 MJ in 6 seconds, using only 0.2 milligrams of fuel (6).

1.2 Current Context

Fusion requires at least 25 more years of development before it can become commercially viable. However, there have been many recent improvements in the energy generation process, including new methods to prevent as much damage as possible to the surrounding materials, a portable reactor that can harvest deuterium, and a device known as a spherical tokamak that can generate fusion more sustainably. Additionally, throughout the last decade, the number of private fusion companies has increased, despite the decline of public funding.

2 Fundamentals of fusion & fission

2.1 The science of fusion

Fusion involves combining two or more nuclei to produce energy. The most common fusion pathway involves two different hydrogen isotopes: deuterium (D), which has one neutron, and tritium (T), which has two neutrons (7). Fusion reactions are commonly seen in stars, including the sun, which contain large amounts of hydrogen (8). As shown in Figure 1, combining deuterium and tritium through fusion produces helium, a neutron, and some energy.

For fusion to occur, the system must reach approximately 100 million degrees Celsius, and the fuel must be pressurized to 10 times Earth's atmospheric pressure. The extreme conditions for fusion are required due to the electrostatic repulsion between the deuterium and tritium nuclei in their natural state. This repulsion can only be overcome when the temperature and pressure are sufficiently high, enabling the nuclei to fuse despite their inherent tendency to repel one another (9, 10).

In this environment, the two hydrogen isotopes will fuse and be in a plasma state, where the deuterium and tritium are stripped of their electrons, leaving only protons and neutrons. When the deuterium and tritium fuse with one another, there will be a loss in mass, where the mass of the reactants is greater than that of the products. The mass lost in this process gets converted into fusion energy (7).

$$
{}_{1}^{2}D + {}_{1}^{3}T \rightarrow {}_{2}^{4}He + 3.5MeV + {}^{1}n + 14.1MeV
$$
$$
= {}_{2}^{4}He + {}^{1}n + 17.6MeV
$$

Figure 1: The equation for D-T fusion. The 3.5 MeV of energy is the energy released from helium and the 14.1 MeV is the energy released from the neutron (7)

Another fusion reaction, the D-D reaction, uses two deuterium atoms to create energy in the same way as the D-T fusion (7). However, as shown in Figure 2, its products are different, releasing tritium and hydrogen in addition to 4.03 MeV. This form of fusion requires only deuterium, making it the more convenient fusion process when comparing the materials needed. However, the tritium product can be dangerous for humans and can increase the risk of cancer in certain circumstances (11). This is due to the radioactivity of tritium, which can cause mutations in the body. Tritium is released in the gas phase during the D-D fusion and can enter the body through inhalation and ingestion. Additionally, the tritium gas will sometimes mix with the oxygen in the atmosphere, becoming tritiated water (HTO), which has the same properties as water. While in this liquid state, some people might have mistaken it for water, unknowingly ingesting this dangerous liquid. Another disadvantage of fusion of D-D fusion is its higher temperature cost compared to D-T fusion, where it requires temperatures between 400 million to 500 million degrees Celsius (12).

$$
{}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T + 1.01MeV + {}^{1}_{1}H + 3.02MeV
$$
$$
= {}^{3}_{1}T + {}^{1}_{1}H + 4.03MeV
$$

Figure 2: The D-D fusion reaction (7).

2.2 Nuclear binding energy

The resultant energy from fusion arises from the concept of nuclear binding energy, the energy that keeps the nucleus of an atom tightly packed together. This binding energy is the cost that must be paid when an atom is broken apart into disparate protons and neutrons, and the same amount of energy is released when that atom is formed from those protons and neutrons. Correspondingly, if the binding energy released upon the formation of a reaction product is greater than the binding energies required to break apart each of the reactants, there will be a net energy release.

This is true of the resulting products of both D-T and D-D fusion. This discrepancy in binding energies means there is a loss in total mass as the reaction occurs, as it is converted to energy via $E=Mc^2$.

For D-D fusion, the combined deuterium atoms shown in Figure 3 are around 1 MeV each. This results in only 4.03 MeV per fusion reaction. For D-T fusion, however, the combined binding energy of tritium and deuterium is greater than that of D-D fusion, so the energy generated is greater: 17.6 MeV (13).

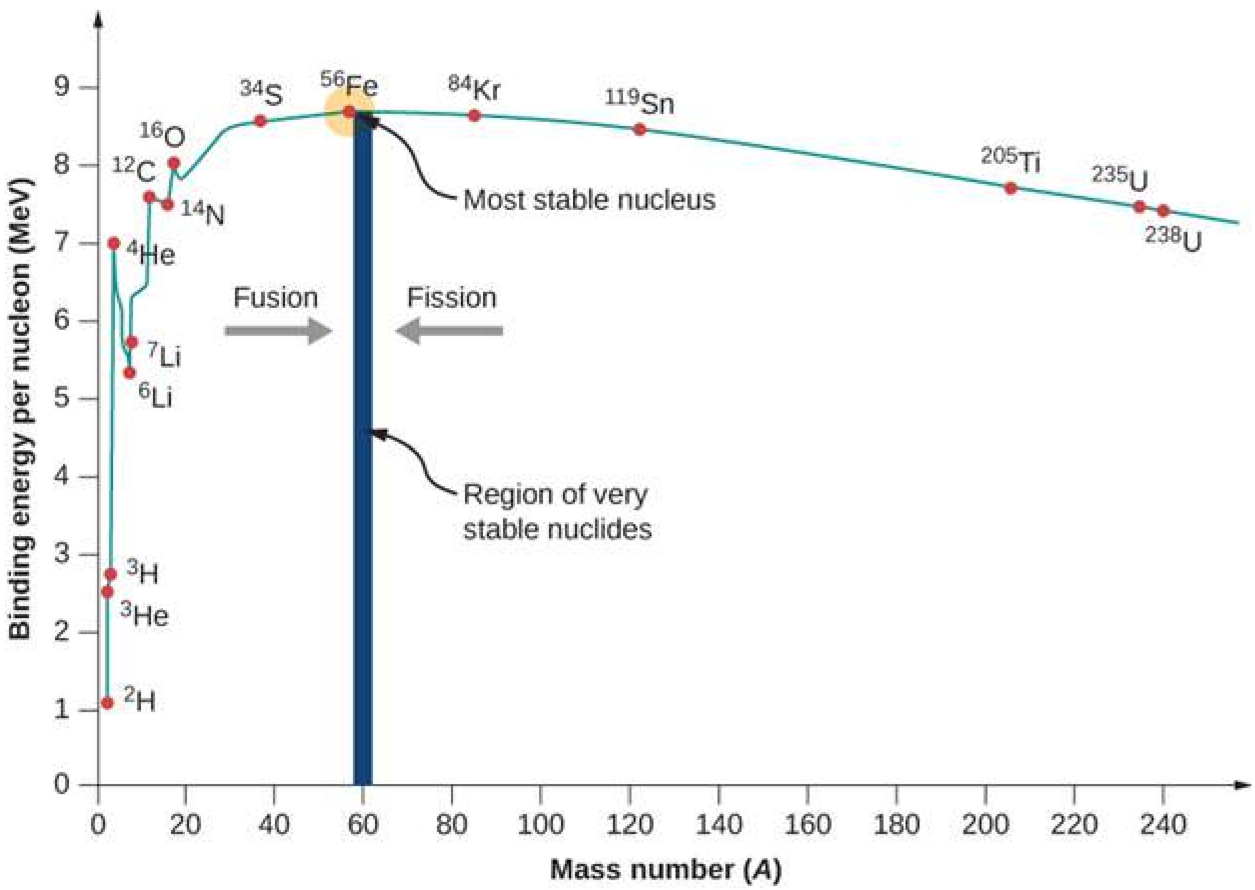


Figure 3: Nuclear binding energies for the most abundant isotopes for some elements, with an interpolated line. Fusion reactions fuse atoms with less binding energy but less mass in order to produce an atom with more binding energy, hence the arrow from right to left. Fission, on the other hand, uses an atom with less binding energy but more mass to create new atoms with more binding energy, hence the arrow from right to left (14)

2.3 Fusion on Earth

Some form of confinement is needed to contain the fuel, temperature, and pressure needed to perform fusion. The two main methods are magnetic confinement and inertial confinement. In magnetic confinement, overlapping magnetic fields from different portions of the device confine the fusion fuel, which would be in the plasma state under the temperatures and pressures required for fusion. This is effective because the magnetic field would influence the electrical charges on the isotopes D and T, allowing the fuel to be contained and controlled. The magnetic fields prevent the plasma from contacting the walls where it is stored as the plasma reaches 100 million degrees Celsius (15). However, even through magnetic confinement, the materials surrounding the nuclear devices and devices used to perform fusion will still get damaged during fusion. The main devices using magnetic fusion are tokamaks and stellarators shown in Figure 4 and Figure 5, respectively.

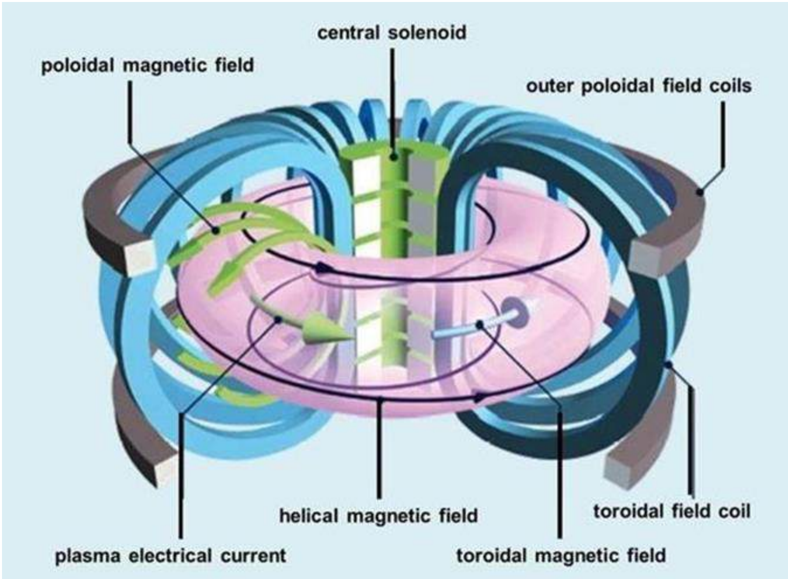


Figure 4: Basic tokamak components include the toroidal field coils (in blue), the central solenoid (in green), and poloidal field coils (in grey). The total magnetic field (in black) around the torus confines the path of travel of the charged plasma particles. Each of the field coils emits a donut-shaped magnetic field, which is used to stabilize the plasma. The electrical current shown is used to heat the plasma to the required temperature (5).

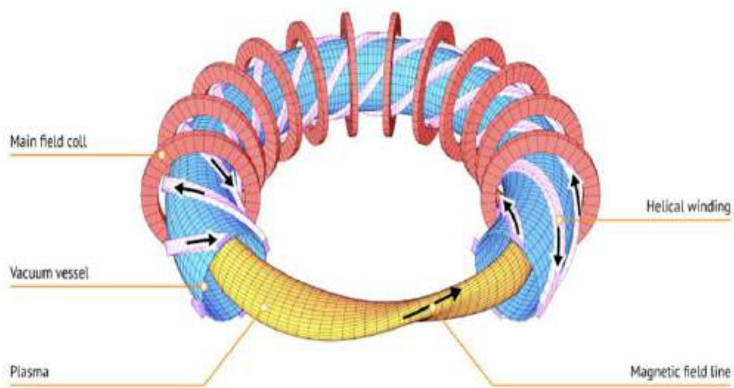


Figure 5: Stellarator using magnetic confinement technology. The main field coils are magnetic coils that generate a strong magnetic field. The vacuum vessel stores the plasma in a low-pressure environment, which is different from the pressure condition needed for fusion as the high pressure typically resides in the plasma itself, not the environment. The helical winding is used to twist the magnetic fields created by the magnetic field coil to maintain the plasma better. The magnetic field line shows the various magnetic fields used to confine the plasma (16)

The second method is inertial confinement, which pinpoints highly concentrated ions or lasers onto a D-T fuel pebble a few millimeters in diameter. This confinement method, which uses a device called a hohlraum, allows the fuel pebble to reach the pressure and temperature requirements for fusion, as shown in Figure 6 (17). This confinement method differs greatly from magnetic confinement, only using the fuel capsule in the middle to contain the plasma with the assistance of magnetic fields.

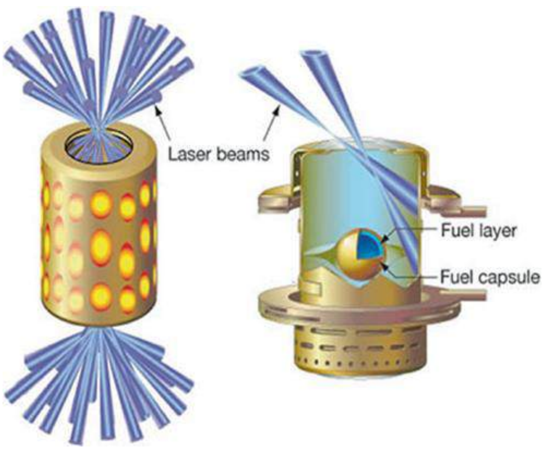
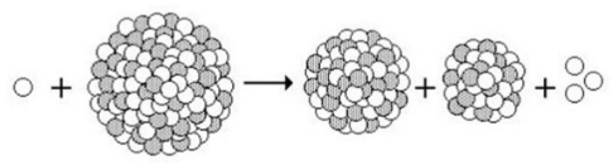


Figure 6: Inertial confinement hohlraum showing lasers pointing at the fuel capsule that contains the fusion fuel. These lasers allow the fuel to reach the required temperature and pressure needed for fusion (17).

2.4 The science of fission

A more well-known form of nuclear energy is nuclear fission energy. The “fission” aspect comes from the analogy that a fluid in the shape of a sphere can form two separate spheres when affected by an external material. Nuclear fission occurs when a neutron gets fired into an atom with many protons and neutrons, such as uranium-235 and plutonium-239, causing the atom to become unstable and eventually split. This split results in a release of energy due to the loss in mass, the same as fusion (18). Nuclear fission products are not pre-determined, but there are several probabilistic outcomes. An example fission reaction is shown in Figure 7, where after striking a neutron into uranium-235, it causes the uranium atom to be unstable, leading to its splitting into fission products and energy. The energy generated by nuclear fission also relates to the binding energy mentioned in 2.2. As shown in Figure 4, the binding energy of Krypton has greater binding energy than that of Uranium. Generally, the sum of the combined binding energy of the nuclear fission products will always be greater than that of the reactants (14).



$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} + \mathrm{Energy} $$

Figure 7: Example of nuclear fission reaction using expected product masses. This reaction produces three neutrons, although small variations in the reaction can change the neutron output. For example, having a product of Barium 142, compared to Barium 141 shown in this figure, would result in 2 neutrons instead of 3 (19).

3 Advantages of fusion

3.1 Climate

Fusion has many potential advantages, including its lack of greenhouse gas emissions during the energy generation process (20).

Deuterium, one of the essential fuel isotopes, is commonly harvested through electrolysis, which does not produce CO2 if a clean energy source powers the cell. Electrolysis uses an electrical cell, shown in Figure 8, and generates the chemical energy to split the hydrogen from water, an abundant source. The water will result in hydrogen and oxygen. The hydrogen harvested will contain protium, the common form of hydrogen with one neutron, and deuterium. The electrical cell separates the deuterium from the hydrogen generated (21).

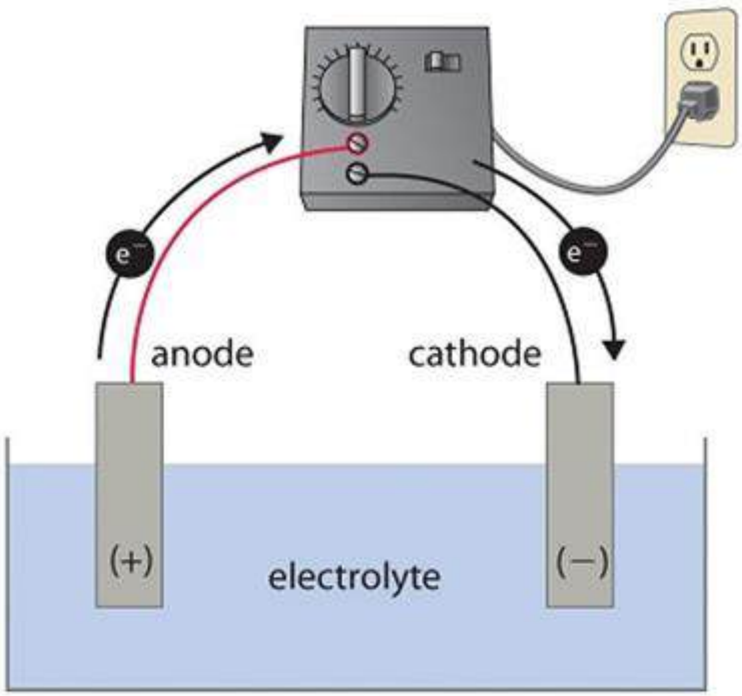


Figure 8: A diagram of how an electrical cell works. The anode is where the oxidation occurs, resulting in a loss of electrons. This loss of electrons moves to the cathode, which is when the reduction, the gain of electrons, occurs. This movement of electrons will facilitate the creation of chemical energy (25).

Tritium is harvested using two methods, most commonly through fusing lithium with a neutron, as shown in Figure 9, where tritium is a product. The lithium reserves within the earth's crust are estimated to be 22 million tonnes of minable lithium (22). However, mining lithium releases around 1.3 million tonnes of carbon annually, which is small compared to the 30.6 billion tonnes emitted by the fossil fuel industry annually, although not negligible (23).

$$ {}^{6}_{3}Li + {}^{1}n \rightarrow {}^{3}_{1}T + {}^{4}_{2}He + 4.784MeV $$

Figure 9: Equation for harvesting tritium using lithium (7)

An alternative way to harvest tritium is from the D-D fusion in Figure 2. The tritium produced in that fusion reaction can be used as material for the D-T fusion. However, harvesting lithium may be preferred because of the lower temperature requirements of the lithium fusion reaction. For instance, a widely used material for lithium fusion is lithium oxide (Li_2O), a compound formed from lithium and oxygen, which can facilitate lithium fusion reactions at temperatures as low as 400 degrees Celsius (24).

3.2 Safety

Fusion also has the potential to be very safe compared to its other nuclear counterpart: fission. Fission can create a chain reaction, where the reaction can proceed uncontrolled and release large amounts of energy, possibly resulting in a reactor meltdown. Since fusion reactions only occur under extreme conditions, there is no such risk of a runaway reaction. If there is any disruption, the fusion reaction would likely stop as the temperature would drop under the required 100 million degrees Celsius (26).

4 Challenges of Fusion

Fusion has numerous challenges that delay its progress to become commercially viable. One of the main challenges is the high-temperature requirement, which makes it difficult to sustain energy generation. In a tokamak, one of the magnetic confinement devices mentioned in Section 2.3, there are usually three separate heating systems, each delivering a million watts of power during fusion energy production (27). The extensive effort required to produce fusion energy makes it more difficult compared to other energy sources like solar and coal, which do not require as much input to generate energy.

Magnetic and inertial confinement can ideally control and store the plasma but do not completely prevent the plasma from damaging surrounding materials, and a more effective method of preventing plasma damage must be determined. In addition, the plasma is extremely difficult to stabilize consistently. This is because during the fusion process, plasma must be contained effectively using the confinement methods mentioned before. However, these confinement methods sometimes display instabilities, causing the plasma to become unstable. The plasma-stability problem highly impacts its usage as fusion energy cannot be generated without a stable plasma, and an unstable plasma can increase the damage to the fusion device’s interior. Lastly, the investment needed to build a fusion reactor is potentially much higher than that of all other energy reactors, as shown in Figure 10. Due to the high capital costs, commercial fusion reactors would require very large investments on behalf of private companies or governments, who may not be willing to take on that level of financial risk.

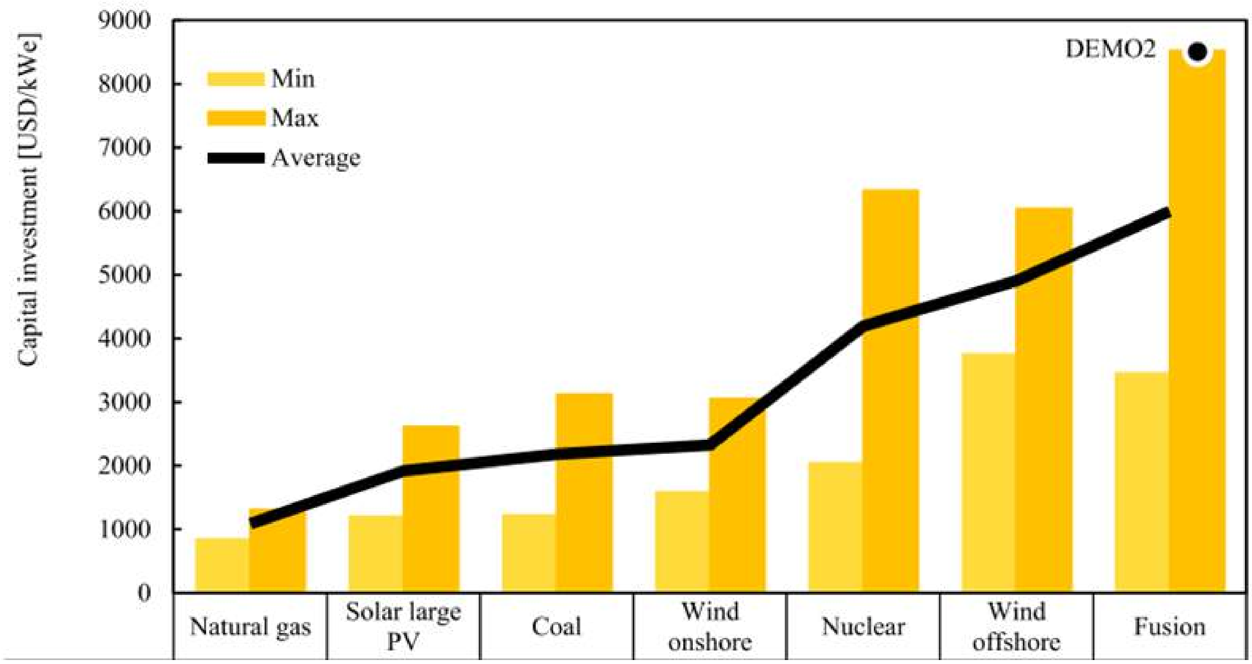


Figure 10: Capital investment required to build different energy power plants in USD/kW. Fusion theoretically has the highest average capital investment. (28)

5 Comparisons to other energy sources

5.1 Coal

Coal energy is one of the most popular forms of electrical energy generation in the United States. As shown in Figure 11, coal energy is generated in coal-fired power plants, where coal is ignited and burned via a combustion reaction used to heat water. The water then evaporates into steam from the combustion heat, turning a turbine and generating electricity.

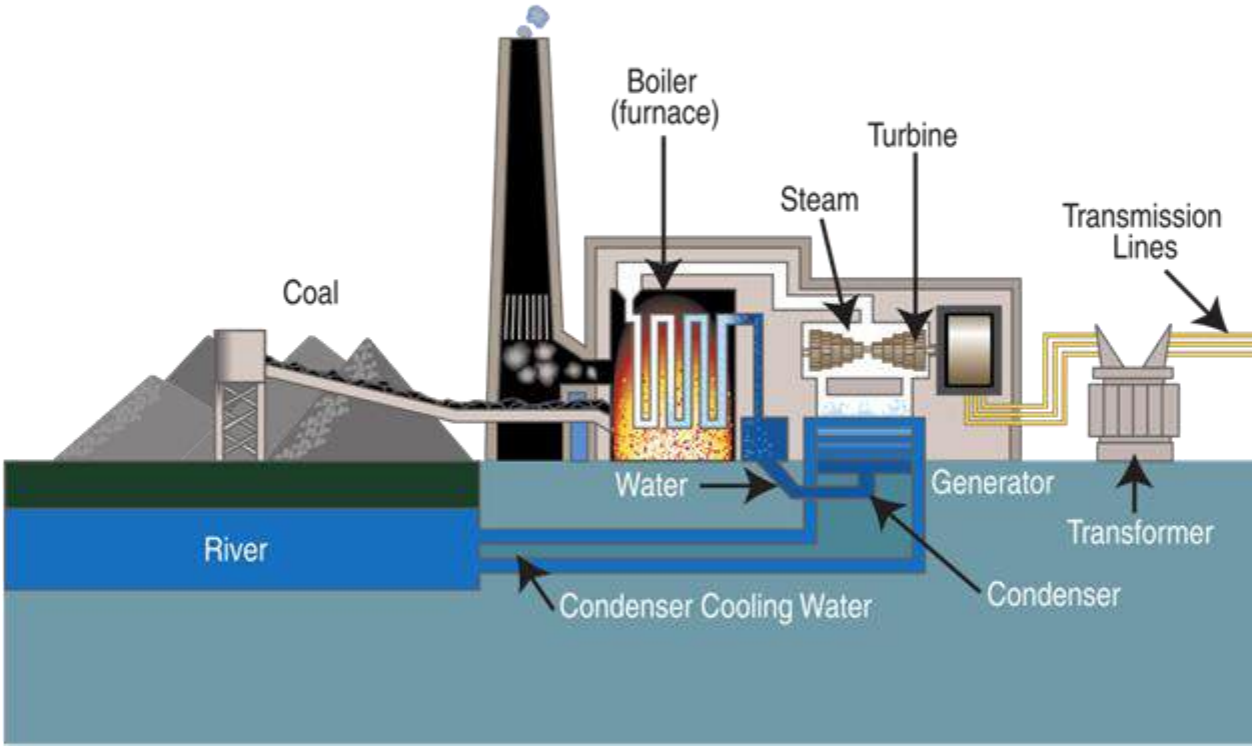


Figure 11: The coal energy generation process (29)

Coal energy is one of the most well-understood and readily accessible energies used in the world today—however, this form of energy generation results in a large amount of carbon emissions. Figure 12 compares carbon emissions per unit of electricity generated, where coal leads all other energy technologies. A possible alternative source to replace coal can be fusion, which only produces clean energy during its process. Additionally, fusion can generate 4 million times more energy than coal without emitting any carbon emissions (30). One flaw of fusion energy compared to coal energy is the requirements needed for fusion to happen on Earth, as mentioned in Section 2.1, with a high-temperature threshold that is difficult to maintain.

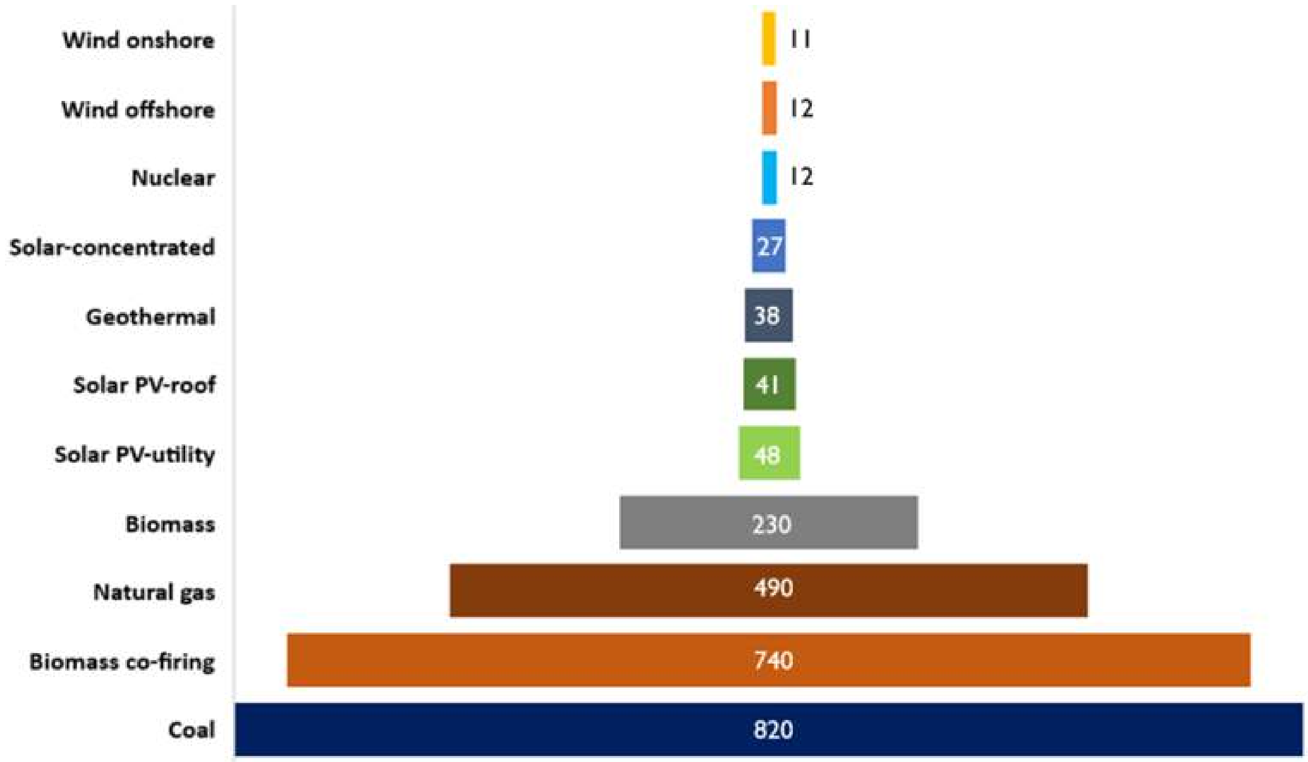


Figure 12: CO2 Emissions per unit of electricity generated. Note that the nuclear section shows the carbon dioxide emitted from nuclear fission, not fusion. Additionally, the carbon emissions from solar energy shown in Figure 13 come from the actual manufacturing of the solar panels. After the panels are created, the solar energy generation process does not emit carbon (20).

Additionally, Figure 13 shows clean, renewable energies like hydropower, wind, and nuclear fission are much safer than fossil fuels like brown coal, coal, and oil. Given the dangers associated with coal energy production, fusion may be a safer alternative.

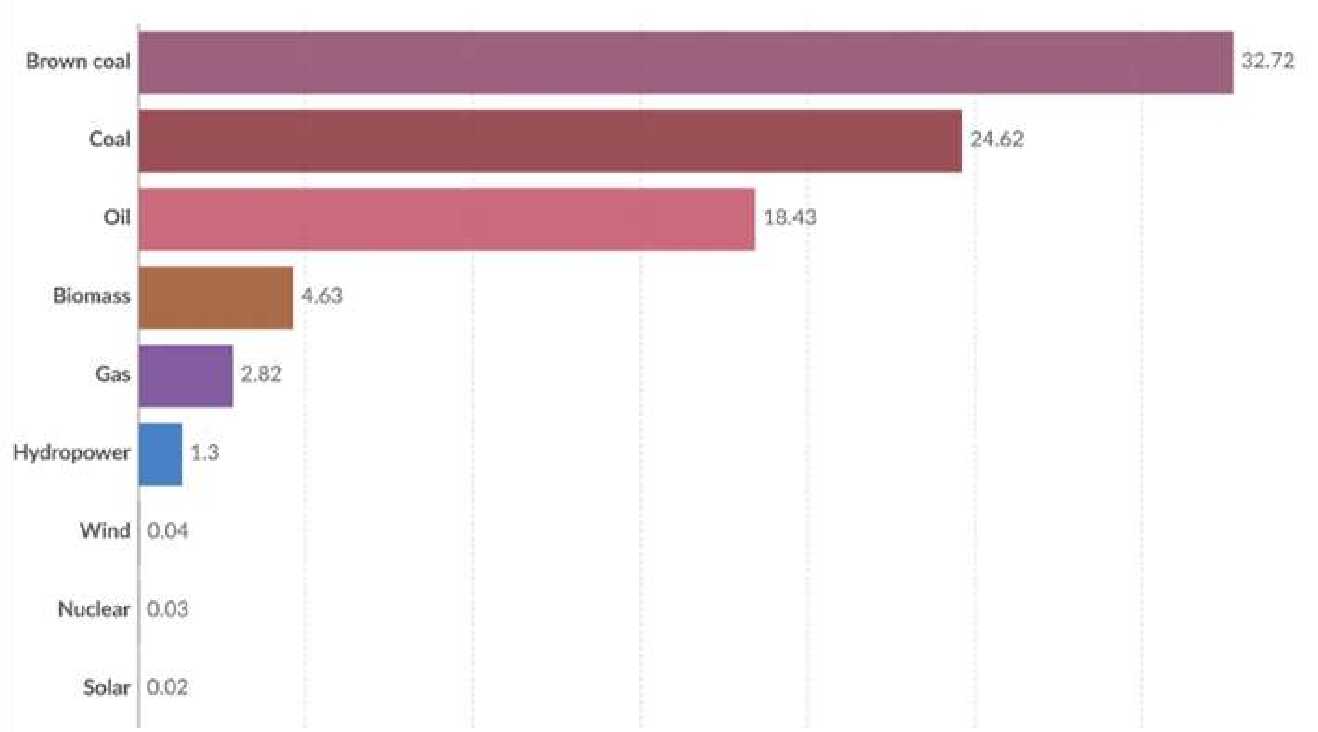


Figure 13: Death rates per unit of electricity production for different types of energy. Brown coal is a type of coal that emits less carbon when ignited but generates less amount of energy. The "nuclear" section is energy generated by nuclear fission (31).

5.2 Solar

Solar energy utilizes the sun to generate energy. Solar panels are usually made of silicon, a material that converts the solar radiation from the sun to usable electricity (32). Both fusion and solar are renewable and clean forms of energy. A benefit of solar energy generation is that it is well-established and was used to power 4.5 percent of the total global electricity generation in 2022. In contrast, fusion energy generation still needs decades to generate energy commercially (33). However, fusion dominates solar in terms of energy production. The JET recently generated around 69.26 megajoules in 6 seconds, which is around 19.23 kilowatt-hour (6). A standard 300-watt solar panel, which takes up an area of 19.5 feet, generates around 1.8 kilowatt-hour in a day (34, 35). In that case, a fusion reactor can produce the same renewable, clean energy at the same rate as 150,000 solar panels using only 0.21 milligrams of fuel. This is significant in terms of meeting the energy generation needs. Additionally, many solar panels would need to be built in order to generate sufficient amounts of energy. This is a problem as harvesting silica sand, a material used to produce the silicon, would release 22.7 kilograms of carbon dioxide per metric ton (36).

Additionally, solar panels are not permanent and will lose their efficiency every 20-30 years (37). This problem can unintentionally make solar panels a technology that would constantly emit carbon emissions as long as solar energy generation is primary. On the other hand, fusion energy primarily needs to concentrate on sustaining the fusion reactions, becoming an alternative form of energy that requires less space, with the Wendelstein 7-X, the largest stellarator in the world, only taking the area of 659 feet, which is the area of only 33 solar panels (38)

Solar energy generation is also largely inconsistent as shown in Figure 14. This unreliability largely affects solar energy's deployability, as for certain portions of the year, solar will generate at most one-half of its peak energy output. Fusion does not have this problem of depending on a variable source since as long as the fusion reactor is powered at the required conditions, the energy generated from the reactor will be largely consistent. This is essential to meet consumer energy demands.

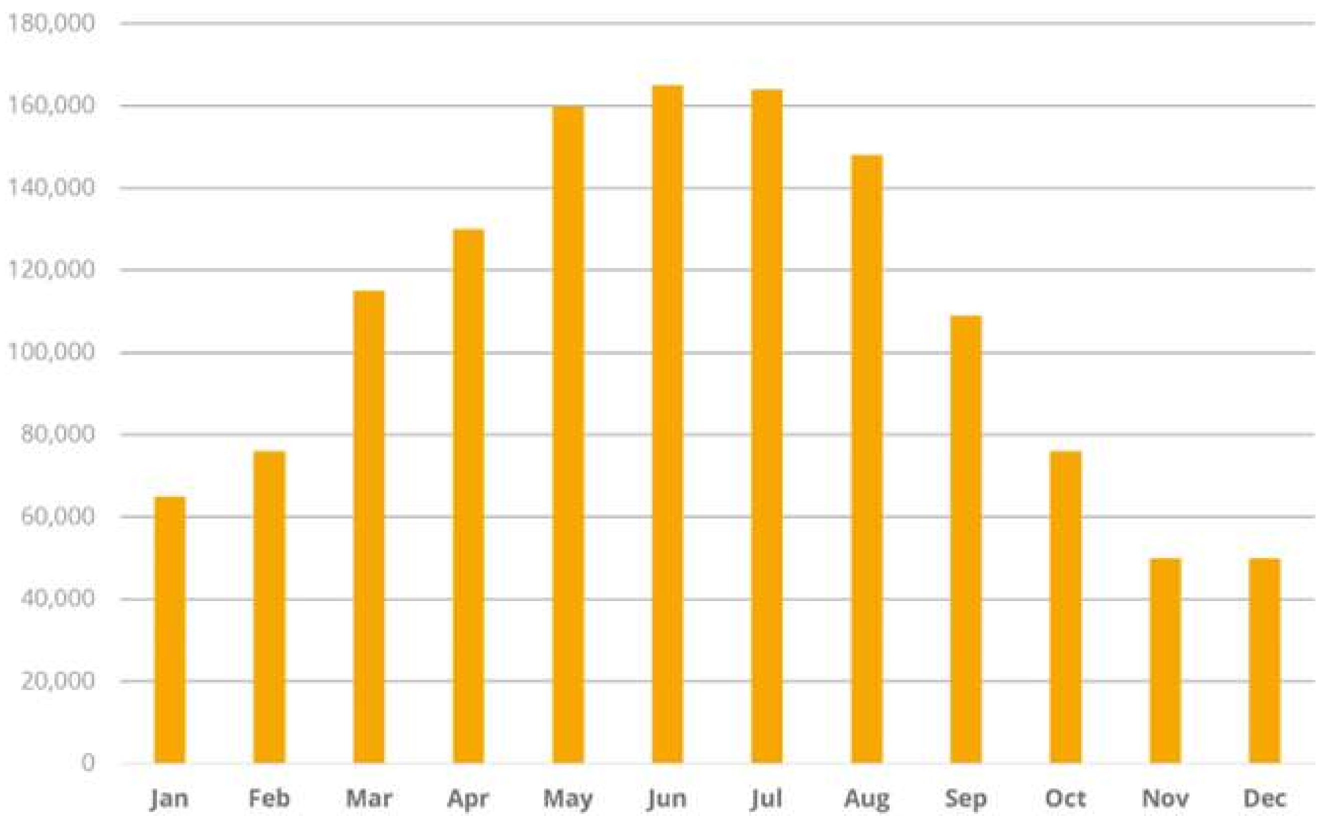


Figure 14: The month vs solar energy production in kilowatt-hours per month in an industrial facility near Racine, Wisconsin (39)

Fusion also has advantages over solar energy in terms of material requirements. In Figure 15, to generate the targeted amount of energy, people would need to invest around 165 billion tons of material into solar energy, far surpassing all other forms of energy generation. This is significant as it shows the massive cost of building solar panels. Overall, while solar energy currently has its positives compared to fusion, it can solve many of the disadvantages associated with solar energy, such as solar's consumption of space and its dependence on the sun.

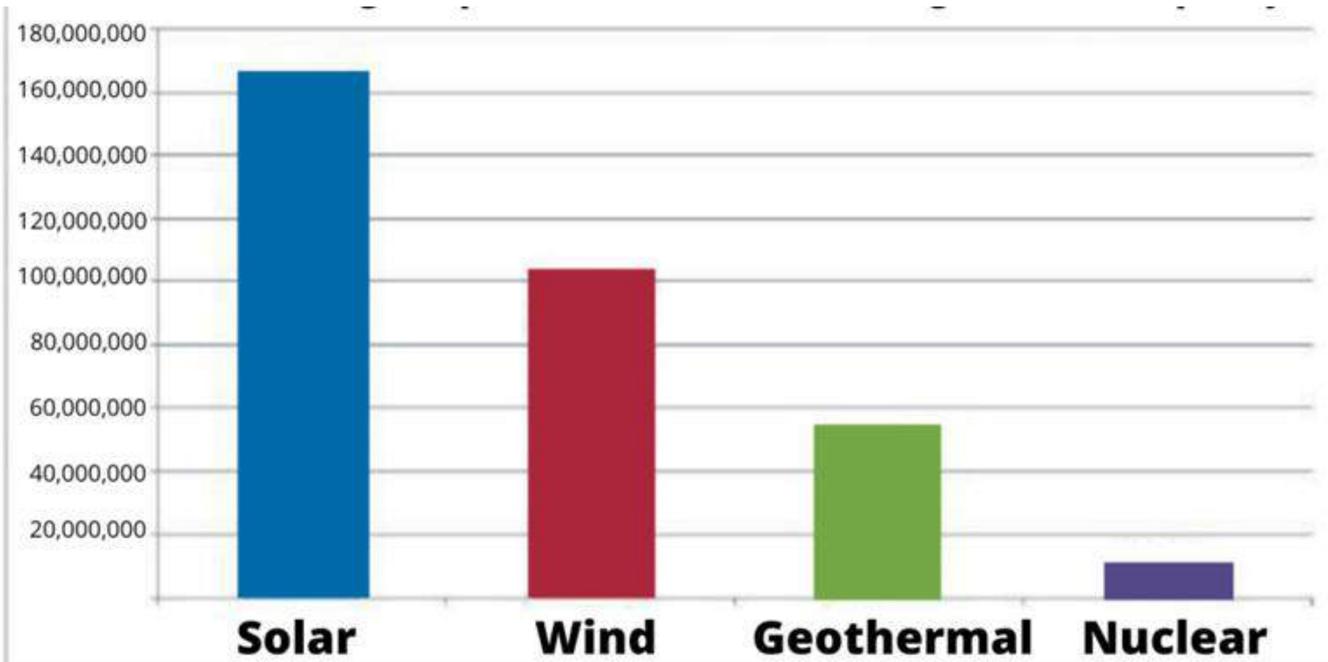


Figure 15: The amount of material required (tonnage), to build a 10,000 terawatt-hour generation capacity needed. The nuclear section shown in this graph is the tonnage required for nuclear fission, not nuclear fusion (40).

5.3 Nuclear fission

Similarly to coal and solar, fission is currently more developed than fusion in terms of commercially generating energy because the conditions needed for fission are far more achievable than those required for fusion. Like fusion, the fission process itself does not emit any form of carbon emissions; however, mining uranium produces carbon dioxide.

A key advantage of fission energy is its clean energy, which has been harnessed effectively. As demonstrated in Figure 16, the reduction in carbon emissions due to the use of fission reactors is growing rapidly, and fusion energy has the potential to enhance this reduction further, although the amount of possible impact cannot be speculated today.

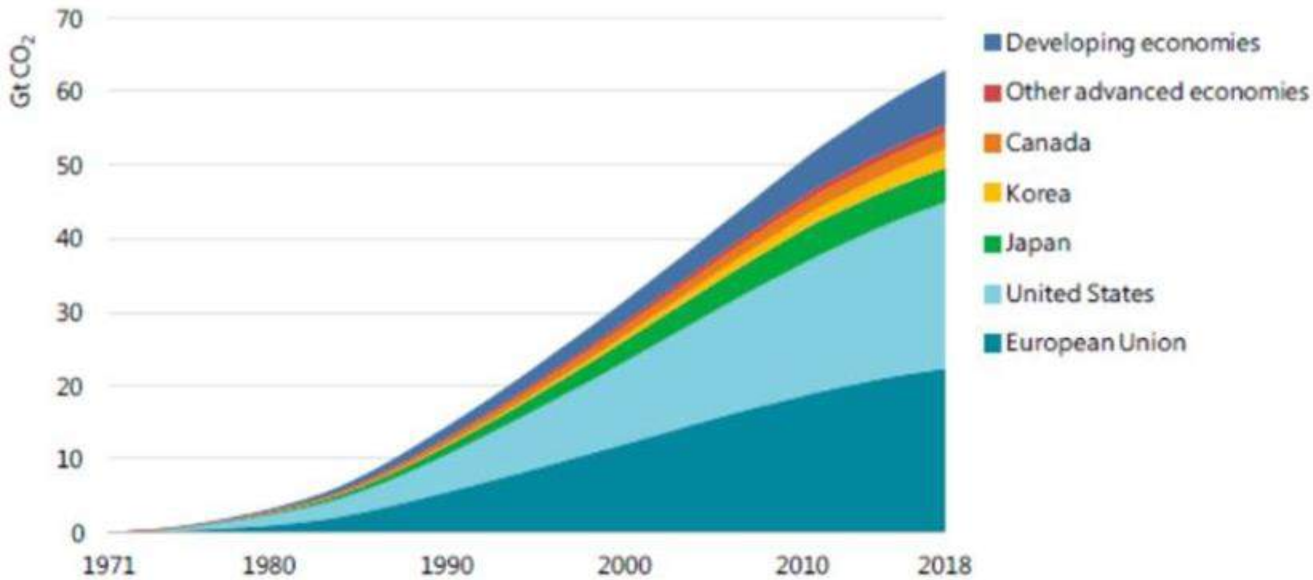


Figure 16: The amount of carbon emissions avoided by fission by various countries from 1971 to 2018. GtC02 means gigatons of carbon dioxide (41).

However, fission has the possibility of producing a chain reaction, which can lead to reactor meltdown and the emission of several reaction products, a trait nonexistent in the fusion reaction. Possible fusion products include krypton and barium, which can be hazardous to humans. Krypton can cause loss of consciousness or even death, and barium can cause extreme breathing difficulties, which can also be fatal (42, 43). Similarly to fusion, the fission reaction can include tritium as a byproduct.

The dangers of fission's high-level radioactive waste were seen in the Fukushima nuclear disaster (2011) and the Chernobyl disaster (1986), where the fusion reactors in Fukushima and Chernobyl had reactor meltdowns. These meltdowns emitted radiation that killed around 2300 people in Fukushima and 4000 people in Chernobyl (44, 45). The aftermath of reactor meltdowns from fission is also very significant in the long term. As shown in Figure 17, the doses of radiation from a fission reactor meltdown can last an exceptionally long time. This means that any civilians affected by a fission reactor meltdown will have to bear the harmful effects of the fission products for at least 27 years, with many likely dying from the symptoms before the radiation dissipates.

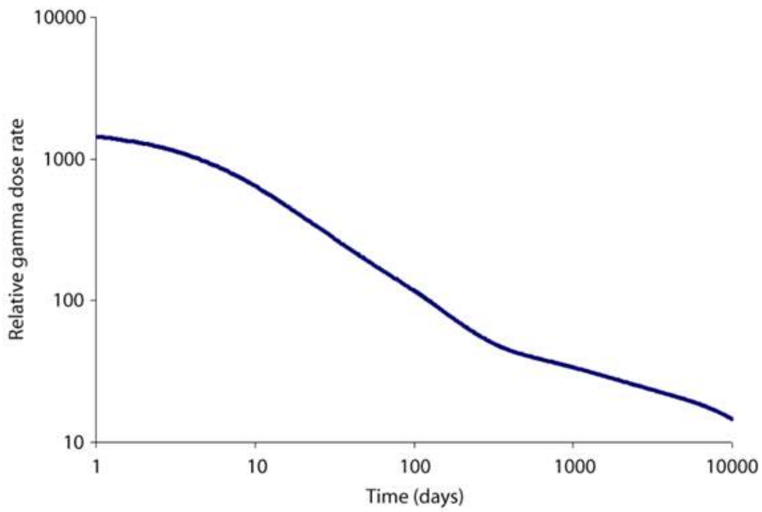
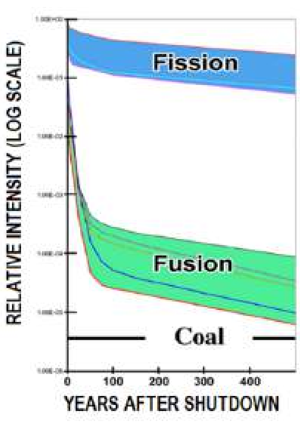


Figure 17: The external relative gamma dose for a person in the Chernobyl disaster site. 10,000 days is 27 years (46).

As illustrated in Figure 18, fission produces much higher radiotoxicity than fusion. Long after shutdown, fission reactors maintain a high level of radiotoxicity for hundreds of years, whereas fusion reactors are expected to start with lower levels of radioactivity, which will likely diminish significantly within the first 50 years. The extreme decrease in fusion radiotoxicity can be attributed to the radioactive decay of tritium as shown in Figure 19, as tritium contributes to fusion's radiotoxicity emissions. Additionally, a single fusion reaction generates four times more energy than a single fission reaction, illustrating the potential for fusion to become a larger component of worldwide energy generation than fission (47).



Plant model	FW/blanket structure	Tritium generating material	Neutron multiplier	FW/blanket coolant
1	vanadium alloy	Li_2O ceramic pebble bed	none	helium
MINERVA-W	low activation martensitic steel	liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	water
MINERVA-H	low activation martensitic steel	Li_4SiO_4 ceramic pebble bed	beryllium	helium
4	SiC/SiC	liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	liquid $Li_{17}Pb_{83}$
5	Low Activation martensitic steel with SiC/SiC insulators	liquid $Li_{17}Pb_{83}$	$Li_{17}Pb_{83}$	helium and liquid $Li_{17}Pb_{83}$
6	SiC/SiC	Li_4SiO_4 ceramic pebble bed	beryllium	helium

Figure 18: Relative radiotoxicity of fission and fusion reactors versus time after shutdown. The bands correspond to differences in the fuel cycle (reprocessing) for fission and the choice of

structural material for fusion. The bottom black line is the radiotoxicity of coal (48). The table on the right shows the different fusion/fission plant models used to create this graph comparison and information on each of these models.

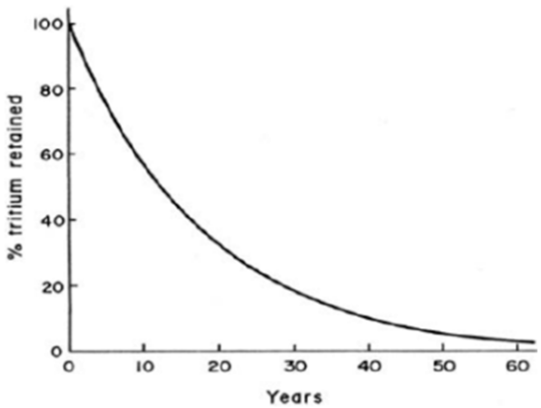


Figure 19: Radioactive decay curve of tritium from a test in Al-Shanafiya, Iraq (49)

6 State of the industry

6.1 Recent advancements

There have been numerous advancements in fusion within the past few years. In 2022, the International Atomic Energy Agency reported a total of 143 fusion devices, including tokamaks, stellarators, hohlraums, and alternative concepts, as shown in Figure 20. Eleven of the 143 devices are under construction, while twelve have been designed but have not yet started construction. The goal of harnessing fusion energy is being implemented worldwide, ranging from the United Kingdom to Russia to South Korea. However, many of these fusion devices will only be completed 10-20 years from now (20).

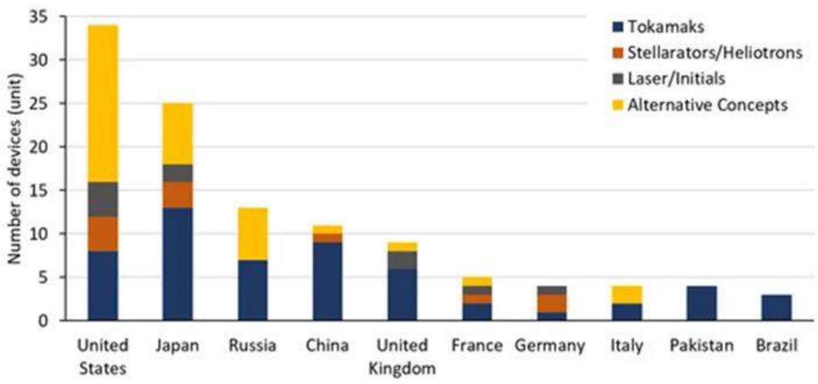


Figure 20: Top 10 countries with planned, under construction, and operating fusion devices, (20).

Another advancement is the increasing number of fusion companies in the world. Figure 21 illustrates that the number of private fusion companies has increased fivefold within the last fourteen years, showing that many people around the world are starting fusion companies because they have begun to see the potential of fusion as a possible energy source. Additionally, these advancements are widespread, with these private companies being located in Canada, the UK, the EU, China, Japan, and Australia. As these companies grow and advance, it could help fusion energy become one of the primary sources in the future.

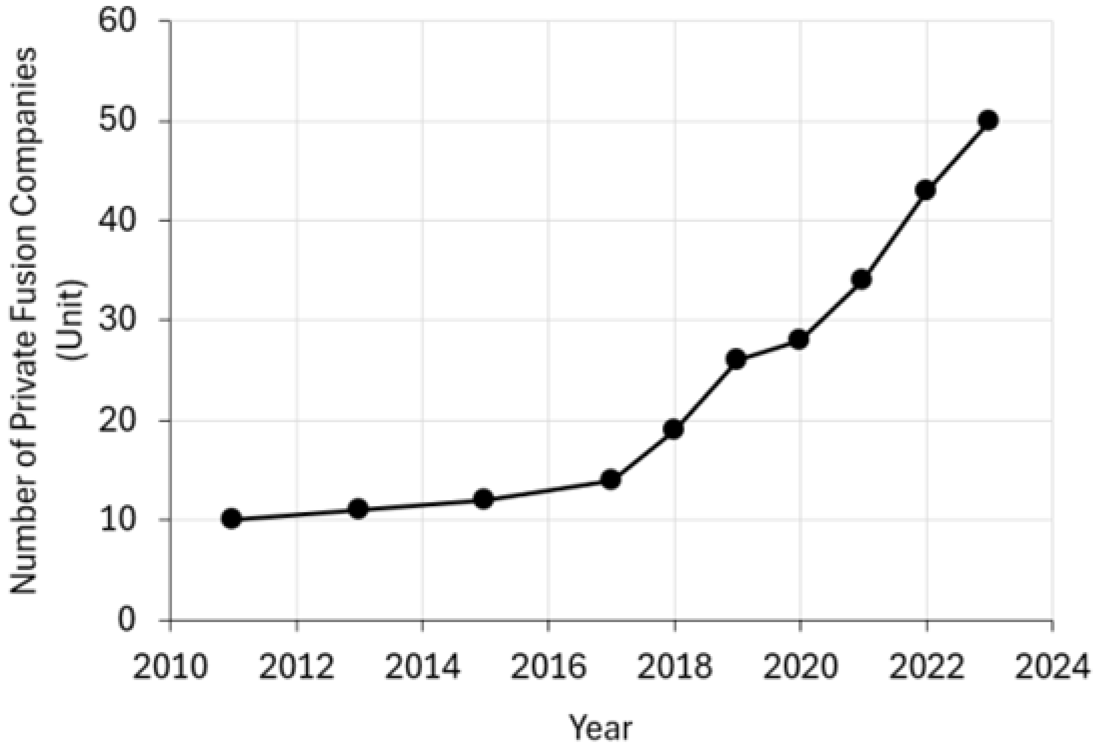


Figure 21: Number of companies involved in fusion worldwide from 2010 to 2024. (20)

In 2023, the International Thermonuclear Experimental Reactor (ITER), the biggest fusion project researching ways to bring fusion into the mainstream, developed a strategy to stabilize plasma better for its tokamak using four phases. The first phase is to heat and stabilize the fusion fuel in the tokamak to its required temperature using the periodic bursts that occur within plasma during this heating process. The second phase uses magnetic fields to shape the plasma and maintain its state. During this phase, researchers will increase the plasma current and the flow of electric charge through the plasma to stabilize it effectively. In the third phase, natural plasma instabilities begin to happen and the fourth phase is the transportation of the plasma out of the tokamak. Using this method, the plasma was stabilized for a duration that lasted five times longer than the typical energy confinement time. This increase in plasma stability is significant because improved plasma confinement prolongs the duration of fusion reactions, enhancing energy production and minimizing plasma-induced damage, addressing some of the critical challenges associated with fusion energy (50).

As of 2024, the creation of a portable deuterium reactor was reported. In this reactor, an electrolytic cell within its core extracts deuterium from water. This portable reactor allows deuterium to be transported more easily. In turn, this can make obtaining fusion fuel more convenient. Researchers used 1.5 liters of water sourced from the Gornja Trepca region in Serbia for three experiments, shown in Figure 22. The figure shows the effectiveness of the deuterium reactor at harvesting a large amount of deuterium from water, especially when compared to the deuterium within the water before electrolysis. This advancement could enable the construction of fusion devices in locations far from water sources, greatly expanding the potential sites where fusion reactors can be created.

	Concentration of D_2O (ppm) (Before Electrolysis)	Concentration of D_2O (ppm) (After Electrolysis)
1st Experiment	148	525000
2nd Experiment	148	753000 (Surface)*[1]
3rd Experiment	148	856000 (Bottom)*[2]

Figure 22: Before-and-after concentration of D2O for the electrolysis process, showing at least a 3550x increase compared to the initial deuterium value (51).

Another technology being developed is the spherical tokamak, which uses D-D fusion to generate energy and offers advantages in terms of lower cost and reduced plasma damage compared to conventional tokamaks. As shown in Figure 23, the conventional tokamak and the spherical tokamak each offer distinct spatial advantages. The conventional tokamak provides more width, whereas the spherical tokamak has a greater height. Spherical tokamak's compact nature can reduce the amount of plasma leaking out from the magnetic fields, which in turn, reduces the possibility of an unstable plasma. Additionally, the compactness of the spherical tokamak can help achieve more pressure from the emitted magnetic fields due to the small amount of space these fields need to cover. The compact design of the tokamak can also enhance the pressure generated by the magnetic fields, as these fields need to cover a smaller volume. Since the spherical tokamak is more compact, it can be cheaper to manufacture while maintaining the conditions needed for nuclear fusion.

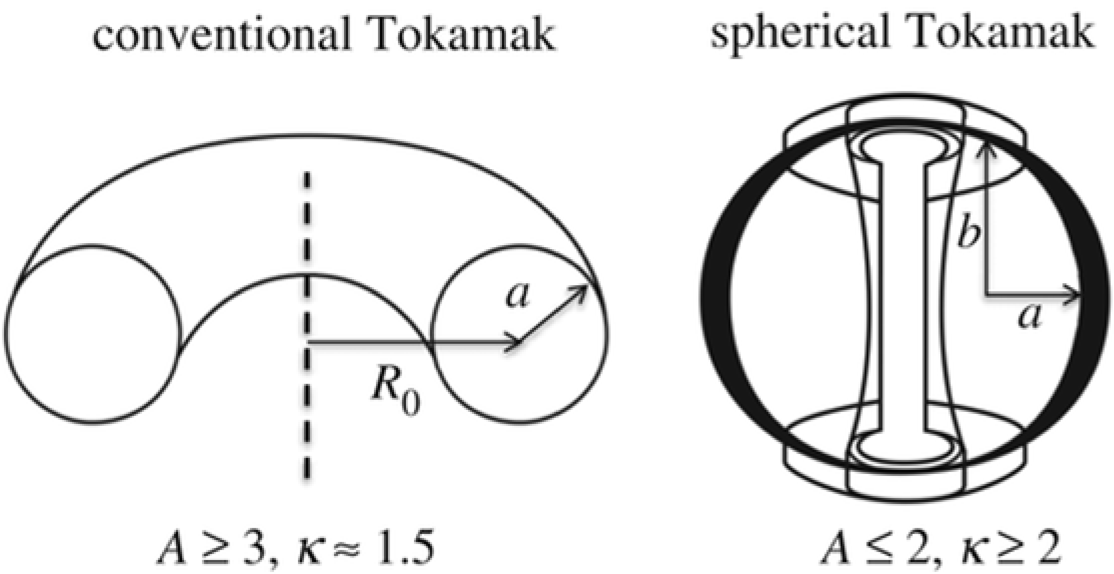


Figure 23: Schematic of conventional and spherical tokamaks. The aspect ratio A = R0/a and the elongation κ = b/a. (52)

Compared with other fusion devices, as shown in Figure 24, the spherical tokamak has a relatively high triple product. This observation can be attributed to its compact nature, which accelerates the pressure and temperature needed for fusion reaction while stabilizing the plasma efficiently to generate as much energy as possible. Currently, the ST40 is better than a majority of fusion devices in terms of achieving the fusion conditions but still requires more development to create commercial fusion energy.

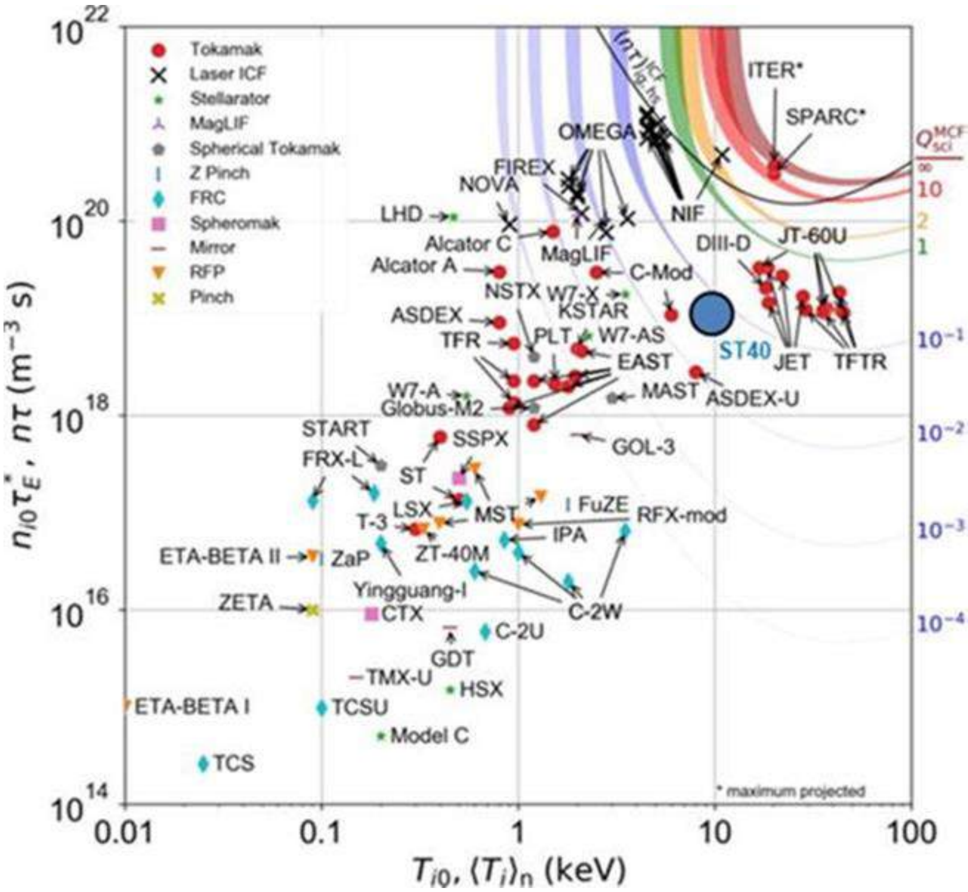


Figure 24: The triple product (measure of how well a device reaches fusion conditions) vs plasma temperature for several fusion devices worldwide. The spherical tokamak is labeled as the "ST 40" dot (the big purple dot). In this graph, the x-axis represents the plasma temperature. A fusion device requires at least 10 keV to generate commercial fusion energy, and the spherical tokamak ST 40 still needs to reach that mark. On the y-axis is the triple product, which measures how well a device reaches the required fusion conditions, where the ST40 is one of the higher recorded fusion devices (53).

6.2 Funding

One challenge that fusion faces is the recent lack of public funding from the United States. As shown in Figure 25, total fusion funding has been slowly dwindling, with the current fusion energy investment being only half of that of the peak fusion energy investment around the 1980s. This is very significant as ITER, one of the research facilities that this funding goes to, has the most powerful tokamak up to date, being able to generate 10 times the amount of heat needed to kickstart the fusion reaction, ultimately resulting in a net positive gain in energy generation. Even though ITER is being supported by other places like China, Europe, Japan, India, the Republic of

Korea, and the Russian Federation, the loss in funding from the United States will undoubtedly limit the rate at which ITER's research progress advances (54).

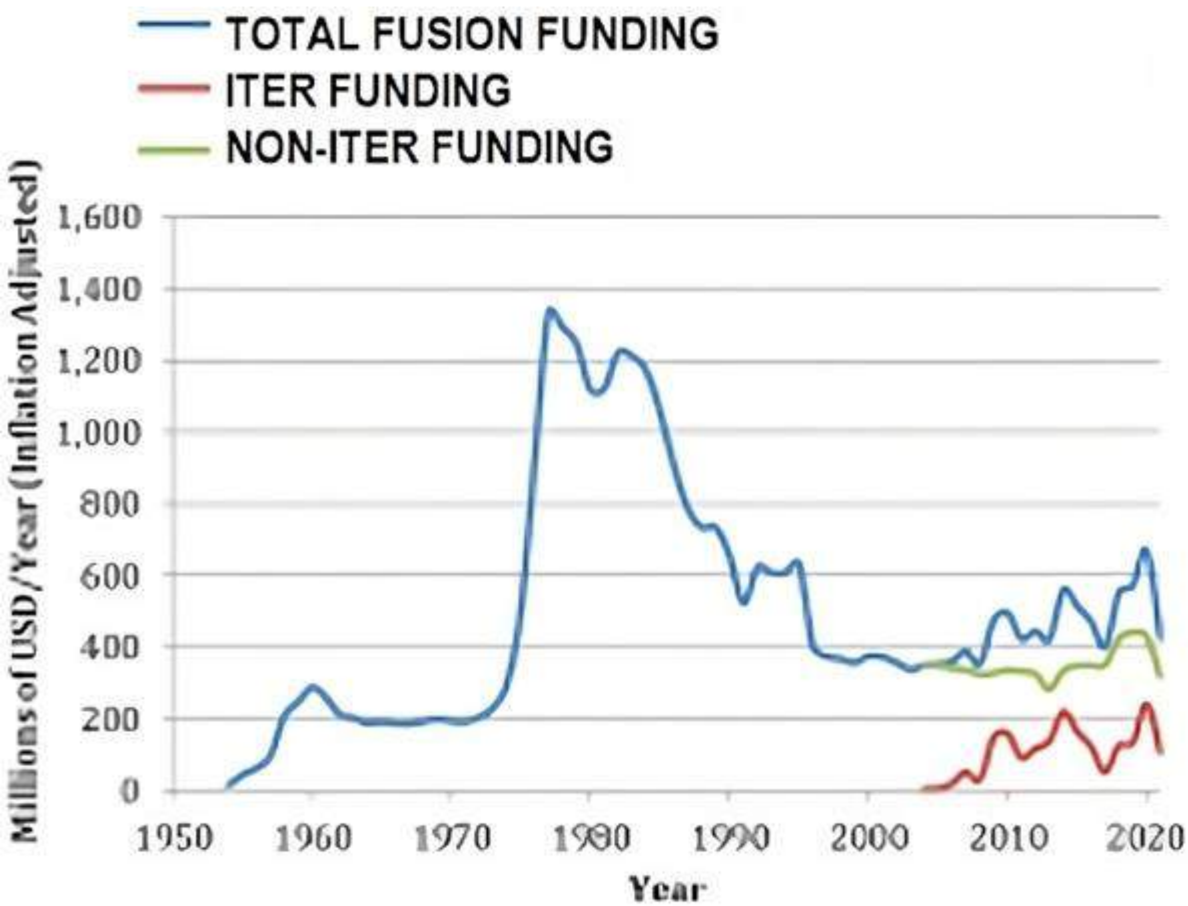


Figure 25: Funding for Fusion Energy in Millions of Dollars (inflation-adjusted) from 1950 to 2020 from the United States Government (55).

7 Discussion

When I began this project, I had thought that fusion would be an energy that could quickly positively impact the world. However, as I kept researching through online articles and research papers, I realized that the current situation of fusion still has a lot to be desired, and it would take a long time before it can be commercially viable. One problem of fusion that stood out to me during my research is how difficult it is to contain plasma. When I first read about magnetic and inertial confinement, I thought plasma could be easily contained. However, as I read more articles, I realized that this problem is more challenging to solve than I initially believed due to the intense heat that both the plasma and the temperature environment emit. Another thing that surprised me about fusion is how much energy a fusion reaction will generate. When I imagine how fission and fusion generate energy, I always visualize that fission would generate more energy due to how energy explodes out of the atom when it splits. I was surprised that fusing two atoms would generate much more energy than breaking them apart. The radioactive aspect of fusion also stood out to me. I had originally assumed that fusion would not give out any form of radiation. I did not anticipate the amount of radiation that tritium contains and the dangers that it poses to humans.

8 Conclusion

Overall, fusion still requires a substantial amount of time before it can become commercially viable. However, the benefits of fusion to energy production are something to look forward to. After comparing fusion with coal, solar, and fission, fusion's generation rate stood out as it far surpasses other forms of energy, with the price of having harder requirements to fulfill. The comparisons between fusion and other energies shine an optimistic light on the possibilities that fusion can bring to the world if it becomes commercially viable. Currently, advancements in fusion technology are addressing several key challenges, including plasma instability, the cost of constructing fusion reactors, and fuel harvesting. These developments are significantly contributing to the progress of fusion energy.

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