Important Challenges Currently Facing Nuclear Fusion

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Nuclear fusion has incredible possibilities to impact energy generation on Earth, however there are many obstacles that scientists will need to overcome before fusion will become a viable source of electricity. Obtaining the temperatures required for fusion is incredibly difficult, specifically getting past the plasma burn through phase and breaching the radiation barrier. This is a difficult task, especially for new fusion companies just getting started. Reactors will also have to reach high Lawson Criterion and optimize their beta value to achieve a high energy output. Fuel selection will be paramount to the success of a reactor; aneutronic fuels are beginning to make headway among new startups, however the significant tradeoffs of these fuels should be taken into consideration. Finally, the location of the first fusion powerplants will be integral to the advancement of nuclear fusion as a viable energy source, and these initial markets should be selected intelligently. Fusion will have to compensate for the high capital cost of building a reactor, however it does benefit from having the lowest levelized cost of electricity, even in comparison to solar and wind farms. This paper does not cover all the current and future issues facing the advancement of nuclear fusion, only a handful of the ones we find most important.

Introduction

Nuclear fusion is the process by which stars produce energy. Stars achieve fusion through two reaction chains, namely the proton-proton (p-p) chain or the carbon-nitrogen-oxygen (CNO) cycle. Both contain a hydrogen burning mechanism which is essentially the fusion of 4 protons into a ^{4}He nucleus.[1] This is very similar to what we are trying to replicate on earth, using magnetic and inertial fusion. Magnetically confined fusion (MCF) is the process where magnetic fields are used to confine a plasma to fuse nuclei. MCF has yet to sustain a nuclear reaction that can produce energy breakeven, a phenomenon when the power released by the reaction is equal to the required heating power (also called Q=1). Inertially confined fusion (ICF), on the other hand, initiates fusion via the compressing and heating of targets, typically pellets of some sort, filled with thermonuclear fuel. The US National Ignition Facility (NIF) uses ICF and has reported to have performed experiments that have surpassed the static self-heating boundary (the fusion heating has exceeded the energy losses from conduction and radiation).[2]

In the past year, nuclear fusion has had a huge influx in funding, specifically in the private sector. In 2021, fusion saw over $2.5 billion in investments, which has allowed for many startups to take the stage.[3] Privately owned fusion companies have popped up all over the world, and many are planning to demonstrate net positive fusion energy within the next few decades and have working powerplants not long after. Commonwealth Fusion Systems (CFS), for example, was founded in 2018 and has raised $1.8 billion as of 2021. CFS plans to have commercially relevant net energy from fusion with their SPARC reactor by 2025, and complete their first fusion power plant, ARC, early into the next decade.[4] With the effects of climate change worsening, there is pressure to find a more sustainable energy source to replace fossil fuels, with funding of renewable energy reaching an all-time global high of $755 billion in 2021.[5] If given the proper funding, nuclear fusion has the potential to fill this role as a sustainable alternative for fossil fuels.

While fusion energy has significant advantages over other energy sources, such as a low external energy cost, it does face its fair share of problems. The most obvious being the plasma physics and material science challenges, which have prevented fusion breakeven in MCF reactors thus far. Aside from that, however, there are more nuanced issues such as plasma burn through, reaching necessary Lawson Criterion, power optimization, fuel selection, and the future economic prospects of fusion energy. The goal of this paper is to discuss the current state and some of the challenges facing magnetically confined fusion. While inertially confined fusion is important and making enormous progress in their field, it is not within our scope. This paper will explore the importance of temperature in fusion (Section 1), plasma beta in toroidal plasmas (Section 2), fuel types and selection (Section 3), and future aspects of the economics of fusion energy (Section 4).

Importance of Temperature

With so many new fusion startups and reactor designs coming into fruition, it is difficult to understand how far along each of these reactor schemes are. One of the major obstacles new reactors must face is reaching and sustaining an adequate temperature for fusion. The temperature at which these reactors can achieve is vital in determining their viability and chance at producing energy. Even in early stages of plasma confinement, the ability of a fusion reactor to overcome the barrier of plasma burn through is crucial. As the reactors continue to develop and pass this stage, the temperature they can maintain is critical to the Lawson Criterion and their chances at breaking even.

Plasma Burn Through

Plasma burn-through is the full ionization of a gas into a plasma and is fundamental in any magnetically confined fusion experiment. The application of an electric field accelerates gaseous atoms causing them to collide. These initial collisions result in the ionization of more electrons, producing a Townsand avalanche. During this preliminary phase, the gas has not yet reached a high enough temperature to become fully ionized and emits line radiation in the form of Lyman and Balmer Series. The Lyman alpha emission, a transition from n=2 → n=1, is in the ultraviolet range and thus difficult to measure. The Balmer emission (n=3 → n=2), however, emits a visible photon, commonly called H-alpha or D-alpha.[6] Figure 1 (e) shows the D-alpha emissions during plasma burn-through as measured in JET during the plasma burn through phase.[7] Because both the D-alpha emissions and radiated power (d) are proportional to deuterium atom density, the subsequent decrease after the radiation threshold indicates the full ionization of the gas. The radiation emitted can result in significant loss of heating power, so getting past this barrier is very important. Once the plasma is fully ionized, the electron temperature (c) will begin to increase, causing a decrease in plasma resistance. This allows for an increase in plasma current (b) and the generation of a poloidal magnetic field. A lower toroidal loop voltage (a) is required to increase the electron temperature which results in improved overall plasma confinement.

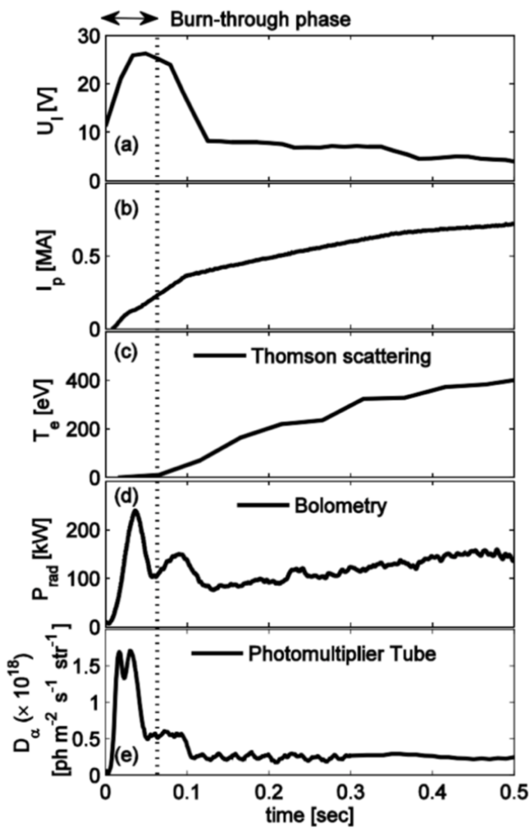


Figure 1: From Fig. 1 Kim, H.-T. et al/ Plasma Physics and Controlled Fusion 55 (2014). Typical Experimental data during the plasma burn-through phase measured in JET (#77210); (a) Toroidal loop voltage U_l (Note, at JET $E_l \sim U_l/20m$), (b) Plasma current I_p, (c) Electron temperature T_e (Thomson Scattering), (d) Radiated power P_{rad} (Bolometry), (e) D alpha emission (Photomultiplier tube). [7]

A significant obstacle to overcome in startups with magnetically confined plasma is plasma burn-through, as it requires significant ohmic heating and magnetic confinement to breach the radiation barrier successfully. The plasma temperature of a reactor is a good measure of the company's progress and overcoming the burn-through period is an important first step for these new reactors. If they can achieve these conditions at a realistic plasma density, then it is a good indication of a viable project.

Lawson Criterion and the Fusion Triple Product

Developed in 1955 by John D. Lawson, the Lawson Criterion is a figure of merit for nuclear fusion research that relates the energy being generated by fusion reactions to the energy lost to the environment. He concluded that the conditions for fusion are as follows: a high temperature for particles to overcome the Coulomb barrier, a sufficient confinement time, and sufficient density ($n\tau_E$). The confinement time being the time that a plasma is maintained at a temperature above the critical ignition temperature. For a reaction to yield more energy than it receives, this temperature must be maintained for a minimum length of time which is dependent on both the fuel type and density. There is a critical density of ions that must be maintained to ensure that the probability of collision is high enough to achieve a net yield of energy from the reaction. Lawson defined the minimum conditions for productive fusion as the product of ion density and confinement time, known as the Lawson Criterion.[8]

The triple product is similar to the Lawson Criterion, but in addition to the Lawson Criterion, it includes the parameter of temperature and is defined as the product of ion density, confinement time, and temperature ($n\tau_E T$). This is especially useful as it is independent of confinement schemes, and therefore can be used to compare various reactor types.

Figure 2 plots the achieved Lawson parameters versus temperature for MCF, MIF, and ICF experiments along with contours of scientific energy gain, Q_{sci} (fusion energy released divided by the energy delivered to the plasma fuel (MCF) or the target (ICF)). From this graph, we can see the importance of temperature and achieved Lawson criterion are in attaining energy breakeven and gain. Tokamak reactors and laser driven ICF are currently showing the highest Lawson parameters, triple products, and Q_{sci}. However, newer fusion concepts are rapidly advancing, with companies pursuing fusion in the private sector exceeding the breakout performances of early tokamaks. While there are more factors that contribute to the viability of commercial fusion energy, we can see the achieved Lawson parameter of a device is a good indication of a reactors ability to produce energy.[9]

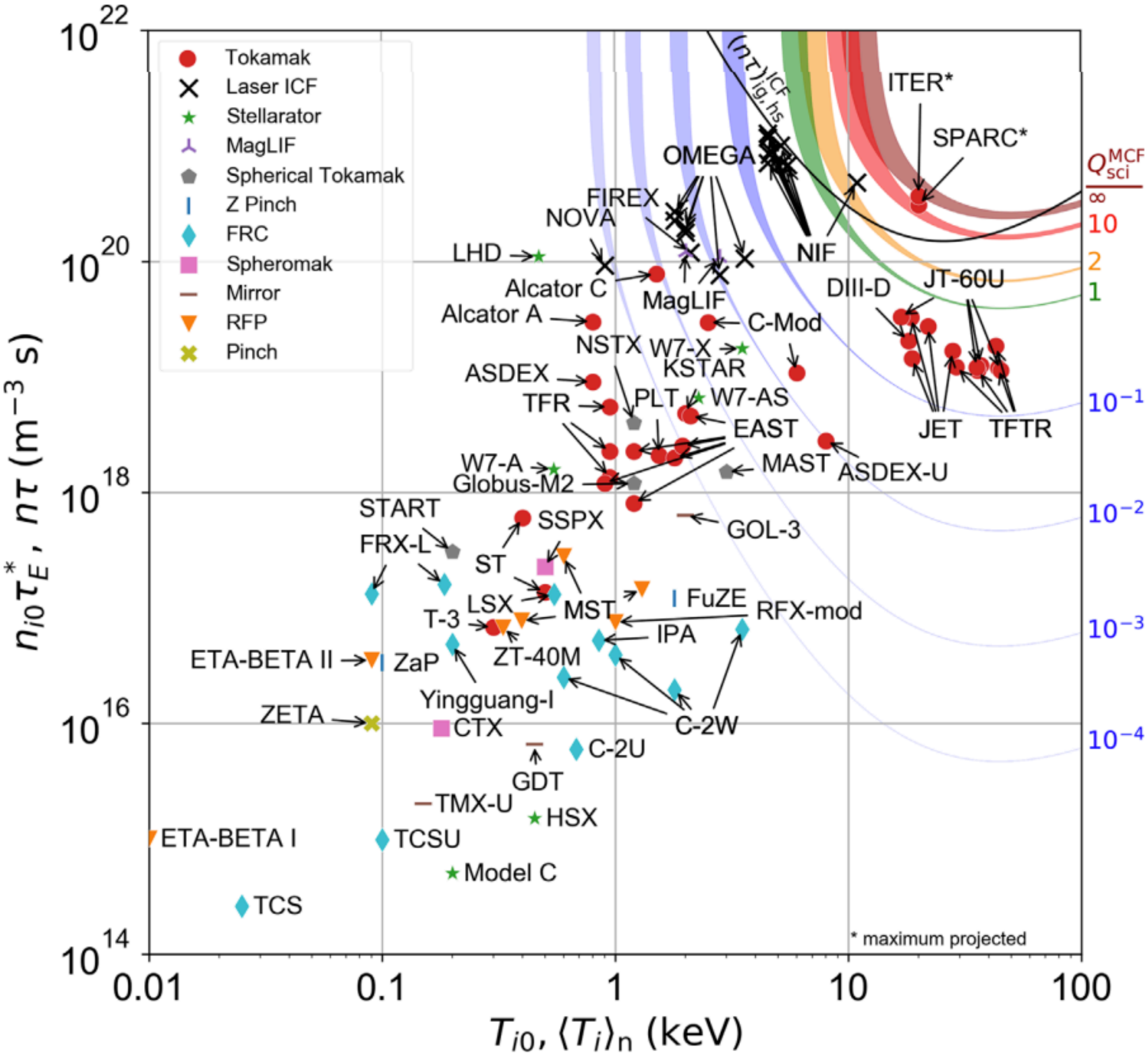


Figure 2: From Fig. 2 Wurzel et al/ (Submitted to Phys. Plasmas 2022). Central ion density (n_{i0}) and central ion temperature (T_{i0}) used for MCF, generic density and neutron averaged ion temperature ($\langle T_i \rangle_n$) used for ICF, and modified energy confinement time which accounts for transient heating (τ_E^*) used to calculate Lawson parameters. Various contours in the upper right correspond to the required Lawson parameters and ion temperatures required to achieve the indicated values of scientific gain for MCF (colored contours) and ICF (solid and dotted black contours), assuming representative density and temperature profiles, external-heating absorption efficiencies, and D-T fuel. [9]

Beta in Toroidal Plasmas

Another figure of merit in most confinement schemes with a strong toroidal magnetic field is the beta value. Beta is defined as the plasma pressure over the magnetic pressure which can be written as:

$$\beta = \frac{2nk_BT\mu_0}{B^2/2\mu_0}$$

(Eq. 1)

Beta must be less than one and in practice, is typically around .01 or 1%. Many numerical studies have been carried out in order to determine a beta limit against ideal MHD instabilities, one of the most used being the Troyon Beta Limit:

$$\beta \leq \beta_{crit} \equiv \beta_N \frac{I}{a\beta_0}$$

(Eq. 2)

Normalized beta (β_N), also known as the Troyon Factor, is a numerically determined coefficient of value β_N = 0.028 (2.8%) when I (current) is in megamperes. This limit shows that a smaller external magnetic field and minor radius are favored for stability, with the highest value of I/aB_0 occurring for elongated, triangular cross sections.[10]

Beta acts as an important figure of merit not only for stability, but also for fusion power, as we can define fusion power in terms of beta:

$$\text{Fusion Power (Watts)} = n^2\langle\sigma v\rangle E_f V$$

$$\text{Fusion Power} = \beta^2 \frac{B^4}{2\mu_0} \frac{\langle\sigma v\rangle}{(k_BT)^2} E_f V$$

(Eq. 3)

This is extremely important, as beta is limited to some value for a particularly magnetically confined fusion device and is proportional to power. The magnetic field to the 4th power is also proportional to fusion power, so if a reactor optimizes to produce a large value of beta, then fusion power scales as B^4.

Fuel Types

When selecting a fuel, there are factors that must be considered such as fuel abundance, ignition temperature, energy yield, etc. While there are many fuel types to choose from, the most prominent is Deuterium-Tritium reaction (D-T), which is being widely used in many fusion reactors (Eq. 4).

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 17.59 MeV $$

(Eq. 4)

D-T is most used mainly because of its comparatively low ignition temperature of 13.6 KeV and high energy yield of 17.6 MeV. Figure 3 shows the Lawson Parameters (3a) and Triple Products (3b) as a function of temperature for certain values of energy gain (Q) for the most common fuels.[8] From these graphs, it is evident that D-T has the highest maximum reactivity and triple product occurring at the lowest temperature, making it the most accessible fuel.[9] The greatest issue with D-T fuel is that much of the energy produced from this reaction is stored in the neutron, making the neutronicity (fraction of energy released through neutrons) quite high. This is problematic, especially when it comes to material selection for plasma facing components, as the effect of neutron activation on metals can be extremely damaging and the lifespan of the metals is greatly reduced.[11] Additionally, tritium is not a naturally occurring element due to its short half-life, and therefore must be created. Tritium breeding is a method to create tritium and involves a lithium-7 blanket and a high energy neutron. This process is planned on being tested at the International Thermonuclear Experiment Reactor (ITER) however, it is important to note that tritium breeding has never been attempted on a large scale.

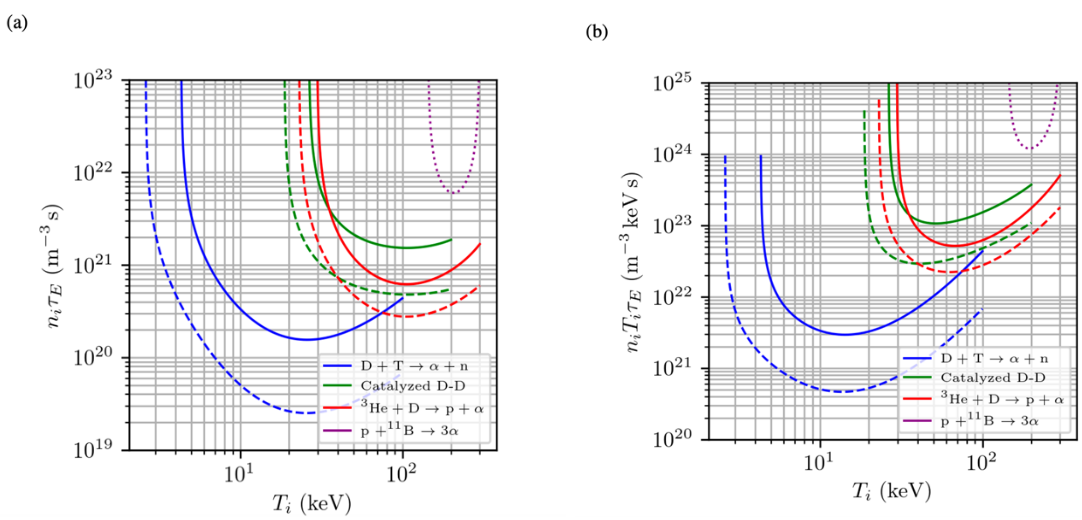


Figure 3: From Fig. 31 Wurzel et al/ (Submitted to Phys. Plasmas 2022). Required (a) Lawson parameters and (b) triple products vs. T to achieve $Q_{fuel} = \infty$ (solid lines), $Q_{fuel} = 1$ (dashed lines), and $Q_{fuel} = 0.5$ (dotted line, p-B11 only) for the indicated fuels assuming $T = T_e = T_i$. Neither fuel breakeven ($Q_{fuel} = 1$) nor ignition ($Q = \infty$) appears to be possible for p-B11 if $T_e = T_i$. [9]

Deuterium Deuterium (D-D) reactions are another possibility, though overall not a very practical choice. Deuterium is abundant on earth; however, the D-D reaction has two branches with each having a 50/50 probability. One branch (Eq. 5a) produces a neutron while the other produces a proton (Eq. 5b).

$$ {}_{1}^{2}\mathrm{H} + {}_{1}^{2}\mathrm{H} \rightarrow {}_{2}^{3}\mathrm{He} + {}_{0}^{1}\mathrm{n} + 3.27MeV \tag{Eq. 5a} $$

$$ {}_{1}^{2}\mathrm{H} + {}_{1}^{2}\mathrm{H} \rightarrow {}_{1}^{3}\mathrm{H} + {}_{1}^{1}\mathrm{H} + 4.03MeV \tag{Eq. 5b} $$

The products of these two branches include a tritium and helium 3 atom, and because of this, the products of this reaction can also react with the reactants and produce D-T and D-He3 reactions. However, because the D-He3 reaction requires much higher temperatures, this is not expected to contribute to the overall fusion energy. Including the subsequent D-T reactions that can be produced, the overall calculated energy of the D-D fusion energy then becomes 12.5 MeV though the neutronicity of the reaction is also raised.[11] Because the D-D reaction occurs at a higher temperature than D-T and has a similar neutronicity of .66, D-D is primarily used as a "warm up" in fusion reactors for D-T fuel due to the abundance of deuterium (in comparison to tritium).

The last two notable fuel types are Deuterium-Helium3 and Proton-Boron11, which are similar in that they are aneutronic (a fuel is termed aneutronic when the neutronicity is less than 1%) and thus considered advanced fuels. Helium3 is not abundant on earth, however, and must be bred, or in the future, mined from the moon.[9] Boron 11 is abundant on earth, but the p-B11 reaction requires exceedingly high temperatures over 100 KeV and has a lower reactivity. Figure 3 shows just how much higher the temperature required for breakeven (Q=1) for the p-B11 reaction, and does not show ignition (Q=∞) to even be possible for this fuel.

Table 1: Important Parameters of Four Most Important Fusion Reactions

Fuel Type	Neutronicity	Temperature [keV]	$\langle \boldsymbol{\sigma} v\rangle/T^2$ [$m^3/s/keV^2$]
D-T	0.8	13.6	1.2410-24
D-D	0.66	15	1.2810-26
D-He3	~0.05	58	2.2410-26
p-B11	~0.001	123	3.0110-27

From Table 1.2 *Fusion Physics*, (2012) 24. [11]

Table 1 describes the neutronicity, temperature, and reactivity ($\langle \boldsymbol{\sigma} v\rangle/T^2$) for each reaction at various temperatures for each fuel. The temperature required for these advanced fuels is significantly greater than what is required for a D-T reaction, and their reactivity values are smaller than D-T, overall making them much less attainable. The reactivity is important because it is proportional to fusion power for toroidal plasma, shown in Eq. 3. With the limitations on beta, the reactivity should ideally be as high as possible in order to maximize power output. While these advanced fuel types are certainly appealing with their negligible neutronicity, the required conditions to sustain the plasma at present will be very difficult to achieve.

Many different companies and organizations are experimenting with these various fuel types, though only a select few are using aneutronic fuels. ITER, SPARC, and JET operate or plan to operate with D-T fuel. A common theme among companies using aneutronic fuels is that they are using alternate confinement schemes: TAE Technologies' Linear Colliding Beam Reactor, Norman, and future reactor, Copernicus, is planning to use p-B11, and Helion Energy's pulsed heating reactor (Polaris) is set to use Deuterium-Helium 3.

These startups using aneutronic fuels have the benefit of not dealing with neutrons and relaxing the material constraint, though they still have much to overcome with the extremely high temperature and low reactivity required for ignition. D-T with its low ignition temperature, high energy yield, and high reactivity, deuterium-tritium fuel is the most practical choice for current reactors. In the future, with more advanced technology, scientists should look to these advanced fuels, but it will most likely be a D-T fuel that powers the first MCF reactor to breakeven.

Economics of Fusion Energy

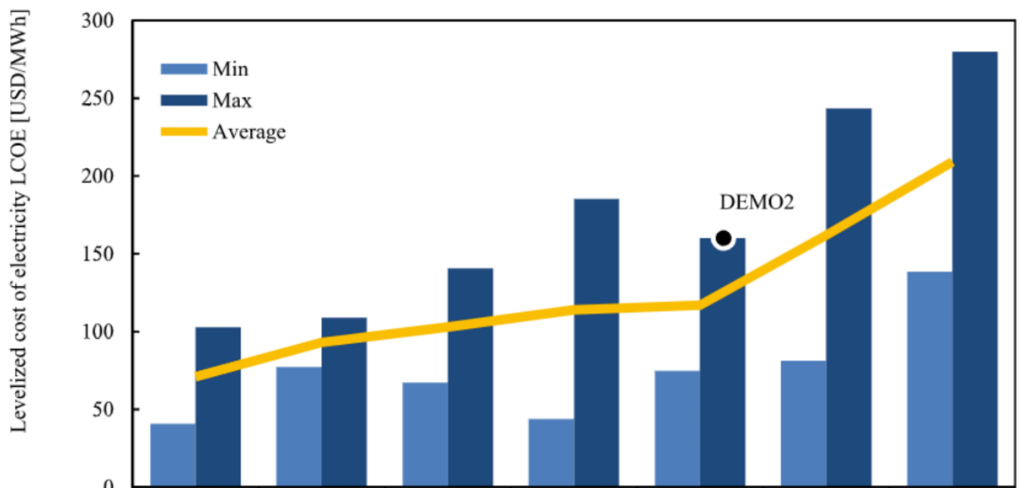
In the future, once initial fusion reactors have demonstrated energy gain, fusion power plants will make their entrance into the worldwide economy, though not without facing several challenges. Fusion reactors have high capital costs and an overall higher levelized cost of electricity (LCOE). LCOE is defined as

$$LCOE = \frac{\sum_{t=0}^{T_L-1} \frac{(IN_t+C_t+I_t)}{(1+r)^t}}{\sum_{t=0}^{T_L-1} \frac{E_t}{(1+r)^t}}$$

(Eq. 6)

Where *t* denotes the current year, T_L the economic lifetime of the plant, *C* the annual operating costs, *IN* the annual investments, *I* the interest, *r* the discounted rate, and *E* the annual electricity production.[12] The levelized cost of energy can be used to compare energy costs across different energy types as it takes a holistic calculation that includes upfront and operating costs. Using the DEMO2 model (a more advanced DEMO1 based on more optimistic physics assumptions, e.g., a current drive steady state plasma), the LCOE for fusion was found to be ~160 $/MWh in the case of zero profitability, with a minim sale price of electricity of ~175 $/MWh. This would still be several times higher than the current market price of electricity which is ~34 $/MWh (2015 in EU stock market), which is problematic for the future of fusion, especially when it comes to securing investors.[12] By increasing the profitability index to 1, it would result in a minimum sale price of electricity of 312 $/MWh, which significantly higher than current LCOE of both renewable and fossil fuels.

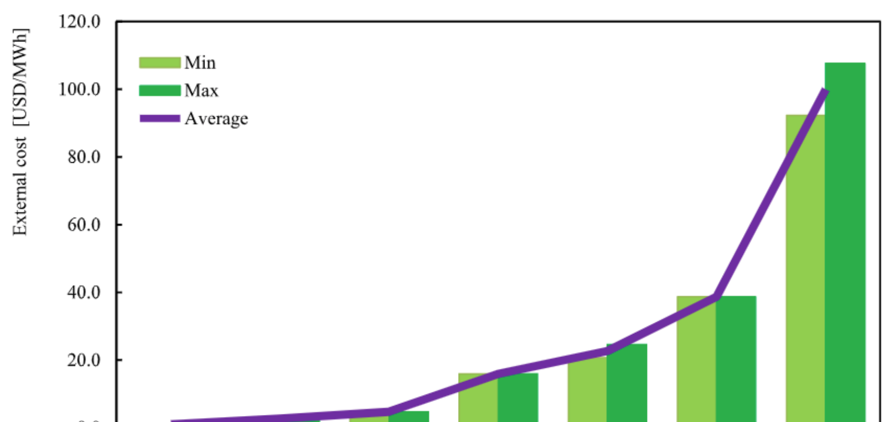
While this seems very high, as more reactors are built, there will be a gradually acquired know-how (i.e., learning factor), which will cause the cost to decrease. Based on an average high-tech novel industrial project, we can assume that by the construction of the 10th fusion power plant, this cost could decrease by up to 40%. As well, if fusion power plants are made to be more efficient, the LCOE can be further reduced. By increasing the net efficiency from 23% to 30%, the minimum sale price of electricity would decrease by up to 21%. Additionally, because of the inherent safety of fusion reactors to both humans and the environment, there will be no increase in cost associated with ensuring nuclear safety (currently a trend in the fission industry) or protecting the environment.[12] Overall, the investment cost of fusion power plants will decrease from the first plant onwards as fusion power plants become more advanced and efficient. Figure 4 shows the LCOE calculated for fusion compared to other energies, showing min, max, and average energy cost. This calculation shows fusion to be less expensive than both offshore wind and large solar photovoltaic plants, but still significantly higher than fission, coal, natural gas, and onshore wind.



	Nuclear	Coal	Natural gas	Wind onshore	Fusion	Solar large PV	Wind offshore
Min	41	77	67	44	75	81	138
Max	103	109	140	185	160	243	280
Average	71	93	103	114	117	162	209

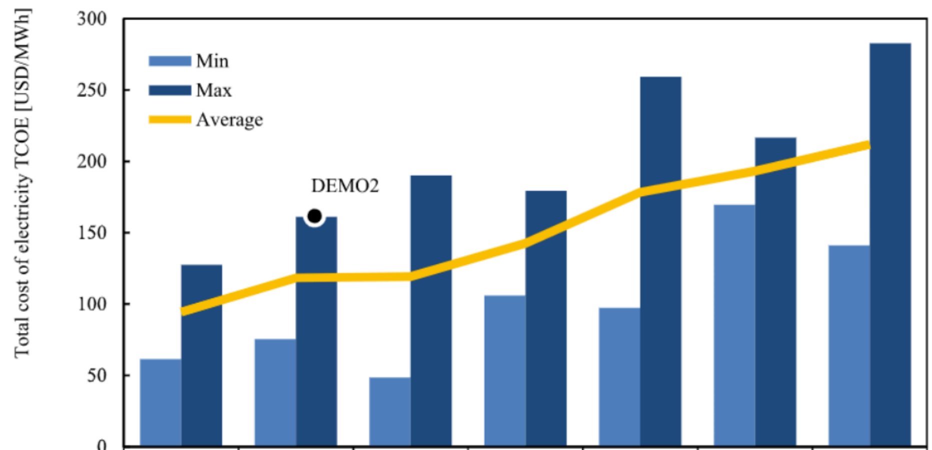
Figure 4: Levelized Cost of Electricity Comparison
From Fig. 11 of S. Entler et al/ Energy 152 (2018) 489-497. [12]

However, coal and natural gas's low LCOE advantage quickly goes away when external costs are factored in. External costs are costs not included in the market price and refer to uncompensated social or environmental effects. This can range from damage to human health or the effect on ecosystems and biodiversity, to the impact on resource depletion. For example, carbon has an estimated social cost of $31 per ton of CO_2 in 2010 USD.[13] When just the external costs are considered, nuclear fusion has the lowest cost (Figure 5), and when factoring in the external costs to the levelized cost of energy, fusion has the second lowest average cost (Figure 6).



	Fusion	Wind offshore	Wind onshore	Solar large PV	Nuclear	Natural gas	Coal
Min	0.9	2.7	4.7	16	21	39	92
Max	1.1	2.7	4.7	16	25	39	108
Average	1.0	2.7	4.7	16	23	39	100

Figure 5: External Costs of Selected energy sources according to ExternE Methodology
From Fig. 9 of S. Entler et al/ Energy 152 (2018) 489-497. [12]



	Nuclear	Fusion	Wind onshore	Natural gas	Solar large PV	Coal	Wind offshore
Min	61	76	49	106	97	170	141
Max	127	161	190	179	259	217	283
Average	94	118	119	143	178	193	212

Figure 6: Total levelized cost of electricity including external costs (total cost of energy)
From Fig. 12 of S. Entler et al/ Energy 152 (2018) 489-497. [12]

These results indicate that fusion has an incredibly limited environmental impact, but a high LCOE. Even with the external costs factored into the LCOE, fusion still must compete with fission and onshore wind, and this is only applicable if more strict safety and environmental measures are put in place. However, this is a trend that is being seen around the globe as movements to end global warming are gaining traction. The EU aims to be climate-neutral by 2050, so in countries aspiring to achieve this or similar goals, fusion could certainly take a share of the market.

While in the long term, there could be a place for fusion in the global economy, the first fusion reactors built will still have an elevated LCOE. As well, it is important to note that while fusion is becoming more efficient and established, other renewables will be on a similar trajectory. Because of this, the location in which the first commercial reactors are built will be of great importance to the overall success of fusion energy. By first introducing fusion energy into specific markets with higher energy prices, fusion would be able to gain a dominant market share and have the footing to expand.

Table 2 shows a selection of elevated wholesale electricity prices from around the world. For example, Singapore has a wholesale electricity price of 110 $/MWh_e$ since 95% of the electricity comes from natural gas which must be transported via pipelines from neighboring countries such as Indonesia and Malaysia. Additionally, because Singapore is an island with a dense population, they will need an energy source that is able to deliver lots of power without taking up much space. Both the elevated cost of energy and geographical nature make it an ideal initial market for nuclear fusion.[14] This is true for many geographically isolated places with dense populations that cannot afford large solar and wind operations.

Table 2: Regional Wholesale Electricity Prices

Market	Benchmark	Price ($/MWh$_e$)	Market (GW)
Singapore	Average wholesale price	110	6
Japan	Average wholesale price	92	108
U.S.	Northern CA wholesale price	61	38
Poland	Baseload wholesale price	60	17
Italy	Baseload wholesale price	59	33
U.K.	Baseload wholesale price	55	35
Slovenia	Baseload wholesale price	55	2
Portugal	Baseload wholesale price	54	5
Spain	Baseload wholesale price	53	27
Estonia	Baseload wholesale price	51	1
U.S.	Average wholesale price	39	445
World	Power from gas, coal, and nuclear (2035)	–	2283

From Table 1 M. Handley et. al/ Journal of Fusion Energy 40 (2021) [14]

Once a fusion powerplant becomes established in one of these high-priced wholesale electricity markets, it will be able to expand to neighboring areas. The power plants could also integrate other methods to maximize revenue such as thermal storage, which could help to keep it competitive with other energy sources.[15]

Summary

Nuclear fusion has the potential to replace fossil fuels, however there is much that it needs to overcome before that can happened. New fusion startups have significant barriers to overcome, specifically temperature related. Once surpassing plasma burn through, MCF reactors will have to achieve high Lawson criterion and select appropriate fuel types. As well, in order to have a chance at achieving $Q \geq 1$, reactors should optimize beta so fusion power scales as B^4. As for the economic future of fusion, the first fusion powerplants will suffer from the inherently high levelized cost of energy, however this can be mitigated by introducing fusion plants into markets with elevated wholesale electricity prices, and benefit from the increasing drive for finding an alternative to fossil fuels. While nuclear fusion faces many difficulties, it without a doubt can have a place in the future electricity markets as a sustainable and low impact energy source.

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