

# Re-examining the role of nuclear fusion in a renewables-based energy mix

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## ABSTRACT

Fusion energy is often regarded as a long-term solution to the world's energy needs. However, even after solving the critical research challenges, engineering and materials science will still impose significant constraints on the characteristics of a fusion power plant. Meanwhile, the global energy grid must transition to low-carbon sources by 2050 to prevent the worst effects of climate change. We review three factors affecting fusion's future trajectory: (1) the significant drop in the price of renewable energy, (2) the intermittency of renewable sources and implications for future energy grids, and (3) the recent proposition of intermediate-level nuclear waste as a product of fusion. Within the scenario assumed by our premises, we find that while there remains a clear motivation to develop fusion power plants, this motivation is likely weakened by the time they become available. We also conclude that most current fusion reactor designs do not take these factors into account and, to increase market penetration, fusion research should consider relaxed nuclear waste design criteria, raw material availability constraints and load-following designs with pulsed operation.

## 1. Introduction

Nuclear fusion is often assumed to be the preferred source of base-load energy in a far-future energy mix; i.e. that once the technology is demonstrated, fusion's advantages make it a clear choice for low-carbon energy generation - assuming it is cost-competitive (Bustreo et al., 2019). However, the relative advantages and disadvantages of fusion as a long-term energy source are complex. Rather than assuming cost-competitive fusion would be a clear choice, we instead argue the cost will be broadly similar to fission, then review fusion's distinguishing features in the context of a post-carbon energy grid. This allows us to consider which broad scenario would be required in order for fusion to play a significant role in future energy supply. This analysis differs from previous work (such as (Cabal et al., 2017) and (Anyaeji, 2017)) by including recent results of fusion materials research and implications of climate scenarios involving urgent decarbonisation with low-cost renewables.

After first giving the background context for fusion research, we justify some general premises describing relevant features of a post-carbon energy scenario and of future fusion power plants. We then examine advantages and disadvantages of fusion relative to other firm

low-carbon sources, and summarize with recommendations for the fusion research program. The logical structure of our analysis is visualised in Fig. 1.

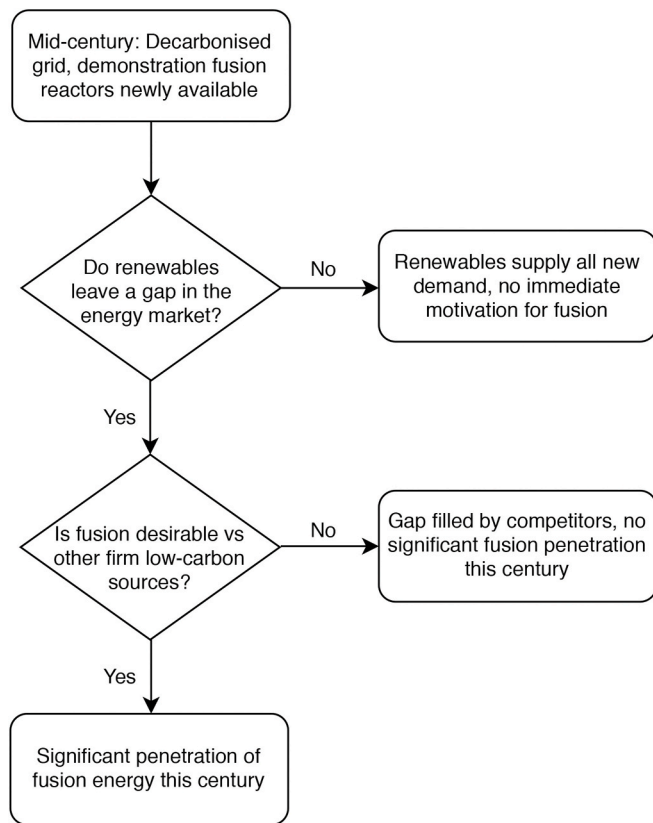
## 2. Background

Predating Keeling's observation of rising atmospheric CO<sub>2</sub> levels (Keeling, 1960), research into commercial fusion power was originally motivated by its relative advantages over nuclear fission: non-proliferation, safety from meltdown, no long lived radioactive waste, a high power density, and abundant fuel. This motivation was strengthened following the Three Mile Island and Chernobyl nuclear disasters, as degrading public sentiment toward nuclear power sources led to stagnation of new-build nuclear, opening a potential niche for commercial fusion (Schneider et al., 2011).

Whilst anthropogenic climate change has been acknowledged since the early 1970s, and the IPCC has issued reports since 1989, only very recently has focus started to shift towards the urgent need for complete decarbonisation by 2050 (Rogelj et al., 2018). Fusion's value proposition has changed to meet this: the benefits of zero-carbon energy generation in particular are now emphasised, as well as arguments made for

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**Fig. 1.** Scenario analysis for a post-carbon future. In order for fusion to significantly penetrate the energy market this century, various conditions must be met within the market, policy, and fusion technology sphere.

advantages over renewables, such as baseload supply, higher energy density, and geographical independence.

Currently the majority of global fusion efforts are working towards ITER, an intergovernmental-scale project to build the first tokamak aiming to demonstrate plasma energy breakeven. ITER is set to operate at full power in 2035 and is projected to cost around \$22 billion (Kramer, 2018). Most governmental fusion programs plan for an ITER-like demonstration fusion power plant (known as Demo) to be completed sometime after ITER. Demo would demonstrate the necessary technologies, such as integrated tritium breeding, required to generate utility-scale baseload power. Most governmental fusion programs (such as those proposed by China (Zhuang et al., 112010) and Korea (Kim et al., 1088)) use designs similar to the EU-DEMO1 design (Federici et al., 2002). We acknowledge efforts to accelerate development by downsizing reactors using high-temperature superconducting (HTS) magnet technology (Sorbon et al., 2015) but defer discussion of these until the end.

### 3. Premises

We first state six premises which could apply to the future energy mix or to fusion power technology in general. The first two premises relate specifically to fusion technology: they arguably apply to all fusion devices, but are especially relevant to those operating with magnetically-confined fuel. The latter four relate to the features of the future global energy mix.

To be absolutely clear, we are assuming these premises to be true and exploring the resulting consequences; they are not intended as definite predictions, but are proposed as plausible and having implications worthy of consideration.

#### 3.1. Plasma physics challenges are solved

We assume that plasma physics is understood well enough to design a commercial plant that can reliably operate in a scenario with sufficient plasma confinement for significant fusion power. We do not mean that knowledge of plasma confinement is enough to completely surpass the broad limits set by current confinement scaling laws (Petty; I. P. E. G. o. C. and Transport) (we exclude any possibility of “tabletop fusion”) or significantly relaxed constraints on material properties of plasma-facing components (Linsmeier et al., 2007). This is currently not the case, and many major plasma physics challenges remain (as reviewed in the ITER physics basis (Shimada et al., 2007)).

This premise also excludes any power plants using a pure deuterium plasma or so-called aneutronic fuel mixtures, such as  $D^3He$ ,  $p^6Li$ , or  $p^{11}B$ . This means a fusion power plant must use a deuterium-tritium fuel mixture and deal with the resulting high-energy neutrons. While a fusion power plant without significant neutron activation would have enormous advantages, the physical arguments that this is likely impossible (Rider, 1995, 1997) are well-known.

#### 3.2. Materials science challenges are solved

We assume that the materials challenges (Rowcliffe et al., 2018) are solved to the minimum extent to allow for operation of a fusion reactor using materials similar to those being considered for use in Demo (Federici et al., 2017). This includes plasma-facing materials that can withstand high heat loads (Ueda et al., 2017) and structural materials (Stork et al., 2014) that keep embrittlement and swelling issues at acceptable levels. We do not assume that the materials used will not become nuclear waste through neutron activation.

#### 3.3. Energy grids will decarbonise without fusion

Reduction of carbon dioxide emissions to net-zero by 2050 (Rogelj et al., 2018) will be one of the most important factors steering the evolution of the energy sector. With the EU committing in 2017 to targets which effectively require net-zero electricity supply by 2050 (Working Paper 1976/2016 R, 2017), we assume a 95–100% decarbonised power sector (Jenkins et al., 2018a). Hence we assume that the 2050 energy mix will comprise only zero-carbon technologies: fossil fuel power plants with carbon capture and storage (CCS), nuclear power plants, and renewables.

The EU fusion roadmap states “[Demo] will be operational around 20 years after high power burning plasmas are demonstrated in ITER” (Donné and Morris, 2018), setting the earliest date for a commercial fusion plant to 2055.

Even after developing a demonstration reactor, the adoption of fusion plants must experience the so-called “valley of death” in which early plants have high capital costs and long build times, whilst not yet providing the optimised return on investment which would finance innovation (Cardozo et al., 2016). This will be exacerbated by the challenges of developing new supply chains (Surrey, 2019).

Although this EU timeline is representative of governmental fusion research worldwide, there are also now several private companies aiming to develop commercial fusion power plants significantly earlier (Sorbon et al., 2015; Sykes et al., 2018). However, due to the remaining physics, engineering and materials science challenges, this paper will assume that global energy supply is almost entirely decarbonised without contributions from fusion - whether publicly or privately funded.

This premise does not rely on decarbonisation being achieved by any specific date, only that decarbonisation occurs before widespread availability of commercial fusion power. The IPCC 1.5 °C and Euro-Fusion timelines do not need to be interpreted as immovable dates in the context of this paper, only as a strong indication of events occurring in that order.

### 3.4. Energy supply infrastructure is chosen primarily on the basis of monetary cost

We assume that the choice of low-carbon energy sources is driven primarily by monetary cost and not military, geopolitical or other environmental reasons.

Given that a zero-carbon society is by definition more environmentally-conscious, we will also consider the possibility that alternative metrics, such as the Energy-Return-On-Invested (EROI), will be prioritized in future (Carbajales-dale et al., 2012).

### 3.5. Renewables will dominate decarbonised grids

The cost of renewable electricity will continue to fall (Electricity Generation Co, 2016). According to McKinsey: “cheap renewable energy and batteries fundamentally reshape the electricity system [...] by 2030 new-build renewables will outcompete existing fossil generation on energy cost in most countries” (Tryggestad et al., 2019). Renewables are projected to reach high fractions (74% globally by 2050) even without assuming significant carbon regulations (Tryggestad et al., 2019) or subsidies (Lazard’s Levelized Cost o, 2019).

Scenarios intended to meet stronger decarbonisation targets display similarly high grid fractions: the IPCC (Masson-Delmotte et al., 2018) state that “In 1.5 °C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (high confidence).” BP’s most recent projections envisage a scenario meeting net-zero by 2050 in which renewables collectively supply around 60% of primary energy demand globally (BP, 2020).

The UK Committee on Climate Change similarly predicts that for meeting the 1.5°C target a renewable fraction of 78% is desirable. A share of only 60% is dubbed a “cautious” approach, because they predict that if higher fractions of renewables are possible, for example through long-distance interconnects, cheaper storage, or more demand-side management, an even larger share would likely reduce overall costs (Net Zero Technical report, 2019).

Therefore both the business-as-usual and high-decarbonisation scenarios still feature high fractions of renewables. Our assumption here is that any future decarbonised grid involves a high fraction of renewable generation.

Once decarbonisation has been achieved the energy mix will likely still evolve as innovation occurs. However, though the value of fusion should be continually reassessed as the market develops, if our premises remain true then our conclusions would still apply.

### 3.6. Fusion energy will not be as cheap as renewable electricity

Intuitively, fusion plants are economically similar to fission plants: large capital costs, resulting from generator turbines, cooling, concrete shielding and containment, high safety standards, nuclear licensing, decommissioning, and nuclear waste management; a high fraction of ongoing costs dedicated to operation and maintenance, components replacement and interest repayments; and relatively low fuel costs. Magnetically-confined fusion also specifically requires large and expensive magnets.

Entler (Entler et al., 2018) modelled the cost of a 1GW EU-Demo fusion power plant concept, finding a levelized cost of energy (LCOE) of 175\$/MWh with a direct capital cost (with contingency) of \$7.4 billion (all costs quoted in 2018 USD). Fusion’s LCOE is sensitive to the initial capital cost (Sheffield and Milora, 2016): a capital cost of \$3.9 billion for 1GW suggests a LCOE of 83\$/MWh, whereas using a similar capital cost to Entler’s Demo design (\$6.2 billion) yields a LCOE of 121 \$/MWh. Generally increasing the cost of the fusion technology by \$1 billion increases the cost of electricity by 16.5 \$/MWh. Setting the capital cost of the fusion-specific technology to zero results in a LCOE of 72 \$/MWh, which borders current prices for renewables, but is clearly physically implausible.

Entler (Entler et al., 2018) finds the effective operating and decommissioning costs alone for their fusion power plant concept come to 27 \$/MWh. However, this assumes no long-lived radioactive waste, an assumption which we examine later in this paper.

Given that ITER and Hinkley Point C are both projected to cost over \$20 billion each (Kramer, 2018; Haas et al., 2019), we assume a cost over 100\$/MWh is more realistic. For comparison, Lazard suggests that currently the LCOE of large solar PV is between 40 and 46\$/MWh, onshore wind between 29 and 56\$/MWh and offshore wind at 92 \$/MWh (Lazard’s Levelized Cost o, 2019).

Therefore we assume both utility-scale solar and onshore wind to be significantly cheaper than fusion by the time fusion becomes commercially viable, and possibly indefinitely.

## 4. Discussion

### 4.1. Can renewables handle it all?

Several studies conclude that it is possible to meet national energy demands using only renewable sources (including geothermal and hydroelectric) (Jacobson et al., 2018; Connolly and Mathiesen, 2014; Ram et al., 2019; Ueckerdt et al., 2015; Child et al., 2019; Zappa et al., 2019). In specific cases it is actually cheaper than the cost of a business-as-usual scenario, with the caveat that energy grid composition is extremely region-specific and often includes long-distance energy transfer with international grid integration (Pleßmann and Blechinger, 2017). For example Jacobson (Jacobson et al., 2018) comprehensively analyses multiple scenarios where an all-renewables grid with storage provides load-following power at economically viable electricity prices.

A scenario in which the decarbonisation challenge is met entirely by renewables, without the need for “baseload” energy sources, would have no clear motivation to include fusion. Assuming renewables and storage remain the cheapest option (including cost of energy storage) then, according to premise D, they would meet any subsequent increases in demand, without nuclear waste, safety or proliferation issues.

### 4.2. Limits to penetration of renewables

Renewables do have significant disadvantages that must be overcome for an all-renewable grid to be feasible, the most challenging of which is temporal intermittency of supply. Some combination of energy storage, some other highly dispatchable energy source, and long-distance interconnects must be used to cope with fluctuating grid loads (Gils et al., 2017). While (Ziegler et al., 2019) shows that electrical storage may not be competitive if relied upon completely, utilising batteries (like scenario C in (Jacobson et al., 2018)) can reduce costs drastically. However, diversified energy mixes which include firm non-renewable backup are almost always cheaper overall (Mileva et al., 2016; Sepulveda et al., 2018; Brick and Thernstrom, 2016). Being energy-sparse, large-scale renewables deployment also entails significant land-use impacts (Herendeen, 2019) and so is disadvantageous when land is high-value or energy demand is dense (e.g. for megacities).

### 4.3. The desirability of fusion in this new context

Instead, imagining a decarbonised scenario with high - but not total - renewable penetration by the second half of the 21st century, other low-carbon sources will need to fill the supply gap.

When large-scale fusion deployment becomes plausible, the grid composition will be significantly different to today: new sources will have to work in tandem with the high renewables fraction. Such a grid will value flexibility - as predicted for integrating both fission (Cany et al., 2016) and gas with CCS (Mechleri et al., 2017) with intermittent renewables. If fusion cannot provide this service it may be excluded to alternative markets which require baseload.

The options for firm low-carbon generation are principally nuclear

fission, nuclear fusion, and gas with carbon capture and storage. As fusion will be competing with these sources, we now attempt to assess its relative merits, focusing on constraints likely to be imposed by the materials science and engineering challenges of developing a near-term fusion reactor design.

#### 4.3.1. Load-following

Within a grid with large fractions of intermittent renewables, dispatchable energy sources that can match demand will lower overall system costs (Mileva et al., 2016; Sepulveda et al., 2018; Brick and Thernstrom, 2016; Herendeen, 2019; Cany et al., 2016; Mechleri et al., 2017; Jenkins et al., 2018b). This is expected for CCS (Brouwer et al., 2015), fission (Jenkins et al., 2018a) and fusion (Bustreo et al., 2019). For baseload plants, access may be improved by long-distance interconnects which smooth out supply variations (Hamacher et al., 2013), but even in that scenario dispatchability will still be highly valued.

This raises the question of technical challenges for a fusion power plant to load-follow rather than supplying baseload. This has been answered briefly for the EU-Demo concept, concluding that it would be possible to reduce the fusion power by about 50% (Maisonniere et al., 2005). However, this is complicated by knock-on effects associated with reduced plasma power output (Ward and Kemp, 2015).

In any magnetic-confinement design there will be tension between load-following directly with the plasma power output and control of the plasma. Whether devices operate in pulsed or steady state modes (Federici et al., 2002; Donné and Morris, 2018), real-time control systems must “pilot” them through a multidimensional parameter space, avoiding regions dangerous to the plasma confinement. Load-following significantly increases the number of trajectories which must be understood and safely managed; for this reason the EU-Demo design is currently assuming a single operation scenario. In practice this means running the same plasma pulse scenario repeatedly, with the same duration and energy output.

Alternatively, coupling a Demo-sized reactor in pulsed operation with a thermal battery between blanket and turbines would allow for smoothing of variable grid demand, but it would also significantly increase the cost (Homonnay et al., Hayward; Vanter et al., 2012). There are suggestions for instead co-generating hydrogen (Sheffield and Milora, 2016), though this would decrease overall energy efficiency. It should be noted that this approach could also be taken with renewables or fission to allow for long term energy storage.

Similarly, running a fusion plant at full power to generate heat (see section 4.3.6) whilst simultaneously co-generating load-following electricity could improve the economics of load-following, as has been studied in the context of small modular fission reactors (Locatelli et al., 2015).

Fission has already demonstrated load following by directly altering the power output from the fission core (Cany et al., 2016), so this is not an area where fusion has any clear advantage. While fission cores respond more slowly than tokamak plasmas due to decay heat and fuel poisoning constraints (Ponciroli et al., 2017), they could also couple to thermal or hydrogen storage technology.

Of the low-carbon technologies, gas with CCS is the most suitable for load following; gas turbines are regularly used as “peaker” plants, and adding CCS doesn’t directly impinge on this capability (Mechleri et al., 2017; Domenichini et al., 2013).

It should also be noted that the financial model of a large fusion plant (high up-front costs, low fuel costs) is not in favour of lowering energy output. If low demand can force a plant to reduce output, the relative opportunity cost of dormancy will become significant. Sources where fuel prices are a large fraction of total costs benefit more when flexible operation is required (Mechleri et al., 2017). It would therefore be unlikely for load-following fusion plants to be competitive economically unless there was some opposition to gas with CCS that disincentivised their construction (e.g. lack of subsidies, lack of available CO<sub>2</sub> storage,

public opposition, infrastructure leakage preventing emissions compliance (Alvarez et al., 2018), etc.), or a use-scenario for fusion at scale that significantly improved its load-following economics (e.g. desalination or other co-generation (Locatelli et al., 2015)). Quantitative market modelling studies should examine this question more rigorously.

#### 4.3.2. Waste production

One of the commonly stated advantages of fusion over fission is the misconception that it will not produce “long-lived” radioactive waste (Federici et al., 2002; Gorley, 2015).

In the 1980s the fusion materials community discussed methods to reduce the volume of long-lived radioactive waste generated by neutron activation (Brager et al., 1985). In 1982 the U.S. Department of Energy decided to aim for significantly reduced volumes of high-level nuclear waste (the UK definitions of different waste classes are given in Fig. 2) by limiting the radioactive lifetimes of fusion waste materials compared to fission materials (Conn et al., 1983). This was implemented by introducing a “low-activation” or “reduced-activation” material criterion, which was defined as (Gorley, 2015):

“The materials selection for fusion energy’s nuclear waste production, after an initial ~100 years removal from the reactor, can be disposed of in low-level waste repositories.”

For this purpose reduced-activation (or low-activation) structural steels were designed, and neutronics modelling concluded these steels would meet the low-activation criterion and hence only be classified as low-level waste (LLW) (Gorley, 2015; Conn et al., 1984; Kohyama et al., Ehrlich; Klueh et al., 2000; Gilbert et al., 2018; Lindau et al., 2005). EUROFER97 reduced-activation steel is the leading fusion structural material that was designed by the Eurofusion effort (Gaganidze et al., 2018) and has been chosen as the neutron-facing structural material in the EU-DEMO1 reactor design (Federici et al., 2002).

However, the latest research using the EU-DEMO1 design, by Gilbert et al. (2019) (Gilbert, Eade, Rey, Vale, Bachmann, Fischer) and Bailey et al. (2020) (Bailey et al., 2020), suggests that the EUROFER97 steel (used for the first wall, breeder blanket and divertor components) will always exceed the reduced-activation criterion, and hence be classed as intermediate-level waste (ILW).

In fact, more intermediate-level waste (ILW) may be produced by fusion than by fission: the European Sodium-Cooled fission Fast Reactor (SCFR) design has a lower percentage of ILW per total reactor steel mass compared to the EU-DEMO1 design (for a similar power output) (Reid et al., 2020).

Fusion-specific structural steels will therefore be classified as intermediate-level waste (ILW) under the UK protocol, with half-lives of thousands of years for EUROFER97. This is a significant volume of radioactive waste: recent EU-Demo designs require 1300–1500 metric tons of steel that will be strongly irradiated and thus become ILW (Someya et al., 2015).

Furthermore, Gilbert et al. (Gilbert, Eade, Rey, Vale, Bachmann, Fischer) indicate that any beryllium used in a Helium-Cooled Pebble Bed (HCPB) breeder blanket could exceed the reduced-activation criterion due to natural uranium impurities (which activate to become <sup>239</sup>Pu and <sup>241</sup>Am in trace amounts, which have extremely long half-lives).

Under current UK nuclear law, ILW requires geological disposal. Therefore, the latest research indicates that fusion plants could produce nuclear waste which requires long-term subsurface disposal, similar to fission plants. Although fusion won’t produce high-level waste (which requires active cooling), and also won’t produce radioisotopes with half-lives of >100,000 years, the need for deep geological disposal still weakens one of the main arguments for fusion over fission.

It is hard to avoid this: the elements responsible are either required for mechanical properties or are present as natural ore impurities in the tens of parts-per-million concentrations, the reduction of which might not be technically or economically feasible. It has been suggested that

Classification	Criteria (Bequerels/kg)	Location of disposal
Very low level waste (VLLW)	$4 \times 10^3$	Standard land disposal
Low level waste (LLW)	$< 4 \times 10^6 \alpha, 12 \times 10^6 \beta/\gamma$	Surface disposal
Intermediate level waste (ILW)	$> 4 \times 10^6 \alpha, 12 \times 10^6 \beta/\gamma$	Deep disposal
High level Waste* (HLW)	No limit	Deep disposal

**Fig. 2.** UK radioactive waste classification defined by the Nuclear Decommissioning Authority ((Radioactive Wastes in the, 2017): Radioactive Wastes in the UK: UK Radioactive Waste Inventory Report, Tech. Rep. (Nuclear Decommissioning Authority, 2017)). \*High level nuclear waste is defined as waste in which the temperature may rise significantly as a result of their radioactivity, so this factor must be taken into account in the design of storage or disposal facilities.

the structural materials could be recycled (Pace et al., 2012), however the social, technical and economic aspects of recycling hundreds of tons of nuclear waste for use in a new reactor have not been proven even in concept.

It should be noted that this is specific to UK regulatory law and would not necessarily apply internationally. As explained in Gilbert's paper (Gilbert, Eade, Rey, Vale, Bachmann, Fischer), the levels of  $^{14}\text{C}$  that make EUROFER97 problematic in UK law are not a problem under French regulations, and conversely the levels of  $^{94}\text{Nb}$  which would be problematic for French regulators would not be an issue under UK regulatory law. Additionally, the levels of both  $^{14}\text{C}$  and  $^{94}\text{Nb}$  do not constitute the need for geologic disposal in Japan at all. It is therefore conceivable that the fusion community could lobby for a separate, internationally consistent categorisation for fusion structural waste based on arguing that inert steel poses a lower risk of biosphere penetration than waste from fission. It is unclear how easy this would be and, if not possible, an alternative solution could be to relax the LLW criterion altogether and accept that fusion will generate ILW.

#### 4.3.3. Proliferation

Despite valid concerns, fusion does still have an advantage over fission in terms of nuclear non-proliferation as safeguarding measures are potentially much easier.

Tritium is used in thermonuclear weapons but is of little use by itself since it requires fissionable material in the primary stage. Goldston et al. (Goldston and Glaser, 2012) explored the possibility of using the 14.1MeV fusion neutrons to generate fissionable material, but concluded this would be difficult to perform clandestinely and relatively straightforward to halt unilaterally, assuming appropriate detection safeguards were in place. They also considered the potentially problematic possibility of boosting conventional atomic weapons with tritium.

If we compare fusion to advanced fission concepts, the overall picture changes. Generation IV fission reactors should, depending on the design, boast impressive non-proliferation credentials: advanced reprocessing and fast burnup of plutonium within the core of the reactor (Behar, 2014) results in a smaller inventory of fissile material on site.

The use of a thorium cycle is also argued to have better non-proliferation credentials. However, the  $^{233}\text{U}$  that thorium produces through neutron capture is weaponisable, with the IAEA categorising  $^{233}\text{U}$  on the same basis as plutonium (IAEA, 1980). Proponents conversely argue that  $^{233}\text{U}$  has a high  $^{232}\text{U}$  content - a strong gamma emitter - which therefore potentially makes it difficult to handle safely and easy to detect and safeguard against - though the extent to which this is true is disputed (Hesketh and Worrall, 2010).

Whilst fusion is superior to traditional fission in terms of proliferation, it is harder to conclude its superiority over possible advanced fission concepts, which may be competitors by the time fusion enters the market.

#### 4.3.4. Energy return on invested

Relative monetary cost of a technology does not completely reflect

the associated environmental damages, and one suggestion for a more comprehensive metric has been the Energy Return On Invested (EROI) (Carbajales-dale et al., 2012).

Estimates for EROI of energy sources vary in the literature, but broadly indicative comparisons of different current UK electricity sources have been made (Raugei and Leccisi, 2016). The highest EROI found was hydroelectricity (170) followed by fission (87), wind (50–52), gas (41 - albeit without CCS) and PV (10–25). Only one study has estimated the EROI of a fusion power plant (at  $\sim 27$ ), but for a reactor design from 1975 (White and Kulcinski, 2000). We will therefore instead now try to place general bounds on the most optimistic possible value for fusion and other advanced nuclear technologies.

As fusion's fuel is energetically dense and relatively abundant, then for either optimistic (Lozada-Hidalgo et al., 2017) or routine (RAE, 1978) estimates of enrichment costs, its fuel cycle still has a high EROI. However, the EROI of the complete system is limited by the energy invested in the device required to unlock that potential energy

$$\begin{aligned}
 \text{EROI} &= \frac{\text{Energy Generated}}{\text{Energy Invested}} \\
 &= \frac{Pt_L}{Mt_L + FPt_L + I} \\
 &= \frac{1}{\frac{M}{P} + \frac{1}{\text{EROI}_F} + \frac{I}{Pt_L}},
 \end{aligned} \tag{1}$$

where  $P$  is reactor output power,  $t_L$  is the plant lifetime,  $M$  is the maintenance energy cost per unit time,  $F$  is the energy cost of mining and producing fuel per unit of useable output energy,  $I$  is the one-off energy cost of building and decommissioning the plant infrastructure, and  $\text{EROI}_F = 1/F$  is the EROI of the fuel alone. Clearly, even if  $\text{EROI}_F$  were infinite, system EROI does not tend to infinity, instead

$$\text{EROI} \rightarrow \frac{1}{\frac{M}{P} + \frac{I}{Pt_L}}. \tag{2}$$

As discussed under premise F, any fusion power plant will require significant physical infrastructure, balance-of-plant, maintenance, and decommissioning. Therefore, to roughly estimate fusion's EROI, we assume the energy costs associated with plant construction, maintenance, and decommissioning (i.e. everything but the fuel procurement) are comparable to that of a fission plant of similar power output. For fission pressurised water reactors (PWRs), the fuel cycle requires about half the total energy input of the whole technology life cycle (Weißbach et al., 2013), so even if the fuel were available for zero energy cost, the overall EROI would only approximately double to  $\sim 170$ . This represents an upper bound since we also know that the fusion reactor "island" has a minimum size (Freidberg et al., 2015), and that the power-generating plasma of a fusion plant has a lower volumetric power density than the core of a fission plant ( $\sim 1.2\text{MW}/\text{m}^3$  for EU-DEMO1 vs  $\sim 300\text{MW}/\text{m}^3$  for a SCFR).

Although optimistic, this EROI is considerably higher than any existing (widely-scalable) technologies, implying a possible place for

fusion in ecologically conscious grids. Similar arguments apply to advanced fission fuels, where fissioning the  $^{238}\text{U}$  increases the EROI of the fission fuel by more than an order of magnitude, in a similar-sized reactor. But the threefold advantage of fusion over wind (even including storage (Carbajales-dale et al., 2014)) might be jeopardized by fusion-specific demand for elements which are energy-intensive to extract (e.g. beryllium, tungsten, rare-earth metals such as yttrium for superconducting magnets).

#### 4.3.5. Resource supply

Whilst it is true that fusion has access to an abundant source of deuterium and lithium fuel, it remains uncertain whether other reactor-relevant resources could become severe limiting factors. Using Fasel's (Fasel and Tran, 2005) approach but with updated availability estimates (Jaksula, 2020a), current accessible resources of terrestrial lithium could provide 2800 years of fusion power. But the increase in competition with other industries, notably batteries for energy storage and electric vehicles (EVs), could consume these reserves much faster - potentially within decades (Bradshaw et al., 2011). As this usage of lithium is purely chemical - hence isotope-agnostic - an economy could be established whereby enriched  $^6\text{Li}$  is used solely by fusion reactors and 'depleted'  $^7\text{Li}$  used by the energy storage industry. But this may not be likely, given that the EV industry is forecast to undergo extensive growth before fusion is commercialised (Global, 2019). Bradshaw (Bradshaw et al., 2011) simply assumed a "worst-case" scenario, but the implications of lithium demand economics for fusion deserve more detailed study in future work.

Access to lithium in seawater would increase potential reserves for fusion and energy storage by several orders of magnitude, but the economic and environmental costs of processing the necessary quantities of seawater must be considered. Considering purely the energy efficiency of extracting from the ocean (Bardi et al., 2010), the currently-projected EROI for lithium burned through fusion is only slightly  $> 1$ .

Fission also faces limitations in the availability of economically extractable uranium. The estimated uranium lifetime for the current light-water reactor (once-through) is  $\sim 100$  years at 2002 world nuclear electricity generation with known conventional uranium resources but increases beyond  $\sim 2000$  years if Generation IV nuclear reactors are considered (Uranium 2003: Resources, 2004). However, it should be made clear that these numbers are conservative (Schneider and Sailor, 2008). Additionally, thorium supply could theoretically be 3 times greater due to the greater abundance (Schaffer, 2013).

Unlike for fusion fuels, the EROI of extracting these fission fuels from seawater was evaluated as being  $< 1$  when using contemporary technologies (Bardi et al., 2010), but research is ongoing (Alexandratos and Kung, 2016). On the other hand, next-generation nuclear could alternatively use spent fuel and unenriched  $^{238}\text{U}$  which, along with the closed nature of their potential fuel cycles, means that it could greatly exceed 90 years (Gabriel et al., 2013).

Comparing this to gas with CCS, there exists an estimated upper limit on the amount of carbon storage available but this still allows for a high uptake of CCS until 2100 (Budinis et al., 2018). These plants maintain a positive EROI despite the high energy cost of CCS, which results in a 6–20% reduction in the energy output (depending on plant design).

The beryllium used as a neutron multiplier in several fusion blanket designs is also a serious concern. As of 2018, the estimated identified world beryllium supply was 100,000 metric tons, mined at a rate of 230 metric tons per year (Jaksula, 2020b). If a beryllium-based breeder blanket is selected for a DEMO reactor, a maximum of 200–300 reactors could be constructed (Bradshaw et al., 2011). The beryllium cannot be fully recycled because it is transmuted during neutron multiplication, making it necessary therefore to seek additional reserves or use an alternative. Unfortunately the choices for neutron multipliers are

fundamentally limited by nuclear physics, which leaves one of the only other options as lead, which must be used in liquid eutectic form and thus creates additional operational problems (Malang et al., 2011; Jun and Tortorelli, 2020).

Magnetically-confined fusion schemes face another potential resource shortage in the liquid helium coolant required for the superconducting magnets (Bruzzone et al., 1088). The total helium inventory contained in the number of fusion DEMO reactors needed to supply 30% of global energy demand is around 2% of the global helium resource, and helium has an exponential reserve index of around 100 years. Bradshaw (Bradshaw and Hamacher, 2013) concludes that even accounting for the helium directly produced by the D-T fusion reaction, fusion as a non-sustainable consumer of helium would exacerbate an already critical supply situation. Substitution is challenging because of the low molecular mass required. This constraint could be managed with foresight, active management of the resource supply chain and geopolitical cooperation, but large uncertainties remain. However, Bradshaw also calculates that even energetically-costly extraction of the required helium from air would only lower Fusion's EROI by around 1%.

Renewables and gas with CCS also face material shortages of crucial elements, notably: indium, gallium, and silver for photovoltaics (Tao et al., 2011), neodymium for wind, and nickel and molybdenum for CCS (Bradshaw et al., 2011; Kleijn et al., 2011). It should be noted though that all these cases are limited by electrical or chemical processes, rather than nuclear reactions, and so there is arguably more potential for research into alternatives or recycling.

It must also be noted that all figures representing the amount of extractable material are inherently conservative and subject to revision. This can be seen in the increase in lithium resources from 25.5 to 80Mt between 2010 and 2020 (Jaksula, 2020a), as the increase in lithium demand intensified both the search for new reserves and the development of new extraction methods intensified also.

It is therefore clear that fusion has an advantage over current generation fission in terms of fuel availability in the near term, but this advantage may not extend over advanced fission concepts.

#### 4.3.6. Can fusion supply heat?

Heat at different temperatures is required for industrial and domestic use, and it comprises a significant fraction of global energy usage (International Energy Outl, 2019; Thompson, 2013). An analysis of the 14 top greenhouse-gas-emitting industries in the United States (37% of the total industry energy demand (McMillan and Narwade, 2018)) outlined the supply composition of heat of varying temperatures: 0.6%, for low temperature ( $< 100^\circ\text{C}$ ); 60.1%, for medium temperature ( $100\text{--}400^\circ\text{C}$ ); and 39.3% for high temperature ( $> 400^\circ\text{C}$ ) [McMillan and Ruth, 2019]. Uses in the upper tier are then further stratified based on the required temperature.

Fusion can provide low and medium-temperature heat via the primary coolant (a maximum temperature of  $\sim 300^\circ\text{C}$  in water cooled designs (Tobita et al., 2018)) or after the first high-pressure expansion stage (up to 700C with liquid metal and helium coolants (Abdou et al., 2015)), reaching 86% of the total market demand. Temperatures above this ( $> 800^\circ\text{C}$ ) are technologically unattainable [ (Abdou et al., 2015) for both fission and fusion designs. As it stands, gas with CCS would fill this gap.

Since most heat demand can be supplied electrically, renewables could compete with fusion to provide low- and medium-temperature heat (Wilson et al., 2013). However it must be noted that some renewables (e.g. solar) provide significantly less power during winter months when domestic heat demand peaks. Also, demand for industrial heat is typically constant so there is potential for fusion (or fission) power plants to supply a post-carbon market with baseload heat.

#### 4.3.7. Fission-fusion hybrids

Fission-fusion hybrids (Freidberg, 2009) are reactors which utilise fissionable material in the blanket of a fusion device, allowing fusion neutrons to trigger non-critical fission reactions to generate additional power (Manheimer, 2009). A key part of this concept is that the fuel need not be  $^{235}\text{U}$ , for example it could be recycled  $^{238}\text{U}$  waste.

Hybrids would alleviate many significant challenges facing fusion designs. By reducing the required fusion energy gain, the concomitant heat exhaust loading, reactor size and associated cost are all significantly reduced. Achieving a tritium-breeding ratio  $> 1$  becomes significantly more straightforward. Furthermore, power output would be much higher for the same size reactor vessel, as most of the power production would come from the blanket instead of the plasma (Manheimer, 2009). The higher power output at lower capital cost could make hybrid electricity inherently cheaper than “pure” fusion, assuming the increased costs of the non-fusion-specific requirements are low enough.

Hybridisation would, however, nullify some of the purported advantages of fusion over fission, namely non-proliferation (although this is disputed (Manheimer, 2014)) and the LLW criterion; hybridisation has thus been generally disregarded. But if we reconsider its value proposition in light of a relaxed waste criterion, and accept fusion will produce ILW, then it is a much smaller jump to accept that HLW and actinides will also be produced. But the only significant qualitative difference between a fission-fusion hybrid and a pure-fission device would therefore be the absence of meltdown risk.

In summary, hybrid devices could better compete with next-generation fission through reduced plasma physics complexity, lower LCOE, and inherent safety from meltdown, but this comes at a cost with regards to waste and proliferation concerns.

#### 4.3.8. Summary

In a decarbonised grid dominated by cheap intermittent renewables, power generation will likely need to follow demand. Fusion energy could do this to some extent, which would increase its competitiveness relative to gas with CCS, the technology most economically-suited to fast load-following in a post-carbon world.

There may exist low-carbon heat markets for which fusion is better-suited, but it will not have exclusive access.

Once realistic engineering and materials constraints are considered, the characteristic advantages of fusion become less clear, and the difference between fusion and fission (especially generation IV fission concepts) becomes finer. We summarize some of this complexity in Fig. 3.

Fusion could potentially achieve a very high EROI, but so could advanced fission fuel cycles, and in both cases the maximum achievable value is significantly constrained by the size of the required power plant.

Given that any practically realisable fusion device is likely to produce nuclear waste which requires deep geological disposal, the step towards a fission-fusion hybrid becomes more acceptable. This presents the possibility of building an intrinsically meltdown-proof,  $^{238}\text{U}$ -burning hybrid reactor, which would not only solve many of the hardest problems with designing a “pure” fusion device, but could provide significantly cheaper electricity.

#### 4.3.9. Sensitivity to assumptions

Clearly the scenarios presented in this paper are highly speculative, and rely on many assumptions. While it’s impossible to be exhaustive, by using our framework we can at least discuss possible implications of changing some of those assumptions:

- If LLW could be achieved (most likely through regulatory change) then fusion would have a much clearer advantage over fission.
- If very compact fusion reactors can be developed then they may manage to undercut fission or gas with CCS plants. However our earlier analysis still indicates that the balance-of-plant required outside the fusion reactor itself might prevent them reaching a lower LCOE than that of future renewables.
- If very strong unexpected mineral supply constraints apply (such as cartelisation of production of certain rare-earth metals, or refusal to trade uranium internationally) then that could be a limiting factor for deployment of various technologies.
- If some geopolitical advantage of fusion technology (such as independence or compactness) is prioritized by governments, then that may be a reason for them to pay a premium price.
- If renewable buildout is stymied such that premise E is violated, it could mean firm sources form the backbone of the decarbonised grid.
- In a net-zero scenario in which renewables don’t reach 100%, the failure to develop or deploy CCS benefits other low-carbon dispatchable sources such as nuclear considerably.
- If any of these caveats apply to a specific region, then that region could develop infrastructure following a different pathway.

#### 4.4. What is the current strategy?

##### 4.4.1. Public

The major government-led national and international fusion efforts are pushing towards broadly similar designs: large tokamaks which provide baseload electricity.

A representative example is given by the Eurofusion roadmap (Donné and Morris, 2018) which emphasises the need for more materials science research “so as to avoid permanent waste repositories and allow recycling”. It also generally advocated for baseload because “a predictable baseload electricity supply is needed to handle short-term and seasonal variations in the renewable sources”. Furthermore, it states that “The ultimate goal is commercial electricity”, with no mention of supplying heat directly.

The UK’s recently-announced Spherical Tokamak for Energy Production (STEP) project (U.K. Atomic Energy Authority, 2019) will be examining many of these socio-economic and environmental issues in more detail.

##### 4.4.2. Private

There are also now many private enterprises ostensibly planning to demonstrate fusion energy production on timelines accelerated relative to the Eurofusion roadmap.

Most of these concepts still have similar characteristics to the conventional government-led programmes’ designs. Although the confinement technologies being pursued vary widely, the necessity of neutron production and tritium breeding implies these designs will have similar waste production, safety cases, and material supply constraints.

These companies generally plan to achieve net-power output in devices which are much smaller than those which follow the trajectory of the Eurofusion roadmap, with an aim of significantly reducing LCOE by reducing initial capital cost. Many of these designs rely on recent developments in Rare-Earth Barium Copper Oxide (REBCO) high-temperature superconducting magnet technology in order to scale down the required reactor size (Sykes et al., 2018). (Essentially following the “raise magnetic field strength” strategy described by Freidberg (Freidberg et al., 2015).)

The implications of compact reactors are discussed above, but the other significant difference for these enterprises is the projected timelines (Kramer, 2018; Sykes et al., 2018). If they can produce a

	Intermittent Renewables (wind + solar)	Gas + CCS	Fission (e.g. PWR)	Gen IV Fission (e.g. Sodium-cooled fast reactor)	Fusion	Fission-Fusion Hybrid
LCOE	cheap (excluding energy storage)	medium	expensive	expensive	expensive	expensive (but < fusion)
Long-term waste	no nuclear	CO <sub>2</sub> storage	high-level nuclear	high-level nuclear (but spent nuclear fuel < fission)	likely intermediate-level nuclear	high-level nuclear
Nuclear safety risk	no nuclear risk	no nuclear risk	meltdown risk	meltdown risk, but passively-contained	risk of nuclear accident, but not meltdown	risk of nuclear accident, but not meltdown
Weapons proliferation risk (fissile material on site)	no	no	yes	yes	no (but tritium produced)	yes
Resource constraints	rare-earth metals (depends on substitutability)	gas reserves	Uranium-235	Can use Uranium-238	Lithium, but possibly Beryllium	Can use Uranium-238
Scalability	require intermittency solutions at high penetrations	limited by CO <sub>2</sub> storage locations	high	high	high	high
Areal energy density	low	high	high	high	high	high
Load-following	no	fast	rate-limited by thermal inertia	rate-limited by thermal inertia	rate-limited by thermal inertia	rate-limited by thermal inertia
Burn actinide waste?	no	no	no	yes	yes	yes
EROI	~ 50 (wind without storage) ~ 20 (solar without storage)	~ 40	~ 85	≤~ 170	≤~ 170	≤~ 170
Technology readiness level (TRL)	9	8	9	8/9	2/3	3/4

Fig. 3. Table of the relative advantages and disadvantages of various energy sources.

commercially-competitive reactor in time to scale up before decarbonisation, they could displace fossil fuel plants. This would change the outlook for fusion significantly, but is reliant on very optimistic technological progress.

## 5. Conclusions

There is currently a clear motivation for fusion. Renewables alone likely will not present an optimal solution to the energy supply problem (Jenkins et al., 2018b), so grids will benefit from dispatchable low-carbon backup. Fusion would be one competitor in that market (Bustreo et al., 2019), and has some unique advantages over both current fission and gas with CCS, so even in our simplified scenario continued fusion technology development should be pursued on that basis.<sup>1</sup>

However, fusion energy research originally intended to solve a somewhat different set of problems to those which will face a post-carbon grid in the future. Additionally, the established relative advantages of fusion energy are somewhat vague, especially surrounding nuclear waste production. With these extra constraints, fusion is more similar to fission than it first appears; the largest remaining differences are non-criticality and non-proliferation, so these advantages should be pushed while waste is relaxed.

However, in such a renewables-dominated (and market-dominated) scenario, fusion may only end up significantly contributing to post-carbon global energy supply in a scenario where:

- Renewables and energy storage cannot solve the decarbonisation problem alone,
- Fusion can help mitigate renewables' intermittency problems,
- Or fusion can find a niche market such as baseload industrial or district heating,
- Production of nuclear waste which requires deep geologic disposal is seen as acceptable,
- The remaining advantages of fusion over fission are enough to motivate development.

If none of these things happen, fusion may be relegated to being a

post-CCS or post-Uranium technology, to a much smaller market, or simply never become an established technology.

Therefore fusion programmes should consider:

1. Seriously studying the feasibility and benefit of the low-level waste criterion, and consider abandoning it, especially for first-of-a-kind devices,
2. Aiming for a dispatchable, load-following reactor design,
3. Supplying heat as well as electricity

The fusion research community should also explore several additional questions:

1. What might the full lifecycle Energy Return On Invested be for modern designs of commercial fusion power plants?
2. Which materials and elements currently being considered in fusion prototype designs cannot be scaled to hundreds of GW-sized reactors on sustainability or resource availability grounds?
3. Is the recycling of activated materials from reactor structural materials actually plausible or desirable?

In order to secure the confidence of large-scale private-sector investors, fusion projects will likely need to be able to answer these questions. However we believe most current conventional fusion reactor concepts and research programmes do not consider these aspects in detail.

## 6. Policy implications

- By the time the government fusion programmes demonstrate fusion energy production, the global energy grid will likely have changed very significantly.
- A fusion reactor supplying baseload electricity might be obsolete by the time a demonstration device is built.
- The fusion community should consider output power modulation when defining research goals.
- Fusion research should consider relaxing the low-level waste criterion to accept intermediate-level waste.

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<sup>1</sup> There are also many non-energy-related arguments for the value of fusion research to society, such as spin-offs (Buckingham and Loving, 2016), multiple-use technology development (Bruzzone et al., 1088), skills training (Reid, 2014), interdisciplinary crossover (Diamond et al., 1088), international collaboration (McCray, 2010), public science education (Malcolm-Neale, 2019), and potential high-impulse space propulsion technologies (Santarius, 2005).



## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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