The commercialisation of fusion for the energy market: A review of socio-economic studies

Thomas Griffiths, Richard Pearson, Shutaro Takeda, Michael Bluck

1. Introduction

Nuclear fusion (the process that powers the stars) promises increased, low-carbon energy security if it can be commercially realised. Unlike fission, it benefits from enhanced safety aspects, (it does not require a chain reaction for operation) and reduced radiological waste (it does not produce elementally heavy spent fuel). The IEA's latest flagship World Energy Outlook report does not consider fusion a future energy source for either electric or non-electric applications, and neglects its potential to contribute towards global net-zero emissions in 2050. Beyond the IEA, there are no major institutions, (outside of fusion specific think tanks), looking into future energy strategy that consider fusion as a potential contributor to the energy mix. This decision is justified from a lack of immediate progress in ITER, the cornerstone of fusion's public endeavours. Importantly, the presence of fusion in these reports is key to decision making for potential investors and energy policy makers. At present, fusion is faced with the challenge of making predictions about its future prospects before it has been realised as a technology. In corollary, fusion is required to answer critical questions levelled to the community: what form does it take, how much it will cost, why do it, and, based on the previous questions, when will it be realised (all relative to other technologies).

The purpose of this review is to expose socio-economic areas that need further research, and from this assist in making recommendations to the fusion community, (and policy makers and regulators) in order to redirect and re-purpose fusion for commercialisation:

(i) Role/Market Share - when commercialised, **what** form does it take, **where** does it fit into a future energy system?
(ii) Cost - compared to other technologies, **how** much will fusion cost?
(iii) External outcomes - **why** do it?
(iv) Timescales - **when** is it likely that fusion reaches commercialisation?

2. The Role of Fusion

By 2050 it is likely that the electricity market will already be saturated with low-carbon technologies (1). By taking a step back from the electricity narrative, the optimum role of fusion can be considered by asking some basic questions. If electricity is already covered, what non-electric applications could there be for fusion energy? Are these applications cost competitive? What is the socio-economic impact of utilising fusion in this way? It is also important to note that as of 2018 electricity made up only 20% of the world's total energy demand (which will rise to 25% by 2040 (1)), leaving three quarters of demand available for fusion to potentially fulfil. Thus, it is important to consider fusion as an energy source outside of the electricity domain, such as in applications that are dominated by fossil fuels and not easily replaced by low-carbon alternatives.

Which of these non-electric applications are applicable for fusion? For the purposes of this paper, fusion is considered as a technology that can not only contribute to climate targets, but also provide long-term sustainable energy for human kind, hence enabling significant inroads to global energy demand. Therefore, the applications considered are hydrogen production, desalination, district heating, and the use of process heat. Although, it is important to note that if it was possible for fusion to be used in other applications (such as production of PET isotopes, transmutation, and space propulsion), as well as direct energy production, it could demonstrate a significant advantage over other competing technologies.

2.1. Electricity

Usually, scenario based analyses are used in order to predict the severity of carbon restrictions placed in future contexts (2), (3), (4), (5). Discount rates are also found to have a large impact on the materialisation of fusion (5). Moreover, reductions in discount rates increased fusion's penetration from 4% to 23%, aligning with findings from costing studies that estimate up to ∼90% of the cost of electricity is encapsulated in capital costs (6), (7). When increasing the capital cost by 30%, fusion was predicted to have no market share by 2100. However, a decrease of 30% leads to a market share of 43% in the same time-frame, which aligns with suggestions made by (8) that the cost fusion will need to be reduce in order to see penetration before 2050. The technologies competing for a share in the market within all these studies are Carbon Capture and Storage (CCS), fission and renewables.

In a follow up study (contrasting the findings of (9) and (2)), it was found that those countries with less affinity for affordable renewable energy but high energy demand, such as Turkey, Korea and Japan, had the most inflated regional fusion plant capacity (10). In addition, fusion's electricity market share is small when investment costs are increased by 30%, as seen in (5).

To summarise, the materialisation of fusion is directly linked to the introduction of climate change drivers in all the above studies. The findings can be split into well defined themes:

(i) When there are no climate change drivers, fusion is not an emergent technology due to global market dominance of cheaper, and already established fossil fuels.
(ii) Fusion obtains a market share when climate change drivers are in place, with the inclusion of carbon taxes. However, there is no significant contribution to near future climate targets. This is mostly down to high overnight capital costs, competition from other technologies, volume of required resources, and thus timescales required for large scale deployment of a global reactor fleet.
(iii) Cost has the biggest impact on fusion's emergence, with market shares observed only when costs are reduced relative to current predictions.

Perhaps the most important of these is cost, where direct contributions to climate targets are only achievable when significant reductions are implemented. If the fusion community is to continue to fulfil its potential of solving the energy crisis, then it should attempt to do so with a different approach to first of a kind (FOAK) reactors, i.e., seeking to implement a lowest cost design that can be adapted and improved in later iterations, rather than attempting to create the perfect product at the first attempt.

If future de-centralised energy systems are mostly comprised of intermittent renewables, then complementary sources which can meet different demand scenarios will be required. There are numerous examples in the literature of load following technologies reducing overall costs (11), (12), (13). Thus, fusion's capacity to demonstrate load-following characteristics enhance its suitability as a future energy source. In addition, it was initially thought that, due to slow power ramp-up times arising from inherent safety concerns, fission could not adequately load follow. However, there have seen several studies that discredit this theory, leaving fusion with further ground to make up in the "fission vs fusion" debate (14) (15). Issues that fusion will need to overcome in order to improve its grid agility include outages caused by plasma disruptions and periods of start-up. These have been shown to lead to disturbances in future grids, (16) (17). Disturbances of this kind raise questions as to the applicability of pulsed devices in future grids, such as those using inertial confinement methods.

2.2. Non-electricity

In terms of hydrogen production, there are four potential methods that a fusion reactor could use:

(i) Water electrolysis
(ii) Steam electrolysis using nuclear heat (600-1000°C) (18), (19).
(iii) Thermochemical processes (600-900°C) e.g., sulphur-iodine cycle (20), (21), (22).
(iv) Reformation of fossil fuels and biomass through nuclear heat (700-1100°C) to produce *blue* hydrogen (23).

Potential issues arising from production of hydrogen are the escape of tritium into the environment, and the need for large volumes of deionised water in thermochemical processes. These issues however, could in fact benefit fusion by providing start-up fuel, which would otherwise be synthesised or purchased at great expense (24), and also through co-generation with desalination plants. In addition, blue hydrogen not only results in the production of CO_2, (which relies on the use of CCS), but also uses fossil fuels to extract the hydrogen. Considering the well documented exploitative nature of fossil fuel extraction, this may not be the best option for fusion to pursue.

Initial studies such as (25) and (26) discuss the potential for fusion electricity and heat to be used for producing desalinated water. The primary motivation for use of fusion for this process stems from an estimated usage of desalination facilities in 150 countries and 300m people. At present these services are provided through the of use other carbon intensive technologies (27). (28) links a reactor design from the ARPA-E project the production of 0.9m^3/day of fresh water. A potential secondary advantage to fusion for desalination is that lithium may be obtained from seawater and extracted for fuel use in fusion plants. The assumed figure for carbon footprint of a desalination plant 66gCO_2/kWh are not in agreement with those highlighted in the Externalities Section. As a technology with a key purpose of disrupting the carbon intensive options for producing fresh water, it is odd to see that the weighted importance of carbon footprint is lowest compared to other factors considered (such as area, discharge, water quality, and community).

District heating of homes offers significant contributions to CO_2 emissions in the UK, totalling 18% (29). As a concept it is able to reduce carbon footprint, whereby a large and central source for heat from a collection or *district* of buildings can provide ample space for heating of the water. Current district heating installations in the UK provide 2% of overall heat demand (residential, public and industrial sectors). Overall, there is a lack of fusion for district heating studies in the literature. However, it has been demonstrated that, depending on the demand of the system, district heating's inherent use of waste energy increases overall plant efficiency to 80% in Light Water Reactor's in Helsinki (18). Thus, district heating can play an important part of global reduction in carbon emissions.

In the European Union, high temperature (>400°C) heat accounts for 26% of demand from industrial processes, with the most significant contribution coming from fossil fuels (30). In terms of emissions, the process heating sectors account for 14% of the UK's carbon footprint (31). These include: manufacturing of mineral products, food and drink, and iron and steel industries. The aforementioned encompass the highest-energy consuming sectors within the UK, making up 50% of total process heat consumption (29). Despite a lack of fusion based process heat studies in the literature, analogies can once again be made with fission, such as the Gemini project, involving the EU, Japan and Korea, which will supply process steam to industry (32).

3. The Cost of Fusion

What is meant by the term *cost*? This is important to consider, as studies have interpreted this in a variety of ways. For example, early studies from (33) and (34) assume fusion's external costs to be minimal, and therefore postulate that total costs are encapsulated by internal costs alone. The vast majority of existing literature investigates the cost of fusion as a source of electricity, however this paper will also evaluate studies estimating the cost of the non-electric applications outlined in Section 2, i.e., hydrogen, desalination, process heating, district heat and industrial uses.

3.1. ***Electricity***

In order to predict fusions economic competitiveness as a producer of electricity with other technologies, costing studies often seek to estimate a *levelised cost of electricity* (LCOE). This is simply the ratio of total cost and total energy output over the lifetime of a reactor. Initial estimates suggested that upon entry to the market, fusion's LCOE could be similar to competing technologies (35). Subsequent studies have shown a large range of values varying from 40-165mill/kWh. See Table 1.

(38) investigated the techno-economic potential of fusion, and a second generation DEMO-type plant would achieve a Net Present Value (NPV) equal to initial investment: $312 mills/kWh. Furthermore, taking data from the study assumes that fuel, waste disposal and decommissioning represent 3% of total cost of electricity (39). Attempts to place a valuation on fusion energy are also available from (40), who through modelling, quote anywhere between zero and $30 trillion. It is found that valuation is strongly dependent on the success of CCS and fission, where increases in the capacity of these technologies see fusion's valuation lowered. Similarly, valuation significantly increases with accelerated timescales of materialisation and aggressive carbon restrictions. These findings align with the findings of market share studies mentioned in Section 2 from (9), (2), (5), (4), and (10).

Unlike current solar PV and wind technologies which harbour reliable cost predictions as a result of being well established in the market, fusion is an unrealised technology and therefore possesses many uncertainties that affect cost. Therefore, it is important to try and unpack some uncertainties that lie within the values in Table 1. Not only does the number and range of different values confuse understanding of fusion's cost against other technologies, but several other pitfalls are uncovered when attempting to examine analogies with other technologies in closer detail. Firstly, the validity of making comparisons based on cost reduction or *learning* factors should be considered.

Table 1: Various LCOE estimated by paper and year

Year	LCOE Value (mills/kWh) (Paper)
1993	40-50 (35)
2001	70-130 (34)
2001	65-100 (36)
2002	80-100 (25)
2002	70-130 (9)
2003	90-165 (2)
2005	50-100 (33)
2006	64-140 (37)
2017	60 (7)
2018	75-160 (38)

Learning factors are economic trends seen when FOAK technologies enter a market, whereby the cost of producing subsequent products decreases with each iteration. It is also a good metric for the commercial success of any FOAK technology and is clearly represented across all renewables in the energy sector. Secondly, the values from each study form a range that the calculated LCOE lies within. Taking 70-130 mills/kWh from (34) as an example, the size of the scale means that the low end of the estimate may prove economical, and the high end, costly. Thirdly, there is the impact of inflation to consider. Principally, this stifles the ability to analogise one LCOE calculated from 2001 dollars and another calculated from 2016 dollars. Crucially, it also muddies costs comparisons of reactors examined at different times periods. Lastly, almost all of these values have been calculated using different assumptions, such as confinement time and capacity factors. This means that no two LCOE values have resulted from identical, or even similar calculation methodologies. Looking beyond a direct LCOE analogy, both (7) and (41) share similar assumptions in design specification, such as energy confinement, bootstrap physics, cooling systems, and construction materials, leading to withdrawal of a useful comparison between the capital cost's share in LCOEs. For (7) this was 88% and for (41) it was 75%, the main difference for (7) being that the modularity and interchangeable components of the reactor lead to accelerated effects of learning factors.

3.2. ***Non-electric applications***

As per (42) the estimated levelized cost of hydrogen (LCOH) ranges from \$1.87 to \$3.24/kg, where reductions arise from the implementation of carbon pricing at the point of commercialisation. In (43) the cost of hydrogen produced from water splitting using fission is \$2/kgH_2. The predicted cost of desalination processes from (28) is 0.53-1.94\$/m^3, however this may change if the plant was also used as means to provide lithium for fuel of fusion plants. In terms of district heating, a case study from Lyon, demonstrated that the use of gas and electric boilers over district heating systems lead to 111% and 135% increases in annual energy bills. Drawbacks include increased initial investment compared to other options, and that nuclear district heating becomes more expensive than boilers when electricity prices exceed that of gas by 3.5% (44). Countering increased initial investment costs, the upfront capital cost of manufacture can be significantly reduced if it is included in the initial build phase of the plant. This is advantageous to fusion which (currently) has no constructed commercial plants to speak of (30). In terms of fusion for process heating, there are currently no costing studies within the literature. However, analogies can be drawn where the levelised cost of electricity can provide insight into the cost of thermal energy from fission reactors. For example, assuming that the cost of electricity encompasses cost of inputs and outputs, a Pressurised Water Reactor with an efficiency of 35% that produces electricity at 78–120\$/MWh will harbour a thermal energy cost of 7.42–11.42\$/GJ, which is comparable to that of natural gas: 3.5-8\$/GJ (45).

4. The Externalities of Fusion

In terms of energy security and environmental impact, the potential advantages of fusion energy are well known, despite not yet being a commercial technology. Yet, few studies have explored the possible spill over benefits of fusion and scrutinised external socio-economic topic areas, such as sustainability, carbon footprint, job creation, regional benefits, and GDP. In 2020, (46) sought to address a variety of identified problem categories, with an overall aim of conducting an external review of fusion and its practices. These categories were geo-economic, geo-political, geo-sociocultural, and geo-technological. The proposed mechanism for the external review is to model in line with the International Energy Agency's Global Commission for Urgent Action on Energy Efficiency. In terms of geo-economics, benefits are evident from increased knowledge of the business acumen for the private and public

Table 2: A comparison of carbon emissions for competing technologies

Technology	Fusion	Offshore Wind	Onshore Wind	Solar	Fission
CO_2Emissions (gCO_2/kWh)	9 - 22.2	15.6	9	15.8-38.1	15-50
Study	(48), (49), (47)	(54)	(54)	(55)	(54)

sector projects, as well as the subsidy models that will aid in bringing FOAK reactors to market against low-carbon competitors. In terms of geo-politics positives can be drawn from ITER as a blueprint for international diplomacy. In terms of geo-technologies, the commercial viability of compact reactors and tokamak "lock-in" provides further evidence for the need of external reviews, especially from markets that fusion breakthrough would open, such as magnet technologies. The study strongly advocates the use of "open innovation diplomacy" to diminish risks of global market autonomy from single vendors in such markets. Through multi-regional input-output analysis, (47) takes reactor data from (6) to investigate the corresponding footprint for fusion investment. Geographically, the study finds that 47% of total production occurs within Europe, and 20% occurs within the US. China and Europe experience the creation of 183,000 full time equivalent jobs, i.e., 133.6 FTE/MW. With the exception of solar CSP, this exceeds that of all other renewables (47). The calculated estimate of 11.4gCO_2/kWh for CO_2 emissions aligns with 9gCO_2/kWh from (48), but disagrees with the value of 22.2gCO_2/kWh (49). See Table 2 for comparisons with other potential competitors.

The results from (47) are based upon cost assumptions that do not align with those of other studies. As an example, tritium breeder blanket, first wall, and divertor costs are assumed to be zero as a result of being encapsulated within operation and maintenance budgets. Whereas (7), (41) assume that blanket and first wall costs are captured by capital costs. An important observation in (47) that is not encapsulated in (48) and (49) is the emissions from mining materials for fusion. In addition to this, not only is the reactor data from (48) from a 46 year old study, but the data for $kgCO_2$/tonne of material is cited from the lead author's own thesis. EUROfusion highlights climate change and public acceptance as two of the most uncertain socio-economic drivers facing fusion. As seen in Sections 2 and 3, fusion's emergence, market share and value is improved when aggressive carbon policies are in place. Recall also, that China, the US, and Russia are all predicted to be market leaders upon materiality of fusion. These regions are all committed to the terms of the Paris Agreement, but uncertainty lies in whether this commitment will be demonstrated fully. Evidence for this can be drawn from China and Russia's inability to meet climate targets (50), (51), (52), (53), and the US's recent temporary withdrawal from the agreement altogether.

5. The Timescales of Fusion

Studies attempting to estimate the *when* for fusion come in a variety of forms. For example, it is important to outline that rather than making a prediction for an exact date of fusion materialisation, studies seek to answer a broader question, such as its role and market share. Note that for the purposes of this paper, fusion will have materialised when it makes up 1% of global energy mix, as suggested by (56). Early strategy investigations, (57), estimated that an accelerated DEMO schedule would provide electricity to the grid by 2034, and by 2040 under a standard one (58). In reference to (56), which outlines the Laws of Emerging Technology Development, this is usually one order of magnitude per decade. Taking the assumption that the market is open for exploitation with no hurdles impeding materiality, (8) modelled the cost and potential speed of deployment for fusion. The study showed that, via the ITER roadmap, fusion materialises in 2070 in the form of a Gen-III DEMO, assuming a learning factor of two per factor of ten of installed power.

The use of learning factors from fission studies are more representative of those likely to be seen in fusion, than of those from solar and wind projects. This renders the use of solar and wind gradients for fusion in (8) less realistic. An overlooked assumption in other studies are construction times. In (57), ITER's is quoted optimistically, and now erroneously, as eight years. The same estimate is given for DEMO which, despite no finalised design specification let alone construction phase, will have 4x the thermal output of ITER, and harbours greater complexity in physics and engineering, and increased size, casting further doubt on timescales produced in roadmaps. Attempts to achieve accelerated targets for DEMO via the implementation of assertive design and construction schedules may carry too much of a financial risk for investors. This is because advanced schedules will result in the construction of DEMO preceding the design of the inner vacuum vessel components. In addition, 10 year construction times, (as quoted in (57), (4), (7), (5)), engenders the prevention of improvements in reactor iterations (59). This is because investors would be required to order new iterations of reactors prior to the completed construction of it is predecessor.

6. Recommendations and conclusion

The external review mechanism proposed in (46) and the adherence to EU taxonomy criteria of sustainable energy sources are certainly positive examples of methods that fusion can use to leverage itself against other energy sources in the global green initiative. In addition, recommendations for public-private partnerships in producing a net pilot plant before 2040 in (60) presents a positive step towards achieving greater cost certainty needed for investors. Importantly, further positives from external review actions can objectify ITER's role not just as a crucial player in fusion research and development, but also as a geo-political indicator for the role fusion can play in international diplomacy, especially between tensioned nations, such as the US, China and Russia.

At present, reactor designs present in literature have been shown to lack economic competitiveness when placed in future energy system models. Why is this? What research gaps are presented therein? Uncertainties still present a major issue, where values are simply used and assumed with no accompanying empirical evidence. In terms of potential roles for fusion outside of electricity generation there are many gaps to exploit as only a few have been covered thus far (28), (23). Moreover, these have not as yet been studied in the context of reactors beyond those in the public domain. In terms of sociological impacts of fusion, this paper compares the first results of fusion's effects on job creation and GDP. Once again this was not done for reactor types mentioned previously, therefore representing further possible research avenues. In addition, it would be interesting to investigate how non-electric pathways for fusion affect job creation and GDP.

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