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

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Abstract
Progress in the development of fusion energy has gained momentum in recent years. However, questions remain across key subject areas that will affect the path to commercial fusion energy. 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 orient fusion for commercialisation: When commercialised, what form does it take? Where does it fit into a future energy system? Compared to other technologies, how much will fusion cost? Why do it? When is it likely that fusion reaches commercialisation? Investigations that have sought to answer these questions carry looming uncertainty, mainly stemming from the techno-economics of emerging fusion technology in the private sector, and due to the potential for applications outside of electricity generation coming into consideration. Such topics covered include hydrogen, desalination, and process-heat applications.

1. Introduction

Nuclear fusion (the process that powers the stars) promises increased, low-carbon energy security if it can be commercially realised. However, the fusion community's current focus is on technology development for a proof of concept, i.e. a working reactor for energy generation. Outside of this, limited research exists that seeks to resolve unanswered questions on commercialisation. Through investigating this narrative, this paper aims to reveal gaps in order to develop appropriate strategic pathways for policy makers, regulators, investors and the vendors themselves. Unlike fission, it is passively safe (it does not require a chain reaction for operation), and will not produce high level 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—that are looking into future energy options that explicitly consider fusion as a potential contributor to the energy mix. This decision is justified from a lack of immediate progress in ITER, the device developed via international collaboration that represents the culmination of decades of publicly funded R&D in fusion over the past four or so decades. Importantly, the lack of focus on fusion as a viable option is key to decision making for potential investors and energy policy makers. Therefore, in order to be considered in energy forecasting outside of the fusion community, fusion needs to demonstrate it is potential in areas beyond simply providing greener energy security.

Nevertheless, it is important to consider how the private sector has influenced fusion’s trajectory, where at present there is a focus towards ‘agile innovation’, with ‘simpler’ and ‘shorter’ development cycles [1]. Currently the branches of fusion research consist of public projects such as ITER, JET, MAST-U, NSTX-U, and private projects such as, Tokamak Energy, Helion Energy, First Light Fusion, Commonwealth Fusion Systems, TAE Technologies, and General Fusion. Many of these organisations are private companies working
in tandem with public sector grants¹. Inclusive of the aforementioned projects, there are many examples of fusion experiments worldwide that are utilising different confinement methods. These are summarised below:

(a) Magnetic confinement (MCF): in this method, the super-heated fusion plasma is held away from material surfaces (in order to prevent damage) by a union of toroidally arranged magnetic fields, such as in Tokamaks. This is the most heavily researched confinement method and will be utilised by ITER and DEMO. Other examples include: High-beta Tokamak Extended Pulse devices [4], Stellerator such as Wendelstein 7-X [5], Reversed Field Pinch devices such as the RFX-Mod experiment [6], and Tandem Mirror devices such as Gamma-10/PDX (investigating divertors) [7].

(b) Inertial confinement (ICF): operating in a pulsed system, this method can be achieved either through the use of lasers, or Heavy Ion Fusion. In laser confinement fusion, the high intensity system compresses and super-heats the fuel into plasma at high pressure, thus inducing fusion reactions and the subsequent release of energy. Examples of such experiments include the National Ignition Facility (NIF), which recently achieved marked success in the steps towards fusion ignition [8].

(c) Z-Pinch confinement: these devices are able to control the plasma by utilising the electromagnetism produced by the plasma itself. In-theory, this negates the need for expensive and intricate external electromagnet systems seen in Tokamaks [9]. Examples include the Mega Ampere Generator for Plasma Implosion Experiments (MAGPIE) at Imperial College London, UK [10].

(d) Inertial electrostatic confinement: this method uses electric fields rather than magnetic ones to confine the plasma. Theoretically, energy losses during sustained plasma heating regimes are minimised in these devices, making them more suitable for aneutronic fuels [11].

(e) Combined confinement techniques these include: Flow Pinch (using sheared flows and Z-Pinch configurations [12]), and Magneto-inertial/Magnetised Target Fusion (MTF) (using the compressional heating of ICF alongside aspects of MCF [13]), such as in General Fusion’s design specifications [14]. Field-reversed configurations (FRC) hold fusion plasmas in closed magnetic field lines, with high-beta (β, normalised plasma pressure, see section 3.2.4) [15]. Examples of aneutronic experiments include Helion Energy and TAE Technologies [16, 17].

Besides output of economic models from EUROfusion’s Socio-economic Studies working group, the research approach of public projects is technology driven, leaving topic areas such as commercialisation relatively underdeveloped e.g. [18]. Therefore, for those private enterprises proclaiming accelerated timelines, simplified engineering and cheaper designs, a development of understanding of how best to deploy such a reactor for commercialisation, is needed. 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, the fusion community is required to answer critical questions levelled to the rest of society: what will it cost? Why do it? And, based on the previous questions, when will it be commercially realised (all relative to other technologies)?

The role of fusion as an electricity source has been analysed extensively [19–27]. However, studies looking into non-electricity applications (desalination, district heating, hydrogen production, and process heat for industrial applications) are limited in comparison. This is because current research rarely draws meaningful quantitative data from modelling that is useful to policy makers, regulators, and investors. This is somewhat surprising for several reasons: (a) given that the electricity market covers only 20% of global primary energy consumption and (b) the market likely to be saturated by other technologies by the time fusion is commercialised, leaving fusion’s potential exposed and with no role to fill. This is explored in section 2.

There are many studies that have attempted to calculate the cost of fusion. The mechanisms for which are dependent on the context of the study, i.e. is the goal to predict the cost of a single fusion reactor placed in today’s electricity market, or for a group of reactors in 100 years from now? It is important to note here that almost all existing studies relate cost to a reactor producing electricity and not non-electric applications. These questions can be further constrained through predictions of cost behaviour for a reactor utilising present day technology, versus a reactor using future technology. What is important here is that once again for fusion—an unrealised technology—the latter prediction is more complex. Thus, with limited historical or evidential data, generating assumptions becomes more challenging, and leaves the results of any modelling vulnerable to increased uncertainty. The sources of uncertainty and how they affect the commercialisation of fusion are explored in section 3.

By it is proponents, the potential technological advantages of fusion over fission and other renewable sources are well known. However, recent studies challenge the assumption that fusion fuels, commonly cited

¹ Note that there are many more examples of both public and private projects, comprehensive list of which can be found in [2, 3].
as being abundant and geographically widespread, are without issue [28–31]. In general, the potential advantages (or disadvantages) are in need of further analysis to gain understanding fusion's impact on areas such as resource availability, job creation, GDP, and carbon footprint. Specifically, it is important to understand how crucial areas, such as supply chain for the manufacture and maintenance of future fusion reactors, are affected. These areas are analysed in section 4.

Once these questions are understood and examined, the question of when fusion will be ready can be assessed. It is noted here that estimations of timescales from roadmaps of private enterprises are rarely the result of modelling and the use of data, but more commonly are the outcome of setting a target date for the technology to be ready, arguably as a means to entice potential and current investors, and to spur technology development. Other estimations reveal the emergence of fusion based on unrealised reactor technology, and this will be explored in section 5.

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, policy makers, and regulators in order to redirect and orient fusion for commercialisation:

(a) Role/Market Share—when commercialised, what form does it take? Where does it fit into a future energy system?
(b) Cost—compared to other technologies, how much will fusion cost?
(c) Externalities—why do it?
(d) Timescales—when is it likely that fusion reaches commercialisation?

2. The role of fusion

As of 2018, electricity made up only 20% of global primary energy consumption (which will rise to 25% by 2040 [32]), leaving three quarters of demand available for fusion to potentially fulfil. It is also likely that by 2050, due to pushes for global decarbonisation, the electricity market will already be saturated with low-carbon technologies [32]. Not only is there a strong likelihood that these will have become cheaper with time, but they will also be more widespread and be coupled with greater storage potential, rendering it difficult for fusion to compete for market share. Further barriers arise from the stringent power generation, and grid connection requirements set by regulators. Using the UK as an example, any project that desires to generate electricity with an onshore capacity >50 MWe is considered a ‘national infrastructure project’, meaning that it must obtain a Development Consent Order as per the 2008 Planning Act. Such projects are then investigated by the Planning Inspectorate before a recommendation is submitted to the Secretary of State for Energy and Climate Change. Any project that wishes to have a grid connection must first obtain an agreement from National Grid Electricity Transmission (NGET). The generator must demonstrate adherence to the Connection and Use of System Code (CUSC) Framework Agreement, complying with the CUSC and the requirements of the Grid Code (i.e. the rules related to planning, operation and use of the electricity transmission network) [33].

By taking a step back from the electricity narrative, the optimum role of fusion can be considered by asking some basic questions. If the electricity market is already provided for, what non-electric applications could there be for fusion energy? Are these applications cost competitive? Whilst these questions relating to cost and socio-economics are covered in sections 3 and 4, the potential market application for fusion should be assessed.

What is the socio-economic impact of utilising fusion in this way? Note that questions relating to cost and socio-economics will be covered in sections 3 and 4. 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. With this in mind, it is important to mention the difficulty fusion energy faces in breaking into non-electric markets. Another important consideration in non-electric applications are potential barriers to market penetration. Fusion energy is not likely to be used initially to establish a new sector, and is more likely to break into an existing one. This comes with its own challenges, most notably that it must conform to existing market norms and compete with incumbents [34]. Thus in the case of the hydrogen sector, the narrative of fusion as a novel technology penetrating into a small capacity, niche market is likely to be difficult to justify. Stemming from previous ideas on technology emergence and market diffusion, including by Bonvillian, Weiss, and Gallagher et al this concept is shown for the fusion context via a traffic light quadrant diagram in figure 1, whereby the two axes, technology and market, visualise how transitioning from the status quo (existing market, existing technology) to either new technologies and or new markets represents the most challenging evolution for fusion to achieve [35]. Contrary to the above traffic light system used in this paper, Weiss argues that innovation whereby new

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Figure 1. A quadrant diagram demonstrating different market-technology sectors:

(a) Incumbent: existing technology, existing market, represented by renewables for electricity production.
(b) Innovation (1): existing technology, new market, represented by renewables for hydrogen production. The transition from the incumbent sector to this one denotes a challenging evolution to achieve.
(c) Innovation (2): existing market, new technology, represented by fusion for electricity production. The transition from the incumbent sector to this one denotes the least challenging evolution to achieve.
(d) Radical innovation: new market, new technology, represented by fusion for hydrogen production. The transition from the incumbent sector to this one denotes the most challenging evolution for fusion to achieve. It is therefore argued that instead, making the transition from Innovation (2) to this sector represents a more achievable, but still challenging evolution.

Technologies can enter existing markets is harder than finding new markets for existing technologies. As an identified legacy sector, this case is seen as an energy industry-specific problem [35].

Which non-electric applications are relevant for fusion? An early study categorised these applications into near-term applications, transmutation, space propulsion and hydrogen production [36]. For near-term applications, it was suggested that fusion reactions could be a possible source for inexpensive positron emission tomography isotopes that are used in cancer diagnosis processes, as well as the production of neutrons in deuterium-deuterium reactions for homeland security [36]. For transmutation, the removal of long lived radio-isotopes in spent fuel, the production of fissile isotopes, and the jettison of weapons grade plutonium are suggested as possible uses. For space propulsion, the physical and technological requirements at the time are not well understood, and thus, this concept is not explored further [36]. Since then, a study in the Journal of Spacecraft and Rockets has summarised fusion’s case for deep space propulsion, suggesting that a pulsed, Z-pinch magneto-inertial fusion device supplies the most cost effective propulsion method, providing journeys to Mars in less than one year [37]. It is suggested that hydrogen production could be achieved through thermo-chemical water splitting, in both high and low temperature electrolysis. One possible benefit of commercial pathways such as hydrogen production is that the plant specifications are aligned with those required for electricity production, meaning that development pathways for electricity production efforts still remain valid until a choice can be made on which pathway is best for fusion to exploit. Studies from Sheffield et al and Nicholas et al further investigate this narrative through cogeneration between hydrogen and electricity [31, 38, 39].

In addition to these non-electric applications, studies have investigated the potential for high temperature fission reactors for use in desalination, process heat, district heating, and industrial steel manufacture. As the operational temperatures for high temperature fission reactors and fusion reactors are comparable, it can be assumed that these can be applied in a similar way as possible alternative applications for fusion [40]. This is unsurprising as fusion reactors represent a source of heat and a means to raise steam in a manner similar to fission. That said, some of the issues of safety and security, regulation, waste and public attitudes are considerably lessened for fusion which may make them particularly attractive in these roles. For the purposes

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2 The study explains that fusion energy will not be the method that spacecraft lift off from Earth, the most effective method for this is still the use of chemical fuel.
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 humankind, hence enabling significant inroads to global energy demand. Therefore, the applications considered are hydrogen production, desalination, district heating, and the use of process heat. 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 by exhibiting versatility and breadth in its range of uses across different sectors in energy demand.

2.1. Electricity
Usually, scenario-based analyses are used in order to predict the severity of carbon restrictions placed in future contexts [20–23]. Discount rates are also found to have a large impact on the materialisation of fusion [23]. These scenarios were modelled by Tokimatsu et al using cost data outputs alongside uncertainties to predict economically competitive costs of electricity (known as break-even prices) [20]. Outputs estimated that fusion’s share of global electricity production would be 30% by 2100, assuming a cost reduction rate of 1% and carbon tax reductions of 10%. Further scenario analysis has been conducted [21–23]. Data inputs for modelling carried out by Han and Ward were gathered ‘externally’ from the GEM-E3 model [21]. It considers interactions between the environment, energy systems and economies across different global regions. These inputs can be classified into policy, technology, supply and demand (i.e. population, GDP, and household growth). The characteristics of the scenarios employed varied costs of fusion (cheap vs expensive) and different carbon restrictions (550 ppm, and a base case with no restrictions). Similar scenarios were used in by Cabal et al with the addition of a carbon tax OECD (Organisation for Economic Co-operation and Development) countries, starting from 0$/tCO\textsubscript{2} in 2020 and rising to 50$/tCO\textsubscript{2} in 2100 [22]. In both studies, fusion had no market share as a result of competition from cheaper alternatives. Under restrictions, fusion’s market share by 2100 was found to be 40%. Further investigation from a follow-on study by Cabal et al analysed the effect of discount rates on fusion’s emergence [23]. 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 [24, 25]. 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 Lopes Cardozo et al 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 [26].

Regional distribution of fusion also has an effect on its emergence. For example, in the studies from Tokimatsu and Cabal, North America, Western Europe, Japan and Russia are the earliest to benefit from fusion, before China and Southeast Asia some decades later [20, 22]. In a follow up study [23], 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 [27]. In addition, these studies show that fusion’s electricity market share is small when investment costs are increased by 30%, as shown by Cabal et al [23]. Three shared socio-economic pathways used were developed from O’Neill et al: Sustainability, Middle of the Road and Fossil Fuel Development [41], all of which share similar characteristics to scenarios presented by Cabal et al [23]. These characterise environment, social dependencies, human development, population and urbanisation and energy policy, based on modelling by Riahi et al [42].

2.2. Discussion
To summarise, the materialisation of fusion is directly linked to the introduction of climate change drivers in all the above studies. The findings in section 2.1 can be split into well-defined themes:

(a) 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.

(b) 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.

(c) Cost has the biggest impact on fusion’s emergence, with market shares observed only when costs are reduced relative to current predictions.

\[^{3}\text{Here external describes models that are not developed purely for fusion research and are used across other industries and socio-economic studies.}\]
Perhaps the most important of these is cost, where direct contributions to climate targets are only achievable when significant reductions are implemented. If fusion energy is to fulfil its potential of solving the energy crisis, then it may benefit from attempting 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. This is especially important for countries with high energy demand, such as India and China, that may be encouraged to opt for alternative, more carbon intensive, and cheaper alternatives to fusion until it becomes cost competitive, which according to these studies, will not be until 2100.

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 [43–45]. Thus, fusion’s capacity to demonstrate load-following characteristics enhances 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 been several studies that discredit this theory, leaving fusion with further ground to make up in the ‘fission vs fusion’ debate [46, 47]. 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 [48, 49]. Disturbances of this kind raise questions as to the applicability of pulsed devices in future grids, such as those using inertial confinement methods. The later contribution from China predicted by Tokimatsu et al [20] and Cabal et al [22] can be called into question following the recent development of their contribution to ITER, through the Experimental Advanced Superconducting Tokamak (EAST) reactor research programme [50–52]. This programme precedes their own DEMO-type FOAK, (Chinese Fusion Engineering Test Reactor) billed for construction in the 2030s [53]. Further contributions to ITER’s design from Korea’s Korea Superconducting Tokamak Advanced Research (KSTAR) encourage their inclusion in regional fusion predictions.

There are many uncertainties that lie within the research and development of fusion technology. However, as summarised above, the characteristics of the future energy market is pivotal to fusion’s emergence. Have carbon policies in the form of ppm restrictions and or taxes been implemented (conditional on regional/global climate policy)? When will fusion have a FOAK reactor ready (conditional on fusion R&D)? At what rate can fusion energy grow and become more widespread, and which countries will have it first (conditional on reactor cost, regional infrastructure, industrial capacity and resource availability)? On this, the predictions made by Gi et al regarding countries with high energy demand and low availability for cheap renewable energy are called into question when observing Japan’s recent investment into increasing their renewable capacity from 19% in 2019 to 24% in 2030 [27]. The IEA highlight offshore wind investments that will result in an installation of 10GW (half of Europe’s total current capacity). How competitive is the cost of fusion compared with other technologies (conditional on the cost of other technologies?)4 Will fusion obtain a discount rate for early investments to reduce capital costs (conditional on government stance on fusion, see policy section below)? What other technologies will fusion be competing with for a market share (conditional on success of CCS technologies)? On this, it is interesting that Cabal et al found fission to be one of fusion’s main competitors. In terms of cost, fission will likely increase with time due to fuel scarcity and the trending decrease in affinity for fission technologies [23].

Accounting for these uncertainties in modelling studies such as those conducted by Cabal and Gi is easier said than done. External models, such as GEM-E3 are required to accurately predict goods and services markets, and calculate capital, energy, and supply and demand of labour and other goods. In addition, it has to implement structural features such as policy orientated instruments (i.e. taxation) along with geographical trade linkages, as well as analyse the trade-off between economic effects of climate policy instruments, such as Feed-In-Tariffs, taxation, and restrictions. Naturally, the use of an instrument with so many inputs inherently contains uncertainty. That said, the use of outputs from external models such as this in two of Cabal’s studies [22, 23] can offer reduced input bias compared with ‘fusion only’ models such as those used by Tokimatsu et al [19, 20] and Gi et al [27]. In addition, GEM-E3’s use across the energy sector in non-fusion research outputs makes comparative studies easier to analyse.

2.3. Low-temperature applications

As a heat engine, like fission, fusion will employ a thermodynamic cycle, such as Rankine or Brayton, incorporating either a water-steam, helium, or CO₂ cycle to produce electricity. At least half of the energy output is lost as low temperature (<300 °C) waste heat from the turbine exit. As with fission or combined

4 This is in turn dependent how their cost will change with time, which is dependent on many things (importantly, government subsidy continuation via green policies and resource availability). However, it is likely that they will only get cheaper.
heat and power (CHP), there is inevitably some loss in diverting this waste heat for other purposes (typically ∼15% of nominal electrical output).

2.3.1. Desalination

Initial studies, such as those from Sheffield et al and Borisov et al, discuss the potential for fusion electricity and heat to be used for producing desalinated water [39, 54]. According to World Energy Outlook, the water sector’s electricity consumption is predicted to rise by 80% by 2040, with desalination expecting to be responsible for 20% of this demand [55]. Motivation for use of fusion for desalination processes stems from the estimated usage of facilities in 150 countries and >300 m people, with primary usage coming from Middle Eastern countries such as UAE, Saudi Arabia, Qatar and Kuwait. At present these services are provided through the use of other carbon intensive technologies [56]. Moreover, whilst it is not currently possible to store electricity at grid level, it is possible to store water. Thus, through cogeneration, it is possible to utilise a plant desalination during off peak periods. Despite limited research in fusion applications, there exist numerous examples of fission desalination applications. Notwithstanding the differences in the method of energy generation, the way in which desalination can be achieved between fusion and fission technologies is similar, see below. In 2015, 9 fission desalination projects existed worldwide that were either in planning or operational [57–65]. The IAEA has linked interest in SMRs for desalination to advantages such as higher economic viability, smaller reactor size (less space required), and smaller construction times (leading to reduced costs) [66]. It anticipates that by 2030, 96 SMR-desalination projects will be in operation worldwide [67].

The production of fresh water can be achieved through both thermal, and membranous based methods. Often requiring large amounts of energy as heat, thermal technologies produce fresh water through a phase change process. This is where water is evaporated, and then condensed to remove dissolved salts:

(a) Multi-stage flash (MSF): as the name suggests, desalination is achieved through various chambers that distil water using reductions in pressure with each stage [68]. It accounts for 80% of Middle Eastern projects [69], and 60% of global desalination [70].

(b) Multiple effect distillation (MED): this is an early method that utilises preheaters, condensers and distillation units to produce freshwater. Despite being more limited in global use, it is less energy intensive than MSF and therefore may experience an increase in capacity in the future [71, 72].

Membranous processes work by water permeating through a semipermeable membrane, leaving behind a retentate of concentrated salt solution. They mostly rely on electricity as the main source of energy, as oppose to heat in the thermal processes above. The most notably used processes are:

(a) Reverse Osmosis (RO): accounts for 45% of global capacity. It uses high pressure (50–80 bar) to surpass osmotic pressure and achieve desalination [73]. This is the most efficient of all processes (including thermal ones), and is capable of producing various grades of water quality, such as drinking and agricultural water [74, 75].

(b) Electro-dialysis (ED): this uses the force of potential difference to transport ions through a semi-permeable membrane to achieve desalination [76]. Globally, this process is used most commonly for brackish water desalination [77].

(c) Membrane distillation (MD): using a vapour pressure gradient, this process achieves desalination by the passage of water molecules through microscopically porous hydrophobic membranes [78]. This has been shown to generate high standards of water quality compared to other methods, and is functional through the use of waste heat [79, 80].

Hooper suggest that a GW fusion plant capacity could lead to production of 10 million3 d−1 of fresh water [81]. Given that as of 2019, the global production of freshwater was ∼95 million3 d−1 [82], it seems unrealistic for one facility to be capable of producing 1/10th of global capacity. That said, Hooper states that such large capacity would require unrealistic infrastructure to distribute the water. Thus, MW capacity reactors such as Zap Energy’s sheared-flow-stabilised (SFS) Z-pinch configuration that could co-generate with electricity are more well matched and provide better efficiencies than GW reactors [83]. It is claimed that the most well matched process for this is reverse osmosis, which obtains higher efficiencies than other processes for fusion desalination. 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

5 This is water that is found in natural environments with a high salinity than fresh water, but lower salinity than seawater.
footprint of a desalination plant \(66 \text{ gCO}_2 \text{ kWh}^{-1}\) are not in agreement with those highlighted in section 4. 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) [81].

2.3.2. District heating

District heating can play an important part of global reduction in carbon emissions. According to a 2014 report, the share of world global energy consumption from the heating of homes, buildings and domestic water was 15% [84]. The share increases in areas with lower average temperatures, for example The European Union consumes 22% of demand for domestic heating of homes alone [85]. In the UK, domestic heating of homes offers significant contributions to \(\text{CO}_2\) emissions, totalling 18% [86], yet current district heating installations in the UK provide only 2% of overall heat demand (residential, public and industrial sectors).

Recent investment totalling £320 m will contribute to a proposed increase of 18% by 2050 [86]. As means to utilise heat from generation plants, district heating 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 or steam that can be distributed to urban areas. In systems which are fossil-fuel based (such as natural gas), prices have been historically low. In the future, carbon taxes and availability will (and are) driving prices up. The deployment of fusion technology in conjunction with district heating systems would provide an additional revenue stream for the operator, perhaps radically changing the economics relative to other sources. This mirrors the considerations for cogeneration for nuclear fission [40].

Indeed, there are key advantages for fusion in that public acceptance is also likely better as the effectiveness is location dependent and fusion is more easily located near demand centres in this context. Despite difference in any heating system, some core characteristics remain constant [87–91]:

(a) Size: the effect of economies of scale is significant, whereby the cost incurred to produce the heat is reduced as the size of the heat source increases.

(b) Distance: when the distance between the source of heat and its consumers is smallest, the losses due to transport are minimised.

(c) Reliability: if the source of heat is prone to periods of shutdown, then backups must be in place to ensure demand can be met.

(d) Load factors: if the source of heat is co-generated, then during periods of high demand, load factors have the potential to increase by 40%.

(e) Temperature: depending on the heat efficiency of transport networks, the source of heat must be able to supply hot water at temperature within the range 70°–130°.

Recent work from Cano-Megías et al represents some novel contributions to fusion district heating research. They present: a supercritical \(\text{CO}_2\) cycle, a helium Brayton cycle, and a steam-water Rankine cycle for a DEMO-type fusion system, studying the combined production of heat and electricity [92]. When combined with electricity production, improvements of efficiency up to 20% and 4% were obtained for Rankine and Brayton cycles, respectively. Outside of fusion, fission district heating (NDH) has been demonstrated in 51 facilities across 8 countries, where a small fraction of total reactor thermal output is used in the heating system [90]. In terms of distance and temperature, nuclear facilities are placed at large distances away from urban areas due to implications of public acceptance and safety, rarely do examples exceeding 50 km exist [90]. This makes the concept of a NDH facility more difficult, where thermal losses can reach up to 30% if water retention time within the transportation system is high [91]. That said, both Minkiewicz and Reński & Hirsch et al demonstrate that long distance transport of heat can be achieved in certain cases [93, 94]. In terms of efficiency, Jaskółski et al illustrated that NDH systems will increase overall plant efficiency by 5%, where 250 MWh\(_{\text{th}}\) can be utilised [95].

Historically, there has been a pervading view that district heating is viable only for new urban developments where the heat distribution network is constructed as part of the construction process. The replacement of existing infrastructure with district heating is widely assumed to be economically unattractive, although this must be considered against the range of technologies that are being proposed for the replacement of fossil fuels for building heating (electric, heat pumps, hydrogen). All technology replacement will involve some incurred cost to transition. Some studies have shown that the investment cost of district heating schemes are comparable to other technologies, irrespective of whether these are new or involve retrofitting of existing urban developments. They also suggest that district heating provides a revenue stream for the operator comparable to that due to electricity generation [96]. If such studies are correct, this would be transformative for the economics of small fusion reactors, lending themselves to near-urban siting. That said, much depends on the nature of the network—these costs are based on existing (so-called 2nd or...
3rd generation) systems. Cost comparisons for future 4th generation systems are more uncertain, incorporating a much more diverse grid [97]. 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 [98]. In terms of how it compares with competing technologies, Leurent et al investigated the potential of NDH against electric boilers (EB), gas boilers (GB) and large scale heat pumps (LSHP) in an urban area of France [99]. Not only was it found that NDH offered a longer life time per installation, (40 years—compared with 16 for EB, and 20 for GB and LSHP), it also emitted 68% less greenhouse gas emissions (GHG) than GB and 41% less than EB. This aligns with the findings of another study by Leurent et al from 2018, who found that the implementation of NDH systems reduces emissions by 10MteCO$_2$/a [100].

Some potential obstacles for a fission powered NDH system highlighted by Leurent et al do not necessarily apply to a fusion powered one [90]. For example, a fission plant may undergo a political shutdown due to a globally significant nuclear accident, whereas fusion plants would most likely, not. That said, every 18 months–2 years (depending on design), a fission powered NDH system will need to shutdown for a refuelling period of ~2 weeks, and despite the process requiring entirely different expertise and systems, fusion plants will have to do the same when refuelling. Regardless of fission or fusion power, NDH outages require the use of back-up generators (which are likely to be diesel or battery powered) in order to meet demand. Thus, the importance of the reactor capacity factor is increased, and the suitability of pulsed fusion designs for such applications becomes an important factor. There also exist obstacles that apply to fusion and not fission powered NDH systems. For example, the discontinuity between nuclear and heat industry sectors engenders a difficult potential market breakthrough path for both fission and fusion. However, for fusion, this is made worse by nature of itself being an unrealised technology. In corollary, the role of policy, discount rates and government subsidy is key in the future of fusion powered NDH systems.

2.4. High-temperature applications

2.4.1. Hydrogen

For the past half century, a hydrogen economy has been pitched as an answer for fossil fuel replacement [101]. Be it the 1973 oil embargo [102], or the 1990s when climate change was starting to be considered a key political issue [103, 104], it is still yet to gain significant traction despite numerous apparent benefits and applications. Via fuel cells, it can be used in: cars (as demonstrated by Hyundai and Toyota [105]), industrial vehicles (Anglo American mining trucks [106, 107], CMB.TECH’s delivery truck and excavator [108, 109]), ships and aircraft (as demonstrated by CMB.TECH’s passenger ferry [110, 111], and Airbus’s ZEROe concept [112]), the replacement natural gas as a source of heat [113], the storage of surplus output from wind and solar to stop curtailment [114, 115], chemical feedstocks [116–118], and the replacement coke as a means of extracting metallic iron from it is ore [119, 120]. Green hydrogen is considered to be a vital element of the required technology mix for zero-carbon, and demand temperatures of at least 600 °C [121]. So what is holding hydrogen back? In short: the replacement of fossil fuel infrastructure is a substantial task, it is an energy carrier and not a primary fuel (i.e. like electricity it must be produced by something else before being consumed), the acceleration and development of battery technology (and use across various key sectors), and it is not easy or cheap to make. It also has challenges associated with high pressure storage: its energy storage per unit volume is less than fossil fuels, it has relatively low density, it requires very high gas pressures for storage, and suffers from leakage by diffusion [122].

The relatively low hydrogen density together with the very high gas pressures for storage, leakage by diffusion and the cyclic stability of the cylinders are important drawbacks of the technically simple and on the laboratory scale well-established high-pressure storage method. Despite limited use in the current energy sector, hydrogen has some key benefits that could see it is industrial use increase on the road to decarbonisation. Not only is it able enact bulk storage of energy for long periods, but it is also an agile energy vector that can be transported using similar infrastructure to oil and gas [123]. There are four potential methods that a fusion reactor could use to generate nuclear hydrogen (NH):

(a) Water electrolysis from nuclear electricity.
(b) Steam electrolysis using nuclear heat (600 °C–1000 °C) and nuclear electricity: this process is more efficient (50%), and lower cost (requires 35% less electricity) than water electrolysis [98]. In Poland, 13 high temperature fission reactors (400 °C–550 °C) will be used for hydrogen production [124].
(c) Thermochemical processes (600 °C–900 °C) e.g. sulphur–iodine cycle: various fission studies exist that are investigating the viability of this process [125, 126]. In Elder and Allen’s study efficiencies of ~50%

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6 This is not to be confused with energy storage per unit mass, which for hydrogen is very high compared to other fuels.
were achieved when the reactor outlet temperature varies from 850 °C–950 °C [127]. A Korean research centre is developing an integrated 50 NL·H⁻²/h scale demonstration of the SI cycle [128].

(d) Reformation of fossil fuels and biomass through nuclear heat (700 °C–1100 °C) to generate blue hydrogen: together with methane, this process produces seven tonnes of CO₂ for every tonne of hydrogen yielded [105], thus requiring CCS. In a study from Kimura et al, this process potentially generates hydrogen from fusion at significantly better efficiency than other proposed methods, such as electrolysis from renewable sources, with little CO₂ emission [129].

In 2013, Germeshuizen and Blom postulated that hydrogen produced by thermo-chemical processes (hybrid-sulphur) from a fission plant was used as an alternative reducing agent to manufacture steel [130]. It was found that utilising NH alongside steel making reduced carbon emissions by 63%. Potential issues arising from production of hydrogen are the permeation or release 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 [30], and also through cogeneration with desalination plants. In addition, blue hydrogen not only results in the production of CO₂, (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.

2.4.2. Process heat

According to the IEA, the industrial sector was responsible for 37% of total final energy use in 2018, and accounted for 24% of global emissions (8.5GtCO₂). In order to meet the Sustainable Development Scenario, the industrial sector must decarbonise to at least 7.4GtCO₂ [131]. 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 [132]. In terms of emissions, the process heating sectors account for 14% of the UK’s carbon footprint [133]. These include: manufacturing of mineral products, food and drink, and iron and steel industries. The cement industry is responsible for 5%–6% of total anthropogenic CO₂, and about 4% of global warming [134]. Decarbonisation of transport (such as synthetic fuels) and other process industries require temperatures 350 °C–500 °C. Such temperatures are well beyond those of waste heat, providing two broad routes for fusion cogeneration: extraction of high temperature heat before the turbine inlet, or the electrical boosting of low temperature heat. The aforementioned industries encompass the highest-energy consuming sectors within the UK, making up 50% of total process heat consumption [86]. The use of heat in industry can be grouped into seven main categories [135], all requiring characteristic temperatures and thermal heat supply:

(a) Basic Metals: iron, steel, aluminium and copper manufacture.
(b) Chemicals: gases, fertilisers, plastics, paints, pharmaceuticals, and detergents.
(c) Coke and refined petroleum.
(d) Cement.
(e) Food and beverages.
(f) Non-metallic minerals: glass, ceramic, bricks, lime and concrete.
(g) Pulp and paper.
(h) Wider Industry: vehicle manufacture, construction, and textiles.

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. The project involves the EU, Japan and Korea, and aims to conceptualise a design, provide a framework for licensing, and develop a business plan for full scale demonstration of a High Temperature Gas-cooled Reactor (HTGR) cogeneration system for the supply of process steam to industry [136, 137]. As of 2020, the Minister for Energy in Poland had approved the project and was seeking sites for construction [138]. Using data from the Department of Energy and Climate Change, Peakman et al investigated the suitability for different fission technologies to provide nuclear process heat (NPH) to industry [135, 139, 140]. For those processes that require too higher temperature for NPH systems, Peakman et al recommends that (nuclear generated) hydrogen be used to bridge the gap to further decarbonisation. This is because it can store energy; can be used as a feed-stock in industrial processes, and for meeting industrial and domestic heating demands. See figure 2 to visualise how different temperature requirements of these processes match up with the fusion heat.

7 It is important to distinguish between the process emissions from chemical reactions in manufacturing, and fuel consumption. E.g., iron production which produces CO₂ regardless of energy source: Fe₂O₃ + 3CO → 2Fe + 3CO₂.
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. Firstly, cost is either internal, (i.e. those relating to contributions from manufacture, operation and maintenance, fuelling and decommissioning that affect the cost of electricity (or other entity), or external, (i.e. those that are not manifested in consumer payments, such as health and environment). For example, early studies from Ward et al and Cook et al assume fusion’s external costs to be minimal, and therefore postulate that total costs are encapsulated by internal costs alone [18, 143].

In terms of financing fusion power plants, it is predicted that the cost profile, from construction to decommission, will share some similarities with that of fission [144]. Crudely, the construction phase is the most costly, with less funds needed for operations and maintenance phases. Thus, the cost of capital carries the most weight for overall costs, meaning that even compact designs will incur high interest rates. An important aspect for potential financiers to consider in such projects is the associated risk, such as cost escalation, either in capital and or operating phases, or unforeseen drops in plant performance. Webbe-Wood highlights that state owned assets carry the advantage of being able to take on these risks more freely, as cost increases of this type are less severe for them than private enterprises. Additionally, it means that the plant operator turns a profit from energy production and sales without having to leverage any risk [144]. With the current paradigm shifting towards private enterprises in fusion development, this is an important detail to assess.

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. desalination, district heat, hydrogen, and process heat for 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:
Figure 3. An illustration of the apparent decline in the estimated cost of fusion electricity in the last two decades at the same pace as other renewables, especially solar PV. This is not to be confused with the learning factor after FOAK, see section 3.2. It is also important to note the uncertainty contained within costing estimations of fusion electricity, see section 3.2 for further details. See table A1 for reference data.

\[ \text{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} (I_t + M_t + F_t)}{\sum_{t=1}^{n} E_t (1+r)^t}, \]

where \( I_t \) is the investment expenditures in the year \( t \), \( M_t \) is the operations and maintenance expenditures in the \( t \), \( F_t \) is the fuel expenditures in the year \( t \), \( E_t \) is the electrical energy generated in the year \( t \), \( r \) is the discount rate, and \( n \) is the expected lifetime of the system, with units of mill kWh\(^{-1}\).\(^8\) Initial estimates suggested that upon entry to the market, fusion’s LCOE could be similar to competing technologies [145]. Subsequent studies have shown a large range of values varying from 40 to 165 mill kWh\(^{-1}\). For comparison, initial LCOE values for renewables and their corresponding studies are also given. See figure 3 for a graphical representation of this reference data.

In a 2018 study, Entler et al. investigated the techno-economic potential of fusion, and a second generation DEMO-type plant would achieve a net present value (NPV)\(^9\) equal to initial investment: $312 mills kWh\(^{-1}\) [147]. Furthermore, taking data from the study assumes that fuel, waste disposal and decommissioning represent 3% of total cost of electricity [148]. Attempts to place a valuation on fusion energy are also available from Turnbull et al., who through modelling, quote anywhere between zero and $30 trillion [149]. 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 [19, 20, 22, 23, 27]. Other costing methods in literature include those that take a top-down approach, such as those conducted by Lopes Cardozo et al. in 2016 and 2019 [26, 150]. This involves the theoretical deployment of a reactor with specific thermal output into the future energy market, and then working backwards towards the present to predict the investment per Watt necessary for successful commercialisation. See section 5. Initial studies by Woodruff et al. have explored the costs of non-conventional reactor types, finding that such designs using modules benefit from cost savings from shortened construction times (resulting from increased compactness, which itself leads to lower capital costs), and manufacture and transport of complete modules [151].

3.2. Discussion

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.

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\(^8\) A mill is equal to 1/1000 of a U.S. dollar, or 1/10 of one cent. Mills per kilowatt-hour (kWh) equals dollars per megawatt-hour (MWh).

\(^9\) NPV is a way of measuring profitability in economics by accounting for interest rates. It is the difference between the present value of incomings against outgoings, where positive values indicate financial benefit for the investor, and negative values indicate financial loss [146].
that affect cost. Therefore, it is important to try and unpack some uncertainties that lie within the values in figure 3. 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. 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. This downtrend of cost occurs due to system efficiency and capacity factor enhancement, the greater scale of energy production and therefore energy sold, and development of industrial ties within mass produced manufacturing and operational industries. Secondly, the values from each study form a range that the calculated LCOE lies within. Taking 70–130 mills kWh$^{-1}$ from Cook et al as an example, the size of the scale means that the low end of the estimate may prove economical and the high end costly [18]. Thirdly, there is the impact of inflation to consider. Principally, this stifles the ability to compare 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 studies from Chuyanov and Gryaznevich & Waganer 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 [25, 152]. For Chuyanov and Gryaznevich, this was 88% and for Waganer it was 75%, the main difference for the former study being that the modularity and interchangeable components of the reactor lead to accelerated effects of learning factors.

The nature of making performance predictions about an unrealised technology means that crucial input parameters are simply assumed as per the vendors design specification, rather than being based on empirical experimental evidence. For example, Chuyanov and Gryaznevich cited a capacity factor of 95%, whereas Delene et al assumed a capacity factor of 80% [25, 153]. By remembering that fusion is yet to boast a net energy gain experiment, it is possible to see why quoting such high capacity factors (in the case of Delene et al, this was based on the capacity factor of fission plants at the time) can be seen as overly optimistic.

In a similar vein, construction times estimated across literature could be considered under-estimated. For instance, [147] quotes a 1 GWe reactor construction time of 6 years, and [153] 10 years for a 3 GWe reactor. Note that the schedules put forward in these studies presume efficient manufacturing processes and industry backing, i.e. they will be constructed by energy companies. This means that any scrutiny levelled towards them from comparisons with public research facilities with no investor schedules, should be judicious. In addition to this point, they will also be functioning to provide electricity to the grid and will not be a preliminary science experiment. ITER will have a thermal output of 500 MW, 1/6th of the capacity used in the study from Delene et al [153], however larger thermal outputs do not necessarily mean larger construction times and this will most likely, come down to engineering complexity.

Costing calculations requiring crucial input parameters, such as construction time and capacity factor, are rarely presented based on evidential calculations. Instead, these parameters are often assumed and simply quoted, thereby forgoing any careful consideration needed to understand how they affect cost. By virtue of being widespread across many topic areas, it is important to summarise areas that are well studied, and those that require more focus. A study from Lackner et al represents an early attempt to categorise areas of technology R&D that require attention in order to reduce uncertainty [154]. With the inclusion of the last two additions for this review, these were:

- plasma physics,
- divertor physics,
- structural and functional materials (including fuel),
- waste handling and management (including remote handling),
- regulation, licensing, and associated activities.

It is not within the confines of this review paper to perform an evaluation of these topics and their accompanying literature, as this would constitute enough content to warrant an entire review for each of the subjects alone. Instead, the review will attempt to answer how the least well researched areas (in the opinion of the authors, the latter three categories) might impact the cost of a fusion reactor. As a short note on tritium breeder blankets (TBBs), ITER will test an Li pebble bed blanket configuration for which, due to a number of factors, costs are high reduction pathways are challenging [155]. Alternative liquid blanket designs are not without their challenges (such as material-liquid compatibility as regards corrosion, and flow channel
design) [156], however they are cheaper to manufacture and maintain [157]. Costs of breeder blankets are also driven up by the necessity for remote handling during replacement of components upon depletion of Li. ITER (comparatively small compared with any designs for commercial reactor designs based on the same ITER technology, e.g. the EU DEMO [158]) will possess 80 blanket segments that will weigh up to 80 tonnes be 12.5 m long. Replacement of these plasma facing components is thought to take on the order of months of non-stop work, reducing overall plant capacity factor, therefore directly affecting the cost of electricity [159, 160].

In terms of external costs, it is noteworthy that the nuclear industry must adhere to stringent frameworks to pay for external costs. This contrasts the fossil fuel industry, who to this day, only pay for external costs in the event of a scandal. In a study conducted in 1978, it was found that as due to the release of high concentrations of thorium and uranium into fly ash, higher levels of harmful radionuclides were detected from the smokestack of a coal plant compared to that of modern PWR and BWRs [161]. More recently, US democrats have threatened to bring in legislation (totalling $500 billion) that will tax fossil fuel companies as a means to force the payments of external costs to mitigate climate change [162].

3.2.1. Structural and functional materials (including fuel)
In terms of structural and functional materials, Chuyanov et al conducted a sensitivity analysis of the LCOE with neutron wall loading, and found that their relationship to be inversely proportional [25]. By ensuring sustained fusion power, one increases the amount of electricity produced per unit time, and loading tends towards the value of 1/N, where N is equal to the number of modules. Something the study does not consider, is how the lifetime of the modules affected by the increase in wall loading are affected, where large irradiation exposures lead to increased material degradation and therefore require regular replacement, increasing costs. The regularity of replacement will also have an effect on the classification of waste, see section 3.2.2 below.

Fuel cycle aspects of fusion power plant are rarely considered within costing studies in the existing literature. As an example, Tokimatsu et al assume that the need to account for a fusion fuel cycle is not important due to the self-perpetuating nature of breeder blanket technology; a commercial D-T reactor is automatically assumed to breed its own fuel [20]. This presumes that tritium is not necessary for the reactor start-up process. Whilst Zheng et al and Konishi et al suggest that an external start-up quantity of tritium is not needed, as it can be produced by starting with only a D-D initial fuel mix [163, 164], most assessments suggest that an external source of tritium will be required for start-up. For instance, the study by Chuyanov et al find that approximately 4 kg of tritium is necessary for start-up; constituting 4% of the total capital cost of their particular concept, at a cost of $140 m [147]. Glugla et al project that ITER may require 18 kg of tritium along course of its operation [165], and thus could represent a significant issue for supply in future development [30, 166]. However, it is noted that ITER is an experimental device with no tritium breeding capability, and is thus not representative of a future commercial fusion plant. Instead, what is important with ITER using such a significant quantity of tritium is that it may contribute substantially to the exhaustion of already limited global tritium supplies.

Regardless of the need for start-up tritium, lithium is an essential component in any future fusion blanket technology as the breeder material, and therefore it can be considered as a primary fuel, albeit indirect. Despite having a crustal abundance of 60 ppm and a global reserve estimate of 80MT [53], Wang et al find that to support a fleet of D-T fusion reactors in the long-term may be problematic based on the available current terrestrial (land-based) deposits [167]. However, it is noted that this study was conducted in 2012, and in the past decade, new lithium reserves have been successfully prospected, principally due to increased demand for new lithium battery technology [168, 169]. Moreover, the conclusion by the same study was that a ‘backstop’ of extracting lithium from the ocean means that long-term availability of lithium is not problematic. More of a problem is that a commercial fusion reactor must be designed with a tritium breeding blanket that can attain a tritium breeding ratio (TBR) of above unity to ensure tritium self-sufficiency, as no external source of tritium is expected to be available in quantities to support a commercial fusion fleet. To obtain a TBR of above unity with only lithium is significantly challenging.

The first issue with lithium breeding that affects TBR is that the two stable isotopes of lithium, lithium-6 and lithium-7, interact with neutrons differently depending on the energy. The isotope of lithium that has a higher affinity for producing tritium is lithium-6. However, as lithium-6 only makes up 7.4% of all natural lithium on Earth, breeding blankets are expected to require the enrichment of lithium in lithium-6. The cost of lithium-6 has been estimated at $13 000 per ton in [170]. However, lithium-6 is not produced at any significant scale commercially and cannot be purchased on any open markets [171], and thus this cost must be taken as a calculated estimate only, subject to substantial uncertainty. Historically, lithium-6 was produced only for military use, and in the U.S. was produced in the order of several hundred tons around the mid-20th
Interim waste generation EU-DEMO studies have been shown to produce ILW, with the main difference being that fusion costs will not peak during the decommissioning phase. In practice, even with the use of reduced-activation steels in first wall and divertor components, first generation EU-DEMO studies have been shown to produce ILW [180, 182], and in some cases exceed the volume of ILW compared with some fission plants [183], as pointed out by Nicolas et al [31]. In a specific study from Bailey et al, steel that experiences plasma level neutron fluxes rarely reaches LLW criteria, with those more aligned to containment vessels meeting such requirements [184]. Under EUROfusion design specifications, this means that DEMO alone will be responsible for the production of 1300–1500 tonnes of ILW, and therefore under current UK law, is subject to management via geological disposal [185]. This law change, and the threshold level of waste that requires geological disposal is lowered, fusion could therefore be faced with similar waste issues to fission. The UKAEA also acknowledges the production of ILW from fusion, but caveats this by postulating that it would account for <1% of the UK’s total waste inventory, claiming a ‘significant proportion’ would achieve LIW classification after 100 years [186].

The Committee on Radioactive Waste Management CoRWM have outlined what waste can be expected from fusion power plants, including: the bio-shield (i.e. reinforced concrete), reactor components (dependent on the material and degree of neutron subjection), and lastly tritiated wastes (from cooling systems and fuel cycle components) [187]. The report acknowledges that both reactor components and tritiated wastes are likely to be classified as ILW, with those components that require regular replacement continually contributing to the waste output. The report, along with another from the UKAEA, states that no HLW is expected to be produced [186]. An important consideration made is that more regular replacement may result in those components at risk of ILW classification achieving a LLW classification instead, but at the expense of an increase in waste volume. Another important consideration is that of the toxic metal content within components (such as Be), that may result in failure to meet the ILW non-radiological criterion.
Suggested mitigation for these challenges includes that of recycling radioactive materials in future fusion systems, and it is noted that efforts to achieve this may be outweighed by economic consequences, and incompatibility of the reused component in an updated reactor system [188]. A 2012 report that estimated the disposal costs ILW at a UK geological disposal facility to £9170 m\(^{-3}\), (this is on top of the fixed cost of £4 billion for constructing and maintaining the facility itself) [189].

3.2.3. Regulation, licensing, and associated activities
The level of scrutiny that fusion finds itself under will have a large effect on its regulatory liability. This is because regulation affects the time taken for an industry to come to market, and in corollary also affects costs via regulation fees to bodies, such as the Nuclear Regulatory Commission in the US and Office for Nuclear Regulation in the UK. Some reports have suggested that bodies (specifically the NRC) employ a regulatory framework that embodies measured approach, accounting for risk in long and short term, avoiding the scrutiny of fusion [190]. In a recent report, the Nuclear Innovation Alliance (NIA) suggests that the NRC make significant reforms to their regulatory framework, thereby reducing fees for new license fee applicants [191]. Although this report does not mention fusion specifically, reforms such as these engender the drive for low-carbon advanced nuclear energy and aligns with the climate goals of the US. Other studies have suggested that, despite possessing different risks, fission’s inherent safety culture should be transferable to fusion as basis for future development, especially in SMRs [192]. In the coming years, pivotal policies will be brought into legislation regarding the sustainability of energy sources, and fusion’s ability to adhere to the criterion set by these strategies greatly affect it is investment potential. See section 4.1.

In terms regulation in the UK, the UKAEA has comprised a set of proposals for a regulatory framework for fusion energy. It’s primary aims were to investigate the current framework, and suggest if changes are necessary for the coming decades [186]. An important consideration made is that current fusion facilities are not defined in legislation as nuclear installations, and as such are not subject to the same regulations as fission plants. This means that, facilities are bypass the need for a nuclear site license, and can be regulated by the environment agency (EA) and the health and safety executive (HSE), as per other radiological practices (such as in medicine), rather than the by the Office for Nuclear Regulation (ONR). Another approach suggested is the analogous with that of fission, regulated by ONR and EA, thus requiring a nuclear site licence. The report acknowledges that the existing framework may require alteration as fusion moves from an R&D phase, to a power plant phase, highlighting the best way to implement such changes is via early engagement with developers during their respective design and development stages. Another important consideration is that future power plants breeding their own tritium would not fall under either the Nuclear Cooperation Agreement with Canada, or the safeguard arrangements regulated by ONR.

3.2.4. The potential impact of non-conventional confinement methods on cost
Some fusion experiments are attempting fusion without using tokamak MCF methods. The main reason for this is because the designs being investigated are (in some cases) aneutronic, and (in-theory) more efficient, cheaper, and simpler. Predominantly, these experiments are being conducted by private sector enterprises, such as General Fusion (not aneutronic), TAE Technologies, and Helion Energy. All three of these are utilising a combinatorial form of fusion, merging magnetic and inertial methods via MTF and FRC (see section 1). How do these methods present such advantages?

(a) Aneutronic: in conventional systems (i.e. tokamaks that will use deuterium-tritium fuel), the majority of the energy from the fusion reaction will be carried away by the neutron (14.1 MeV out of a total 17.6 MeV). This presents several challenges. Firstly, it means harnessing fusion energy from neutrons, which as uncharged particles, do not undergo Coulombic interactions, thus making the neutron energy difficult to convert into useful, thermal energy. Secondly, and arguably most importantly, it reduces challenges associated with neutron irradiation. This means that damaging phenomena such as ionising radiation, sputtering, embrittlement, erosion, cracking and neutron activation in reactor components and materials are decreased.

(b) Efficiency: there are two branches to this: (1) plasma efficiency, and (2) energy generation. (1) Plasma efficiency refers the quantity \( \beta \), or normalised plasma pressure, which is the ratio of plasma pressure to magnetic pressure. It is a measure of the efficiency in which the plasma is confined within the magnetic field. The higher the \( \beta \), the higher the efficiency. As mentioned in section 1, high-\( \beta \) plasma regimes are achieved in these non-conventional systems. A high-\( \beta \) regime is a desirable feature in fusion systems because higher economic power balances are obtained [15]. Spherical Tokamaks, such as Tokamak Energy’s ST-40 are also able to achieve high-\( \beta \) [193]. (2) As explained above, aneutronic systems release the majority of fusion energy to the product ions, rather than neutrons. Because the ions are charged, direct energy conversion from the ion’s kinetic energy into a voltage could be exploited, however this
technology is yet to be proven. Thus, the need for thermodynamic, Rankine-type steam turbines, complex cooling systems and corresponding energy losses are negated.

(c) Low-cost: this does not imply that fusion will be cheap, and should be taken as low-cost compared to MCF tokamaks using D-T fuel. The theoretical decrease in costs mostly arises from the aneutronic systems, namely because this would result in less requirements for remote handling, reactor maintenance, biological shielding, and safety, all of which will be sure to incur significant costs, both capital and ongoing. In MTF systems especially, very high fusion power densities can be achieved. This means, if one assumes the capital cost of a system scales with size, that in theory, a smaller system can be used and capital costs can be reduced. Smaller and more modular systems (e.g. Helion’s 50 MW machine) are better suited to decentralised energy grids, and are also more suited to urban settings than larger power plants that will take up more space. Other reasons arise from the absence of powerful and expensive low temperature and or high temperature superconducting magnets to contain the plasma, as in conventional Tokamak MCF systems.

(d) Simple: this advantage is often synonymous with low-cost, where a simpler system will (usually) cost less, and take less time to manufacture. For example, systems that will use fuels without tritium, a scarce, non-naturally occurring and therefore expensive substance, are said to be more simple because they will negate the need for a breeder blanket, therefore cost less as a result (see section 3.2.1).

None of these advantageous theories have yet been put into practice. Not because the experiments have not been able to achieve their goal, but because a working prototype is yet to be built, and roadmaps and milestones must first be completed. This therefore presents a gap in research for techno-economic analyses for non-tokamak-MCF fusion, especially within these private sector companies that are proposing advantages mentioned above. Why is there so little publicly available research from private sector companies? Intellectual Property. According Carayannis and Draper, a total of 163 patents have been filed by the Fusion Industry Association member companies, 112 of which came within the last 5 years [194], falling under ~20 different patent classification codes. Whilst this is a good example of technology diversification and progress in research development pathways for these potential leapfrog companies, and thus for fusion commercialisation, looming uncertainty prevails over unanswered socio-economic and geo-political questions in fusion [195].

3.3. Low-temperature applications

3.3.1. Desalination

Economically, the 2021 market for desalination has an estimated valuation of US$14.5 billion, with the potential to grow to US$35.5 billion over the next decade [196]. The cost of producing fresh water is dependent on a variety of parameters, such as:

(a) Degree of salinity in the feed water: brackish water desalination much cheaper (0.07US$ m$^{-3}$) than that of seawater 0.5US$ m$^{-3}$ due to the presence of less contaminants [197].

(b) Desalination method: by virtue of requiring more fuel to vapourise the feed water, thermal techniques (MSF—1.10US$ m^{-3}$ and MED—0.80US$ m^{-3}$) are more expensive than membrane methods (RO—0.70US$ m^{-3}$) [198]. That said, it has been shown that increasing the top brine temperature improves the productivity of MSF [199], and improvements in efficiency can be achieved through its use in cogeneration plants [200].

(c) Energy source for desalination: in terms of the energy source used for desalination, it has been shown that renewable sources can cost up to 5× that of conventional systems, depending on the system. Wind has the lowest cost of renewable sources at 1.10US$ m$^{-3}$ [201, 202], followed by geothermal at 2.3US$ m^{-3}$ and solar, between 3.30–10.50US$ m^{-3}$ [203, 204].

(d) Capacity of the plant: the larger the energy output of the system, the lower the cost of water (0.5US$ m^{-3}$ for large systems and 1.78US$ m^{-3}$ for smaller ones) [197], and also the more freshwater produced.

In terms of nuclear desalination, see table 1 for a detailed cost comparison between different fission reactors, and differing methods of desalination, where the cost range is between 0.47–1.35US$ m$^{-3}$. For fusion, the predicted cost of desalination processes from Hooper is 0.53–1.94US$ m^{-3}$, however this may change if the plant was also used as means to provide lithium for fuel of fusion plants [81].

3.3.2. District heating

Cano-Megias et al present a techno-economic analysis of fusion district heating research for several applications: a supercritical CO$_2$ (sCO$_2$) cycle, a helium Brayton cycle, and a steam-water Rankine cycle for a DEMO-type fusion system, studying the combined production of heat and electricity [92]. It was found that
Table 1. Cost comparison between different nuclear fission reactor types and method of desalination, adapted from [205].

| Reactor type                        | Desalination process | Water production capacity (m$^3$ d$^{-1}$) | Cost (US$ m$3$/a$) / Currency year | Reference     |
|-------------------------------------|----------------------|------------------------------------------|----------------------------------|---------------|
| Pressurised heavy water reactor (PHWR) | RO                   | 120 000                                 | 0.47/1999                       | [206]         |
| Pressurised water reactor (PWR)     | MSF                  | 2750                                     | 1.35/2009                        | [207]         |
| Nuclear heating reactor (NIHR)      | Hybrid RO + MED      | 250 000                                 | 0.50/2012                        | [208]         |
| System-integrated modular advanced reactor (SMART) | MED | 250 000                                 | 1.20/2002                        | [209]         |
| Advanced Passive PWR (AP-600)       | RO                   | 43 676                                   | 0.52/2006                        | [57]          |
| Pebble Bed Modular Reactor (PMBR)   | MED                  | 39 703                                   | 0.74/2006                        | [57]          |
| Canada Deuterium Uranium (CANDU)    | MED                  | 22 000                                   | 1.00/2017                        | [210]         |
| Central Argentina de Elementos Modulares (CAREM) | RO | 10 000                                   | 1.50/2016                        | [66]          |
| Small Nuclear Heat Plant (SNHP)      | MED-TVC              | 178 451                                  | 1.14/2013                        | [211]         |
| Large Nuclear Heat Plant (LNHP)      | MED-TVC              | 178 451                                  | 1.22/2013                        | [211]         |

sCO₂ cycle, and Rankine cycle systems prove economically viable, whilst a helium Brayton cycle does not. If placed in a carbon priced system, further cost improvements are made. Despite containing little in the way of uncertainty or sensitivity analyses for the estimated cost reductions, if future investigations included such analysis and were repeated with non-DEMO type reactors, then valuable costing comparisons could be drawn between different reactor types, especially in smaller reactors and spherical tokamaks. Beyond [92], there exists a lack of fusion-based studies on this topic. That said, comparisons can be drawn with those done in fission in order to make conclusions on the potential suitability for future fusion applications, and investigations therein. In the study from Leurent et al, it was found that the levelised cost of heat (LCOHheat) was 60.3US$/MWhth\textsuperscript{10} for a NDH system [99]. This can be compared with 102.45US$/MWhth for EB, 90.40US$/MWhth for LSHP, and 42.95US$/MWhth for GB. It was also demonstrated that the initial investment required for NDH systems is >4× that of GB, >3× but 2× less than LSHP. In addition, due to the longer lifetime of NDH systems than EB, LSHP and GB (see section 2.3.2) the prices of other technologies remain constant due to the need for reinstatement of investment at the point of installation for new systems. Whereas for NDH systems, during the 40 years of operation the LCOHheat of NDH will come down to approximately 38.85US$/MWhth, which is comparable to cheapest GB price. Working with 2015 prices, the use of GB and EB over NDH systems leads to 111% and 135% increases in annual energy bills (this can be compared with LSHP, which is cheaper by 59% and 77%, respectively). Importantly, the implementation of a carbon tax of 42US$/tCO₂ lead to a LCOHheat lower than GB for NDH. Drawbacks of NDH systems highlighted include increased initial investment compared to other options, and that NDH becomes more expensive than boilers when electricity prices exceed that of gas by 3.5% [99].

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 [132]. This agrees with Leurent et al’s findings, where the cost of a retrofitted upgrade to a PWR with a DH system falls between 0.05 and 0.09US$/MWhth [99]. In a study from the same group of authors, Leurent et al highlighted that carbon tax implementation was synonymous with positive NVP estimates [100]. Specifically, by assuming a LCOHheat 72.15US$/MWhth, 3 studied urban areas supplied by NDH would be economical when taxes as low as 5.55US$/teCO₂ were implemented. Conversely, certain areas with an annual heat supply of <125GWhth/a remained uneconomical even with a carbon tax as high as 111US$/teCO₂. These only proved economical when the total heat supply share to the area was 25% or higher.

3.4. High-temperature applications

3.4.1. Hydrogen

As discussed in section 2.4.1, the scope for a hydrogen economy has both merits and challenges. In terms of investment, BloombergNEF (BNEF) have estimated that funds in excess of $150 bn are needed by 2030 in order to implement a hydrogen economy [213]. As highlighted in section 2.4.1, there are four main methods of hydrogen production that fusion energy can utilise. The IAEA’s Hydrogen Economic Evaluation Program (HEEP) software estimates hydrogen production costs to fall to between 1.58 and 3.66$ kg$^{-1}$.

\textsuperscript{10} All values from this study have been converted from € (based on 2015 values) to USD using exchange rate data [212].
Table 2. Summary of water electrolysis, steam electrolysis, and thermochemical hydrogen production costs of existing technologies.

| Energy source                  | Production method        | Production capacity (tonne d⁻¹) | Capacity factor (%) | Cost of hydrogen ($ kg⁻¹) | Reference         |
|--------------------------------|--------------------------|---------------------------------|---------------------|---------------------------|-------------------|
| Wind (Offshore)                | Water electrolysis       | 4–65                            | 28–31               | 5–9                       | [217–219]        |
| Wind (Onshore)                 | Water electrolysis       | 50                              | 98                  | 5.33                      | [220]            |
| Solar PV                       | Water electrolysis       | 10                              | 20                  | 12.1                      | [221]            |
| Nuclear fission (APWR)         | Water electrolysis       | 345–1382                        | 90                  | 3.56–5.46                 | [222]            |
| Nuclear fission (HTGR/HTTR)    | High temperature steam electrolysis | 345/321–964                  | 90               | 2.24–3.19                 | [222]            |
| Biogas                         | High temperature steam electrolysis | 0.87                        | 100                | 2.47                      | [223]            |
| Geothermal                     | High temperature steam electrolysis | 86.4                         | 80                 | 1.9                       | [224]            |
| Solar Thermal                  | Thermochemical (HyS cycle) | 100                            | 47-100             | 3.19–7.27                 | [225, 226]       |
| Nuclear fission (VHTR/HTGR/GT-HTR/HTR-PM) | Thermochemical (S-I cycle) | 50.1–591.8                   | 90                  | 2.46–5.36                 | [222, 227]       |
| Geothermal                     | Thermochemical (Cu-Cl)   | 10                              | —                  | 2.05                      | [228]            |
| Nuclear Fission                | Fossil fuel reformation  | —                               | —                  | 1.87-3.24                 | [216]            |

(£0.04–£0.09 kWh⁻¹) using nuclear fission energy in four nuclear reactor/hydrogen concepts [214]. However, green hydrogen production is not a mature technology and these predictions carry much uncertainty [215]. Hydrogen production using fusion should ideally match these costs to be competitive. That said, there are intrinsic advantages for fusion over fission that must also be considered in any cost-benefit analysis. First, there are specific barriers to the deployment of fission for high-temperature cogeneration, such as the transmission of high-temperature heat over significant distances. For fission, this is impractical, so generators would ideally be sited close to the industrial user. There are obvious safety and regulatory issues for fission in this regard. Fusion (especially small fusion) would not have these barriers (at least the same extent). Moreover, it may become viable for industrial end-users to own and operate the reactor, thus guaranteeing control of supply. This would, inter-alia, encourage new investment in fusion technology—a potentially virtuous development cycle. As it stands, there are a limited number of nuclear studies that have produced costing data and none for fusion (to date). Thus, costs of production included below include non-nuclear applications, see table 2:

(a) Water electrolysis—costs of which are wholly dependent on cost of electricity.
(b) High temperature steam electrolysis.
(c) Thermochemical processes (600 °C–900 °C) e.g. sulphur-iodine cycle.
(d) Reformation of fossil fuels and biomass through nuclear heat (700 °C–1100 °C) to generate blue hydrogen. As per the study from Nam et al, the estimated levelised cost of hydrogen (LCOHₜₕₚ) ranges from $1.87 to $3.24 kg⁻¹, where reductions arise from the implementation of carbon pricing at the point of commercialisation [216].

3.4.2. Process heat
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$/MWh⁻¹ will harbour a thermal energy cost of 7.42–11.42$/GJ⁻¹, which is comparable to that of natural gas: 3.5–8$/GJ⁻¹ [162]. The use of NH (at a cost of US$3.00 kg⁻¹) in steel making was shown to increase the cost of production by 12.8% [130].

4. The externalities of fusion
In terms of energy security and environmental impact, the potential promises of fusion energy are well known. The EU’s EUROfusion research group Socio-Economic Studies for Fusion has explored these
areas via scenario based analyses that are analogous to those in this paper. Yet, few studies have explored the possible spillover benefits of fusion and scrutinised external socio-economic topic areas, such as sustainability, carbon footprint, job creation, regional benefits, and GDP. In 2020, Carayannis et al recently 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 defined as: geo-economic, geo-political, geo-sociocultural, and geo-technological [229].

The proposed mechanism for the external review by Carayannis et al is to model in line with the International Energy Agency's Global Commission for Urgent Action on Energy Efficiency. To first approximation, such a review would consider the following types of benefits/impacts: In terms of geo-economics, benefits are evident from increased knowledge of the business acumen for the private and public 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, Carayannis et al argue that ITER has been a segue for technological ‘lock-in’ in tokamaks, highlighting four mechanisms that have led to this being the dominant approach in research. Thus, the study highlights the need of external reviews, especially from new spin-off technologies from the development of fusion, such as advanced magnets. Carayannis et al strongly advocates the use of ‘open innovation diplomacy’ to diminish risks of global market autonomy from single vendors in such markets [229].

Rather than being positioned as a mature industry with commercial ties to manufacturing, fusion instead finds itself nascent, in the R&D phase with bespoke components and equipment being produced. However, through multi-regional input–output analysis, Banacloche et al takes reactor data from Maisonner’s 2005 study to investigate the corresponding footprint for fusion investment as mature industry [24, 230]. This includes assessments of transactions in supply and demand for goods and services, and the associated geographies that are affected (i.e. the *global value chain*), and *value added* estimates (which refer to the difference between production cost and sale price of a product, inclusive of depreciation and labour). Geographically, the study finds that 47% of total production occurs within Europe, and 20% occurs within the US. Both these region’s share of production is lower than their value added, highlighting that the majority of exportation of reactor components is domestic, rather than international, with sectors such as construction mining and corporate business enjoying the most benefit. Regions such as Russia, China and Japan are most prominent suppliers components for operation and maintenance systems. Banacloche et al postulate that China and Europe experience the creation of 183,000 full time equivalent jobs, equating to 133.6 FTE MW⁻¹. With the exception of solar CSP, this exceeds that of all other renewables [230]. The calculated estimate of 11.4 gCO₂ kWh⁻¹ for CO₂ emissions aligns with 9 gCO₂ kWh⁻¹ from [231], but disagrees with the value of 22.2 gCO₂ kWh⁻¹ [232]. These metrics are considerations that the fusion industry should contemplate as it grows. See figure 4 for comparisons with other potential competitors.

### 4.1. Discussion

Evidence for diplomacy from fusion goes back to the inception of fusion energy in the 1950s following Eisenhower’s ‘atoms for peace’ address from the IAEA, and with the tokamak. Of Russian design and later adopted by others, tokamak concepts were presented at the first Fusion Energy Conference (FEC) in Salzburg, Austria, in 1961 and at the second FEC in Culham, United Kingdom, in 1965, before the conception of ITER between Reagan and Gorbachev in 1985 [233]. With reference to challenges relating to geo-technologies by Carayannis et al, those design concepts that are progressing in R&D, gaining ample funding and thus displaying commercial promise [3] should remain distinct from each other in order to prevent ‘lock-in’ of one technology type, leading to innovation roadblocks.
The results from Banacloche et al are based upon cost assumptions that do not align with those of other studies [230]. 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 the studies from Chuyanov and Gryaznevich & Waganer assume that blanket and first wall costs are captured by capital costs [25, 152]. An important consideration that Banacloche et al [230] observes that is not encapsulate by White and Kulcinski & Tokimatsu et al is the emissions from mining materials for fusion [231, 232]. In addition to this, not only does the reactor data from White and Kulcinski come from a study in the 1970s, but the data for kgCO$_2$/tonne of material is from one source and has not been replicated in other studies beyond the author’s thesis [231]. As such, there lacks a reliable range of data to draw from. Thus, studies of this type that use pivotal assumptions should be the subject of continual assessment. 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 are improved when aggressive carbon policies are in place. Recall also, that pro-fusion regions are committed to the terms of the Paris Agreement. However, in making challenging commitments nations may struggle to achieve their goals in reality. Evidence for this can be drawn from inabilities to meet climate targets and in certain cases, withdrawal from the agreement altogether [234–238].

Fusion’s investment potential is of crucial importance to it becoming a commercial entity. In recent years, private developers have achieved marked success in attaining investment for R&D, especially in the US and the UK [3, 239]. In the public sphere, fusion projects in the UK and the US have gained funding from their respective governments [240, 241]. In an open letter from 2020, the Fusion Industry Association (FIA) have argued for building a public-private cost share partnership strategy for fusion power. It is argued that this would attract investment from both native and foreign enterprises, accelerating the date of commercialisation, reducing risk, and strengthening shared knowledge [242]. Instead of implementing programmes themselves, Pearson highlights that public laboratories have the ability to provide advancements in R&D to support private endeavours, but only if the pace of private enterprises is matched [243]. This aligns with the findings of Nuttall et al, where such collaboration should target production of core fusion concepts and enabling technologies therein e.g. high temperature superconductors [2]. A real-life example of this is NASA in the US, or the Rolls-Royce SMR program in the UK. At present, the EU commission is compiling a Taxonomy that aims to facilitate simpler investment opportunities in what it deems as sustainable enterprises, be it projects or companies, in order to ensure the goals of the European Green Deal are achieved [244]. At first, nuclear energy was not included within the Taxonomy, however following a subsequent assessment by the Joint Research Centre that found nuclear energy to be sustainable, separate regulation has been proposed that will enable its addition to the taxonomy [245]. Given that any EU company wanting to invest in a non-EU enterprise (and vice versa) must adhere to the Taxonomy criteria, this has far reaching consequences for the nuclear industry, and for fusion and its prospects for commercialisation.

As mentioned in section 2.2, it is not straightforward to predict the severity of climate change mitigation and accompanying policies in future scenarios. The main reason for this is because there exists only one policy that bridges multiple nations towards a common goal, and that is the Paris Agreement. In theory, this policy is seen as pivotal to the global efforts of combating climate change. However, recalling that, as per section 2.2 fusion’s emergence as a commercial technology is best achieved when climate change mitigation drivers are in place, in reality this policy is rendered impractical when attempting to withdraw valid results from predictive studies, and investigate the optimum role of potential breakthrough technologies such as fusion. Firstly, irrespective of the clear target in global temperature reduction, its mission statement contains no constraint on when this must be achieved beyond ‘mid-century’. In addition to this, there exists no direct method of converting temperature reductions to concentrations of CO$_2$, beyond the knowledge that they share proportionality. Without comprehensive understanding of CO$_2$ concentrations affect global temperature, it is therefore overly optimistic to expect nations with the largest output of CO$_2$ concentrations, such as the US and China, to work towards this goal and create valid policies favouring green future energy systems. In addition, the lack of time limit means that these carbon intensive nations are able to decide for themselves when they want to achieve the target. Given that no two nations are identical, this can be somewhat reconciled, however only up to point due to the implementation and severity of policies being at the mercy of governments and their own agendas.

4.2. A word on public perception in fusion

Despite many advantages, there are many that oppose the use of fusion as a future energy source by virtue of being under the nuclear umbrella and being confused with fission amongst the public [246]. It is therefore prudent to discuss the studies seeking to understand why this is the case, so that the fusion community can prepare themselves adequately. Studies that have engaged in earmarking how this communication can be
improved in order to unburden fusion from fission are of pivotal importance. In order to investigate improving communications, [247] used various types of discussion materials. For media materials, it was found that the scientific concepts of fusion were confused with fission, concurrent with the findings of Turcanu et al [248]. In addition, the outlets themselves showed clear bias either for or against nuclear energy in general, especially in those articles discussing Fukushima, drawing a parallel with the findings of Schmidt et al [249]. For environmental materials, the groups found material to be easier to understand than those from other source materials, despite showing clear signs of antinuclear political biases and agendas, agreeing with the results from [250]. Interestingly, it was shown that comprehension of the scientific aspects of fusion energy amongst the public seemed to vary with socio-economic status, with further agreements are found from Oltra et al, where describing fusion as a new technology against fission as old technology produced positive perceptions [250]. These discussions tended to deviate to risk based topics when initially discussing the benefits of fusion, where internet based sources often attempt to describe fusion as the opposite process to fission, or the process that powers our Sun. Benefits of public engagement are highlighted in the UKAEA fusion energy regulation white paper, acknowledging that local community consultations with developers would increase transparency and education on protection for the public and the environment [186]. Overall, these findings impress the need to demonstrate clear communication, and honesty with regards to potential risks, such as waste, radionuclides, inherent safety issues, to all audiences, in order to eliminate the blurred line of the nuclear brand.

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 what is meant by see. Some within the fusion community will deem this to be when there is a sustained plasma burn with a Q > 1, others will consider it seen when there is delivery of electricity to the grid from a reactor. It is therefore important to state that roadmaps from enterprises, both public and private, are not considered to be credible sources for timescales of fusion. Many developers have published pathways to commercialisation that are a moonshot approach, i.e. all milestones are achieved with no showstoppers, delays, and assume that there is adequate funding for all the activities at each step (which implicitly also requires support from national laboratories). The reality might be that steps take longer, but the message is that ‘we have to try’. That is not to say that the timescales are un-achievable, but these are often optimistic in order to attract investment and are lacking in accompanying data that back up predictions. Note that for the purposes of this paper, fusion will have commercialised when it makes up 1% of global energy mix, as suggested by Kramer and Haigh [251]. Early investigations, from Lackner et al, estimated that an accelerated DEMO schedule would provide electricity to the grid by 2034 [154], and by 2040 under a standard one [252]. In reference to Kramer and Haigh, which outlines the Laws of Emerging Technology Development, this is usually one order of magnitude per decade [251]. Taking the assumption that the market is open for exploitation with no hurdles impeding commercialisation, Lopes Cardozo et al modelled the cost and potential speed of deployment for fusion [26].

5.1. Discussion

The use of learning factors from fission studies are more representative of those likely to be seen in fusion, than those from solar and wind projects. This renders the use of solar and wind gradients for fusion in the study form Lopes Cardozo et al less realistic [26]. An overlooked assumption in other studies are construction times. In the study from Lackner et al, ITER’s is 8 years, now proven to be erroneous [154]. The same estimate is given for DEMO which, despite no finalised design specification let alone construction phase, will have 4 × the thermal output of ITER, and harbours greater complexity in physics and engineering, and increased size, casting further doubt on timescales produced in roadmaps. It should be acknowledged that Lackner’s study is from 2001, and thus any scrutiny must recognise that when understanding these timescales in the present day, it is easy to make criticisms [154]. Note also that the timescales are not representative of the paper’s definition for commercialisation, and that a further period of growth is required until 1% of the energy mix is achieved. Attempts to achieve accelerated targets for DEMO via the

11 Law 1: When technologies are new, they go through a few decades of exponential growth, which in the twentieth century was characterised by scale-up at a rate of one order of magnitude a decade (corresponding to 26% annual growth). Exponential growth proceeds until the energy source becomes ‘material’—typically around 1% of world energy. Law 2: After ‘commercialisation’, growth changes to linear as the technology settles at a market share. These deployment curves are remarkably similar across different technologies.
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, a construction time of 10 years, (as quoted in several studies [22, 23, 25, 154]), engenders the prevention of improvements in reactor iterations [150]. This is because investors would be required to order new iterations of reactors prior to the completed construction of its predecessor. To add to construction uncertainties, Lopes Cardozo's study highlights that there is a finite level at which fusion can grow, and this is dependent on the reactor lifetime [26]. In short, it states that in order to remain economically favourable, the capacity to build reactors must equal the rate at which they are decommissioned once fusion reaches saturation in the market. As a result, the linear growth that precedes saturation must have a maximum level, if not, then in theory there exists reactor building infrastructure that will left useless once commercialisation is reached. Furthermore, Lopes Cardozo et al 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. Recalling the assumed annual reduction rate from Tokimatsu's study of 2.3%, equating to roughly 25% decrease per decade in the first quarter century and then 0.25% for the next, this represents a steeper learning factor [19].

Conversely to the public sector, private sector developers are iterating fast, through a combination of private funding and a desire to explore alternative fusion pathways. As a result, a paradigm shift towards ‘agile innovation’ has been triggered. This ‘simpler’ and ‘shorter’ development cycle approach sets apart private projects from those in the public sphere, enabling them to develop and implement the latest technology available to them by focusing of building machines and facilities quickly [1]. Examples of such practices are shown by TAE technologies [17], Commonwealth Fusion Systems’ ‘Devens’ site [253], and Tokamak Energy [254].

6. Conclusions and summary

This paper has provided a comprehensive overview of the socio-economic issues surrounding fusion energy, and how they might affect its commercialisation. Principally, topic areas have targeted present uncertainties around the optimum role of fusion, how much it will cost, what its externalities are, and when it will be commercial. Areas that need further research have been highlighted and are summarised below.

6.1. The role of fusion

- In terms of potential roles for fusion outside of electricity generation, (such as desalination, district heating, hydrogen, use of process heat for industry) multiple pathways for techno-economic investigations exist. There are a number of commonalities within each of these applications that any investigation of this type should scrutinise: they should seek to uncover if the apparent advantages from using fusion for these processes are upheld, and to discover any hidden disadvantages. In addition to capacity factors, they should also attempt to understand how the role of policy, discount rates, and government subsidy affects commercialisation of fusion.
- A large proportion of investigations have not as yet focused on reactors beyond those in the public domain, thus leaving private leapfrog enterprises open for exploitation. Useful analogies have been drawn from studies conducted in the fission domain, especially where fusion offers advantages that fission cannot.
- It is still unclear what the nature of the thermodynamic cycles will be for fusion reactors and hence the impact that high temperature cogeneration might have on their operation and economics. Fusion reactors operating at high temperatures could have pre-turbine entry temperatures in excess of 600 °C, much like HTGRs in fission. There would be considerable impact on electrical output due to the extraction of the heat prior to the turbine (much greater than low temperature applications). Alternatively, reactors could operate at lower waste heat temperatures, and use their electrical output to boost temperatures for the application. Optimal arrangements would depend strongly on the nature of the reactor, the cogeneration application, product pricing and energy pricing.
- Despite having a profound impact on the rate of fusion commercialisation in electricity production studies, the fusion community should not rely on the implementation climate change mitigation policies in order to become commercial (even if that is, arguably, a less damaging route for the planet). Doing so involves too much of a reliance on government policy that will be different for every country.
- Investigations on non-electric pathways for fusion and their effect on job creation and GDP would be beneficial to the energy community. That said, the fusion community should be cautious on using any non-existing sectors as segue for commercialisation, as this may prove too much of a challenge.
6.2. The cost of fusion

- At present, reactor designs present in literature have been shown to lack economic competitiveness when placed in future energy system models. A dominant reason for this is due to being reliant on either carbon tax implementation or carbon emission restriction on other technologies.
- Uncertainties still present a major issue, where values are simply used and assumed with no accompanying empirical evidence. What is clear from these models is that fusion's regional emergence will be highly dependent on government, and where such instances of anti-nuclear political rule dominate, fusion commercialisation may suffer.
- Studies investigating the cost of energy from different fusion reactor types are limited beyond the once conducted by Woodruff et al [151]. Further analysis is needed to focus deduce, how the method of confinement (inertial [255], magnetic [256–259] or inertio-magnetic [14, 260]) and therefore the type of plasma device (laser or tokamak) impacts the cost of the machine.
- Further costing analysis should be conducted around both the fusion fuel cycle and remote handling in fusion power plants, either during operation and or refuelling, as this may constitute a significant additional and unconsidered cost.
- The economics of high temperature applications for fusion are much more uncertain than those for low temperature. The uncertainty for low temperature applications resides in the cost of fusion alone. For high temperatures, there is uncertainty due to the nature of the fusion technology, its cost, and the value of the low-carbon process heat applications, most of which are yet to reach maturity.
- Deeper understanding of the classification of waste created by fusion is also needed, both radiological and non-radiological, including a potential revision to existing classifications based specifically on the fusion risks and waste types.

6.3. The externalities of fusion

- The external review mechanism proposed by Carayannis et al and the adherence to EU taxonomy criteria of sustainable energy sources are positive examples of methods that fusion can use to leverage itself against other energy sources in the global green initiative [229]. Further work should consider how the investment potential of fusion can be improved through the use of specific financial instruments and collaborations between public research labs and private enterprises.
- Recommendations for public-private partnerships in producing a net pilot plant before 2040 presents a positive step towards achieving greater cost certainty needed for investors [261].
- 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.
- In terms of sociological impacts of fusion, this paper compares the first results of fusion's effects on job creation and GDP. For non-conventional reactor types mentioned previously, studies of this type are limited, thereby representing further possible research avenues.

6.4. The timescales of fusion

- Construction times quoted in studies for new iterations of power plants are often optimistic, falling short of considering the advancements in physics and engineering parameters required for upgraded new builds. This results in a warped perception of the scaleability of fusion capacity from FOAK reactors to maturity and commercialisation.
- In order to upscale infrastructure for economic commercialisation, supply chains must be ready. This will ensure consistency in vital topic areas such as: construction times and reactor lifetime, construction/ component replacement capacity, and new power plant iteration timescales.

Data availability statement

No new data were created or analysed in this study.
Appendix. Data tables

Table A1. Estimated LCOE values from various fusion studies, with actual values from wind and solar projects in the same year.

| Year | Fusion [reference] | Wind Onshore/offshore [reference] | Solar CSP/PV [reference] | Large hydro [reference] |
|------|-------------------|---------------------------------|--------------------------|------------------------|
| 1993 | 40–50 [145]       | 190/— [262]                     |                          |                        |
| 2001 | 70–130 [18]       | 130/130 [262]                   |                          |                        |
| 2001 | 65–100 [153]      | 130/130 [262]                   |                          |                        |
| 2002 | 80–100 [39]       | 120/130 [262]                   |                          |                        |
| 2002 | 70–130 [19]       | 120/130 [262]                   |                          |                        |
| 2003 | 90–165 [20]       | 110/110 [262]                   |                          |                        |
| 2005 | 50–100 [143]      | 105/110 [262]                   |                          |                        |
| 2006 | 64–140 [263]      | 110/115 [262]                   |                          |                        |
| 2017 | 60 [25]           | 60/130 [262]                    | 40/8.8 [262]             | 4.9 [262]              |
| 2018 | 75–160 [147]      | 45/120 [262]                    | 15/7.0 [262]             | 3.8 [262]              |

Table A2. Adapted from [140], this shows a breakdown of the different temperature and heat demands of industrial processes, and thus the suitability for supply by NPH systems.

| Sector                        | Temperature (°C) | Heat demand (TWh) | Suitable for NPH |
|-------------------------------|------------------|-------------------|------------------|
| Basic metals                  | >1600            | 14                | ×                |
| Chemicals                     | 300–1000         | 26                | ✓                |
| Coke & refined petroleum      | 300–750          | 45                | ✓                |
| Cement                        | 900–1500         | ×                 |                  |
| Food & beverage               | 300–500          | 26                | ✓                |
| Non-metallic minerals         | >1000            | 23                | ×                |
| Pulp & paper                  | 300–500          | 14                | ✓                |
| Wider industry n/a            |                  | 67                | ✓                |

Table A3. A comparison of carbon emissions for competing technologies.

| Technology | Fusion | Offshore wind | Onshore wind | Solar | Fission |
|------------|--------|---------------|--------------|-------|---------|
| CO₂ Emissions (gCO₂ kWh⁻¹) Study | 9–22.2 | 15.6 | 9 | 15.8–38.1 | 15–50 |

References

[1] Pearson R J, Costley A E, Phaal R and Nuttall W J 2020 Technology roadmapping for mission-led agile hardware development: a case study of a commercial fusion energy start-up Technol. Forecast. Soc. Change 158 120064
[2] Nuttall W J, Konishi S, Takeda S and Webbe-Wood D 2020 Commercialising Fusion Energy ed W J Nuttall, S Konishi, S Takeda and D Webbe-Wood (Bristol: Institute of Physics Publishing)
[3] FIA and UKAEA 2021 The global fusion industry in 2021 Technical Report (London: Fusion Industry Association) (available at: www.fusionindustryassociation.org/about-fusion-industry)
[4] Maurer D A et al 2011 The high beta tokamak-extended pulse magnetohydrodynamic mode control research program Plasma Phys. Control. Fusion 53 74016–24
[5] Klinger T, Andreeva T, Bozhnenkov S, Brandt C, Burhenn R, Buttenschön B, Fuchert G, Geiger B, Grulke O and Laqua H P 2019 Overview of first Wendelstein 7-X high-performance operation Nucl. Fusion 59 112004
[6] Ziai M, Dal Bello S, Marrelli L, Puatti M E, Agostinetti P, Agostini M, Antoni V, Auriemma F, Barbian M and Barbui T 2017 Overview of the RFX-mod fusion science activity Nucl. Fusion 57 102012
[7] Nakashima Y, Ichimura K, Islam M S, Sakamoto M, Ezumi N, Hirata M, Ichimura M, Ikeyama Y, Nishio T, Imai T and Kariya T 2017 Recent progress of divertor simulation research using the GAMMA 10/PDX tandem mirror Nucl. Fusion 57 116033
[8] Zylstra A B et al 2022 Burning plasma achieved in inertial fusion Nature 601 542–8
Partanen R 2017 Decarbonizing Cities: Helsinki Metropolitan Area: Providing District Heating, Power and Transportation Fuels With Advanced Nuclear Reactors (London: Energy for Humanity)

Leurent M, Da Costa P, Jasserand F, Rämä M and Persson U 2018 Cost and climate savings through nuclear district heating in a French urban area Energy Policy 115 616–30

Leurent M, Da Costa P, Rämä M, Persson U and Jasserand F 2018 Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries Energy 149 454–72

Bockris J O 2013 The hydrogen economy: its history Int. J. Hydrog. Energy 38 2579–88

Bockris J 1977 Environmentally clean fuels for transportation Environmental Chemistry (Berlin: Springer) pp 583–604

Awad A H and Veziroglu T N 1994 Hydrogen versus synthetic fossil fuels Int. J. Hydrog. Energy 9 355–66

Bockris J 1999 Hydrogen economy in the future in2 Int. J. Hydrog. Energy 24 1–15

The Economist 2020 After many false starts, hydrogen power might now bear fruit The Economist (available at: www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit?giftId=af09a9262-155a-4e91-ac7f-83d4e3a52cb0)

McKay D 2021 The drive to hydrogen fuels takes off again after 30 years finweek 2021 10–11

Van de Voorde M 2021 Utilization of Hydrogen for Sustainable Energy and Fuels vol 3, ed M Van de Voorde (Berlin: de Gruyter & Co)

CMB.TECH 2021 Van Moer Logistics and Delhaize put first dual fuel hydrogen truck from CMB.TECH into operation (available at: https://cmb.tech/news/van-moer-logistics-and-delhaize-put-first-dual-fuel-hydrogen-truck-from-cmb-tech-into-operation)

CMB.TECH 2021 CMB.TECH and Luyckx present hydrogen-powered excavator (available at: https://cmb.tech/news/cmb-tech-and-luyckx-present-hydrogen-powered-excavator)

CMB.TECH 2021 HydroBingo, the first hydrogen-powered ferry, has been presented (available at: www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit?giftId=af09a9262-155a-4e91-ac7f-83d4e3a52cb0)

McKay D 2021 The drive to hydrogen fuels takes off again after 30 years finweek 2021 10–11

Van de Voorde M 2021 Utilization of Hydrogen for Sustainable Energy and Fuels vol 3, ed M Van de Voorde (Berlin: de Gruyter & Co)

CMB.TECH 2021 Van Moer Logistics and Delhaize put first dual fuel hydrogen truck from CMB.TECH into operation (available at: https://cmb.tech/news/van-moer-logistics-and-delhaize-put-first-dual-fuel-hydrogen-truck-from-cmb-tech-into-operation)

CMB.TECH 2021 CMB.TECH and Luyckx present hydrogen-powered excavator (available at: https://cmb.tech/news/cmb-tech-and-luyckx-present-hydrogen-powered-excavator)

CMB.TECH 2021 HydroBingo, the first hydrogen-powered ferry, has been presented (available at: https://cmb.tech/news/hydrobingo-the-first-hydrogen-powered-ferry-has-been-presented)

Timperley J 2020 The fuel that could transform shipping (available at: www.bbc.com/future/article/20201127-how-hydrogen-fuel-could-decarbonise-shipping)

Oxford Analytica 2020 Hydrogen is key to lower-carbon long-range transport Emerald Expert Briefings (Bingley: Emerald Publishing) (https://doi.org/10.1108/OXAN-DR257377)

Dodd P, Staffell I, Hawkes A D, Li F, Grünewald P, McDowall W and Ekins P 2015 Hydrogen and fuel cell technologies for heating: a review Int. J. Hydrog. Energy 40 2065–83

Cai G and Kong L 2017 Techno-economic analysis of wind curtailment/hydrogen production/fuel cell vehicle system with high wind penetration in China CSEE J. Power Energy Syst. 3 44–52

McDonagh S, Ahmed S, Desmond C and Murphy J 2020 Hydrogen from offshore wind: investor perspective on the profitability of a hybrid system including for curtailment Appl. Energy 265 114732

Huang C, Tang K K, Kelley J H and Berger B J 1979 Demand and supply of hydrogen as chemical feedstock in the U.S.A. Int. J. Hydrog. Energy 4 287–96

Nicita A, Maggio G, Andaloro A P F and Squadrito G 2020 Green hydrogen as feedstock: financial analysis of a photovoltaic-powered electrolysis plant Int. J. Hydrog. Energy 45 11395–408

Rambhujun N, Saad Salman M, Wang T, Prathcana C, Sapkota P, Costalain M, Lai Q and Aguey-Zinsou K-F 2020 Renewable hydrogen for the chemical industry MRS Energy Sustain. 7 E33

Bhaskar A, Assadi M and Somehsaraei H N 2020 Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen Energies 13 758

Kim J, Lee H, Lee B, Kim J, Oh Y and Lim H 2021 An integrative process of blast furnace and SOEC for hydrogen utilization: techno-economic and environmental impact assessment Energy Convers. Manage. 250 114922

Wu W, Ding H, Zhang Y, Ding Y, Katayip P, Majumdar P K, He T and Ding D 2018 3D self-architected steam electrode enabled efficient and durable hydrogen production in a proton-conducting solid oxide electrolysis cell at temperatures lower than 600 °C Adv. Sci. 5 1800360

Züttel A, Remhof A, Borgschulte A and Friedricha O 2010 Hydrogen: the future energy carrier Trans. R. Soc. A 368 3329–42

Heap R 2016 Potential Role of Hydrogen in the UK Energy System (London: Energy Research Partnership)

Wrochna G and Warsaw J S 2017 Possibilities for deployment of high-temperature nuclear reactors in Poland Technical Report: Committee for Analysis and Preparation of Conditions for Deployment of High-Temperature Nuclear Reactors (Warsaw: Ministry of Energy)

Roeb M, Agafiotis C and Sattler C 2015 Hydrogen production via thermochemical water splitting Compendium of Hydrogen Energy (Cambridge: Woodhead Publishing) pp 319–47

Dincer I and Zafirakis C 2016 Hydrogen production by thermal energy Sustainable Hydrogen Production (Amsterdam: Elsevier) pp 163–308

Elder R and Allen R 2009 Nuclear heat for hydrogen production: coupling a very high/high temperature reactor to a hydrogen production plant Prog. Nucl. Energy 51 500–25

Hahn D 2016 Generation IV concepts in Korea Handbook of Generation IV Nuclear Reactors (Cambridge: Woodhead Publishing) pp 335–71

Kimura H, Takeuchi Y, Yamamoto Y and Konishi S 2005 Hydrogen production from biomass using nuclear fusion energy Int. J. Hydrog. Energy 30 151–66

Germeshuizen L M and Blom P W 2013 A techno-economic evaluation of the use of hydrogen in a steel production process, utilizing nuclear process heat Int. J. Hydrog. Energy 38 10671–82

Levi P, Vass T, Mandonov H and Gouy A 2020 Tracking industry 2020 Technical Report (Paris: International Energy Agency) (available at: www.iea.org/reports/tracking-industry-2020)

International Atomic Energy Agency 2017 Opportunities for Cogeneration With Nuclear Energy (IAEA Nuclear Energy Series No. NP-T-4.1) (Vienna: International Atomic Energy Agency)

BEIS 2018 Clean growth—transforming heating—overview of current evidence Technical Report (London: UK Government)

Rodrigues F A and Joekes I 2011 Cement industry: sustainability, challenges and perspectives Environ. Chem. Lett. 9 151–66

DECC U K 2013 The Future of Heating: Meeting the Challenge (London: Department of Energy and Climate Change)

Nuclear Cogeneration Industrial Initiative 2014 Technical Report: The GEMINI initiative industry alliance industry alliance clean, sustainable energy for the 21st century Gemini Initiative)
[217] Bertuccioli L, Chan A, Hart D, Lehner F, Madden B and Standen E 2014 Development of Water Electrolysis in the European Union (Fuel Cells and Hydrogen Joint Undertaking)

[218] Olateju B, Monds J and Kumar A 2014 Large scale hydrogen production from wind energy for the upgrading of bitumen from oil sands Appl. Energy 118 48–56

[219] Olateju B, Kumar A and Secanell M 2016 A techno-economic assessment of large scale wind-hydrogen production with energy storage in Western Canada Int. J. Hydrog. Energy 41 8755–76

[220] Saur G and Ramsden T 2011 Wind Electrolysis: Hydrogen Cost Optimization NREL/TP-5600-50408 (National Renewable Energy Laboratory, U.S. Department of Energy)

[221] Shaner M R, Atwater H A, Lewis N S and McFarland E W 2016 A comparative techno-economic analysis of renewable hydrogen production using solar energy Energy Environ. Sci. 9 2354–71

[222] El-Emam R S and Khamis I 2017 Int. collaboration in the IAEA nuclear hydrogen production program for benchmarking of HEEP Int. J. Hydrog. Energy 42 3566–71

[223] Abuşoğlu A, Demir S and Özahi E 2016 Energy and economic analyses of models developed for sustainable hydrogen production from biogas-based electricity and sewage sludge Int. J. Hydrog. Energy 41 13426–35

[224] Kanoglu M, Ayanoglu A and Abuszoglu A 2011 Exergoeconomic assessment of a geothermally assisted high temperature steam electrolysis system Energy 36 4422–33

[225] Hinkey T T, O’Brien J A, Fell C J and Lindquist S E 2011 Prospects for solar only operation of the hybrid sulphur cycle for hydrogen production Int. J. Hydrog. Energy 36 11596–603

[226] Corgnale C and Summers W A 2011 solar hydrogen production by the hybrid sulfur process Int. J. Hydrog. Energy 36 11604–19

[227] Lee T-H, Lee K-Y and Shin Y-1 2014 Preliminary economic evaluation comparison of hydrogen production using GECONs and HEEP code

[228] Balta M T, Dincer I and Hebapi A 2011 Exergoeconomic analysis of a hybrid copper—chlorine cycle driven by geothermal energy for hydrogen production Int. J. Hydrog. Energy 36 11300–8

[229] Carayannis E G, Draper J and Ifimie I A 2020 Nuclear fusion diffusion: theory, policy, practice and politics perspectives IEEE Trans. Eng. Manage. 69 1237–51

[230] Banacloche S, Gamarra A R, Lechon Y and Bustreo C 2020 Socioeconomic and environmental impacts of bringing the sun to earth: a sustainability analysis of a fusion power plant deployment Energy 209 118460

[231] White S W and Kulcinski G L 2000 Birth to death analysis of the energy payback ratio and CO2 gas emission rates from coal, fission, wind and DT-fusion electrical power plants Fusion Eng. Des. 48 473–81

[232] Tokimatsu K, Hondo H, Ogawa Y, Okiano K, Yamaji K and Katsurai M 2000 Energy analysis and carbon dioxide emission of tokamak fusion power reactors Fusion Eng. Des. 48 483–98

[233] Barbarino M 2020 A brief history of nuclear fusion Nat. Phys. 16 890–3

[234] You X 2021 China should ‘rapidly’ close 186 coal plants to help meet its climate goals, study says (available at: www.carbonbrief.org/china-should-rapidly-close-186-coal-plants-to-help-meet-its-climate-goals-study-says)

[235] Stringer D and Kan K 2021 China’s dirty recovery will make curbing climate change tougher (available at: www.bloomberg.com/news/articles/2021-03-11/china-s-dirty-recovery-will-make-curbing-climate-change-tougher)

[236] Harvey F 2021 China ‘must shut 600 coal-fired plants’ to hit climate target (available at: www.theguardian.com/world/2021/apr/15/china-must-shut-600-coal-fired-plants-to-hit-climate-target)

[237] Gabbattis J 2021 Analysis: which countries met the UN’s 2020 deadline to raise ‘climate ambition?’ (available at: www.carbonbrief.org/analysis-which-countries-met-the-uns-2020-deadline-to-raise-climate-ambition)

[238] Zhang H-B, Hondo H, Ogawa Y, Okiano K, Yamaji K and Katsurai M 2000 Energy analysis and carbon dioxide emission of tokamak fusion power reactors Fusion Eng. Des. 48 483–98

[239] Barbarino M 2022 On the brink of a new era in nuclear fusion R&D Nat. Rev. Phys. 4 2–4

[240] Banks M 2021 UK announces five potential sites for prototype energy plant Phys. World 34 10ii

[241] Advanced Research Projects Agency 2020 GAMOW—galvanizing advances in market-aligned fusion for an overabundance of tokamak fusion power reactors Fusion Eng. Des. 48 483–98

[242] FIA 2020 Building a public-private partnership cost-share program for fusion power Technical Report (Washington, DC: Fusion Industry Association)

[243] Pearson R 2020 Fusion innovation: understanding the engineering challenges to commercial fusion Commercialising Fusion Energy vol 1, ed W Nuttall, S Konishi, S Takeda and D Webb- Wood (Bristol: Institute of Physics Publishing) ch 10, pp 160–96

[244] EU Technical Expert Group 2020 Taxonomy: final report of the technical expert group on sustainable finance The European Commission

[245] Group of Experts 2021 Technical assessment of nuclear energy with respect to the ‘do no significant harm’ criteria of regulation (EU) 2020/852 (‘taxonomy regulation’) Technical Report

[246] Jones C R, Yardley S and Medley S 2019 The social acceptance of fusion: critically examining public perceptions of uranium-based fuel storage for nuclear fusion in Europe Energy Res. Soc. Sci. 52 192–203

[247] Prades A, Horlick-Jones T, Oltra C, Navajas J and University C 2008 Investigating lay understanding and reasoning about fusion technology End-of-Project Report: Executive Summary on the Lay Understanding work for EUROFUSION: Technical Report

[248] Turcanu C, Prades A, Sala R, Perko T and Oltra C 2020 Fusion energy: a deeper look into attitudes among the general public Fusion Eng. Des. 161 111891

[249] Schmidt L et al CIE-MAT 2015 Media analysis of fusion executive summaries for EUROFUSION: public discourse on nuclear energy before and after Fukushima (Institute of Social Sciences, University of Lisbon (ICS-UL))

[250] Oltra C, Delicado A, Prades A, Pereira S and Schmidt L (EUROFusion) 2015 Social construction of fusion in the web: a content and thematic analysis of the presentation of fusion on the internet EFDA WP12-SERF-ACIF-T01.1 (Center for Energy, Environmental and Technological Research)

[251] Kramer G J and Haigh M 2009 No quick switch to low-carbon energy Nature 462 568–9

[252] International Atomic Energy Agency 2001 ITER-FEAT Outline Design Report (available at: www.iaea.org/ publications/6295/iter-feat-outline-design-report)

[253] Commonwealth Fusion Systems 2020 Commonwealth fusion systems at Devens—timeline (available at: www.csfatdevens.info/)

[254] McNamara S (Tokamak Energy Team) 2019 Tokamak energy and the high field spherical tokamak route to fusion power APS Division of Plasma Physics Meeting Abstracts vol 2019 p BO8.014

[255] Speaith M L et al 2016 Description of the NIF laser Fusion Sci. Technol. 69 25–145

[256] Kaye S et al 2019 NSTX-NSTX-U theory, modeling and analysis results Nucl. Fusion 59 112007
[257] Milnes J, Ayed N B, Dhalla F, Fishpool G, Hill J, Katramados I, Martin R, Naylor G, O’Gorman T and Scannell R 2015 MAST upgrade—construction status Fusion Eng. Des. 96–97 42–47

[258] Creely A J et al 2020 Overview of the SPARC tokamak J. Plasma Phys. 86 865860502

[259] Kwon M, Oh Y K, Yang H L, Na H K, Kim Y S, Kwak J G, Kim W C, Kim J Y, Ahn J W and Bae Y S 2011 Overview of KSTAR initial operation Nucl. Fusion 51 094006

[260] Binderbauer M W et al 2015 A high performance field-reversed configuration Phys. Plasmas 22 056110

[261] National Academies of Sciences, Engineering and Medicine 2021 Bringing Fusion to the U.S. Grid (Washington, DC: National Academies Press)

[262] IRENA 2021 Renewable power generation costs 2020 (available at: www.irena.org)

[263] Gnansounou E and Bedniaguine D 2005 Potential role of fusion power generation in a very long term electricity supply perspective: case of Western Europe (SESE-V) (International Atomic Energy Agency)

[264] Kaldellis J K and Apostolou D 2017 Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart Renew. Energy 8 72–84

[265] De Wild-Scholten M J 2013 Energy payback time and carbon footprint of commercial photovoltaic systems Sol. Energy Mater. Sol. Cells 119 296–305