Decarbonising the electricity supply

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ABSTRACT

With the ice caps disappearing, extinctions occurring at a terrifying rate and wildfires becoming more common and extreme, a rapid and drastic reduction to carbon emissions produced by electricity production is of paramount importance. However, electricity is also needed for water treatment, sewage disposal and access to it improves healthcare, education and quality of life. It also reduces the at home burning of fuels, along with the associated negative health implications and deaths.

As the developing world industrialises, technology advances and the global population grows, the use of electricity will increase further. The total decarbonisation of electricity will come from energy efficiency improvements and carbon neutral generation from renewables, nuclear fission and nuclear fusion. The aim of this report is to evaluate the different low carbon sources of electricity, as well as other potential decarbonisation methods. It will then identify what steps are required to mitigate the most devastating impacts of climate change. It will also discuss the long term solutions required to maintain a sustainable and carbon neutral electricity supply, despite worldwide increases in electricity demand.

1. Introduction

In a 2018 report the Intergovernmental Panel on Climate Change (IPCC) stated that it is likely that between 2030 and 2052, the world will hit a 1.5°C temperature increase above preindustrial levels [1]. This has been updated in the 2021 sixth assessment report, to being likely occur in the early 2030s [2].

The earth has already warmed by between 0.95-1.2°C with around 1.1 °C being the most likely [2]. Some of the consequences can already be seen and will be long lasting or even irreversible.

The IPCC report on 1.5°C global warming [1], the 2020 Ecological Threat Register from the Institute for Economics & Peace (IEP) [3], and the 2021 IPCC sixth assessment report [2] all explain the calamity of global warming clearly. Human driven climate change is caused predominantly by an increase in greenhouse gasses in the atmosphere, mainly CO_2. There is a 97% consensus in published climate research, by climate scientists, that it is humans that are causing climate change [4,5]. The scientific consensus is clear, climate change is caused by humans. The atmospheric CO_2 levels were the highest that they have been in at least 2 million years as of 2019 [2]. Since 1850 the atmospheric CO_2 concentration has risen by 48%. This is a larger rise than occurred over the preceding 20,000 years. In fact, 19 of the 20 warmest years on record have occurred since the year 2000 [6].

If further climate change isn't prevented it is expected that:

- *Loss of ecosystems, habitats, and biodiversity, as well as the extinction or endangerment of many species*. A meta–analysis of 27 studies and 976 species, undertaken in 2016, found that 47% of local extinctions were caused by climate change [7].
- *Increased frequency and intensity of droughts, flooding, extreme temperatures, and extreme weather*. The number of natural disasters in 2019 was more than ten times the number experienced in 1960 [1,3]. Over the last few months we have experienced deadly heatwaves, wildfires and extreme flooding. Parts of Germany

received 148 litres of rain per square metre within 48 hours in July of 2021. This is roughly 1.85 times the amount they normally in the entire month [8].

- *More frequent, intense, and widespread wildfires* [1]. The devastating bushfires across Australia in 2019-2020 killed or displaced as many as three billion animals. It also killed at least 33 people, with smoke inhalation linked to more than 445 deaths. On top of this the Amazon and California were also on fire in 2020 [9].
- *Increased risk of invasive or disease carrying species spreading* [1]. Melting Ice can also release frozen pathogens. In 2016, in Russia, melting ice caused by climate change led to the release of anthrax to the local population and wildlife. 72 people were hospitalised, one child died as well as 2,300 reindeer [10].
- *Rise in ocean temperatures, acidity and decrease in oxygen levels* [1]. This can have devastating effects on local wildlife and marine populations, such as coral reefs. Since 1995, half of the great barrier reef has been lost [11].
- *Melting ice sheets and rising sea levels* [1]. Between 1901 and 2018 the mean global sea level increased by around 0.2m (between 0.15 and 0.25m) [2].
- *Climate refugees*. Many areas will become inhospitable due to rising sea levels, agriculture loss and extreme weather. It is estimated that as many as 1.2 billion people are at risk of being displaced by 2050 [3].
- *Reduced productivity of aquaculture, fisheries and both crop based and animal based agriculture, leading to potential food shortages* [1].
- *Risks to food security, water supplies and public health*. By 2050 the number of people facing moderate to severe food insecurity is expected to increase by around 75% [1,3].
- *Economic devastation of countries, especially developing countries*. One 2021 study found that some countries could lose up to 19% of their GDP by 2030 due to climate change [12].
- *Resource wars*. The number of water related conflicts and violent incidents has increased by 270% over the last decade [3]. If climate change makes water and food poverty common place, then it is likely that wars over resources will become more frequent.

The larger the temperature increase the more severe the impact of global warming will become. An increase of 2°C compared to 1.5°C, will result in twice as many plants, twice as many vertebrates and three times as many insects losing more than half of their geographic range. Coral reefs will decline by 70-90% if warming is limited to 1.5°C but will die out by more than 99% if warming hits 2°C. On top of this the majority of other global warming impacts will also be more severe, such as more frequent extreme weather events, higher risk of vector-borne disease transmission and larger risks to food security [1].

The international atomic energy authority predicts that the worlds electricity usage will almost double between 2020 and 2050 and that energy consumption will increase by 39% [13]. This is supported by similar estimates of a 79% increase in electricity and a nearly 50% increase in energy consumption according to the US energy information administration [14]. Regardless of the exact amount it is widely accepted that over the next 30 years there will be a significant growth in both electricity and energy usage across the globe. This is driven by a range of factors including population and economic growth, as well as technological advancements. This increase is mainly attributable to developing countries outside of the OECD [15].

Currently, electricity makes up around 17-19% of the worlds energy consumption with between 25,000-27,000 Terawatt-Hours (TWh) of electricity produced in 2019 [13,16]. This share of the world's energy supply is expected to grow to around 27% by 2050 [13].

As energy requirements grow and more electricity is generated each year, there is an extreme urgency to decarbonise energy production to avoid catastrophic, irreparable damage to the planet and the associated biodiversity loss, climate refugees and loss of life from diseases and extreme weather.

Table 1
Summary of electricity generation by source in 2019, both globally and in the UK. All values are rounded to 2 sf. [16,17].

	Electricity Generation Worldwide 2019		Electricity generation UK 2019	
	(TWh)	**Share (%)**	**(TWh)**	**Share (%)**
Coal	9800	36	6.9	2.1
Oil	830	3.1	1.0	0.31
Gas	6300	23	130	41
Nuclear fission	2800	10	56	17
Hydropower	4200	16	6.0	1.9
Solar	720	2.7	13	3.9
Wind	1400	5.3	64	20
Other renewables	650	2.4	37	11
Other	230	0.87	7.8	2.4
Total renewables	7000	26	120	37
Total electricity generated	27000	100	320	100

Table 2
Summary of deaths, LCOE, power density, capacity factor and CO_2 emissions of several sources of electricity. The costs of nuclear were found using different sources then the other electricity generators. Different sources often used different methodologies and had significantly varying values. All values are rounded to 2 sf where possible.

Electricity supply	Deaths per Terawatt-hour	Global weighted average levelized cost per Kilowatt-hour in USD	Median power density in W_e/m^2	Capacity factor % (USA 2020)	Equivalent CO_2 Emissions (g/kWh)		
	[17,18]	[19]	[22]	[23,24]	[25]	[17]	[26]
Lignite (Brown coal)	33	0.055-0.15	N/A	N/A	N/A	N/A	1100
Coal	25		140	40	820	960	890
Oil	18		190	N/A	N/A	690	730
Gas	2.8		480	57	490	460	500
Biomass	4.6 (including pollution deaths) 0.016, 0.010 (excluding air pollution)	0.076	0.08	58 (wood) 63 (other biomass)	230	37	45
Nuclear fission	0.01 (2016 study – post Fukushima) 0.074 (2007 study)	0.069 [20] 0.13-0.20 [21]	240	93	12	9	29
Wind	0.035,0.092	0.039 (onshore) 0.084 (offshore)	1.8	35	12,11 (offshore, onshore)	11	26
Hydropower	0.024	0.044	0.14	42	24	16	26
Solar	0.019,0.014	0.057 (PV) 0.11 (concentrating)	6.6	25 (PV) 21 (Thermal)	48,41,27 (Utility, roof, concentrating)	30	85
Geothermal	0.010	0.071	2.2	74	38	N/A	N/A

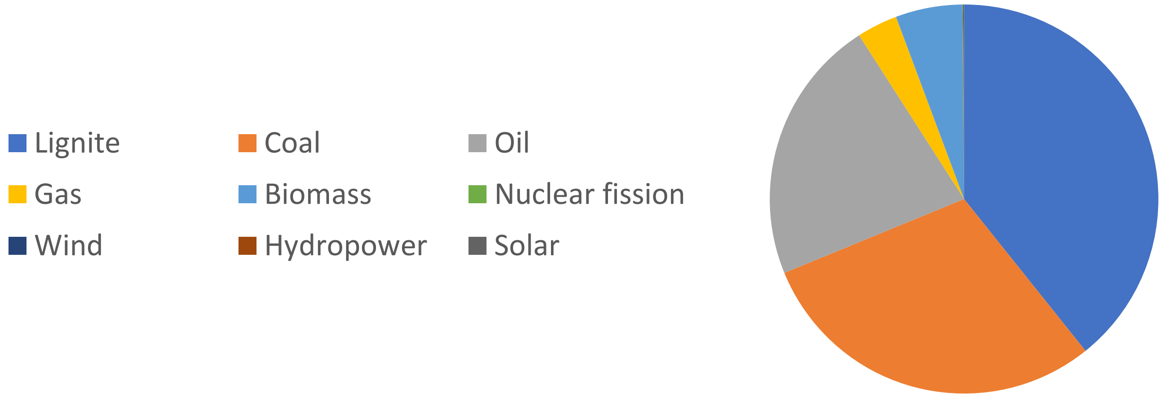

Figure 1
Pie chart showing the relative number of deaths per terawatt-hour for the energy sources in table 2 [17,18]

To accomplish the necessary decarbonisation of electricity carbon neutral generation will be required. This will be from a mixture of nuclear fission, nuclear fusion and renewables, as will be discussed in the next 4 sections. Sections 6 and 8 will discuss decarbonisation through energy efficiency improvements and negative carbon technologies respectively. Topic 7 will discuss some of the externalities associated with the different sources of electricity generation, and topic 9 will explore policy requirements for achieving carbon neutral electricity.

2. Nuclear fission reactors

A fissionable nucleus becomes unstable when hit with a neutron splitting into two smaller, similarly sized nuclei and fast neutrons (around 1-2Mev). These neutrons can then induce further fission reactions in a process known as a chain reaction; this produces exponentially more energy over time. A nuclear fission power plant runs on a controlled version of this reaction. Some elements are fissionable with thermal / slow / low energy neutrons (energies around 0.02eV), such as U-233, U-235 and Pu-239. Some will only undergo fission with fast / high energy (often around 1MeV or above) neutrons, such as Th-232 or Pu-238. Most fission reactors are thermal reactors (slow neutrons) that use uranium as their fuel source. Natural uranium is around 0.7% U-235 and the rest U-238. In thermal reactors only the U-235 fissions, releasing around 200MeV (3.2×10^{-11}J) of energy per fission. Uranium fuel is normally enriched to allow for criticality to be reached (a state where the number of neutrons produced by fission remains constant with time). This involves increasing the proportion of U-235 in the fuel from about 0.7% to around 3-5% [27-29].

2.1. Benefits of fission

Low carbon: Fission produces a similar amount of CO_2 as the renewables and is considered a low carbon energy source (See table 2). It produces around 29 tonnes of CO_2 per GWh compared with 85 tonnes for solar and 26 tonnes for wind. This is significantly less than fossil fuels, such as lignite (brown coal) which produces 1054 tonnes or coal with 888 tonnes of CO_2 per GWh [26].

Reliable: Unlike some renewables, nuclear is not an intermittent power source. Nuclear power stations can often run for a year or two without interruption, refuelling or needing repairs [30]. This makes it to be a good baseload supply. In America, in 2020, nuclear fission plants had the highest capacity factor (actual energy output / maximum possible energy output) of any energy source at 92.5%.

The fission capacity factor was (see table 2): 1.6x natural gas, 2.3x coal, 2.2x hydroelectric, 2.6x wind and 3.7x solar photovoltaic (PV) [23,24].

Sustainable: It has been estimated that the amount of accessible uranium contained in ores and phosphates amounts to around 27 million tons. This includes both discovered and undiscovered resources. However, some estimates are more than a thousand times this figure and some are slightly below it. On top of this, there is roughly 4.5 billion tons of uranium in the planet's oceans, some of which will be accessible and is potentially extractible on an industrial scale. Additionally there is the potential use of Thorium as a fuel, which is three times more abundant in the earth's crust than uranium. Fast breeder reactors could also be used in the fissioning of natural uranium, which extracts around 60 times as much energy as current thermal reactors [31].

The current usage of uranium each year is roughly 70,000 tonnes [32,33]. We have already discovered around 8 million tonnes of uranium metal that is extractible at a cost of between $40 and $260/kgU, but we expect there to be a lot more undiscovered [34]. This means that with currently discovered uranium in thermal reactors, we could continue with our current nuclear generation for around 115 years. Introducing fast reactors into the mix (multiplying by 60) we get over 6800 years at our current generation.

This is using a low estimate for our uranium resources and ignoring thorium, as well as the uranium in oceans, which is estimated to be over 560 times as massive as the 8 million tonnes we just used. Even if only a small amount of uranium is extractible from the oceans, and land based uranium and thorium resources are smaller than we expect, we can still use fission for a long time. The fuel is, however, not infinite and will eventually run out.

Large power output: fission reactors can produce large amounts of energy from a small amount of fuel. In fact, a kilogram of natural uranium could produce as much energy as 20,000 kilograms of coal in a thermal reactor [35] - 82 TJ/kg for U-235, 0.57 TJ/kg for natural uranium ($82 \cdot 0.007$ since only 0.7% of natural uranium is U-235) and 30MJ/kg for coal [36,37].

Plant size can vary in size from several megawatts up to several Gigawatts [35]. The Hinkley Point C 3.2 GW plant currently under construction, will supply an enormous 25 Terawatt hours of electricity each year. This is around 8% of the UK's current electricity generation [38]. Fission reactors also require relatively little space for this large electricity production so have a high power density (see table 2).

Safe: Unlike energy production methods such as fossil fuel plants, nuclear fission doesn't produce harmful and hazardous gasses. This means it impacts the health of nearby communities less. Even including the deaths from accidents such as Chernobyl, Fukushima and Windscale, the death rate per Terawatt-hour is low (0.01-0.07) and comparable with that of renewables (0.01-0.09 excluding biomass and 4.6 for biomass) and significantly below that of the fossil fuels (2.8-33) (see table 2). Newer reactor designs are also generally more meltdown resistant and safe, with many being built to have passive safety features that trigger automatically, shutting the reactor down. Living near a coal fired power plant will actually net you more exposure to radiation than living near a properly functioning nuclear reactor [17,18,39].

Low operating costs and long lifetime: The fuel for nuclear fission plants is only a small proportion of the total cost of electricity generation. At least 60% of the Levelized Cost Of Electricity (the cost per unit of electricity produced – LCOE) of nuclear power comes from the capital cost. The fuel for nuclear plants accounts for only around 14% of the overall cost.

The operating cost of a fission plant is generally lower than for fossil fuel plant and is very predictable with minimal chance of inflation. With an expected lifetime of around 60 years and a very high capacity factor, they produce electricity relatively cheaply once the initial construction is completed [35].

2.2. Issues with fission

Long construction times: It typically takes around seven to eight years to construct a fission plant. [40,41]. On top of this is the time required to do public enquiries and get the correct permits which can take several years. This is significantly longer than for installations of solar PV or onshore wind which including planning, development and construction often takes less than three years for large farms. Small installations can be constructed in a matter of months. Other renewables may take somewhat longer, but most still take significantly less time to construct than a fission plant [42,43].

Nuclear waste: much of the waste produced by nuclear fission reactors is radioactive and toxic. Some of this waste has a long half-life and can cause significant damage to the environment as well as the health of local inhabitants if it is improperly stored. It therefore has to be disposed of safely at designated waste sites [27]. It is estimated that Europe's nuclear fleet will generate 6.6 million m^3 of nuclear waste over its lifetime. Across Europe, roughly 2.5 million m^3 of low and intermediate level waste has already been produced and there is over 60,000 tons of spent nuclear fuel (high level waste) in storage (excluding Russia and Slovakia). High level waste (HLW) is the most dangerous. In the UK HLW accounts for 97% of radioactivity from nuclear waste but only 3% of the volume [44].

Proliferation: Nuclear fission plants can be used to generate plutonium, which can be used in nuclear weapons. The spread of fission power plants could lead to an increase in the number of countries with the technology to produce nuclear weapons. However, this is by no means a guarantee that it will lead to nuclear proliferation [27].

Accidents and perception: Nuclear fission reactor accidents are incredibly costly and can cause significant damage to the environment as well as deaths. The actual number of deaths from accidents is low, as can be seen from the very low deaths per terawatt hour for fission (0.01-0.074) [17,18].

The Three mile island disaster didn't kill anyone or cause any environmental issues, but the clean-up still took 12 years and cost $973 million [45].

Even though the number of total deaths for fission reactors is significantly lower than for fossil fuels, the perception of the danger is drastically skewed as a result of small number of large scale accidents such as Chernobyl, Fukushima and Windscale.

In a 2019 Gallup poll 49% of Americans supported the use of nuclear energy as a way of producing electricity with 49% also opposing it [46]. In a further Gallup poll in 2021, 39% of Americans said that more emphasis should be placed on fission in electricity generation with 28% wanting less emphasis. This is still better than for coal with 48% wanting less emphasis and 23% wanting more. The renewables consistently come out more favourable than fission though. In the same poll wind had 66% wanting more emphasis to 16% wanting less emphasis and solar had an even bigger margin of 73% to 10% [47].

Low trend following capability: The majority of fission reactors can't easily follow energy trends due to their high start-up time and the need to have a high capacity factor to be economical. However, in France, where fission makes up over 70% of their energy supply, nuclear power output can be somewhat varied to follow energy trends [27,48].

2.3. Other considerations

Economically competitiveness: Nuclear power plants are very expensive to build. The capital cost of a power plant accounts for at least 60% of the LCOE. A large initial cost with long term repayment is not something sought after by most investors, who generally want dividends quickly from investments [35]. Fission reactors also have a history of cost overruns. For example the 3.2 GW Hinkley point C plant in the UK is expected to cost around 22 billion pounds (an increase of 4 billion from the initial estimate of 18 billion) [49,50]. This trend doesn't hold worldwide however. Countries including China, Russia and South Korea can build plants at a fraction of the cost. This is achieved largely by using a more standardised reactor design, having built up strong supply chains and having supporting policies and regulation in place.

In a 2015 report by the International Energy Agency (IEA) and the Nuclear Energy Agency (NEA), they estimated the investment costs for fission plants per kWe at 3%,7% and 10% discount rates for different countries. These all show the Chinese reactors being less than half the price of UK reactors, sometimes closer to a third of the price [51]. In 2020 China approved the construction of four standardised nuclear reactors with a total power of nearly 4.4 GW. The estimated cost for this is $10.2 billion [52]. This is less than half the cost of the Hinkley Point C reactor but has a 36% higher output power. This is obviously assuming no cost overruns and similar capacity factors, however, it shows that nuclear power can be significantly more cost competitive than it currently is in the UK. There may be differences in regulation and safety standards between countries, which make some countries reactors more costly, but the price can be dropped substantially either way.

2.4. Reactor technology

Moderator: A material used to slow down the fast neutrons produced by the fission reactions to leave thermal neutrons. Some fissionable materials will not undergo fission as a result of collisions with fast neutrons but will from collisions with thermal neutrons [27].

Coolant: The coolant is to stop the reactor from heating up too much and causing damage. It also either directly or indirectly transfers the energy to a turbine for electricity generation [27].

Control rods: Made of a material that can readily absorb neutrons, such as boron or cadmium, the control rods stop a runaway chain reaction from occurring. They do this by absorbing excess neutrons produced by the fission reaction. They can be raised or lowered to alter the number of neutrons in the reactor and completely lowering them into the reactor should completely stop the reaction [27].

Light water moderated reactors (LWR): Around 82% of all reactors worldwide (365) are light water reactors [53,54]. Light water is a good moderator and can effectively slow down neutrons to thermal energies (neutron scattering cross section of 49 barns). Light water however also has a relatively large neutron absorption cross section (0.66 barns) compared to other moderators and so has a high parasitic neutron absorption. An ideal moderator has a high scattering and a low absorption cross section [27,55]. This means enriched uranium (normally around 4% U-235) is required for light water reactors. Light water makes up over 99.9% of all water which makes it easy to obtain [56,57]. Light water reactors typically have a conversion factor, also known as a breeding ratio, which is the fissile fuel produced divided by the amount consumed, of between 0.4 and 0.6. This means that more fissile fuel is used than gets produced when U-238 absorbs neutrons and is converted to fissile Pu-239 [27,58].

Pressurised light water reactor (PWR): PWRs are the most common type of nuclear reactor, with 303 worldwide. This is around 68% of all fission reactors [53,54]. They use light water as both the coolant and moderator and so are a subset of LWR. These reactors are fairly compact due to the high pressure they operate under, around 150 atmouspheres (15 MPa) and at roughly 325°C . They can be made even more compact by using highly enriched uranium as the fuel but they typically use uranium enriched to between 3% and 4.5%. The high pressure increases the power output and improves the thermal efficiency since the water can operate at a higher temperature without vapourising. The control rods are kept at the top of the reactor, unlike in a boiling water reactor, so that if power is lost then the control rods drop automatically and shut the reaction down. The cooling water heats up and passes through tubes which act as a heat exchanger and transfer heat to a secondary water loop. This second water loop is at a lower pressure and so the water vaporises and turns a turbine. This is known as indirect steam generation [27,53,56,59,60].

Boiling water reactors (BWR): BWRs are the second most common type of reactor, with 62 reactors worldwide. This is around 14% of the total reactors [53,54]. These are also LWRs which use light water as both the moderator and coolant. They operate at a lower temperature than pressurised water reactors, at around 285°C and 75 atmospheres of pressure (7.5 MPa). Due to this lower pressure the power to weight ratio and compactness is less than that of a pressurised water reactor. However, as a result they are able to have thinner reactor walls. The overall costs of building, operating and maintaining a BWR are approximately the same as a PWR. BWR have one loop of water rather than two and the coolant water is directly turned into steam which turns the turbine. This is direct steam generation. This means less water needs to flow at any given time but that the water becomes radioactive, so extra shielding of some components is needed. Overall a boiling water reactor is smaller than a pressurised water reactor, since it has no steam generators. BWR use uranium enriched to between 2-4%. The control rods are placed at the bottom of the reactor since they are most effective in the water rather than in the steam. This means they aren't a passive safety system like they are in a PWR [27,53,57,59,60].

Generation IV: These are new and sometimes theoretical reactors that could become a part of the future energy supply.

(Gen IV) Supercritical water-cooled reactor: The super critical water cooled reactor uses a lot of principles from super critical coal plants and boiling water reactors. This should make a transition to them easier than to many other generation IV plants. The critical point of water is 22MPa and 374°C. Above this point the water is neither a gas nor a liquid but a supercritical fluid. It is expected that the temperature of these reactors will be between 500°C and 650°C, with a pressure around 25MPa. The supercritical water directly drives a turbine. They can run with light or heavy water and can use thermal or fast neutrons. The potental use of fast neutrons opens the possibility for them to be used for waste management or fuel breeding, as well as allowing them to use fertile fuels such as thorium. This is explained further under Fast Neutron Reactors. Using supercritical water could increase the efficiency of reactors from around 34% today, to around 44%, as it is beter at transfering heat than normal water. This coupled with a 35% reduction to the amount of heat wasted, as well as smaller containment and safety systems, could lead to lower capital costs (construction costs) and improved economics [27,61,62]

Presurised heavy water reactors: These make up 11% of all reactors, with 49 operational around the world [53,54]. It uses heavy water (water with deuterium replacing the hydrogen) as both moderator and coolant. They work the same way as pressurised light water reactors, with indirect steam generation [53,63]. Since heavy water doesn't cause as high a parasitic neutron absorbtion as light water (with a neutron absorption cross section of 0.0013 barns, only 0.2% that of light water), these reactors can use non enriched, natural uranium. The heavy water doesn't have as high a neutron scattering cross section at 10.6 barns, meaning it takes more collisons to slow the neutrons down to become thermal neutrons. It is much more efficent than light water however, due to the much lower parasitic neutron absorbtion [53,54,63]. The main drawback of using heavy water is that there is very of it little found naturally. Heavy water makes up only around 1 in 20 million water molecules. This makes it expensive for use in a reactor [56,63]. Pressurised heavy water reactors can attain a high fuel conversion ratio, much higher than light water reactors, due to refuling during oppperation and low paracitic neutron capture. They often have breeding ratios of around 0.9 [58].

Graphite moderated reactors: Graphite is a good heat conductor and thermally stable. It is also a good moderator but only when extremely pure, however, it can be obtained inexpensively at these purity levels. At high temperatures graphite can react with oxygen and carbon dioxide in the reactor which reduces its effectiveness, and its low strength and density make it suseptible to being warped. It has a neutron absorbtion cross section of 0.0035 barns, 0.5% that of light water. It has a neutron scattering cross section of 4.7 barns, lower than both light and heavy water [55].

Light water graphite reactor: These reactors use light water as the coolant and graphite as the moderator. There are 12 of these reactors, accounting for around 3% of the worlds reactors [53,54]. They use direct steam generation like BWRs. The fuel used is uranium enriched to around 2-4%. They operate at around 290^{o}C and 70 atmouspheres (7 MPa). These reactors can be refuled during opperaton rather than having to be turned of for a significant amount of time for refuling [27,53,60,64].

Gas Cooled Reactor: Only presently run in the UK, there are 14 gas cooled and graphite moderated reactors, making up 3% of the worlds reactors [53,54]. They use carbon dioxide as the coolant, graphite as the moderator and can be refuled during operation. The specific type of gas cooled reactor (Magnox or gas-reactor) will effect the fuel used. The Magnox reactor use natural uranium and advanced gas reactors use enriched uranium (around 2% enriched). Gas cooled reactors use a two fluid system with indirect steam generation [27,53,59,60].

(Gen IV) Very High temperature gas cooled reactor: These reactors are graphite moderated and helium cooled. At high temperatures, the production of hydrogen and electricity are both significantly more efficient. These reactors aim for temperatures as high as 900 to 1000^{o}C, which is sufficient for the thermochemical production of hydrogen. These reactors are therefore likely to play a large role in the future of energy production, if we transition towards a hydrogen economy, with the design lending itself well to the cogeneration of electricity and hydrogen. The core can be a prismatic block core or a pebble bed core. They can be used to generate electricity through a direct or an indirect steam cycle [27,62].

(Gen IV) Fast Neutron Reactors / FNR: There are only 2 FNRs operational currently [53,54]. These reactors use an element that is fissile with fast neutrons as the fuel (often Pu-239), surrounded by a blanket containing a fertile element (usually depleted uranium / U-238). The fast neutrons produced by the fission reaction, collide with the fertile blanket, and produce fissile material. What this means is that the fertile element absorbs the neutrons and is transmuted into a fissile element. In a further collision with a neutron (normally a low-speed / thermal neutron) this new fissile element can

Uranium fuel is less efficient for fast neutrons than for slow neutrons, which is why plutonium is normally used for FNRs. Uranium enriched to 20% U-235 can be used, however, this is less common. P-239 produces more neutrons per fission than U-235 (around 25% more), allowing for the chain reaction to be sustained whilst also breeding fissile fuel from the fertile blanket.

FNRs are up to 100 times more efficient at converting fertile elements into fissile ones than thermal reactors. A reactor designed to produce more fuel than it uses is known as a Fast Breeder Reactor (FBR) and can produce fuel to be used in thermal reactors. These reactors could be used to extend the world's nuclear fuel resources by roughly 60 times and potentially extend the life span of nuclear energy by thousands of years. If they don't produce as much fuel as they use than they are burner reactor. These reactors can be used to burn long-lived radioactive and toxic actinide waste, recovered from other fission reactors.

Most generation IV fission reactor designs are Fast Neutron Reactors. It is likely that generation IV FNRs won't actually have a blanket of fertile material, but instead will both consume and breed fuel in the core.

FNR are expensive to build, and the price of uranium is too low for FNR to currently be economically competitive with thermal reactors. Their utility comes from the ability to extend nuclear fuel supplies and from their waste burning capabilities. They could also be used to produce power from plutonium removed from decommissioned nuclear weapons. The fast neutrons maximise the fission probability of the actinide waste recovered from normal fission reactors and minimises the neutron capture probability. What this means the waste is much more likely to be burned [27,53,65-67].

Burning the waste reduces the time that it is highly radioactive, from a mater of tens or hundreds of thousands of years, down to around 200-300 years. This makes it much easier to store safely until the radioactivity drops sufficiently to not be an ecological threat. It also significantly reduces the volume of waste that needs to be stored [27,65,68,69].

The fission probability in Fast Neutron Reactors decreases drastically as the temperature rises, which increases their passive safety. Experiments have also shown that metal liquid coolant systems make them less sensitive to coolant failures, than conventional water or gas coolants [27,65,70]

Molten Salt reactor: Another reactor that could rival fast breeder reactors is the molten salt reactor concept. These reactors use a molten fluoride salt as their primary coolant. These reactors operate at a high temperature of around 750ºC and operate near atmospheric pressure. Molten salt reactors come in two forms. A Fluoride salt-cooled High temperature reactor uses a molten salt solely as the coolant, with a solid fuel being used. This is much more similar to current reactor types, so won't be discussed here.

The other type (which here is just referred to as a molten salt reactor) is where the fuel is mixed into the molten salt. Of this latter type, homogeneous molten salt reactors have a single fluid containing both dissolved thorium and uranium. Heterogeneous molten salt reactors have two fluids in separate loops. One contains fertile thorium and the other contains fissile uranium or plutonium. Molten salt reactors can be used as either as breeders or burners. One of the major advantages of molten salt reactors is that the products of the fission can be constantly removed and any actinides can be entirely burned leaving less and shorter lived nuclear waste. They also have a large negative temperature and void coefficients (They become less reactive as temperature and void content, such as steam bubbles, increases), as well as passive cooling and safety features. This makes them much safer than most other reactor designs [27,62,71,72]. Thorium molten salt reactors are considered to be inherently safe by many scientists [27,71-73]. They are also considered more proliferation resistant than most other designs. This is since it produces U-232 mixed into the U-233 bred. This means isotopic separation is required to get the U-233 for use in nuclear weapons. Additionally highly radioactive daughter isotopes are formed which make separation and transport more costly and difficult, as well as making concealing the radioactive material much harder to do [27,74].

Small Modular Reactors (SMR): SMR's are small, standardised reactors that can be produced in a factory and can be small enough to be easily transported (they are 300MWe or less). By virtue of their small size and standardised design they have smaller initial cost, shorter construction times and are designed to be passively safe. They also are more proliferation resistant, have lower operation and maintenance costs and can be used in areas too small for a full-size fission reactor. They can be used individually to power smaller areas. This is especially useful for areas with limited transmission infrastructure or connection to a national grid. They can also be combined together into larger capacity power plants. This allows for the electricity generation capacity of an area to be easily increased over time. It also allows for lower initial costs and investment, with a reduced risk of time and cost overruns. One especially important drawback is that having more smaller reactors spreads the nuclear waste out making it harder to ensure that it is properly contained. Another is that they are untested and also suffer a loss of economies of scale which may lead to them being uneconomical even with the lower cost from standardisation. One further potential issue is that as they may be more widespread, they may receive less oversight. This runs the risk of more small-scale accidents due to miss management [75,76].

Standardisation: Some of the construction issues associated with fission, such as the cost over runs and delays experienced by Hinkley point C, could be significantly improved by a standardisation of design. Hinkley point C is a pressurised water reactor and so isn't the same reactor type as Hinkley point B, which is an advanced gas reactor. There are often significant changes between a reactor and the next one that is built. This means that different challenges are encountered which can slow the progress and raise costs. Using a single standardised design as the basis for a large number of plants (with the exceptions of alterations required by regulators) limits the risk of unexpected issues, improves the economics, improves construction times, allows for building a more stable supply chain and reduces the risk of regulation issues and long public enquiries delaying the construction [40,77,78]. However, there is still a risk of significant alterations being required by regulators, increasing the costs. Countries that use a standardised design, such as Japan and Russia, have been found to have faster construction times than those using a variety of designs. Additionally, having more collaboration between regulators, planners, utilities and constructor as well as having the technology to build their own reactor speeds up construction [40]. As stated earlier China is building 4.4 GW of fission power across four standardised reactors with an estimated cost of less than half that of the 3.2 GW Hinkley Point C plant [52].

Standardisation could also lead to improved safety with several countries reviewing the design. Another advantage is that issues during the construction or operation of a reactor can be learned from and corrected for all future similar plants [77,78]. It also makes cooperation between countries nuclear programs easier if they all are working from the same design. This may not be possible for all countries, however, if several countries have the same reactor design, then supply chains would likely improve, expertise can be shared more easily and replacement parts can be obtained faster [77].

A standardised reactor (most likely a PWR) would allow for a faster and cheaper expansion of fission power in the coming decades.

2.5. Fissions role in the climate crisis

Nuclear fission is carbon neutral, safe and reliable. The use of generation IV reactors could also make it sustainable for thousands of years. It also doesn't have the issues of requiring massive amounts of land, which is severely detrimental to ecosystems, or the requirement of huge amounts of energy storage that plague the renewables. Generation IV plants can also burn nuclear waste reducing its half-life and volume significantly, mitigating one of fissions largest problems. We also have a lot of experience in building and operating fission plants. It may not be a permanent solution due to not being renewable, but it is definitely a contender for a short to medium term solution to the climate crisis. With the potential to be used in hydrogen production it may also help decarbonise other sectors of the economy if a hydrogen economy is implemented.

Therefore, the final question to answer is can it be implemented fast enough and on a large enough scale to significantly decarbonise the electrical sector.

In short quite likely yes. Until the early 1970s the costs and deployment times of constructing nuclear power stations was plummeting rapidly before reversing in most but not all countries. This means the costs and construction times can return to those same levels and likely drop even further [79]. China for example can produce nuclear fission reactors at a fraction of the cost of UK reactors. It may be that initially a standardisation of design is required, settling on one reactor type to mass produce (most likely a PWR). This would speed up construction, lower costs and reduce the risk of time and cost overruns. With a long history of building and operating nuclear reactors, the mass production of a standardised nuclear reactor design seems doable. The alternative is an even more rapid expansion of renewables and energy storage which is also a massive undertaking. It should be said however, that developing countries are less likely to be able to afford fission plants compared to the renewables.

This standardised route would eliminate some of the benefits of alternative reactor types, especially generation IV reactors that can be used to increase the amount of energy extracted from uranium, use alternative thorium fuel, burn nuclear waste and are more meltdown resistant. It however, does not preclude the possibility of steadily replacing older reactors with newer more useful models, such as fast reactors or molten salt reactors. It allows for nuclear fission to be used in the rapid decarbonisation of electricity over the next few decades and then mitigation of the associated issues by employing waste burning and fuel breeding reactors.

At the very least currently operating reactors should not be decommissioned early and should have their lifetime extended if this can be done safely. Additionally, reactors being currently constructed should be completed. Most of the researchers I spoke to agreed that fission is a necessity for at least the next 30 years. Many said significantly longer, with estimates more in the range of 60-100 years. There was some disagreement on whether to scale fission up or to just not decommission current reactors. However, most of this disagreement stemmed from the issue of whether new reactors could be built quickly enough, more than on the merits of increasing fissions prevalence.

3. Nuclear fusion Reactors

Nuclear fusion is the process that powers the sun and occurs when two small nuclei join together and release a large amount of energy. In the sun, the temperature of the core is 15 million°C and the pressure is 150 billion bar. This is possible since the sun is so massive (around 330,000 times the mass of earth). On earth a pressure of 150 billion bar is not realistic. It also would not give sufficient fusion probabilities for electricity production, so we tend to focus on Deuterium-Tritium (D-T) fusion which can be achieved at significantly lower pressures. It does however require higher temperatures (around 150 million°C) [27,80,81]. Other fusion reactions such as Deuterium-Deuterium (D-D) and Deuterium- Helium 3 fusion may become more feasible as technology develops.

Each D-T fusion even releases 17.6MeV compared to 200MeV for U-235 fission [82]. Therefore, a plasma with huge numbers of fusion reactions occurring every second can release massive amounts of energy. The CCFE states that fusion releases around 10 million times as much energy per kilogram compared to the fossil fuels [81]. D-T fusion releases 360 TJ/kg of fuel. This is compared to 82 TJ/kg for U-235, 0.57 TJ/kg for natural uranium and 30MJ/kg for coal. This means fusion releases around 4.4 times as much energy per kg as the fission of U-235, 630 times as much as the fission of natural uranium and 12 million times as much as burning coal. [36,37,82,83].
In D-T fusion a helium nucleus and a neutron are produced. 80% of the energy released during fusion is taken away by the neutron and 20% by the helium nucleus. The neutron will then collide with the blanket of the reactor, transferring its energy to the coolant. This leaves only 20% of the energy available for internal heating to maintain the temperature of the plasma. This means ignition, the point at which a fusion reaction becomes self-sustaining, requires very high energy releases to occur [27,80,81].

3.1. Benefits of fusion

Little waste and greenhouse gas emissions: Helium is the only waste product of D-T fusion and it is an inert gas. It can also be used in the cooling of superconducting magnets and devices used in the fusion reactors. This means disposal and transport of waste is likely to be substantially easier and cheaper than for fission reactors [27,81,84].

Sustainable: The fuel used in fusion reactors is deuterium and tritium. Deuterium is present in water and is incredibly abundant (30g/m^3). It can be easily extracted via electrolysis. Tritium is radioactive and only found in trace amounts on earth. It will be bred from lithium in a reactor, in an interaction with neutrons produced by the fusion. Terrestrial lithium reserves are significant and would likely last for over 1000 years. The lithium present in seawater would be enough to last for millions of years if it can be extracted economically. If the lithium can be extracted from sea water on a large scale, then this helps remove energy security concerns associated with fuel imports, such as those of fission and fossil fuels. If other fusion reactions become viable in the future (especially D-D fusion) then this could lead to fusion being a source of practically inexhaustible energy [27,81,82,84,85].

High energy density: 1kg of fusion fuel could provide as much energy as 10 million kg of fossil fuels. A 1 Gigawatt power station could therefore run for a whole year with less than 1 tonne of fuel [81].

High grade heat: Fusion reactors operate at incredibly high temperatures. They also give out significant heat that can be used in desalination, cement production or hydrogen production amongst many other options [86]. This improves the economics of fusion.

No risk of meltdown: It is incredibly technically challenging to achieve the conditions required for fusion to occur. This leads to the risk of catastrophic accidents disappearing for fusion, since an error would change the conditions, the plasma would cool, and any fusion would cease. In fact, there is never very much fuel actually inside the reactor, normally only enough for a few seconds. This means that the amount of energy that could be released at any given time, is much too low to cause a disaster. This also means that an attack on the power station couldn't cause widespread harm unlike some other energy production methods such as hydroelectric dams or fission. (1,2,6,27) [27,81,84,87]

Little and short lived nuclear waste: There are two sources of radioactive waste from fusion. The first comes from the tritium which has a short half-life of 12.4 years and becomes safe after a relatively small amount of time. The other is from the reactor components that become radioactive during fusion. This is due to the neutron radiation incident on the components and generally, after around 100 years the radioactivity is low enough for these components to be reused or recycled [27,81,84,85]. After 100 years the radioactive waste from a stainless-steel fusion reactor would be around 1 million times lower than that of an equivalent fission reactor [85].

Reliable power: Nuclear fusion, like fission, is expected to be a base-load electricity generator. This means it will produce a continuous supply of electricity. It doesn't suffer from the reliability issue that plagues many of the renewables [27,81,84]

Cost competitive with fission: The power output and cost of a fusion reactor is expected to be fairly similar to that of a current fission reactor. This would make it relatively competitive on an economic front once the economies of scale kick-in to lower costs. Fusion plants have a high risk of cost overruns such as those frequently experienced by fission plants. [84,85,87,88,89]

Low proliferation risk: Fusion makes no use of uranium or plutonium and doesn't produce any fissile materials so has low proliferation risks associated with it [81,84].

3.2. Issues with fusion

Its commercial viability is unproven: Nuclear fusion power stations do not currently exist. Fusion is incredibly difficult to achieve due to the extreme conditions required and has only been done in experimental reactors thus far. The set up cost as well as the running cost and reliability will need to be competitive for it to be able to penetrate into the energy market. This capability has not yet been proven [85,89]. On top of this the requirements for a fusion power plant would far exceed those currently achieved, or even those expected to be achieved by ITER. The power output for electricity generation will have to be around 2-3 times greater than that of ITER, for fusion to be competitive. The tritium quantities burned per year will also need to be magnitudes higher than of any current tokamak. The issues of scaling up to a full power plant may end up being incredibly hard to overcome [84,90]. They will also need to have both a high availability and reliability to be economical.

It is competing with renewables and fission: The effects of climate change can already be seen worldwide. Fusion is not expected to be widely implementable until the latter half of this century, with huge investments in capital needed in the interim [91,92]. The question then obviously becomes whether we should instead use that funding on tried and tested, already implementable but imperfect fission or renewables, expanding the current energy infrastructure and improving energy storage technology and energy efficiency.

Fusion reactors are currently very expensive to build: Fusion reactors use cutting edge technology and operate under extreme conditions. It is also predicted that the reactors will need to be significantly bigger than current fossil fuel power stations to be economically viable. These issues coupled with economies of scale not having kicked in yet leads to high initial costs for fusion reactors [84,85,90,93].

Large reactors: On top of the increased cost caused by a reactor being large it also means that if it breaks down it has a larger impact on overall power production. This makes large scale plants undesirable for utility companies and may discourage investment as a result [85].

They produce some radioactive waste: The nuclear waste from fusion plants comes from neutron bombardment of the reactor walls. This causes them to become radioactive over time and also degrades them. This waste needs to be properly disposed of, the components replaced, and the reactors eventually safely decommissioned, all of which is expensive. Tritium is also radioactive with a half-life of 12.4 years and needs to be safely contained [27,85,93].

Tritium may need to be bred in fission reactors: Tritium can be bred in fusion reactors by placing lithium in the blanket. However, the blanket needs gaps for vacuum pumping, and either fuel and beam injection or driver beams. This means the blanket cannot surround the entire reactor. There may also be losses of tritium and inefficiencies in the tritium production process. If the breeding of tritium wasn't sufficient inside the fusion reactor itself then fission reactors would still be needed to breed extra tritium. This would bring some of the issues of fission energy, such as higher levels of radioactive waste, to fusion [93,94].

Large energy losses: Huge amounts of energy are used by fusion reactors. Around 75-100MW are consumed by auxiliary systems and processes such as helium refrigerators as well as water and vacuum pumping. Significant energy is also used in controlling the plasma or in charging the systems required for an energy pulse e.g. capacitors. This means for fusion to be economical, despite such large energy losses, only high energy outputs (roughly 1 GW or higher) would be economical to run [93,95]. This auxiliary energy requirement could lessen over time with improving technology.

Proliferation risks: Fusion reactors can be made into fission fusion hybrids. These share some of the issues of nuclear fission such as the risk of nuclear weapons proliferation. A fusion reactor produces fast neutrons which can be used to breed fissile material from fertile elements such as thorium or depleted uranium. Tritium is also used in some boosted fission weapons; However, these also require the fissionable material. This means that fusion reactors could be used to produce the fuels for nuclear weapons [93,96,97].

3.3. Magnetic confinement fusion

In magnetic confinement fusion, nuclear fuel is heated up to an incredibly high temperature, until it forms a plasma. A plasma is when the electrons and nuclei of a substance dissociate forming a gas of free charged electrons intermingled with a gas of free charged nuclei. It has no overall charge.

This plasma is a million times less dense than air. Strong magnetic fields have to be used to keep it from touching the walls of the reactor, as this would contaminate and cool it. Auxiliary methods such as neutral beam injection and the input of EM waves are required to bring the plasma up to fusion temperatures. Significant shielding and cooling is also required due to the incredibly high temperature of the plasma, as well as the low temperature requirement of the super conducting magnets. The coolants used are often water and supercritical helium Reactors have a blanket that covers the inner walls of the vacuum vessel. High energy (14MeV) neutrons collide with the blanket and produce thermal energy. The coolant removes this energy and it is utilised in electricity production. The blanket may also contain lithium to breed the tritium used in the fusion reaction. A diverter is used which extracts heat, charged impurities and helium ash produced during the fusion reaction [27,81,95,98-100].

Tokamak: A tokamak is a fusion reactor with a toroidal (doughnut shaped) vacuum chamber containing a plasma and is widely seen as the most promising design to make fusion power a reality. A tokamak is essentially a large transformer. An alternating current passes through the primary coil, it produces an alternating magnetic field which then induces an alternating current in the secondary coil. In a tokamak the secondary coil is a single winding of plasma, instead of a coil of wire. A change in the current or voltage applied to the primary coil will be transmitted via the iron core at the centre of the torus and will alter the current in the plasma. The electrons will accelerate around the torus in one direction and the nuclei will accelerate around in the opposite direction, due to their different charges. The particles flow in a helical path which increases the plasma stability. An unstable plasma is essentially one with turbulence. This turbulence has to be prevented in fusion reactors. A central solenoid allows for a powerful current to be induced in the plasma. A set of toroidal coils (Perpendicular to the plasma flow) surround the vacuum vessel and are used to confine the plasma. The outer poloidal coils (parallel to the plasma flow) help to shape and position the plasma, contributing to its stability [27,98,99,100]

Spherical tokomak: These are shaped more like a cored apple rather than a ring. Studies have suggested that this shape can lead to higher levels of stability, higher β (the ratio of plasma pressure to magnetic pressure) and higher plasma temperatures Another commonly touted potential benefit is that spherical tokamaks may be able to achieve fusion at a substantially reduced size. As a result, some proponents of the technology have suggested that "the way" to fusion may be spherical tokamaks rather than the toroidal structure implemented at ITER. Spherical tokamaks have a few distinct disadvantages. The magnetic coils have to be much closer to the plasma or even inside the pressure vessel. This means they need more shielding from the fast neutrons. It is expected that the central column will need regular replacement due to this radiation. Perhaps the biggest issue is one of priorities. Spherical tokamaks were invented later and with so much momentum behind toroidal tokamaks such as ITER, it may be difficult to get the same levels of funding and research due to their late arrival [27,101,102].

Stellarators: These work on the same principals as tokamaks but via different method. The helical toroidal motion is caused entirely by external magnetic fields and is not induced by a transformer configuration. This requires a more complex set up for the magnetic coils than in a tokamak. This set up leads to closed magnetic surfaces and subsequently low plasma losses. Stellarators are also able to operate continuously (steady state) due to the absence of a large plasma current, like that in a tokamak. This reduces the stress on the components and means they won’t have to be replaced as frequently. The issue of not having resistive heating from the plasma current has been lessened by improvements in auxiliary heating methods such as neutral beam injection and the use of EM waves. Stellarators are currently behind tokamaks in the race for fusion power however they are still a strong contender. [27,100,103,104]

Reversed Field Pinch / RFP: The RFP set up is almost identical to that of a tokamak and can actually be used as a low field tokamak. In the RFP set up, the majority of the magnetic field comes from the plasma current, which is an order of magnitude higher than for a tokamak with the same central toroidal field. This leads to the ohmic (resistive) heating of the plasma to be two orders of magnitude higher. This reduces or eliminates the need for auxiliary heating methods. The outer magnetic field applied to the plasma can be significantly weaker than that in a tokamak or a stellarator. The external coils only produce a small toroidal field in the opposite direction to the central field. In RFP the toroidal and poloidal fields have comparable amplitudes [100,105,106].

Mirror confinement: Mirror confinement involves having 2 “mirrors” that reflect the plasma between each other. This works by having a very strong magnetic field that repels the plasma at both ends and a weaker magnetic field towards the middle of the confinement area. Plasma can leak out of the confinement and since the 1980s the magnetic mirror approach has been largely abandoned [100,107,108].

3.4. Inertial confinement fusion

A cryogenically frozen pellet of Deuterium-Tritium fuel, surrounded by an ablator, with a diameter of a few millimetres, is forced to implode by the application of an incredibly high energy pulse. This heats the outer layer of the ablator, causing atoms on the surface to boil off in an energetic and explosive manner. This causes a simultaneous rapid compression of the inner layers of the fuel. This makes the core incredibly dense (around 100-200 times as dense as its liquid form) and very hot. The fuel in the core can undergo fusion at these temperatures and pressures. The heat generated can cause further fusion in the outer layers, known as ignition. The core of the fuel pellet needs to be compressed uniformly to prevent Rayleigh-Taylor instabilities misshaping the imploding plasma. If the plasma does become misshapen, fusion won’t occur [27,99,100]. Inertial confinement fusion for power generation would produce pulsed power, with likely around five pulses a second. This is a significant increase from the current shot counts which is limited to a few shots daily [109-111].

Laser inertial confinement:
direct laser inertial confinement is when a large number of lasers converge at the fuel pellet and directly cause the implosion and subsequent fusion. This often suffers from non-uniform irradiation and hence non-uniform compression of the fuel pellet however it also can lead to higher gain implosions.
Indirect laser inertial confinement is when the lasers are instead focused on something called a hohlraum. This hohlraum then emits an even flux of x-rays, which is enough to cause the implosion of the pellet. [27,99,112]

Ion beam: This approach uses converging beams of ions to compress the D-T fuel pellet causing the implosion. This method of fusion has largely fallen out of favour as a potential path to fusion energy [27].

Fast ignition: Fast ignition separates the compression and ignition of the fuel. The heating of the fuel comes from a laser rather than from the implosion. This is more efficient. Lasers or particle beams directly compress a thicker fuel pellet, at a lower velocity, than in indirect drive. Then a short (on the scale of picoseconds) and intense laser pulse heats up the fuel to fusion temperatures and compresses it further. This method may lead to higher energy gains by as much as 3-10 times, as well as requiring lower driver energy and reducing costs [100,113,114].

Z – pinch: A cylindrical shell of plasma is oriented in the Z direction on cartesian axes. A current is then induced in the plasma in a fast pulse. This causes it to generate a magnetic field that "pinches" the plasma in towards the Z axis, condensing the cylinder. As the ions in the plasma collide with high kinetic energy some of this energy gets converted into x-rays. These x-rays then heat a cylindrical hohlraum to several million degrees. The hohlraum then emits an even flux of x-rays which causes the implosion of a D-T fuel pellet. The fuel pellet of a Z-pinch can be significantly bigger than those used in laser inertial confinement, with an estimated maximum fusion output of 1.2 GJ, which is roughly 80 times larger than that of laser inertial confinement [27,115].

3.5. Magnetised target fusion / magneto-Inertial fusion

In magnetised target fusion a plasma is condensed to fusion conditions over microseconds rather than nanoseconds like in inertial confinement fusion. The plasma is kept at a higher density than in magnetic confinement but lower than in inertial confinement. It is confined with the use of a magnetic field and then compressed causing rapid heating. This compression can be via lasers, chemical, electromagnetic, or mechanical methods. Magnetised target fusion combines magnetic and inertial confinement techniques and as a result leads to confinement time requirements lower than those of magnetic confinement, but higher than those of inertial confinement, at between 0.1-1 ms. Magnetised target fusion may have the potential to be a cheaper method of achieving fusion than magnetic or inertial confinement. However, some fusion scientists are doubtful of its promise for fusion power production [99,116,117].

3.6. The direct route to fusion

International Thermonuclear Experimental Reactor / ITER (Means the way in Latin): The ITER tokamak weighs 23,000 tonnes and has a plasma volume of 830 cubic meters, around 10 times larger than any tokamak currently operating. It will have a plasma current of 15 MA [118]. In comparison, the Joint European Torus (JET) in England has a plasma volume of 80 cubic meters and a plasma current of 5 MA [119].

ITER will have three heating systems with a total maximum heating capacity of 73 MW. It is being built in the south of France through collaboration between 35 nations. The aim is to build the world's largest and most powerful tokamak, achieving a 500 MW power output for 400-600 seconds. This would be from a 50 MW power input, equivalent to a Q value of 10. A Q value is simply the ratio of power output to power input. This would be the first machine to achieve break even (Q=1) and would significantly beat the current record of Q=0.67, achieved by JET. ITER, however, will not produce electricity from this energy gain. ITER is also expected to achieve a sustained burning plasma at 150 million^{o}C for a significant period of time due to high plasma stability. ITER will be used to test tritium breeding inside the vacuum vessel of a reactor, as well as testing and demonstrating other components such as heating, diagnostics, remote maintenance, and cryogenics [118].

The cost of ITER is contested. The ITER organisation claims that the overall cost will be approximately $22 billion, however, the US department for energy estimates $65 billion. Both of these substantially outstrip the original cost estimate of only $5.6 billion (5 billion euros) [120-122].

ITERs first plasma is scheduled for December 2025, which is a significant delay from the original plan of 2020. D-T operations are scheduled to begin in 2035 [118, 122].

The overall purpose of ITER is to prove that fusion power plants will viable and safe, as well as providing the research necessary for DEMO.

DEMO: DEMO would be an electricity producing, long-pulse Tokamak with the ability to generate tritium. Unlike ITER, which is a single machine, DEMO may be an internationally collaborative machine or many different machines attempting to demonstrate the feasibility of a fusion power station. Demo will need to run continuously or nearly continuously (steady state) and produce electricity both safely and consistently. This is since pulsed power places more strain on the components of the tokamak, so more frequent maintenance and component replacement is required. It will need to demonstrate reliability and be designed to enable easy

maintenance. It will also need to demonstrate tritium self-sufficiency [123,124].
Europe, Japan, Korea, India, China, the USA and Russia are all planning to build DEMO plants [124].
The European DEMO is planned to produce around 500 MW electricity [125-127]. China is planning on doing an intermediate step with the China Fusion Engineering Test Reactor (CFETR) which will produce 200 MW in its first phase, increasing to 1000 MW in its second phase and is set to be built during the 2020s [123,128]. The US is also considering having an intermediate step with the Fusion Nuclear Science Facility being used to develop and test the components and materials needed to produce a DEMO reactor at a later stage. Russia has opted for a different path with plans to build the DEMO-FNS (fusion neutron source), a hybrid reactor [123,124].

The current plans for the European DEMO are for operation in the 2050s [126,129]. Increasing the funding available to ITER and DEMO could significantly cut the time until fusion power plants are available. In order for DEMO to be built around 2040 we would need significant investment now. There is a rarely touted benefit of this kind of rapid investment. The apollo program for example, led to an explosion in microchip technology. The money invested in the moon landing has benefited the US a lot more than it cost [130]. The same could be true of fusion. A properly funded fusion program would deliver advancements across a range of technologies including robotics, sensor technology and magnets. These could then be used in a wide range of technologies, from self-driving cars to nuclear fission decommission robots. Additionally, around three quarters of the European ITER contributions are directed into industry. Fusion research also employs a large number of people directly. That amounts to billions of euros invested into industry and thousands of jobs created [131].

In the UK, there was a massive reduction in energy research funding in the early 1980s which only started to pick back up in the mid-2000s. As of 2013 the research and development budget was still only around half that of the budget in 1974. Nuclear fusion has also received a tiny fraction of this total budget [132]. The funding needs to be much higher to make up for the decades of underfunding it if we are to achieve fusion power production in the next few decades.

3.7. Fusion’s role in the climate crisis

It is unlikely that inertial confinement fusion will be used for electricity production as it shows less promise in that respect than magnetic confinement fusion. It is not impossible, but I think it will remain the less attractive option of the two.
Magnetic confinement fusion needs to increase its Q value by just under 2 orders of magnitude (around 1.7-1.9). Inertial confinement fusion needs to increase its shot rate by around 5 orders of magnitude. For the Q value: $0.67 \cdot 10^{1.8} = 42$ which is between 30 and 50. For the pulse rate: 3 shots a day is equivalent to one every 28,800 seconds. For 5 pulses a second we need around 0.2 seconds per pulse or roughly $28800 \cdot 10^{-5}$ [109-111,133,134].

One thing that needs to be considered is if magnetic confinement fusion will be available soon enough to help solve the climate crisis? Fusion power is a relatively unproven technology, with it currently not having ever reached break even, Q=1. It is likely that it will achieve and significantly past this milestone over the next half decade or so, but it is a microcosm of the main issue. We don’t know how long until working fusion plants can be built. We also don’t have much experience building fusion reactors, which raises the risk of massive cost and time overruns during construction, similar to those seen with fission. This makes them a less safe investment for businesses and governments to pursue. This may be the crucial issue with fusion.

ITER is expected to achieve first plasma in the latter half of 2025 and to reach its full power configuration in 2035. DEMO will likely start construction in the 2030s and be operational through the 2040s. It is predicted that the first prototype fusion plant is likely to be operational around the 2050s. The CCFE, through the STEP program, is attempting to construct a prototype fusion energy plant in operation around 2040 [135].
On top of this it will take extra time to then start producing fusion plants on a large enough scale to significantly decarbonise the energy sector. With more funding and technological innovations, it is possible that this time scale could accelerate somewhat but it is hard to know how significantly. With unforeseen issues or reductions to funding it could potentially take even longer. To increase the speed and decrease the costs, the supply chain needs to start being developed now. The jump from a working prototype around the 2040s or 2050s, to

fusion being a significant part of our energy supply, is unlikely to be a short one. After a working prototype is produced energy companies and governments need to be persuaded to pay to build these reactors on a large scale and quickly. This is made harder by the fact that these reactors would be the first commercial nuclear fusion reactors. Gaining funding to have them mass produced is unlikely until they have been tested for long periods of time and constructed repeatedly.

Fusion reactors will need to be more compact and simpler than those currently being built to reduce costs and speed up construction. The reduced proliferation concerns and the inherent safety of fusion will likely give it a better public perception than fission, however, fusions economics still need to be competitive with those of fission. As the cost of renewables continues to drop, fusion power may need to be cheaper than current fission power to be economically viable when it is implemented.

You may see the issue here. The IPCC said we are likely to hit 1.5^{o}C of global warming above preindustrial temperatures in the 2030s. Even with the best case scenario where we overperform and accelerate fusions timeline, by time nuclear fusion plants are being produced on mass, we will either have made immense progress towards being carbon neutral or we will be in some very serious trouble.

There are other admittedly more dubious claims, that by the early 2030s a fusion plant will begin supplying energy to the grid. Tokamak energy, Commonwealth Fusion Systems, General Fusion, TAE and other private fusion companies have claimed they will have a working fusion reactor, capable of supplying the grid with energy, in the 2030s [136-138]. Most fusion scientists argue that this is entirely unrealistic. Even if we generously assume that the first fusion reactors will be supplying energy to the grid as early as 2030, the time taken to make them become a large part of the energy supply would likely make them suffer the same issue as before. The energy sector will need to significantly decarbonise before fusion can become a large electricity supplier.

This isn't to say that fusion isn't worth pursuing. Fusion has the potential to provide reliable, safe and environmentally friendly energy for millions of years. It is to say instead, that fusion is not the way to solve the immediate issue of climate change. Fusion should be implemented later to replace fission power stations as they shut down and to meet rising energy requirements. Fusion may become especially useful if a hydrogen economy is implemented as the heat output can be used for hydrogen production. If not it is likely to still be paired with desalination plants or cement production.

4. Nuclear fission-fusion hybrid reactors

Fission and fusion can be combined into hybrid reactors. This is where a nuclear fuel is placed in the blanket around a fusion reactor. This fuel can be depleted uranium, used nuclear fuel, natural thorium, nuclear waste containing long lived actinides, natural uranium as well as conventional fission fuels such as enriched uranium and plutonium-239. The high energy fast neutrons produced by the fusion reactor are absorbed by the fuel. These neutrons are significantly higher energy than those released in fission reactions (14 MeV for D-T fusion compared with around 2 MeV for fission reactions). This allows for certain fuels such as Uranium 238 to be utilised (by conversion to fissile Plutonium 239) which isn't used in thermal fission reactors.

If the fuel is fertile, such as thorium, it will be transmuted into a fissile material. This can be used in a conventional fission reactor or used in the hybrid reactor. If the fuel is fissile (or has been converted from a fertile fuel into a fissile one) then it can absorb the neutron and fission releasing energy and more neutrons. These neutrons can cause further fission reactions and multiply the energy from the fusion reaction significantly. This means that the fusion part of the system would not need to release as much energy in a hybrid system to achieve energy gain. Fusion reactors in hybrid systems could therefore be smaller than conventional fusion reactors. Using hybrid reactors as a method of transmuting nuclear waste is likely to be their main purpose. By placing nuclear waste in the blanket long life radioactive elements can be transmuted to shorter life elements that can be more safely stored. Multiple different fusion reactor designs have the potential to be used in a hybrid system [99,139-141].

Hybrid systems are sometimes disregarded with claims that they just combine the worst parts of fission and fusion, and this is not completely without basis. However, it is incomplete information at best. Hybrid reactors are designed to have the beneficial aspects of both fission and fusion reactors while minimising the drawbacks. Whether the benefits outweigh the issues in practice, still remains to be seen.

4.1. Benefits of hybrids

Production of Fissile material: By placing fertile elements in the blanket, the neutrons produced by the fusion reactor can be absorbed, transmuting the fertile elements into fissile elements. These can then be used in normal fission reactors. This significantly increases the time that fissionable materials will be available [139,142,143].

Meltdown resistant: Having the blanket contain fertile elements or Lithium, which can absorb neutrons, reduces the number of neutrons available for fission reactions. This means that it is possible to make a blanket which will allow for a sustained reaction only when the fusion neutron source is active. This would make the hybrid reactor inherently safer than a fission reactor [139,142,143].

Increase production of tritium: By mixing fission materials in with the lithium, the neutron amplifying effects of the fission could lead to higher levels of tritium production [139,143].

Reduced demand on fusion reactors: There is still a way to go between current fusion reactors and those that would be needed for a fusion power plant. Placing fissionable fuel in the blanket could boost the power generation of the fusion reactor significantly. The fusion reactor would be there mainly for neutron production rather than energy generation. For a hybrid system a fusion reactor with a Q value of 2 could potentially be sufficient for commercial power production. In normal fusion power production the reactor would need a Q of at least 10 and likely higher (Q between 20 and 50). This may mean that a fusion reactor that wouldn't be viable on its own could become viable in a hybrid system [140,142,144].

It can burn nuclear waste: Radioactive isotopes, such as the actinides, produced by fission reactors can be transmuted to stable isotopes or short lived nuclear waste. For example, I-129 (half-life 16 million years) and Tc-99 (half-life 213000 years) can absorb neutrons becoming I-130 and Tc-100 which both then quickly beta decay to form stable isotopes. This means we can use sustainable fusion reactors as the neutron source for a nuclear waste burner, significantly reducing the long term risk of the nuclear waste. Both Tc-99 and I-129 are fairly soluble in water and so if something was to break their storage in the hundreds of thousands or millions of years before they became low danger, they could possibly get into ground water and eventually drinking water. Converting them to shorter lived isotopes also reduces the volume of high level waste. The less waste there is the easier it is to contain. This is the same principle as for fast reactors described earlier [139,140,142,145].

It can use more abundant isotopes: Normal fission reactors running on Uranium only use the U-235 for power generation. This accounts for about 0.7% of naturally occurring uranium. Hybrid reactors have much higher neutron energies allowing for the remaining 99.3% (U-238) to be converted into Pu-239, which is a fissile material. This means that a hybrid reactor will be able to obtain around 60x more energy from a kilogram of natural uranium than a conventional thermal fission reactor [65,139,140,142].

Use of hybrid systems may increase the speed of fusion advancement: Fusion research may be boosted by using fusion reactors in active energy production in a hybrid system. Experience gained constructing and operating commercial fusion reactors in hybrid systems could reduce the time until commercially viable, pure fusion reactors can be produced on a large scale [144].

Proliferation resistance: Hybrids can burn nuclear waste products rather than them having to be separated and buried. They also don't require the enrichment of uranium fuel. This could lend to some proliferation resistance to the hybrid concept compared with normal fission reactors. The separation of waste is a large proliferation risk in fission reactors and this can be somewhat avoided via transmutation in hybrid reactors. The enrichment of uranium is also required for making nuclear weapons, so avoiding this step also provides some proliferation resistance [140].

4.2. Issues with hybrids

They are complex: Hybrid power stations need less advanced fusion reactors than a pure fusion power stations would. They do however, still need to be more advanced than any current fusion reactor. They would need a Q value of around 2 and further research would need to be done combining the fusion and fission components effectively. The DEMO-FNS hybrid reactor is planned for construction by the mid-2030s. This means hybrid power plants won’t be available until the 2040s, assuming no significant delays. This means that they will become available only shortly before fusion power plants or possibly even later if there are unexpected technical difficulties [142,144,146-148].

They are expensive to build: Hybrid systems will use fusion reactors which are expensive to build. It will also have extra complexity due to combining fission and fusion reactors. On top of this to be commercially viable they will likely have to have a high power output, all of which increases upfront costs [142,149].

They aren’t fully proliferation resistant: Hybrid reactors offer some potential proliferation resistance by burning waste and not requiring enriched fuel. However, a hybrid reactor could still be used to transmute fertile elements into fissile ones, potentially to be used as the fuel for nuclear weapons.

They don’t fully eliminate nuclear waste: Like Fast reactors, hybrid systems can burn nuclear waste, converting long life radioactive elements to shorter half-life elements. They however, do not eliminate the waste. It is still radioactive and needs to be kept secure until its radioactivity has dropped to a safe level, which may be a few hundred years. Also by being used to breed more fissile fuel, it could lead to higher total levels of nuclear waste in the future.

Uranium prices are low: The advantage of being able to produce fissile elements, is undercut by the high availability and low price of uranium currently. It is cheaper to mine uranium than it is to produce nuclear fuel by transmutation [150].

4.3. DEMO-FNS (Fusion Neutron Source)

The Russian answer to DEMO, the fusion reactor following ITER, is not a fusion reactor at all, but a hybrid reactor. It is planned to produce 40 MW of fusion power and 400 MW of fission power and operate with a Tokamak as the neutron source. The tokamak is to be fairly small, with a major radius of 3.2m and a minor radius of 1m. It will have a plasma current of 4.5 MA. The device is planned for construction in 2033. It will incorporate tritium and fissile fuel breeding as well as minor actinide burning. It is planned to be able to show steady state operation of the tokamak at 40 MW for up to 5000h and produce as much electricity as it uses, approximately 200 MW [148,151]

4.4. Alternative systems

Accelerator driven systems (ADS) and Fast Reactors can both be used for the same purpose as a hybrid reactor.

An accelerator driven system is where an accelerator is the source of the neutrons in a similar set up to a hybrid system. ADS have a higher neutron yield and are expected to be more effective at burning waste than fast reactors. They suffer the same issue of complexity as hybrid reactors, with accelerators being complex on their own and combining them with a fission reactor difficult. Unlike a hybrid reactor, the neutron source does not release energy for electricity production, so all of the energy comes from fission. There are no ADS in operation, and they have received less attention than hybrids and fast reactors in recent decades, so empirical comparisons are difficult to find. They are mainly considered for their waste burning capabilities and less so for electricity production [145,152,153].

Fast reactors are the most mature technology and have already been commercially deployed, though on a limited scale. We have a more than 400 years of total fast reactor experience. It would likely be hard for hybrid systems to enter the market with a more established alternative already present. This is especially true when the alternative is likely to be less expensive and the commercial viability of hybrid reactors is unproven. It is expected however, that hybrid reactors would be more efficient than fast breeder reactors. It is expected that it would take 35 fast reactors to burn the same amount of waste as 4-6 hybrid systems [65,154].

4.5. Hybrid's role in the climate crisis

Similarly to fusion reactors, it is unlikely the hybrid systems will be available until after the energy supply is significantly decarbonised. Their utility is the same as that of fast reactors. They can be used to burn nuclear waste and potentially extend nuclear fuel supplies significantly.

Hybrid reactors are only likely to be employed if fission reactors remain a significant part of electricity production late into this century. Their fuel breeding capacity is useful, only if fission reactors are still in use. Their waste burning capabilities would be useful regardless, however, it is likely that if fission is phased out sooner rather than later, that either fast reactors will be used to burn the waste or that the waste will remain unburned.

If fission is employed for the medium or long term, then research and investment into hybrid reactors should occur. However if fission reactors are being phased out rapidly this will likely not be necessary, cost effective or useful.

5. Renewable energy

Renewable energy is the term used to describe energy production methods that are essentially limitless, most commonly those derived from the sun's energy including solar, wind and biofuels. Renewables are considered to be one of the best potential solutions to decarbonising electricity production worldwide, especially over the next few decades.

5.4. Benefits of renewables

Cost effective: Most renewables are cost competitive with the fossil fuel power plants with wind and solar often being the cheapest power production methods. Fossil fuel power plants have a LCOE of between \$0.055-0.15/kWh. The renewables generally have a LCOE between \$0.04-0.08/kWh and the price of most renewables is dropping annually. Nuclear power LCOE estimates varied from \$0.07/kWh to between \$0.13-0.20/kWh. Tidal and wave power are currently a lot more expensive than the other renewables. This is because they are significantly less mature technology [19,20,21,155].

No / low CO_2 emissions, pollution, and waste during operation: The majority of the renewables produce very little CO_2 or pollution during operation with almost all of their total output being during the manufacturing process. They also don't produce any waste products which have to be disposed of during operation. However, they do all produce some waste via manufacturing and disposal. This is in contrast to the highly pollution, high CO_2 fossil fuels. Nuclear power is low carbon however it produces nuclear waste.

Geothermal power plants can lead to the release of greenhouse gasses and pollutants from the ground. The amount released is still typically a lot less than that released from fossil fuel plants. Information from the early 2000s (2000, 2003) put the average SO_2 released from existing coal plants to be 10.39 pounds per MWh, nearly 30 times that from geothermal plants at 0.35. I should note however that the average for new (built in the 1990s) coal plants at that time was only 3.6 pounds per MWh so 10 times higher than geothermal. Geothermal plants released no nitrogen oxides whereas the average for existing coal plants and the average for new coal plants were 4.31 and 2.96 pounds per MWh respectively [156].

Biofuels are the main exception. They are carbon neutral assuming that the biofuel is produced sustainably and sensibly i.e. any tree that is cut down is replaced with another tree that absorbs a similar amount of CO_2. However, normally the native vegetation that is cleared away is better at absorbing CO_2 than the biofuel crop. This means that less CO_2 gets reabsorbed than is released in burning the native flora, so overall CO_2 is released. Even if the biofuels are grown in a sustainable and sensible way, it increases atmospheric CO_2 levels temporarily as new trees may take decades or even centuries to reabsorb the carbon released. Certain biofuels will grow much faster, but they tend to absorb less CO_2. This means that clearing land for biofuel usage has a high risk of driving further climate change rather than combating it [157-159]. Burning biofuels also releases smoke and pollutants into the area around the power station and they are linked to water pollution.

Safe: The fossil fuels have a higher number of deaths per TWh (2.8-33) than any of the renewables (0.01-0.09 excluding biomass) or nuclear fission (0.01-0.07). Renewable energy systems also don't impact the health of the local population very much due to not releasing harmful pollution.

The one exception is biofuels which do release pollution and therefore has a higher death rate than the other renewables. Biofuels cause more deaths per TWh (4.6) than natural gas, but still a lot lower than lignite, coal and oil (see table 2) [17,18].

Sustainable: The renewables will not run out as they are continually generated. As long as the sun shines and the wind blows we can get solar power and wind power, the same goes for most of the renewables. Geothermal power can be extracted at an unsustainable rate from the ground, as the heat can be extracted faster than it is replenished; However, there will always be heat leaking into the crust from the mantle or generated by radioactive decay. Biofuels are theoretically sustainable, however, that doesn't mean they are inherently. If improperly managed biofuel supplies can steadily decrease [31].

Economic independence and security: Fossil fuels and nuclear power require fuels that often need to be imported, such as oil from Russia and Uranium from Kazakhstan. For the renewables there is no fuel. The exception is biofuels; However, the fuel can normally be produced in the same country as the power plant is based. There is a caveat here though. Often rare earth metals are used in the construction of certain renewables, such as neodymium used in some wind turbines, which do have to be imported [160-162].

Public perception: Unlike nuclear power the renewables have a glowing public image. In a 2019 Gallup poll 49% of Americans supported the use of nuclear energy as a way of producing electricity with 49% also opposing it. In a further Gallup poll, 60% of Americans supported proposals to reduce fossil fuel use, with 80% saying solar needed more emphasis and 70% saying wind needed more emphasis. Only 32% of people polled said nuclear should receive more emphasis, with 35% saying it needed less emphasis. The negative view some segments of the public have of nuclear power is a hurdle to increasing its prevalence in many countries. The renewables don't have this issue [163,164]

5.5. Issues with renewables

limited suitable geographic locations: Almost all of the renewables have location requirements to be economical and efficient enough to compete with fossil fuels. For example wave, tidal and offshore wind cannot be used in landlocked nations and tidal only works in areas with specific costal features. Average solar flux, average wind speed, position, height and direction are all important factors in how effective many of the renewables will be and how much ecological damage they may cause. Solar is most effective when south facing and wind kills more birds if it is high up and near migration routes [31,165]. These requirements for location significantly limit where the renewables can be placed. Compounding the issue is the fact that many of the suitable locations are far from the cities where the electricity is needed the most. This means that more energy is lost during transmission to the consumer.

Extremely low energy density: (See table 2) In a meta-analysis of 54 studies, the average power density of different electricity sources was determined [166]. This is done by taking the average amount of power supplied to the grid and dividing it by the amount of land taken up by the installation.

The energy density of the renewables ranges from 0.08 W_e/m^2 to 6.63 W_e/m^2 compared to 240.8 W_e/m^2 for nuclear and 135.1-482.1 W_e/m^2 for fossil fuels. This means renewables take up a lot more space for the same level of electricity production [166]. The same trend is found across several estimates [167-169]

The average European uses around 125kWh/d and it is double that for Americans. Purposefully generous estimates by the late David Mackay put the spacial requirements for the renewables into context [31].

Covering 75% of Britain with biofuels, placing wind turbines on the windiest 10% of the land and offshore across an area twice the size of Wales, generating the maximum tidal and hydroelectric power possible, having wave machines along 50% of the Atlantic coast and solar panels on all south facing roofs, only generates 114.5 kWh/d per person. However, the estimate for solar farms is significantly better with 5%

land coverage generating 50 kWh/d per person. Geothermal power isn't viable in the UK for electricity production in many if any areas, but we can use geothermal heating to reduce the electricity requirements. In comparison, he estimates that 55 fission reactors covering 0.02% of Britain's land could generate as much as 22 kWh/d per person [31].

Realistic estimates of the maximum amount of energy that can be produced from the renewables are much lower. The realistic estimate from David Mackay, as well as the estimates from the IEE and the Tyndall centre range between 15 and 27 kWh/d per person [31].

Visual and noise pollution: Renewables such as wind, solar and wave sometimes receive push back from local communities for being ugly and/or noisy. This is a minor issue compared to climate change; However, public acceptance and support is important in getting permission for projects to go ahead. This is especially true for onshore wind energy and makes getting permission to build new installations more difficult [170,171].

Land use competition: Most of the renewables require large amounts of space. Some of these renewables have to compete with other uses for the land and still be economical. This is mainly an issue for biofuels, where the crops grown for electricity production could alternatively be grown for consumption. If the amount of biofuels used increases significantly and climate change leads to reductions in crop production, it may be difficult to grow both sufficient biofuels and food in many countries. This issue can be somewhat mitigated for wind and solar where they can both be placed on the same land together making the land use more efficient. Alternatively wind turbines can be placed on farms without significant impacts on the productivity. This provides energy, money for the farmer and is an efficient use of the land [31,172,173].

5.6. Other considerations

Life span: Coal plants have an operational lifetime of between 40 and 60 years and natural gas plants generally have lifespans of around 20-25 years [174-176]. Nuclear is normally built with an intended lifespan of 40 years but this is commonly extended to 60 years. It is believed many fission plants could have their lifespan safely extended to 80 years or maybe even beyond. Some reactors in America have already had their operating licences extended to 80 years [177-179]. The lifespan of the renewables are generally less than those of fission and coal. They are, however, more in line with or beat that of natural gas. The lifetimes are expected to be: wind (20 years), Solar PV (25-40 years) and biomass (20-30 years) [180-182]. For geothermal the underground infrastructure normally lasts longer than the heat pumps at around 25-50 years compared to 20+ years [183]. On the other hand the longest life span of any power production method is hydropower which has been proven to last for 50-100 years [184].

Trend following capability and reliability: The fossil fuels can quickly alter their power output to follow demand. This is not true for solar, wind or wave power which can only alter their power output by being turned on or off. Available wave power varies significantly over time, however, it is much more predictable then wind or solar power and even increases in winter when energy demand is at its highest. Wind and solar aren't as reliable and don't work a large amount of the time. The times of highest demand also may not coincide with when they are available. For example the higher energy usage in winter coincides with solar producing less energy [185-187].

This is not the case for Geothermal, hydroelectric or to a lesser extent tidal, which can all be fairly easily ramped up or down to meet changing demand and aren't impacted as much by changing conditions. Tidal levels alter from one day to the next and hydroelectric dams can run out of water in a drought but generally they are very reliable and predictable. Biofuels can be ramped up or down to follow trends. However, they aren't as reliable since bad weather and climate change can reduce crop yield, leading to less biofuels for electricity production [186,187].

Capacity factor: (See table 2). The capacity factor is the ratio of the amount of energy actually generated to the maximum potential energy output of a power installation. In 2020 in the USA, solar (PV) had a capacity factor of 24.9% and solar thermal had a capacity factor of 20.5%. These are both less than a half that of natural gas (56.6%) with solar thermal closer to a 1/3rd and both are only a little over half that of coal (40.2%). Wind is also quite low at 35.4%. The other renewables however are much more competitive or even beat the fossil fuels on this metric with hydropower achieving 41.5%, Biomass getting 58.4% for wood and 63.2% for other biomass and geothermal getting 74.3%. Tidal and wave are not in use in many places currently and there are none generating power in the USA. One thing to note is that even the renewables with the highest capacity factors are a lot lower than nuclear at 92.5%, with solar coming in at around a quarter of that. This is due to nuclear not being dependent on the weather conditions as well as a requiring a high capacity factor to be economical [23,24].

Water usage: The average water usage of wind and solar PV are less than for any other energy source (43 and 330 L/MWh respectively). The fossil fuels (598 to 3220), nuclear (2290) and geothermal (1022) all have comparable water usage. The most water use by far comes from hydroelectric (4961) and especially biomass power (85100). The estimates for the litres of water used varies wildly, but wind and solar PV being the lowest and hydropower and biomass being the highest is consistent [187-189].

Hydroelectric:

Energy storage: Pumped storage hydropower is when excess energy, produced on the grid, is used to pump water up to a hydroelectric dam located at a high elevation. This water can then be used to generate electricity, through the dams turbines, at a later time when it is needed. As of 2017 97% of the total installed energy storage capacity worldwide was hydroelectric [190].

Flood risk: In 1975 the Chinese Banqiao dam failed, leading to the deaths of between 86,000 and 230,000 people. To prevent similar disasters in the future, locals have to be relocated when a new dam is built, or dams have to be built in areas where no humans live. South Koreas' reservoir-less "peace dam" is designed specifically to prevent a catastrophic flood from occurring if the North Korean Imnam dam is accidentally or purposefully destroyed. There were fears of this occurring during the 1988 Seoul Olympic games, and in 2009 North Korea did release a flood that killed six people in South Korea. If a dam fails it will release huge amounts of water, flooding the local area, killing large amounts of flora and fauna and devastating the local ecosystems [191-193].

Wave and tidal:

Unproven: Wave and tidal power are both relatively unproven technologies. Despite this, they are both expected to make a significant contribution to the future of energy production, due to their immense potential. The UK has around 50% of the total European tidal resource and it is predicted that wave and tidal power could supply as much as 20% of the UKs electricity. However, they both currently have very few operating generators, most of which are relatively small. They are significantly behind more established renewables and will, therefore, not make much of a contribution to global energy production in the near future. They are also more likely to run into unexpected operating issues, such as Wave Energy Converters (WECs) not holding up well in storms, as well as cost and construction time overruns, due to the limited experience constructing and operating them [194,195].

Expensive: Wave energy has an estimated LCOE of between \$0.30/kWh and \$0.55/kWh however prices are expected to drop over time to around \$0.165/kWh by 2030

Tidal energy has an estimated LCOE of between \$0.20/kWh and \$0.45/kWh however prices are expected to drop over time to around 0.11/kWh by 2030.

Comparing these to onshore wind at a LCOE of \$0.039/kWh or hydroelectricity at a LCOE of \$0.044/kWh, tidal and especially wave are not cost competitive even at their 2030 prices. The costs will drop over time, but they will be relatively expensive power generation methods for the near future [155].

Geothermal:

Earthquakes: Geothermal energy can trigger earthquakes. This comes as a result of the digging and also pumping water into the ground [196].

Local cooling: Ground heat is replenished slowly in most areas, from radioactive decay and heat from the mantle. Extracting large amounts of heat from an area could overtime lead to some cooling, lowering the efficiency of the power generation. If done with a small enough / responsibly sized geothermal system this won't actually be an issue [31,197,198].

Biofuels:

Can be used in current engine designs: Some biofuels can be used in current engines and fossil fuel infrastructure, such as pipelines, with little modification. This means that some of the current infrastructure can be modified, rather than being built from scratch, which reduces the costs. In Great Britain over the last few months E10 (contains up to 10% renewable ethanol) petrol replaced the majority of E5 petrol that was previously used [199,200].

Can be made from a variety of sources: crops, manure, waste from crops and algae can all be used to produce biofuels. This diversity means that if one of the biofuel sources is lacking one year, such as due to a drought, the others can be used instead. This reduces the risk of severe reductions to biofuel supply, however, it doesn't eliminate it.

5.7. Solving the reliability issue

One of the major issues with the renewables is the reliability. This is less of an issue if we have a truly diverse energy mix, making use of all of the renewables in tandem. This means that if one renewable is out of action, such as solar at night, then there isn't as large a drop in power production and the other renewables can compensate. If renewables are to become a significant majority or the entirety of our electricity generating capacity, then a diverse portfolio will be of paramount importance.

Energy storage: We will also need to invest heavily in energy storage methods. Hydroelectric dams are able to store energy by pumping water uphill, ready for times of low electricity generation or high demand. However, a lot of countries have limited capacity for hydroelectric dams. Additionally, the amount of energy storage needs to be sufficient for extended periods of low generation, which may last for many hours or several days. This requires a huge amount of energy storage. There are multiple ways to store this energy. Batteries such as lithium-ion and flow batteries, pumped storage, compressed air storage, liquid air storage, fly wheels, hydrogen, gravity storage, collective storage and thermal storage, could all potentially be used to store some of the energy generated. The discharge rates, costs, lifetimes and energy densities vary between different energy storage methods, so a mix will likely be required. The disposal of energy storage technology is also an issue to consider, especially with lithium-ion batteries. Most of the researchers I spoke to envisioned hydrogen playing a key role in the future of energy storage and / or transport. In 2017 there was around 4.67 TWh of energy storage worldwide. To double the amount of renewables in the energy mix, above 2017 levels, the amount of energy storage would have to triple [190].

Hydroelectric dams with pumped storage are likely to play a significant part of global energy storage. It is a mature technology that has been widely implemented already. It is likely to be scaled up, but in a lot of countries such as the UK, it has a significantly limited potential due to the lack of suitable locations. As of 2017 97% of total installed storage capacity was hydroelectric. One IRENA pathway suggested that for the doubling of renewables from 2017 to 2030, the share of hydropower storage would drop to around 45-51%. It is likely that battery storage, especially lithium ion batteries, will make up a lot of the short term increase. It is also likely that flow batteries and hydrogen will be significant players in energy storage long term [190].

Grid interconnectivity / super grid: A super grid could reduce the reliability issues, boost the diversity of power generation and reducing the issues with space constraints experienced by renewables. This is where the electrical grids of many countries are joined together into a much larger "super" grid. This allows for excess electricity to be sent from one country to another. This is useful since the wind may not always blow that strongly in one country, but it will be blowing somewhere. It will be incredibly important if wind and solar end up supplying the majority of the power in our longer term renewable energy generation, as they are both intermittent. If they were both at low output at the same time, then an individual countries power generation would plummet. A super grid creates a huge energy reserve and allows for significant energy diversification. This reduces the requirement for energy storage and the need to curtail generation when supply exceeds demand. Instead the energy can be sold to nearby countries. This will likely lead to reduced electricity costs and boost the economies of renewable resource rich countries. This isn’t actually that radical of an idea. The UK is already connected to energy grids in the Netherlands and France. In 2020, Norway, France, Germany and several other European countries exported significantly more energy than they imported. The idea of a super grid is to generate this exportable energy from low carbon sources and then transporting it using a massive grid system comprising of lots of individual countries grids joined together. The exporting of renewable energy to other countries can be a large economic boost to resource rich countries, whilst also helping to mitigate climate change [201-204].

There are significant technical and political challenges to overcome here. Building a super grid spanning scores of countries, entire continents, or even multiple continents, is expensive and requires a lot of materials and labour. Power losses need to be minimised, which means a super grid would likely need to run on high voltages and direct current, which raises the upfront construction cost. These costs and the construction will fall to countries, who will all need to agree on them for the super grid to be constructed. This is certainly possible but may be difficult to negotiate. Also, protectionism may hamper this idea somewhat, with certain groups and countries worried that a super grid may undercut prices or jobs in their own electricity network. If the political, economical and technical challenges can be overcome, then a super grid would be one of the best methods of improving renewables uptake and eliminating the renewables issues [201-204].

5.8. Renewable’s role in the climate crisis

Renewables are a cornerstone of any carbon neutral electricity plan. Existing reliability issues can be mitigated by a diverse portfolio, coupled with increased energy storage and increased grid interconnectivity. They are low carbon, low polluting and able to be rapidly expanded to replace fossil fuel power stations. This allows for them to offer a majority share of electricity generation worldwide, in both the short and long term. Unlike fusion power or hybrid reactors, renewable technology is already mature, and systems are commercially available. A number of companies have experience in their construction and their costs are steadily decreasing over time. The majority are economically competitive already and some, such as wind, can be the cheapest energy source available. They can be constructed relatively quickly and with less risk of significant time or cost overruns. This means a rapid expansion in terms of installed capacity is more easily achieved than for fission reactors, which we have less recent experience building, are more expensive and take a long time to construct.

The technology of the renewables and associated energy storage is constantly maturing or evolving, and it is likely that this will continue. The energy storage issues need to be overcome as a massive and rapid expansion is needed alongside the renewables. This is a difficult task but feasible.

6. Energy efficiency

A major decarbonisation method that should be considered, is not a way to replace the fossil fuels and high carbon energy sources, but instead to reduce electricity usage. Increasing energy efficiency may just be the single most effective way of decarbonising our energy supply.

Households are responsible for around 72% of the world’s total greenhouse gas emissions [205]. From 2005 to 2018 the energy consumed per household in the UK dropped by around 27% [206]. In this same time electricity generation dropped by 16% which is equivalent to the power output from 2.5 Hinkley point C fission power plants [207] (The Hinkley point C is planned to produce around 25TWh of electricity per year) [206]. This is actually a 24% drop in electricity per person, when considering the 10% population growth during the same time period. This means the electricity saved, primarily via energy efficiency increases, from 2005 generation levels scaled up to the current population, is the equivalent of 4 Hinkley Point C plants [207].

Investing in cost effective energy efficiency improvements, could lead to a 25% reduction in energy usage by 2035. This is the output from six Hinkley point C power stations. With improving technology and the costs of negative externalities of energy production included, it should be possible to halve the energy demand of UK homes in a cost effective way [206].

The final part to consider is that of externalities. Burning fossil fuels produces large amounts of pollution and greenhouse gasses. This causes around 5 million premature deaths and 147 million years of healthy life loss each year. It also leads to climate change, which is an existential threat to human existence, and also destroys ecosystems and biodiversity. These healthcare and climate change impacts are also normally paid for, not by fossil fuel companies, but by taxpayers. Nuclear may not have these issues, but it does produce nuclear waste which if improperly contained, can impact nearby ecosystems. Nuclear accidents, while rare, can cause large numbers of premature deaths, illnesses and contaminate environments making them unsafe for humans. The renewables don't produce significant quantities of greenhouse gas and large scale catastrophic accidents are extremely unlikely for most (but not all) of them. They do however, produce some waste and greenhouse gasses during production, they have to be disposed of eventually, biofuels produce pollution and most of the renewables have significant or even devastating impacts on local ecosystems (see below). Cutting energy usage via increased efficiency means less electricity needs to be generated, which reduces these externalities. This benefits the health of people, reduces impacts on local biodiversity and reduces cost on taxpayers [12]. The reductions in energy usage over time have drastically cut CO_2 emissions. From 1988 to 2019, energy efficiency improvements have been several times more effective at cutting CO_2 levels than the reductions caused by the significant expansion of the renewables [208].

7. Externalities, Job creation and Biodiversity risk

Some mixture of the renewables, fission and energy efficiency improvements will be necessary to achieve the vital, near term decarbonisation of electricity generation.

We, however, cannot view their impacts through the lens of climate change alone. The impacts on communities, individuals and the environment are also important to consider.

7.1. Externalities

An externality is essentially a side effect that isn't accounted for in the normal economics used to discuss something, and impacts others who aren't directly involved. These can be positive or negative. A positive externality for electricity would be higher life expectancies and improved healthcare of those with access to electricity compared to those without. There are, however, significant negative externalities relating to energy and electricity [12].

If the costs caused by local air pollution in developed countries were included, the price of coal would be significantly higher, likely by a factor of two or three [12]. On top of this is the impacts of climate change, premature deaths, health complications, accidents and ecological devastation, are all negative externalities caused by electricity production and usage. They all impact the general population either directly, such as by health impacts, or indirectly, such as via increasing taxes to pay for accidents or healthcare. Air pollution removes a total of 147 million years of healthy life and kills around 4.9 million people every year [12]. This is nearly four times as many deaths as are caused by road traffic crashes each year worldwide [209]. In fact it is estimated that the use of nuclear power saved 1.8 million lives between 1971 and 2009, since unlike the fossil fuels it doesn't release lots of pollution [210]. Pollution raises the risk of strokes, heart attacks, irregular heart rhythms, dementia and can cause asthma [211,212].

7.2. Job creation

Renewable energy provides more jobs per GWh, in comparison to fossil fuels, with some estimates saying several times as many [187]. The job-years per GWh for coal, gas, and carbon capture with storage are roughly 0.11, 0.11 and 0.18 respectively [213] (another estimate has jobs/GWh 0.12,0.15,0.18) [214]. Nuclear has around 0.14 job-years per GWh which is in line with that of fossil fuel power stations however the estimates for nuclear varied a lot more than for the renewables and fossil fuels. Wind creates the least jobs out of the renewables at 0.17 beaten by Biomass, solar thermal, geothermal and small hydro (0.21,0.23,0.25,0.27 respectively). Energy efficiency and Solar PV dominate however with 0.38 and 0.87 job-years per GWh respectively [213]. Another estimate had the average for renewables being 0.65 jobs/GWh and the renewables and energy efficiency combined as 0.8 jobs/GWh [214]. One source has fossil fuels beating nuclear, onshore wind, large hydro, and tidal barrages with nuclear beating the last two in job-years/GWh [215]. All other renewables handily beat fossil fuels and nuclear with the exception of lignite which is more competitive job wise. These estimates varied from one source to another, but the trends largely hold with renewables creating more jobs than fossil fuels per GWh and nuclear creating a similar amount of jobs as fossil fuels. This is in part due to job losses in areas such as mining, such as those due to automation, over recent decades along with a high requirement for installers and technicians for renewable energy [216].

The other important aspect to consider though is that the average pay of jobs in nuclear power is significantly higher than that of renewables and fossil fuels. In the US, the average wage of those working in nuclear power is \$39.19 per hour. This is higher than natural gas (\$30.33), coal (\$28.69) and oil (\$26.59). The renewables, energy efficiency and energy storage don't compete well here. Hydropower is the most competitive at (\$26.97) just beating oil but wind and solar are \$25.95 and \$24.48 respectively, energy efficiency jobs pay \$24.44 and energy storage \$24.36. These are well below that of nuclear, however, they are all above the national median wage of \$19.14 [217].

It is clear that a shift to the renewables and improved energy efficiency will create a lot more jobs than fission and the fossil fuels, however, the average wage is significantly lower, especially compared to fission. This means that a switch to the renewables away from fossil fuels and nuclear power would increase employment in the energy sector but would also decrease the average wage.

7.3. Biodiversity risk

A transition to renewable energy could have a massive impact on biodiversity. The construction of renewable energy plants or turbines along with necessary infrastructure such as roads can devastate local wildlife [218]. The construction can also release greenhouse gasses and pollution and the disposal can equally cause issues. The land usage per GWh of the renewables, is massively bigger than that of other energy sources like fission, sometimes being several hundred times bigger. This means the impact of the renewables is generally felt over a wider area. Solar panels and many turbines, such as wind turbines, contain rare and toxic metals such as chromium or neodymium. The mining and disposing of these metals can cause leakage into the local water supply, harming or killing local wildlife. The mining can also produce greenhouse gasses. Additionally, China controls the vast majority of this rare earth metal mining. This makes it difficult to guarantee energy independence from China, and that the metals are extracted in an environmentally sound way.

Wind and Solar: Solar farms can impact the ambient temperature of their surroundings and along with the use of herbicides and dust suppressants can harm local wildlife populations severely. Concentrated solar has a large water usage which can, in areas of low water availability, cause issues for nearby species that rely on that water [218].

One often touted issue with wind power is that the blades kill birds and bats. Even worse than this, some bats can die from barotrauma. This is where the pressure changes near a wind turbine causes lung damage and internal bleeding [165,219]. Solar panels also kill birds either through collision or by immolation. The number of avian deaths associated with solar are less than that of wind [220].

While the number of bird deaths are incredibly high with 20,000 birds killed by wind farms in 2009 it pales in comparison to the 330000 from nuclear plants and the 14 million from fossil fuel power stations, in that same year. Cats, transmission lines, hunting, vehicles and windows also all kill millions of birds a year. In fact per GWh of electricity per year nuclear kills around 1.5 times (0.42) as many birds and fossil fuel power stations kill around 19 times (5.18) as many birds as wind power (0.27) [165]. This is caused by collisions, climate change and pollution. A 2015 study on the death rates of birds, in the US, from utility scale solar facilities, found that the deaths per gigawatt per year were between 0.0027 and 0.099. This same study found wind to have a death rate of 0.011 which is a lot less than the previous study but it is done with fewer data points so is likely to be less representative overall. However, it is still useful to see that solar has a lower avian death rate than wind. This means that the previous argument, that fossil fuels and nuclear are more deadly to birds, also holds for solar [221].

The other side of this is the type of birds and bats killed. Due to the locations that wind turbines are placed, the birds and bats that die are fairly frequently rare and endangered. This can further impact their already limited numbers and lead to a higher risk of extinction [165,218,222]. A review of 31 studies found that around 78% of the birds that were killed by wind farms were protected songbirds [165]. Lots of rare birds such as endangered raptors are killed every year, putting them at a more severe risk of extinction. Large and unagile birds, as well as those which are slow to reproduce, are the most at risk [165,218,222].

Deaths from wind turbines can be reduced by locating turbines away from migration routes, turning them off at high risk or low visibility times and altering the turbines themselves, such as reducing the rotor speed (the energy loss can be made up by using longer blades which has a minor impact on avian death rates) [165,218]. The survival rates of tortoises around wind turbines are, in some cases, higher than those in nearby near wilderness areas [223].

Hydro: To set up a hydroelectric dam, a river must be dammed. This cuts the water off from some downstream areas, often killing large amounts of the natural ecosystem, as well as flooding and destroying other areas upstream. This fragments populations and decimates natural habitats. The water quality is also diminished by hydroelectric dams. Many fish populations get severely damaged by hydro dams, especially if they aren't able to return to their breeding sites. To avoid this issue, some dams have a "ladder" built that allows the fish to travel up and return to their breeding sites, but their effectiveness is contested. Additionally, the turbines themselves can kill fish that pass through. Hydroelectric dams also produce more greenhouse gasses than most other renewables since in flooded areas the plants will often die and decompose, releasing carbon dioxide and methane [218].

Biofuels: Massive amounts of land are regularly cleared away to give space for biofuels which destroys a huge number of habitats and significantly harms biodiversity. It also often produces a large carbon debt that needs to be paid off. It takes decades for trees to grow to maturity, often over 50 years. In a boreal forest it takes around 70-120 years for a group of replanted trees to grow to maturity. The carbon debt estimates from cutting down a forest vary significantly with one source I found saying 44-104 years depending on forest types and another stating 190-340 years for specifically boreal forests [224,225]. Even if it was the lowest possible option of 44 years it is still a significant issue that makes tree based biofuels next to pointless in terms of mitigating climate change in the short term. The trees that are replanted (such as pine trees) are normally worse at absorbing CO_2 than the forests they replace. All of this makes biofuels fairly carbon intensive.

Biofuels derived from plants often require pesticides unless they are genetically modified to be pest resistant. These pesticides can get into the food chain or impact local wildlife causing significant ecological damage. Fertilisers that are used can also get into the nearby waters and kill wildlife. The pollution produced when burning the fuels also has a large and negative impact on the survival of local species. The crops used are also often invasive species that can spread and compete with native flora. Biofuel crops are commonly monocultures, as this can be more cost effective than crop rotation or crop diversity, however, it depletes the soil of nutrients, reduces the biodiversity of wildlife, and puts the plants at a higher risk of pests or disease wiping out the entire crop. Good examples are sugar cane and palm oil plantations which replace massive areas of wildlands with monocultures [218].

Geothermal: Resources are often located in areas which are high in biodiversity or are around protected areas. The drilling and subsequent seismic activity leads to the emission of greenhouse gasses, pollutants and other elements from the ground. Pollutants such as hydrogen sulphide and boric acid can have major impacts on local wildlife. Geothermal power stations can also cause arsenic to leak into local water supplies. On top of this heat released to the surroundings and the noise from geothermal activity can impact local animal populations [218].

Wave and tidal: We have had relatively few years of operator experience worldwide with wave or tidal, so our evidence of the biodiversity and ecosystem damage is limited. However, they are expected to have significant impacts on local wildlife. They are expected to damage habitats on the seabed and effect the movement and feeding of marine animals and sea birds. They produce some chemical, electromagnetic and noise pollution, all of which could harm local marine life. On top of this the turbines can kill fish and other marine life that tries to pass through [218].

Technology advancements, altered operating conditions and conservation policy requirements could all help mitigate the biodiversity impacts of a transition to the renewables. Fish friendly turbines, turbine speeds requirements and acoustic damping devices could all be used to reduce the impact of turbines on local species. For biofuels the use of crop species that maintain biodiversity and habitats is required, along with crop rotation. Use of monocultures, fertilisers, pesticides and potential invasive crop species should be limited or eliminated due to their damage to wildlife. Carbon capture technology and pollution controls must be used alongside biofuels. The prevention of pollution and greenhouse gas leaks from geothermal activity is also necessary for it to be environmentally sound. The use of no go fishing and marine activity zones around wave and tidal generators could potentially help protect the wildlife in already impacted areas. The use of floating installations or specific depths for wave, tidal and offshore wind may also help reduce their biodiversity impacts. Location choice is also of vital importance to conservation. Wave, tidal and offshore wind should be placed to minimise damage to the seafloor, habitats and marine life. Growing biofuel crops on already poor biodiversity land may actually improve the overall biodiversity. This should be done wherever possible, rather than destroying habitats in more diverse locations such as grasslands or forests. The use of ecotourism could also help bolster biodiversity and conservation efforts in more attractive areas, mainly around geothermal plants and potentially hydroelectric dams, if done responsibly [218].

Nuclear fission also has significant biodiversity impacts. Nuclear fission can pollute and reduce the local water quality as well as changing the waters temperature. The mining of uranium can also lead to uranium run off into local water and the release of greenhouse gasses. If nuclear waste is improperly stored or a nuclear accident occurs, then massive and long term damage can be done to wildlife over a huge area [226,227].

Empirical comparisons between the renewables and nuclears impact on biodiversity are very thin on the ground. Those that are out there often leave out key information in their analysis, such as the widely contested paper by Brook and Bradshaw. In it they conclude that nuclear is the lowest impact energy source. This empiricism however leaves out important considerations like water usage and water pollution which are major issues for nuclear powers biodiversity impact [228].

It is important to note however that the greatest threat to biodiversity is severe climate change and hence the use of low carbon energy sources is a necessity for protecting biodiversity.

8. Negative energy technology

The last thing to consider is if the electricity supply can be not only carbon neutral, but carbon negative. Limiting the amount of CO_2 being released going forward is necessary, but it may not be enough to avoid or mitigate the devastating effects of climate change. The IPCC and IEA both predict that we will need to reabsorb and sequester carbon dioxide that is already in the atmosphere to avoid 1.5ºC global warming [1,229]. Afforestation, reforestation and the expansion of plant life in the oceans is undoubtedly going to play a part, and it is likely that increasing carbon content in soil, such as by the use of biochar, will also play a role. Despite this, negative energy technologies will be required to make a significant enough negative carbon contribution.

Direct air capture (DAC): This is where either air passes through chemical solutions which removes the CO_2, or it binds to a solid sorbent filter and can then be removed and stored. Direct air capture requires little land and water and can be placed close to where the carbon is being stored or used, which reduces transport cost and carbon footprint. This can be powered by any low carbon source of energy, however, one that outputs heat would be the most efficient for solid air capture, where the filters need to be heated to release the CO_2 before it can be captured. If the carbon is being sequestered it has to first be condensed under high pressure, which raises the energy usage and cost. By pairing low/zero carbon electricity plants with carbon capture the overall emissions of the electricity production could become negative rather than just very low or zero [230,231]. The cost of DAC is around $200-600 per tonne of carbon [232]. In contrast it costs $5-50 per tonne for afforestation and reforestation [1]. As of 2020, there were 15 direct air capture plants globally [231].

Bioenergy with carbon capture and storage (BECCS): One negative carbon technology involves coupling carbon capture with biofuel plants. Most biofuels are produced from plants which absorb CO_2

as they grow. These plants or the fuels made from them, such as bioethanol, can then be burned to produce electricity. This process is carbon neutral so long as it is done sustainably and sensibly as previously described. If it is paired with carbon capture technology then some of the CO_2 can be captured and sequestered underground or used. If it is stored underground then the process is carbon negative, so long as the extra carbon released from activities, such as transporting the biofuels, is less than that captured and stored. The main benefit of BECCS is that we are likely to be using some level of bioenergy anyway and adding the carbon capture technology, potentially makes it carbon negative not just low carbon [232,233]. BECCS should be more economical than direct air capture due to the higher concentration of CO_2 present. The cost of BECCS is around $100-200 per tonne of carbon [1].

There have been suggestions by some researchers that BECCS won't actually be carbon negative and will be detrimental, due to the removal of forests. One researcher I spoke to suggested that BECCS could become a significant part of power production, while another said that BECCS is "a scam". BECCS needs to be very carefully researched and regulated to ensure it is sustainable and ecologically sound.

The carbon captured from either method can be used in the production of chemicals, fuels, construction materials or stored underground. There are also innovative emerging applications for the carbon, such as using it to produce fish food. These applications can make the use of negative carbon technologies more economically feasible. However, most of them would result in the carbon being rereleased at a later time, making them carbon neutral not carbon negative. This would still be better than the use of carbon intensive alternatives. The sequestering of carbon underground would remove the carbon from the atmosphere long term and will be required to some degree [231].

9. Policy

9.1. Jobs: As seen in section 7.2. the transition to renewable energy and higher energy efficiency will create more jobs than are lost. It is, however, irrefutable that some jobs will be lost during the elimination of carbon intensive electricity. These will be replaced by jobs with different skill sets and required training. Those who are put out of work by the decarbonisation of electricity may not easily switch into a job in low carbon electricity. The average wage is also lower for energy efficiency and renewable energy jobs, so even those who do transition over successfully will likely end up with a pay cut.

I am writing this a few days after the UK prime minister Boris Johnson stirred up controversy and condemnation, for saying that the closing of the UK coalmines gave "a big early start" to green energy and the fight against climate change. The reason this comment drew so much ire is due to the devastation of communities by these coal mine closures. It is undeniable that those same coal mines would need to be closed during the transition from fossil fuels to green energy. However, the communities and individuals impacted should not be disregarded in a blind pursuit of decarbonisation. To prevent unnecessary damage to and push back from local communities, policies should be put in place to assist those in high carbon electricity generation, with the transition to a green economy. These would likely include provisions for paid retraining programs.

9.2. Time scales: The conceptual design work on ITER began in 1988, three years after initial discussions on constructing an international fusion facility. ITER will not be fully operational with D-T operation until 2035. That is 50 years after the initial discussions started. Additionally, the USA pulled out of ITER over the cost before later re-joining. The funding supplied by countries has altered over time as well [234,235]. As with most multiparter projects, there were arguments over funding and location and with many different countries supplying parts it has been a slow process with massive cost overruns. If there had been a concerted effort to reduce issues with regulation, disagreements were minimised and the construction had been more centralised, the process would have been a lot faster. Financial constraints have also been a problem. As was evident with the Manhattan project and the Apollo program, with a lot of money and effort a very rapid and significant leap forward in technology can occur. With so many countries involved the money to finance innovation properly can be fairly small relative to GDP or even compared to the total investment in the energy market. As businesses get more involved in fusion research, bringing in additional capital, it is likely that fusion advancements will accelerate rapidly. Policies need to be implemented and funding given to accelerate the time scales of emerging technologies that can help decarbonise electricity production. A timeline like that of ITER cannot be allowed to happen again going forward if we are to avoid the most severe impacts of climate change.

9.3. Electricity: In research conducted by the University of Sussex participants were generally willing to make small lifestyle changes. They were, however, much more resistant to highly effective decarbonising changes, which had a significant impact on their life. Around a third of participants chose to eat more vegetarian food, but only 4% actually became fully vegetarian. Similar numbers were observed with choosing low emission cars compared to giving up their car. Participants were also much more resistant to significant alterations that weren't applied fairly to everyone [205]. This makes sense. People rarely want to make sacrifices if they feel that not everyone else is doing so. A clear example is the anger towards MPs that haven't followed the covid restrictions applied to the general public.

The issue is, that if only very few people reduce their meat intake or travel less, then the emission reduction is minimal. Voluntary reductions to carbon output won't be enough to curb the devastating impacts of climate change. A simple enough way around this is to use policies to encourage people to reduce their carbon footprint.

This could be via a carbon tax or reducing the availability of air travel or a myriad of different ways. These need to apply to the wealthy, businesses, and the government in a visibly fair way to reduce the pushback by the public [205]. Any carbon tax or similar decarbonisation incentive must not be regressive. If it is regressive, then there must be a mechanism to return money to citizens, so as to not disproportionally impact the poor ; This already occurs in places like Canada and Switzerland [236,237]. The gilets jaunes protests in France began in response to a proposed rise in fuel prices [238]. This kind of backlash needs to be limited through appropriate and fair economic measures. The affordability of energy for the poor and preventing fuel poverty needs to be a high priority.

Any economic incentive to decarbonise, needs to be sufficient to meet at most 2ºC of global warming. The IMF suggests $75 per tonne (about $83 per ton) as the global average carbon tax [239]. The IEA suggests a carbon tax of $75-100 per ton by 2030 increasing to $125-145 per tonne by 2040 [240]. Most countries either don't have a carbon tax or have one this is woefully shy of what is necessary. Poland and the Ukraine for example have carbon tax rates of around $0.11 and $0.44 respectively [241]. Some countries are much better, such as Sweden at around $119.

Australia introduced a carbon tax in 2012 and emissions dropped substantially, until it was repealed in 2014. After it was repealed, they began to rise again. It is estimated that if the carbon tax wasn't repealed, then the 2020 carbon emissions would be 25 million tonnes lower. The price of electricity dropped slightly after the tax was repealed but then increased back above the price during the carbon tax within 2 years. After 3 years the costs were 14% higher than during the carbon tax [242].

In 2017, global subsidies for fossil fuels were around $5.2 trillion. This money needs to be put into the research and expansion of low carbon electricity and associated technology instead. The IMF estimated in 2019, that efficient fossil fuel pricing from 2015 would have lowered global carbon dioxide emissions by 28% and deaths from fossil fuel air pollution by 46% [243]. In a survey of experts, the median estimate for when climate change will begin negatively impacting the economy was 2025, 41% said that it already is [244].

There are significant issues that need to be overcome if we are decarbonise our electricity supply. Policies and regulation need to be reviewed and altered if necessary. A full policy review should take place, not just slight tweaks. Several of the academics I spoke to stated receiving planning permission was a major hurdle to the rapid implementation of renewable projects. This was especially true for onshore wind, where public pushback can often be greater and gaining approval harder.

Governments must also be willing to give grants and subsidies to the renewables, fission and fusion, if they are needed. Nuclear fission is not economically competitive in most countries currently, and this reduces private investment. It is, however, necessary for fission to remain a part of our energy supply for several decades at least and likely be expanded upon. I expect fission to still play a role into the 2100s. Wave and tidal are also economically uncompetitive currently and it is imperative that they become a significant part of our energy supply long term. This means they need governmental assistance.

Research needs to be funded properly in fusion, wave, tidal, negative carbon technology and energy storage. I also think that funding should be allocated to research for fast reactors or hybrids, SMR and Gen IV fission reactors. They all could or will play a part in the next stages of our electricity supply and research must be funded properly to ensure that they are available in time to avoid catastrophic climate change.

Policies also need to be implemented to deal with the pricing of negative energy technology and energy storage. These technologies haven't been widely implemented globally but are required for the long-term sustainability of electricity production. They need to be priced in such a way to be economically viable and this will likely involve subsidies or similar economic measures such as grants, tax credits and public procurement of CO_2 offsets.

Regulation around emerging technologies also needs to be planned. For example, fusion is inherently safer than fission and produces a lot less and easier to contain waste. Fusion reactors can be set up safely near to population centres and the high-grade heat can be used in industry or heating businesses and homes. Regulating it in the same way as fission would damage its economic viability and hold back progress.

Policies need to be implemented that encourage cooperation and rapid advancement. For example, the renewables are in in competition with each other. An innovation in one technology may not be shared with the rest. This reduces the overall rate of progress and improvement of the renewables. There needs to be some way to incentivise collaboration between the renewable companies rather than competition.

Climate change is an issue of an unprecedented scale, that will need to be solved over several successive governments and across the entire planet. Protectionism and political myopia cannot be allowed to jeopardise our decarbonisation efforts. Electricity policy should be handled by an independent department of energy guided by the facts, to prevent political opportunists or climate deniers from exploiting energy production for their own interests. The issue of climate change is a global one, but the main driver has been the developed world. Developing nations will take the brunt of climate change impacts and it is imperative that the developed world assists poorer countries to decarbonise. International cooperation irrespective of political leanings is of the upmost importance.

On top of this there is a colossal policy and technical challenge that needs to be solved. This is the task of organising, funding and operating a super grid. While connecting as many countries as possible would be the best solution, I think it is more likely that the interconnection will occur between groups of closely aligned countries only, the EU for example. This reduces the policy, regulation and technical challenges somewhat, however, agreeing on who will pay for the construction of the infrastructure, how pricing between countries works and how to balance the grid effectively is still incredibly difficult. If it is done between countries across continents and outside of economic unions this challenge is even bigger. It is not insurmountable; several countries have already been connected so there is somewhat of a framework for how to potentially operate and price a super grid.

Policies need to be put in place to prevent further damage caused by fossil fuels. Many countries, including the UK, are still building new fossil fuel power plants, building new oil fields or mining more coal. The UK government is considering a new oil field which would release so much carbon dioxide (roughly 132 million tonnes) that it would take trees being planted in an area the size of England to remove. Oxfam reports that at least 1.6 billion hectares of new forest would need to be planted (five times the size of India and more than all farmland in the world) to remove enough carbon emissions to reach net 0 by 2050 [245]. This isn't to say that trees aren't a brilliant carbon sink. In fact, stopping deforestation, restoring and improving forestry practices could remove as much CO_2 as 1.5 billion cars (7 billion metric tonnes) [246]. This shows though how much damage we have done to our forests and how much avoidable CO_2 we can prevent from being released by stopping the use of fossil fuels as fast as possible.

Another area of policy that is needed is in the protection of biodiversity. Global cooperation over protecting flora and fauna has been ongoing for decades, with mixed success. However, the rate of extinctions we are already seeing from climate change and the biodiversity risks of building massive amounts of new renewables, requires international cooperation on a scale never before seen. On top of this, policies need to be in place to ensure that the most ecologically sound technology is used whenever possible. Fish friendly turbines, fish ladders and low turbine speeds can all help protect fish for example. It is imperative that as much as is possible is done to prevent catastrophic biodiversity loss, especially since it is unlikely to fully recover from the damage we have already done.

10. Conclusion

Electricity production causes a significant release of carbon dioxide and is a major driver of climate change. It will take a concerted effort by scientist, politicians, businesses and the general public to avoid the calamitous effects of severe climate change. This will require technological advancements, significant policy overhauls and global cooperation.

Realistically wave and tidal power won't be economically competitive or widespread for the next two decades or more. Nuclear fusion electricity generation will also not be feasible until the latter half of this century. The generation IV fission plants and hybrid reactors also won't be constructed on a large scale for decades.

A rapid and severe cut to carbon dioxide emissions needs to occur during the time span before some of these technologies become more widely available. In fact to avoid the cataclysmic impact of climate change, we will likely need electricity generation to be either carbon neutral or preferably carbon negative by the advent of commercial nuclear fusion reactors.

After evaluating the different sources of energy, reading countless reports and having meetings with experts about the renewables, fission, fusion and energy efficiency, I have come to a conclusion on how best to alter our energy systems in the next 100 years.

Energy efficiency: This has to be an integral piece of the puzzle. Energy efficiency increases will likely be the most rapid way to reduce carbon dioxide emissions, whilst also not causing major negative externalities. A concerted effort is needed to improve energy efficiency as rapidly as is possible.

Renewables: A significant expansion of the renewables is also going to be required to stand a chance of getting our energy production to be carbon neutral. In my opinion, the renewables will most likely be the majority generator in the electricity supply, in both the short and long term. However, it is of paramount importance that we get significant diversity of renewable supply to help minimise the reliability issues. Further research should be done on wave and tidal and their potential for later implementation. Research must also be done to limit the ecological damage caused by the renewables to preserve as much biodiversity as possible, as we transition to a carbon neutral society. I think that onshore and especially offshore wind, solar, wave and tidal are likely to, and rightly so, play a large part in our future electricity production. I do think that significant funding and research is needed to try and move away from the use of rare and toxic metals, as much as possible. I have more reservations in regard to hydroelectricity and geothermal, but I still think they are important. Geothermal activity causes earthquakes and releases greenhouse gasses and pollutants. Great care is needed to try and prevent them from causing ecological damage through the release of these pollutants. Hydroelectric dams can cause biodiversity loss by blocking rivers and can cause massive ecological devastation if they fail. Both, however, supply power reliably and have much lower CO_2 emissions and deaths compared to the fossil fuels. Hydroelectric dams can also be used for significant energy storage.

I am somewhat cynical when it comes to biofuels. History has shown repeatedly that when profits are involved, careful restraint and long term sustainability normally go out of the window. Biofuels could theoretically be carbon neutral, benefit biodiversity and be a reliable source of energy, that can follow trends in energy demand. My worry is that it could also be highly polluting, unsustainable, water intensive, devastate biodiversity and create a huge carbon debt. It comes down to how it is managed. Are crops that maximise biodiversity grown on previously low biodiversity land, in a sustainable way, or is a monoculture of an invasive crop, that absorbs little CO_2, grown on previously lush and verdant land with no crop rotation, steadily removing the nutrients from the soil until the same is done again in the next place leaving the land barren. Biofuels need to be regulated to ensure that they are done sustainably, in a way that limits biodiversity loss. If there is not significant oversight, profit margins will likely be placed first and I think biofuels will do a lot more harm than good overall.

Energy storage: To go alongside the expansion of the renewables energy storage capability needs to expand massively. I think this will be mainly hydroelectric and battery storage at least early on, however, other storage techniques such as thermal storage, collective storage and hydrogen should be researched further and may ultimately be pivoted towards in the long term.

Grid interconnectivity: A super grid will be vital to a sustainable carbon neutral energy supply. Without it, some countries can become carbon neutral, however, it is unlikely that the entire world can. A super grid or at least significant international grid interconnectivity, mitigates renewable's reliability issues, allows for greater diversity in the electricity supply, reduces requirements for battery storage and reduces the issue of renewables large land requirements. It also allows for countries which are less politically stable or have insufficient infrastructure to build, maintain, operate and decommission fission plants, to instead import the energy into already their existing grids. For a renewable dominated energy supply, significant grid interconnectivity is going to be required.

Fission: Nuclear fission is likely a necessary but short term solution to decarbonisation. The renewables don't have a strong baseload capability and wont until energy storage and grid connections are improved significantly and more reliable renewables like hydro and geothermal are expanded. This means the base load needs to come from another source with fission being the best option in the short term. Currently running reactors should not be decommissioned, where safe to do so, and any plants being constructed now should be completed.

A standardised fission reactor, most likely a PWR, should play a part in the next stage of our energy production. This standardisation should make the economics more favourable and allow for a more rapid expansion of nuclear fission. This expansion should be limited to countries that are politically stable and agree to non-nuclear proliferation. This is obviously difficult to achieve in reality, but fission savvy countries should only supply fission technology or expertise to these stable and non-proliferating countries. There should also be international oversight to try and prevent the spread of nuclear power becoming the spread of nuclear weapons. There also needs to be oversight on waste management to ensure it is safely stored or disposed of.

This all relies on a rapid approval and construction of new plants starting as soon as is feasible which is possible using an existing design that has previously been safety checked and had public enquiries to reduce the risk for extensive alterations and push back, but it is still a massive undertaking requiring cooperation between countries. Fission power could be used as a baseload supply for countries without fission plants given good enough grid interconnectivity. Small modular reactors, fast reactor technology and other generation IV reactors should be researched further and funded as a potential solution to the waste management issue and longer-term energy production, especially if fusion power takes longer to roll out than planned. It should, at least in the early days of fusion, be used for tritium production to reduce the technical requirements of fusion somewhat.

In the longer term, as energy storage and grid interconnectivity reduces the renewables reliability issues and Fusion power becomes available, fission reactors should stop being built. This is with the potential exception of fast reactors if they become the best solution to the nuclear fission waste management issue. Fission could potentially be a longer term solution, but it runs too many risks in terms of proliferation and waste for me to suggest committing to it long term if there is an alternative. I think there will still be significant fission in the energy mix by 2100.

Fusion: I think it is technically feasible for the renewables alone to eventually meet the needs of the energy supply. However, this would require gargantuan energy storage, significant grid interconnectivity and technical advances. It could also exacerbate the issues of the renewables, such as the risk of blackouts due to not having a stable baseload supply. It would also likely mean we depend more heavily on the most reliable renewables, which are often the most ecologically damaging. I think nuclear fusion is needed in the energy mix.

Magnetic confinement fusion research should be continued while a mixture of the renewables, fission and energy efficiency decarbonise the electricity supply. I don't think it is likely that inertial confinement fusion will play any part in electricity production. Fusion should begin being implemented as soon as possible (likely around 2060-2070) and steadily expanded upon, taking over the base load generation from fission as it is phased out. This is since fusion should have a lot of the benefits of fission, such as high energy density and reliability, but doesn’t produce the same waste or proliferation risk. To allow this to happen as fast as is possible the supply chain needs to be start being developed now.

This won’t be to decarbonise, but instead to allow for a more sustainable energy supply long term, with less issues than a fully renewable or a renewable / fission mix. I think it is unlikely that our initial carbon neutral electricity supply will be long term sustainable, especially if electricity demand increases due to population growth, technological advances, industrialisation and direct air capture usage. Fusion as a baseload supply with a majority renewable generation is likely the sustainable long-term solution we need. A significant amount of fusion power would lesson issues with the renewables such as the huge land requirements and difficulty providing a baseload supply. Fusion will also be used to supply heat for cement production, desalination and potentially hydrogen production.

Hybrid reactors are worth researching for burning nuclear waste, however, I don’t think they are likely to be used widely for breeding nuclear fuel or the production of electricity.

Negative Carbon Technology: To avoid catastrophic climate change, it is imperative that we remove carbon dioxide from the atmosphere, not just reduce how much we emit. In reality our long term goal should be to reduce the amount of CO_2 in the atmosphere back to pre-industrial levels, to reduce the frequency and severity of extreme weather events and other climate change related issues. This requires research and investment into both bioenergy with carbon capture and storage and direct air capture as well as more conventional means like reforestation. Research into other potential methods of carbon sequestering should also be researched and funded. I am sceptical about BECCS realistic impact though. I think DAC is likely to play a significant role, however, biofuels have significant associated issues, which make them the least attractive potentially low carbon energy source, in my opinion. Adding carbon capture technology to biofuels improves them but it doesn’t inherently make them a good choice as many of the other issues remain. Another consideration is the percentage of carbon that needs to be captured for it to be carbon negative. Carbon capture isn’t 100% efficient. It may be that BECCS becomes invaluable as carbon capture technology improves over time. I am sceptical however.

Policy, subsidies and global cooperation: Much of this relies heavily on political will, funding and subsidies. It is likely that fission will need significant subsidies in the short term, at least until supply chains and expertise are built back up to the levels they were once at and improved further. Some of the renewables may also need subsidies, however, they are now generally quite cost competitive. Energy efficiency improvements require laws, regulation and enforcement to ensure rapid progress. Funding will also be required to reduce energy losses, such as improving insulation in houses, to reduce heat losses and therefore energy usage. Energy storage methods will need to have significant research funding and the less economical renewables will still need to be constructed. This is to increase diversity of supply and limit reliability issues. Fusion research as well as that of wave, tidal and negative carbon technology, will need to be funded properly to allow for their later, rapid, implementation. Grid interconnectivity will have to improve drastically with countries agreeing on who has to pay for and construct the new infrastructure. There may also be additional difficulties due to animosity between certain countries and poorer countries having worse grid infrastructure currently that makes connecting countries together more difficult.

Some of this funding and work will come from private businesses however a significant amount will have to come from governments investing in the future. It is also important that policies are implemented to protect wildlife and biodiversity during the decarbonisation of our energy supply especially on biofuels.

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