Dispelling misconceptions of nuclear energy technology: How Generation IV nuclear reactors could become the key to achieving the 2015 Paris Climate Agreement

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ABSTRACT

Climate change is a consequence of the release of carbon dioxide (CO_2) from non-natural sources, the largest contributor being the combustion of fossil fuels to produce electrical energy. Since the 1960's, nuclear energy has been reliably produced on a large-scale with near net-zero CO_2 emissions. The expansion of nuclear energy to tackle climate change is seen as a necessary pillar to meet the Paris Agreement signed in December 2015. However, widespread dissemination of misconceptions and misinformation about nuclear energy has chronically damaged the industry, leading to an erosion of public confidence in the energy source. Dispelling these misconceptions will therefore be integral to reinvigorating the industry's image, and as such I will focus on the three most important misconceptions in this article. These are the downturn in the United Kingdom (UK) nuclear industry market, the limited lifetime of the global uranium supply, and the production of plutonium becoming a significant proliferation risk. Generation IV nuclear reactors have been in development over the last 20 years, and these reactors provide credible solutions to the supply issues surrounding uranium. They will also reduce the production of nuclear waste, proliferation and most importantly of CO_2 emissions. As of 2017, the UK Government has released policy papers and committed to investments that will establish a path to build these Generation IV nuclear reactors in Great Britain.

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I. INTRODUCTION

The Intergovernmental Panel on Climate Change 2013 [1] reports with 95% certainty that humans are the cause of recent climate change, a conclusion with which 97.1% of scientific papers published on climate change agree [2]. CO_2 levels rose with the global temperature after the ice ages [3], as shown in Figure 1. From the 1850s, the industrial revolution and modern era produced nearly twice the levels of CO_2. The difference in temperature, in comparison to that from 150 years ago, strongly suggests that human-activity is warming the globe, again shown in Figure 1. This is fundamental scientific evidence for the role of human activities in causing climate change [4, 5, 6].

How can we mitigate this rise in CO_2? Energy production is by far the largest contributor to CO_2 emissions through the burning of coal, oil and natural gas [7]. Replacing these large-scale energy production methods with a near net-zero CO_2 emitting energy source is therefore one clear answer.

Wind and solar energy are considered major alternative energy source candidates, however, an often misunderstood large-scale, reliable, and near net-zero CO_2 emission energy source is nuclear fission. The need for a "green" energy source will become increasingly important with time as consumption of energy will only increase, regardless of the efficiency savings, with the rapid expansion of electrified rail, vehicles and steel industry. Electrical vehicles consumption alone will increase from 0.03% in 2014 to 9.5% in 2050 [8].

The expansion of Nuclear Energy to tackle climate change is seen as a key stepping-stone to meet the Paris Agreement signed in December 2015, but its success will require increased governmental and public support. This claim echoes statements made by the International Energy Agency [9], Bill Gates [10], the Intergovernmental Panel on Climate Change [6], and the MIT Energy Initiative [11].

As nuclear power has been known to be a reliable, large-scale and safe energy source since the 1960s, why then do we not embrace nuclear energy and expand it greatly to curb climate change?

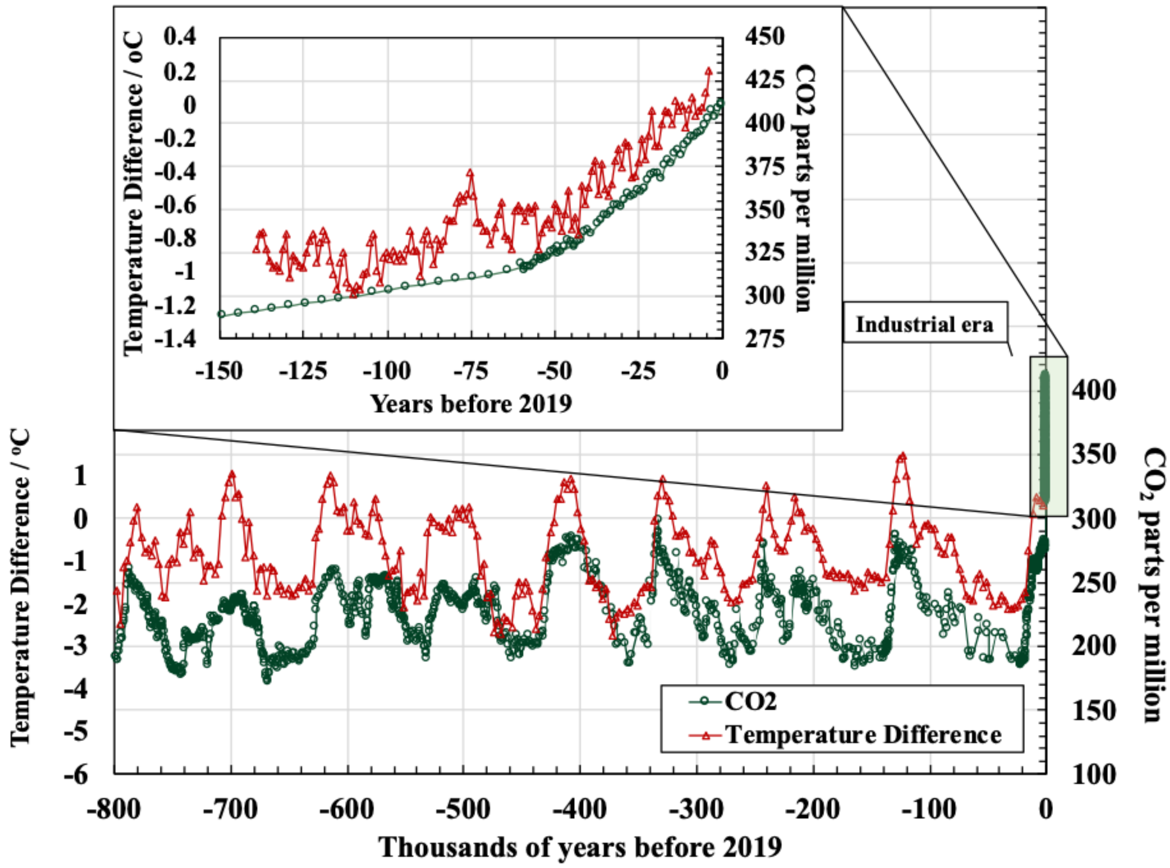


Figure 1: The measurements of carbon dioxide and temperature difference are achieved by monitoring the concentrations of various trapped gases in Antarctica's

ice[1]. The data has been compiled from Vostok and EPIC Dome C ice cores. See reference [4] and [5] for the original raw data. From the last 150 years, it is clear from the trend in CO_2 parts per million that the release as a result of the industrial revolution and modern era. The plotted temperature difference in the atmosphere correlates with the increase in CO_2 emissions.

One reason is the dissemination of misinformation by the media leading to ill-informed policy makers and politicians. Examples include claims that the United Kingdom's (UK) nuclear power industry is slowly dying [12], the uranium fuel supply can only last another 100 years [13] and nuclear reactors are fundamentally a proliferation hazard from the plutonium they produce [14].

Producing scientifically accurate accounts of nuclear energy is therefore imperative in combating the spread of misinformation to the general public, which will in turn lead to increased governmental support for the Nuclear Industry.

The main objective of this article is, therefore, to present an account of the nuclear sector from a scientific perspective, drawing on the author's personal experience of working within the nuclear energy sector. This article will evaluate whether the nuclear power industry is shrinking in the UK, the lifetime of the global supply of uranium, and if weaponisation is the only viable use of plutonium.

II. THE UK'S NUCLEAR INDUSTRY IS SHRINKING

[1] The measurement of CO_2 is a direct measurement of the gas concentration trapped in the ice. The temperature difference measurement is an indirect measurement, based on the ratio of deuterium (isotope of hydrogen) and oxygen-18 (isotope of oxygen) to today's value (see reference [39] for further detail). The reference value is the natural ratio of deuterium found in nature.

There were 448 operational nuclear power stations that produce a total capacity of 392 Giga Watt electrical (GW(e)) output, as of 31 December 2017, and an additional 59 units which will produce 60 GW(e) are under construction. The total contribution to the world's electricity supply is therefore 10%. Further, a conservative estimate from a recent 2018 International Atomic Energy Agency (IAEA) report on world energy [15] estimates an increase to 511 GW(e) by 2030 and to 748 GW(e) by 2050.

The IAEA report assumes that current market, technology and resource trends will continue with no changes made to current laws and regulations. The misconception that the market is shrinking loosely follows the low estimates determined by the IAEA's report. The fact that the industry has not changed significantly since the 1960-1980 rapid construction phase, during which most of these 448 operational reactors were built, does reinforce this misconception.

The UK newest nuclear reactor in construction at Hinkley Point C, England, is using pressurised water reactor technology that has evolved over the decades. This reactor design, called EPR by EDF Energy, has optimised the use of water to cool and moderate a nuclear fission chain reaction. However, the suspension [16, 17] of the Advanced Boiling Water Reactor (ABWR) nuclear power station in January 2019 at the Wylfa site, does not bode well for the UK industry; it had received regulatory approval [18], and Horizon Nuclear Power and Hitachi-GE Nuclear Energy Ltd. were ready to begin construction. It should be noted that the suspension is related to the project's financing and not on a technology or engineering basis.

The suspension has forced the UK Government to reassess its financing model of new nuclear power stations. It is clear from both Hinkley Point C and Wylfa that allowing the free-market to fund a full nuclear power station is not ideal as it would be too great of an expense for a single corporation [19].

This sentiment was echoed by the Secretary of the Department of Business, Energy and Industrial Strategy (BEIS), the Rt Hon Greg Clark MP [20], in an oral statement to parliament where he acknowledged that the current financing model is non-optimal, stating that the government "[…] are therefore reviewing the viability of a Regulated Asset Base (RAB) model and assessing whether it can offer value for money for consumers and taxpayers. I can confirm to the House that we intend to publish our assessment of this method by the summer at the latest."

The RAB model [21] ultimately mitigates the construction risk of projects by enabling investors to receive returns before the project has been completed. If the model was applied to Hinkley Point C nuclear power station, the project could be up to 20% cheaper [22]. This change in the Government's approach might allow the Wylfa project to continue once the announcement is made this summer. The RAB model could be applied to EDF Energy's future reactor at Sizewell C, China Nuclear Systems Ltd's HPR1000 reactor at Bradwell C, and the Moorside site in Cumbria, enabling a strong industry for the long-term future.

If we look to the next 20-50 years, Generation IV nuclear reactor designs have been positioned as 'advanced[2]', passive, safe, proliferation resistant, fuel efficient, and economically favourable nuclear reactors compared to the in-construction Generation III (EPR, ABWR and HPR1000 reactors, for example). The 'Generation' definition for

[2] The term advanced does not actually mean anything tangible unless context is provided. The current Advanced Gas Reactors that are operating in the UK since the 1970s are 'advanced'.

nuclear reactors is shown in Figure 2. However up until 2017, the UK Government has not officially announced any formal involvement with Generation IV reactor designs.

The Clean Growth Strategy was announced by BEIS in October 2017 [23] and outlines the policy to decarbonise all sectors of the UK economy through the 2020s. Specifically for the nuclear sector, the policy released £460 million to support future nuclear fuels, new manufacturing techniques, reprocessing, and advanced reactor design[3]. In addition, the aims of the Nuclear Sector Deal [24], which was launched on 28 June 2018, are to reduce the cost of nuclear technology by 30%, increase the percentage of women in the nuclear industry to 40%, and investing a total of £2 billion in domestic and foreign supply chain contracts by 2030. Further, the Deal shows an interest in Small Modular Reactors (SMR), which are an existing nuclear power station type but are on a smaller scale (300MW(e)), as well as showing an interesting in the funding for Generation IV nuclear reactors (called Advanced Modular Reactors (AMR) within the policy).

The investment released by the Government has ignited the nuclear industry to innovate and move towards the SMR and AMR markets; these markets are in their infancy and, if action is taken quickly enough, the UK could become an epicentre of advanced nuclear technology. Further, the Nuclear Innovation and Research Advisory Board released their 2019 review [25] and recommend the UK Government should invest £1 billion from 2021 to 2026 into the advanced reactor market to meet the Clean Growth Strategy.

[3] Advanced in this context is referencing Generation IV nuclear reactors.

Today's nuclear export market (shown in Figure 3) is dominated by Russia's Rosatom[4] [26], and soon-to-be China's 'go global' policy[5] [27], both of which use their exports as a strengthening mechanisms to grow their spheres of influence. There is potential that the UK could become a significant nuclear export country again with the export of SMR and AMR reactors from the 2030s and beyond. If the UK is to become a nuclear exporter, the overarching message is that investment and policy changes need to continue to enable large-scale production[6] [25] of SMRs and Generation IV nuclear.

So, is the UK nuclear industry shrinking? From the re-evaluation of the financial models to the funding of new nuclear reactors, as well as for the UK's potential to become an advanced nuclear export country, the UK's industry is very much alive.

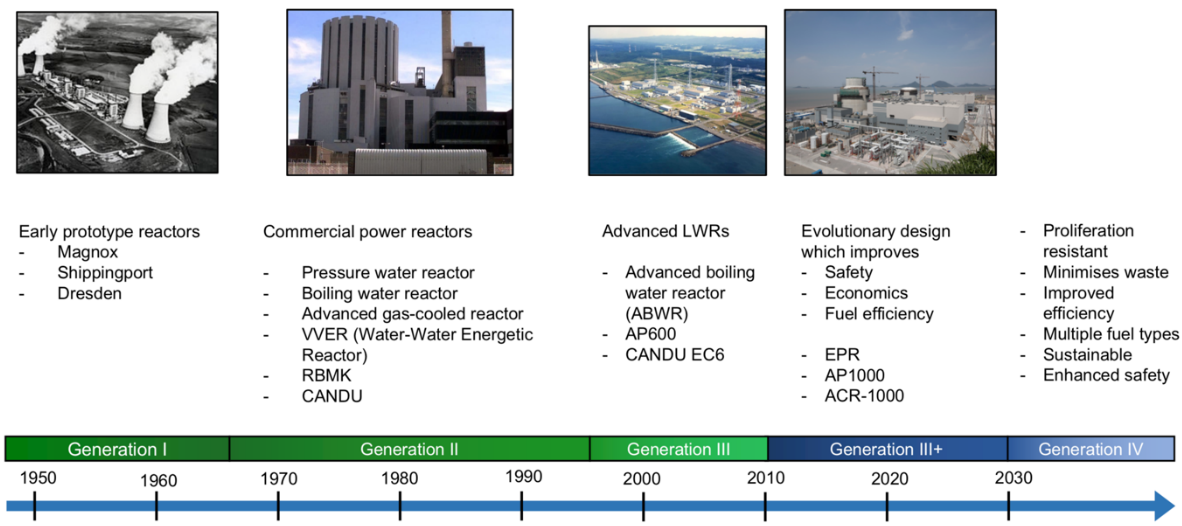
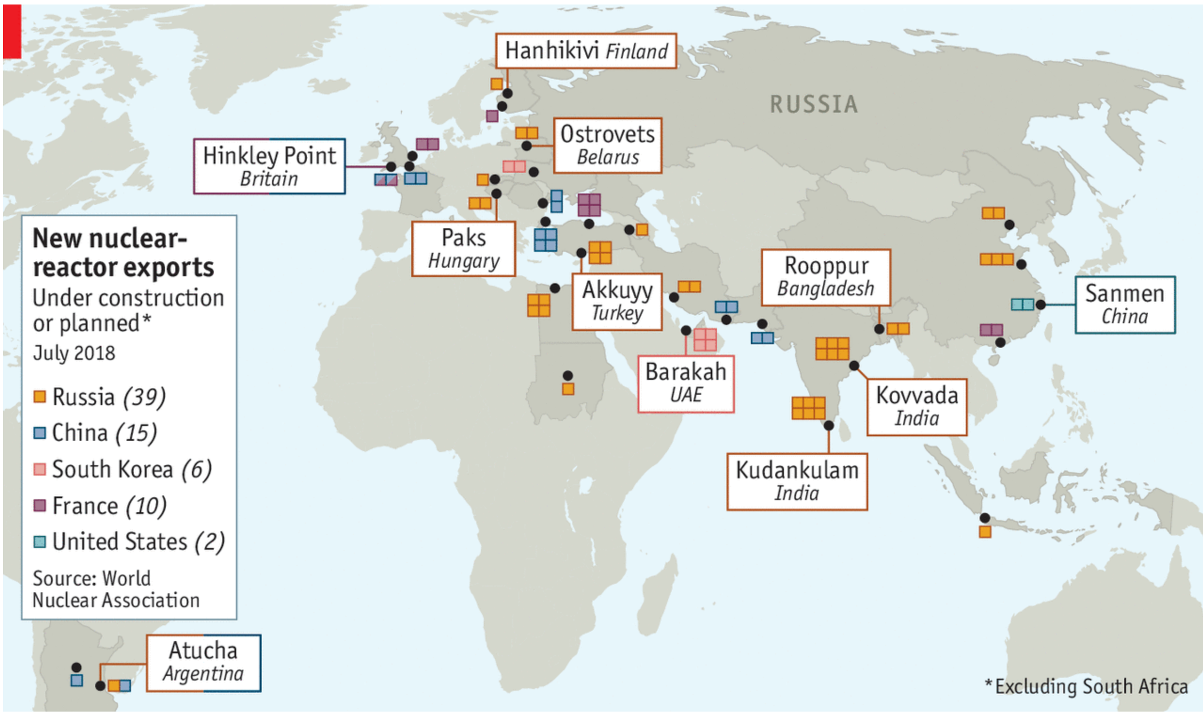


Figure 2: Timeline of the Generation definition for nuclear reactors. (Light Water Reactor (LWR).)

[4] Rosatom is the Russia Federation's state-owned and state-operated nuclear energy corporation.
[5] China National Nuclear Corporation, China General Nuclear Power Group and State Nuclear Power Technology Corporation are the three main communist party-controlled and communist party-led nuclear export corporations.
[6] Large-scale production is defined as more than four nuclear reactors or more.



The Economist

Figure 3: Current (2018) new nuclear reactor exports coloured by country. Figure reproduced from reference [28].

III. THE LIFETIME OF URANIUM

Issues surrounding the lifetime of uranium for nuclear reactors (and weapons) have been raised ever since the energy security issues were realised during the 1970s oil crisis [29]. It is worth noting that during this oil crisis, the French government decided to reduce the country's dependence on oil by producing 72.3% of their electricity through nuclear energy [30]. Climate change was not discussed at the time however their decision has been quite fortuitous; France's CO_2 emission per GDP was less than half of the OECD average in 2014 [31]. This is not surprising when recent analysis (2013) show that nuclear energy reduces the long-term CO_2 emissions [17].

Globally, the total identified recoverable uranium is 6,142,000 tonnes of low-cost uranium metal [29] and 7,988,000 tonnes of high-cost uranium metal. There are two naturally[7] occurring isotopes[8] of uranium; uranium-235 and uranium-237, possessing a relative natural abundance of 0.720% and 99.244% respectively. Generation I-III (1960s to 2030s) nuclear reactors primarily use Uranium-235 although it must first be enriched[9] to maintain a sustainable chain reaction for power production. The assumption made in the IAEA report [29] is that current global nuclear fleet maintains these operating conditions, with no new advanced nuclear reactors deployed, resulting in a 130 year supply of uranium-235.

There are six Generation IV nuclear reactors in consideration, four of which have a 'fast[10]' neutron energy spectrum. Splitting uranium (also called nuclear fission) produces sub-atomic neutrons with a spectrum of energy, with slow[11] neutrons only being able to split uranium-235, not uranium-238. Generation I-III reactors are only able to split uranium-235 because the neutrons are slowed down by either water or graphite (reactor design dependent) and can therefore only utilise 0.720% of the natural uranium supply. Generation IV reactors have neutron energies that range from slow to fast, thus increase the likelihood of fission. The neutrons have enough energy to produce plutonium-239,240,241, and an appreciable fission fraction of heavier transuranic atoms (neptunium, americium, and protactinium) from uranium-238.

The key message is that Generation IV nuclear reactors can theoretically utilise the entire supply of naturally occurring uranium, as fission of both uranium-235 and

[7] Natural references the element can be naturally found on the Earth.
[8] Isotope is the name given to atoms of the same chemical element which have different atomic masses.
[9] Increasing the abundance of uranium-235 to 3-4%.
[10] Fast indicates the neutrons have an energy between 0.5 MeV to 2 MeV.
[11] Slow (or also called Thermal) neutrons have an energy in the range of 0.025 eV.

uranium-238 is possible, leading to a significantly longer supply lifetime than that estimated by the IAEA [29].

If we neglect the assumption that no new Generation IV nuclear reactors will be built, then the natural uranium supply lifetime (T) will be a ratio of potential Generation IV utilisation to the Generation I-III utilisation. While Generation IV reactors could theoretically utilise 100% of the natural uranium, they are limited to an utilisation range between 43.2%-57.6% [32], by engineering, design, economic and fuel cladding material lifetime restrictions [33].

$$\frac{\mathrm{T}}{130\ \text{years}} = \frac{43.2\ \text{to}\ 57.6\ \%}{0.720\%}$$

$$\mathrm{T} = 130\ \text{years} \times \frac{43.2\ \text{to}\ 57.6\ \%}{0.72\%} = \mathbf{7{,}800\ to\ 10{,}400\ years}$$

It can be argued, however, that the future of the uranium supply should not be of a concern to the human race because in a few hundred years, a more optimum energy source such as nuclear fusion energy will have been developed [11].

IV. THE ONLY USE OF PLUTONIUM IS AS A WEAPON.

It is often believed that the plutonium produced from the transmutation[12] of uranium-238 in operating reactors can only be used for nuclear weapons. However, there are two different categorisations of Plutonium containing mixtures, depending on the mixture's composition:

[12] The nuclear process that converts one chemical isotope into another chemical isotope.

i) Weapons-grade plutonium: plutonium-239 with less than 8% plutonium-240. It is not produced in civil operating reactors in the UK because the desire for these reactors are to produce electricity, so the fuel irradiation time is longer[13].

ii) Reactor-grade plutonium: 55-70% plutonium-239 with more than 19% plutonium-240. This grade is produced in all civil operating reactors and comprises about 1% of all used fuel.

Reprocessing is the name given for the extraction of plutonium from spent fuel rods[14]. Sellafield, the nuclear fuel reprocessing, decommissioning site, and home to our nuclear waste, in Cumbria, England, has the world's largest civil stockpile (126 tonnes of plutonium) [34].

Reactor-grade plutonium cannot be weaponised, however, it can be used as fuel for a fast neutron spectrum-based reactor, such as Generation IV nuclear reactors. As explained in Section III, the fast neutron spectrum is able to fission plutonium-239 and -240. This fact enables companies, such as GE-Hitachi in 2011, to propose a Generation IV reactor to be built in the UK that solely uses the plutonium stockpile as reactor' fuel. The reactor, called PRISM, could dispose all of the UK's plutonium stockpile through the generation of 25% of the UK's electricity for the next 100 years [35, 36]. With the recent UK Government's announcement and investment in Generation IV nuclear reactors outlined in Section II, the reality of reducing and removing the plutonium stockpile in Sellafield is therefore within reach.

[13] The longer the irradiation time, the more chance you will convert artificially produced plutonium-239 to plutonium-240 through neutron capture physics process.
[14] Once the fuel rod in a nuclear reactor has been permanently pulled out from the core, it is now classified as spent fuel.

V. CONCLUSION

Climate change is occurring due to the release of CO_2 from non-naturally occurring sources, primarily due to energy production. Nuclear energy is reliable, safe, large-scale, and produces near net-zero CO_2 emissions offering a means of both satisfying the world's energy demands and a method to mitigate climate change.

In order to achieve this ambition, the public perception of nuclear energy requires improvement, through recognition of the existence and viability of sound scientific and technical options to solve the current challenges facing the industry.

Generation IV nuclear reactor technology can provide tangible solutions to reducing nuclear waste through plutonium fuel usage, extend the uranium supply lifetime up to 10,000 years, and revive the nuclear industry. The UK Government has produced multiple policy papers that outline the appetite to develop Generation IV nuclear reactors in the UK; a promising sign.

The future is very bright for the global nuclear industry, research community and energy markets because of the long-term potential of nuclear fusion energy, in addition to the construction and planning required for current reactors, in addition to the Generation IV reactors of the future. Ultimately, Generation IV reactor technology can become a means through which the aims of the Paris Climate Agreement can be met, leading to a large-scale reduction in climate change.

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