The greenhouse gas emissions of nuclear energy – life cycle assessment of a European Pressurised Reactor

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Abstract

Nuclear energy contributes ~10% of the global electricity generation and different views exist on its carbon-intensity and sustainability. Context is crucial to determine the sustainability of new nuclear power generators, making the existence of a global answer to the unresolved question unlikely. This study aims to establish the life-cycle greenhouse gas emissions associated with nuclear energy in Europe given ongoing construction of nuclear generators. Due to the high uncertainty and complexity that characterise construction and operation of nuclear generators, we adopt a multi-method, scenario-based approach. The three methods used are: process-based, input-output, and hybrid life cycle assessment. Scenarios account for different total energy outputs over the life cycle of the nuclear generator, different end of life options, and different sectoral allocations of costs in the input-output calculus. Results for the process-based, input-output, and hybrid methods range between 16.55—17.69, 18.82—35.15, and 24.61—32.74 gCO_2e/kWh, respectively. These are either well above or at the upper end of the range of possibilities (5 to 22 gCO_2e/kWh) stated in a report for the UK's Committee on Climate Change, and significantly higher than the median value of 12 gCO_2e/kWh presented by the Intergovernmental Panel on Climate Change. They are also higher than the values acknowledged by the nuclear industry. Given the severe potential lock-in effects of today's energy choices for future generations, this research questions the role of nuclear energy to meet the UN Sustainable Development Goals and calls for further scrutiny on its sustainability and environmental viability.

Keywords: life cycle assessment (LCA); nuclear power generators; sustainable and renewable energy; electricity; input-output; hybrid LCA.

Nomenclature

AEI – Average energy intensity (method)
EPC – Engineering, procurement and construction
EPR – European Pressurized Reactor
GHG – Greenhouse gas
HLCA – Hybrid life cycle assessment
HPC – Hinkley Point C
IO – Input-output (analysis)
LCA – Life cycle assessment
LCI – Life cycle inventory
LWR – Light water reactor
MRIO – Multi-regional input-output
PA – Process-based analysis
WNA – World Nuclear Association.

Subscripts 'e' and 'th' in energy and power units refer to electricity and primary energy respectively.

1. Introduction

Energy is fundamental to human existence and the world's energy demand is set to rise [1]. SARS-CoV-2, the virus which caused a global pandemic that brought the world to a standstill, changed existing projections for energy demand in 2020 with current forecasts suggesting an overall reduction [2]. Yet, energy demand generally rebounds after global shocks and catastrophic events [3] and it is likely that its upward trajectory before the pandemic will therefore resume. In normal circumstances, nuclear energy contributes about 10% to global electricity generation and is classified by the International Energy Agency (IEA) as a low-carbon energy source [2].

Some controversy and confusion exist over the impact of new nuclear power projects in terms of embodied[1] and whole-life carbon emissions, with questions surrounding methodology, data sources, long-term availability of uranium ore in good concentrations, and selection of non-nuclear comparator projects. Furthermore, the increasing complexity of nuclear projects extends construction programmes, ensuring a significant delay before the embodied carbon invested can be repaid through greenhouse gas (GHG) emission reductions during the operational phase. This is an increasingly urgent point as the widely acknowledged climate emergency means that investing carbon emissions now to garner future savings risks crossing crucial tipping points, if these savings come too late.

Some research supports the IEA view [e.g. 4,5] whereas other studies found that the carbon intensity[2] of nuclear energy is much higher than that of a low-carbon source [6]. Others conclude that nuclear energy does not reduce fossil fuel use nor does it contribute to long-term human wellbeing and sustainable development [7]. A wide range for the carbon intensity of nuclear energy can be found in the academic literature (e.g. 10 to 130 gCO_2e/kWh_e [8]), thus suggesting that no single answer holds true regardless of the context and application of nuclear generators. In addition to significant methodological variations in how carbon intensity is calculated [8], a key point is to understand what energy sources are – if any – displaced by nuclear energy [9]. This implies the need for a focused approach in researching nuclear energy, thus considering the peculiarities of the context. This is the aim of this paper. Owing to the lack of recent available studies in Europe and the ongoing construction of new nuclear plants (France, Finland, UK), we focus on the European context in general and on a particular UK case. Our research is based on life cycle assessment (LCA) and we apply all of its three main methods in our study, notably process-based, input-output, and hybrid analyses. To further strengthen the reliability of our findings, for each method we develop a set of scenarios to mitigate the uncertainty in the input data or in the publicly availability information, and to factor in both the complexity and long-term nature of building, operating, and decommissioning nuclear power plants. Using the latest available evidence and a robust multi-method approach, our work aims to inform academic research and policy debate on the environmental sustainability and viability of nuclear power in Europe.

The paper is organised as follows. The specific context of the UK is presented in Section 1.1, while Section 2 reviews previous relevant work. Section 3 details extensively and transparently methods, data, and assumptions, and it is followed by the results in Section 4. These are discussed in Section 5, while Section 6 concludes the article. A Supplementary

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[1] We use embodied carbon here as a shorthand for embodied greenhouse gas (GHG) emissions to facilitate the readability of our work

[2] Similarly, we use 'carbon intensity' here as a shorthand for mass of CO_2 or CO_2e over unit of energy output, such as gCO_2/kWh or tonne CO_2e/GWh.

Information document accompanies the article to further provide access to the full data behind our results.

1.1. The UK context

The ongoing construction by EDF of the nuclear power station in Somerset – Hinkley Point C (HPC) – is viewed by the industry as a gateway for a new generation of such projects across Europe. In addition, it is seen as a key component of a strategy to simultaneously decarbonise the electrical grid and expand its growth, as heat and transport demands are increasingly loaded onto the grid [10].
HPC will consist of a pair of EPR (European Pressurized Reactor) units of 1.6 GW_e each, meaning the plant will have a maximum output of 3.2 GW_e. EDF proposes that the performance of these reactors will exceed previous reactors, operating for 60 years at 92% of their potential, resulting in a total lifetime electrical output of 1.55 trillion kWh_e (1.55 10^{12} kWh). Furthermore, per unit of output, they will use 17% less fuel than previous reactors. Consequently, EDF reports that life cycle emissions for HPC will be very low, stating, for instance "the total lifecycle emissions of Hinkley Point C will be just 5 gCO_2e/kWh_e. The gas-fired power station equivalent is 490 gCO_2e/kWh – 98 times higher" [11].

The quoted carbon intensity of 5 gCO_2e/kWh_e is significantly lower than values calculated in most previous studies of nuclear power, and the proposed efficiency and long life of the plant are significantly higher than historic data suggests. Therefore, here we set out to provide a world first, multi-method transparent and replicable study with the aim of quantifying the likely carbon impacts and benefits of HPC as viewed through different prisms. Our aim materialises into two different objectives. Firstly, we provide an overview of how life cycle GHG emissions of nuclear power have been assessed in the literature to date; the numbers reported, the factors driving them, and how they will likely change over time. Secondly, we estimate the life cycle (i.e. cradle to grave) GHG emissions of HPC, using the three main LCA methods and publicly available information that is relevant to the plant or the wider context. In addition to the contribution that our work makes to the literature on nuclear energy, it is useful to note that the carbon-intensity of nuclear energy, is also used as input data in other studies, for instance in investigating future scenarios for building renovations [12], thus enhancing the importance of reliable and accurate numbers.

2. Previous work

In this section, previous work on life cycle GHG emissions from nuclear plants is briefly reviewed and, in some cases, adapted to the UK context or to respond to criticisms. This is not intended as a systematic review of the available literature, for which the reader is referred to studies such as the seminal work of Lenzen [8] which takes the reader through the various stages of the lifecycle (uranium mining, milling, conversion to UF_6, enrichment, and fuel fabrication; plant construction, operation and decommissioning; and the various parts of the waste cycle), and provides information on the energy intensities of each of these, or the more recent review by Gralla et al. [7].

A body of work exists with a whole life focus (i.e. cradle to grave), which shows a wide variation in the life cycle GHG emission figures. There are many reasons for this, including different scopes of assessment and different assessment methods. From a review perspective, Kadiyala et al. [13] looked at published LCAs identifying a relatively significant range of variation (6.26 to 28.2 gCO$_2$e/kWh$_e$) and Warner and Heath [14] harmonised 274 LCAs finding median life cycle GHG emissions could be 9 to 110 gCO$_2$e/kWh$_e$. Beerten et al. [15] review in the detail three of the seminal LCAs on nuclear energy, and their harmonisation shows a range of variation of 8 – 110 gCO$_2$e/kWh$_e$, concluding that the background economy plays a crucial role. Lenzen's meta-analysis [8, Table 18] shows intensities ranging from 10 to 130 gCO$_2$e/kWh$_e$ with an average of 65 gCO$_2$e/kWh$_e$. Another meta-analysis by Sovacool [16] screened 103 studies and selected 19 that met standards of recency, accessibility and transparency (but not completeness). The mean value reported is 66 gCO$_2$e/kWh$_e$ (within a much larger range of 1.4 to 288 gCO$_2$e/kWh$_e$). Reasons for the wide range, include incompleteness leading to the low value, and failure to consider the benefits of the co-products from uranium mining leading to the high value. It has also been suggested [17] that the high figure is derived from an extreme scenario that, for instance, implements enhanced uranium mine clean-up activities that are not justified by the hazards posed by the radioactivity and toxicity of the waste rock and tailings. A problem with the analysis by Sovacool [16], also noted by others [14], is that the mean values presented are skewed by outliers. The results of this analysis are presented in Table 1 but with an additional column of data representing the median values which have been extracted from the data in [16].

Table 1. Nuclear power plant life cycle GHG emissions, from [16]. Frontend and backend are the emissions associated with provision of fuel and its disposal, respectively.

	Mean gCO$_2$e/kWh	Median gCO2e/kWh
Frontend	25.1	22.3
Operation	8.2	6.8
Construction	11.6	11.9
Backend	9.2	4.9
Decommissioning	12.0	1.0
Total gCO2e/kWh$_e$	**66.1**	**46.9**

Moving from reviews to research, a recent analysis [18] compared hydro, nuclear and wind power in China, showing that wind energy causes the most environmental impact (~29 gCO$_2$e/kWh$_e$) and double that of nuclear (~12 gCO$_2$e/kWh$_e$). Another recent study in China [19] obtained even lower figures for nuclear power (6.36 gCO$_2$e/kWh$_e$). Identical numbers (6.359 gCO$_2$e/kWh$_e$) are reported in a sister study [20] with the authors openly admitting to the inclusion of cement and steel only for the construction of a nuclear power station. Very low numbers (<10 gCO$_2$e/kWh$_e$) have also been obtained by Koltun et al. [21], focusing on Australia. Other very low values have been produced by Siddiqui and Dincer [22] (3.402 gCO$_2$e/kWh$_e$) who carried out an LCA of nuclear energy in Canada. Similar results emerge also from Simons and Bauer [23] (~5 gCO$_2$e/kWh$_e$) as well as in Serp et al. [24] (2.33 - 5.29 gCO$_2$e/kWh$_e$). Interestingly, similar values (5.29 gCO$_2$e/kWh$_e$) are reported in a detailed study by Poinssot et al [25] solely for the fuel life cycle, thus casting doubt on how similar or even smaller numbers can also include materials, construction, and end of life decommissioning and disposal.

Another research, again focused on China, [26] ranked wind first and nuclear second but this time focusing on the sustainability of power generation. The sustainability focus of the study seems to be more economic than environmental, with a breakdown of the impacts on Global Warming Potential (GWP) not offered to the reader. Additionally, in the brief description of input data it seems that only transportation of construction material is considered and not their manufacture. A different picture emerges from the work of Gibon et al. [27]. Although numerical results in gCO$_2$e/kWh$_e$ are not offered, it can be seen that nuclear generation shows very high impacts on both human health and ecosystems in the climate change category.

The studies above show that a great many variables play a role in nuclear energy generation, meaning that the particular context of a power station is potentially very important. For example, the uranium enrichment method, whether gas diffusion or centrifuge, has a significant impact on electricity demand with gas diffusion being more than an order of magnitude more intensive, but with the associated investment costs being somewhat lower. The variation in GHG emissions that might be estimated from such information is even broader. For instance, if the enrichment is undertaken in France, using nuclear-generated electricity, the choice of enrichment method might not be as significant as it would be in a coal economy. This implies that nuclear power is more effective as a low-carbon option if it and its supply chain operate in an already low-carbon economy, rather than a system still heavily reliant on fossil fuels. In Lenzen's work, for instance [8, Table 18], much of the wide variation in intensities (10 to 130 gCO_2e/kWh_e) is dependent on the carbon intensity of the context in which such activities take place: the best results depended on a low-carbon economy (reliant on nuclear and renewables), and the worst resulted from using very low-grade ores in a coal-based economy.

Uranium ore quality also has a significant influence on the carbon intensity of nuclear energy: poorer quality ores require greater resources to mine, mill, convert and enrich a given quantity of uranium. The current and future significance of this is sometimes debated and sometimes neglected. However, there is some evidence that the ongoing consumption of the best uranium ores will lead to a significant increase in the carbon footprint associated with mining, milling, conversion and enrichment of uranium ore in the future [28]. Lenzen [8] tested the sensitivity of his results to ore grade and found that a move towards 0.01% shales from his baseline of 0.15% ores resulted in a 125% increase in GHG emissions per kWh, to 130 gCO_2e/kWh_e. The average grade of known ores in Australia, which has around 30% of global reserves, is given as 0.045% - which is between the baseline figure and the more pessimistic figure.

Most known uranium is found in ore of low concentrations (less than 0.1%): for example, the Olympic Dam mine in Australia has a typical ore grade of 0.03% [28]. Canadian ores are orders of magnitude more concentrated, but there is much less uranium in total. As the better ores are used up (i.e. ores with higher concentrations of uranium and/or with useful co-products like the copper, silver and gold found in the same rocks in the Olympic Dam mine), it is assumed that the industry will progress to poorer ores. With annual growth in nuclear power of 1.9%, in 50 years the world will be reliant on ores at about 0.01% purity, and lifecycle GHG emissions of nuclear power production will have risen from a current figure of 34 gCO_2e/kWh_e to a new level of 60 gCO_2e/kWh_e as a result [28]. Norgate et al. [28] estimate 'reasonably assured resources' globally at 5.3 Mt of uranium (at a grade of greater than 0.01%). The Nuclear Energy Agency [29] estimated 'reasonably assured resources' at less than $260/kgU at 4400 ktU in 2015. They also stated that a 1 GW_e reactor requires approximately 160 tU (before enrichment) per annum, on average. This value depends on capacity factor, which has risen over time (and then declined after Fukushima), and various operational parameters such as fuel cycle length and burn-up.

On this basis, the requirement for the existing global fleet of just below 400 GW_e is likely to be about 64 ktU per year. This means that, at current rates of consumption, global resources would last until nearly the end of the century. However, as modelled by Norgate et al. [28] for instance, the picture is different if growth in the nuclear power sector is assumed.

Researchers at the US National Renewable Energy Laboratory (NREL) have produced an assessment of lifecycle GHG emissions of nuclear electricity generation [14]. They looked at previous studies and harmonised them, adding or subtracting elements to ensure a common system boundary. They also adjusted to common assumptions such as a 40-year lifetime, a capacity factor of 92% and thermal efficiency of 33%, which reflect the US context. Their headline result was a median of 12 gCO_2e/kWh_e (with an inter-quartile range of 17 and full range of 110). They also carried out a scenario analysis looking at global growth of nuclear power and decreasing market-average uranium ore grade. If nuclear power takes an increasing share (4% annual growth) of the growing market for power, then GHG emissions have the potential to reach 110 gCO_2e/kWh_e by 2050. Under a 'constant share scenario', the equivalent figure is about 85 gCO_2e/kWh_e.

An important caveat is that such findings are founded on an assumption of no technological progression in, for instance, primary energy production. If a 'medium-carbon' future is modelled instead of a high-carbon one, then NREL find that emissions only reach 40 gCO_2e/kWh_e under the 4% annual growth scenario. The calculations presented by Norgate et al. [28] and by Warner and Heath [14] include warnings around the high levels of uncertainty in the extrapolation of existing trends in uranium ore discovery and extraction, and in the carbon efficiency with which it is extracted. For context, the World Nuclear Association's (WNA) 'Harmony programme' [30] proposes 1000 GW_e of new facilities by 2050 at a rate of 25 GW_e per year, rising shortly to 33 GW_e per year (equivalent to approximately 20 new EPRs per annum). It is likely that as most existing plants were constructed before 1990, there will be little left of them by 2050. If the entire fleet of approximately 400 GW_e is replaced with a new fleet of 1000 GW_e by 2050, this would represent average annual growth in available capacity of 3%. This makes the 1.9% growth assumption used in [28] appear conservative, while the 4% growth of market share used in [14] appears to be more of a stretch. Without aiming for a systematic review, in this section we have shown that there exists great variability in the carbon-intensity of nuclear energy, and that context is key to the results produced.

Ultimately, only assessments which are transparent and replicable can be trusted given the sheer complexity and scale of nuclear power plants, and the changing context during the long periods of construction, operation and decommissioning.

3. Methods and data

With such transparency and reproducibility in mind, we extensively present our methods and data in this section.

3.1 Methods

Life cycle assessment (LCA) is the most widely used methodology globally to estimate environmental impacts and repercussions of processes and products. LCA is the compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle [31]. The first studies to undertake LCA, as it is known today, date back to the late 1960s [32] but even studies on the same objects indicated significantly different results [33] and this aspect hindered both broad application and acceptance of this new tool [32]. Things improved from the 1990s onwards, and LCA started to gain momentum through growing activity in the field, scientific journal publications, and, most importantly, the first set of ISO standards which attempted to orchestrate terms, framework, and methodology [32]. Nowadays, in conducting an LCA, ISO standards 14040/44 are key starting points. However, as with any scientific field, research on the LCA methodology itself has produced a number of variants and extensions to the original LCA concept. A review of LCA in its various forms is beyond the scope of this work; the interested reader can find background knowledge for instance in [34]. What is instead important for this article is to briefly introduce the three main LCA approaches since all three have been used in this paper.

3.1.1 Process-based analysis

A process-based analysis (PA) refers to a mix of processes, products, and location-specific data to calculate and establish the environmental impacts of a product system. It generally involves very accurate data on a specific process or product, sometimes even characterised by primary data collection. For instance, Environmental Product Declarations are a good example of PA. Inevitably, the greater accuracy of data and the labour-intensive data collection imply that the system boundary of the analysis is drawn tightly around the product/process being assessed. As a consequence, additional impacts occurring upstream in the supply chain are excluded. This is called "truncation error" since upstream impacts are truncated and ignored. Truncation errors vary with sector but research has shown that they are likely to range between 40% - 70% [35].

3.1.2 Input-output analysis

Input-output (IO) analysis is an economic technique, which uses input-output tables (matrices of sector-based monetary transactions) to map resource consumption and pollutants release throughout the whole economy [36]. Input-output was developed by Russian-American economist Wassily Leontief, which earned him a Nobel Prize in Economic Sciences in 1973. IO captures inter-sectoral relationships within a national economy or a larger region and shows how outputs from one sector become inputs to other sectors. It was Leontief himself who first showed how this technique could also capture environmental repercussions of economic activities [37]. Since then, this field of research has grown steadily, particularly due to increased computing power in the last decade which allows the creation of databases mapping the world's economy [38]. Since IO inherently, in theory, captures all transactions occurring within an economy, it does not suffer from truncation error. However, it is at present impossible to capture economic activity with a granularity that represents the millions of products available to customers. For this reason, different sectors are aggregated into a larger 'umbrella' sector. A classic example is wheat and rice cultivation (which are very different) potentially aggregated in the sector 'Agriculture'. Therefore, IO analyses suffer from the so-called "aggregation error", which might over- or under-estimate specific impacts due to the use of average coefficients.

3.1.3 Hybrid analysis

Hybrid life cycle assessment (HLCA), aims to combine the strengths of the previous two by filling missing process-related information with input-output data. Simple as it may sound, this is quite labour intensive and time consuming. While there is still debate on whether HLCA is actually better than PA [39], research has shown that HLCA is likely to produce more accurate results [40]. Even if the first instances of HLCA date back to more than 20 years ago [41], the field is still in the initial phase of agreeing definitions and methods [42]. There is now growing consensus around the use of HLCA in construction and the built environment with the first databases [43] and tools [44] emerging. A detailed digression on strengths and current challenges in HLCA is beyond the scope of this work but the idea of adopting multiregional input-output (MRIO) data to produce comprehensive carbon footprints is widely agreed upon [45–47].

3.2 Assumptions and Data Gathering

Assumptions were needed in a number of areas to provide input data for our research. These are now presented in turn.

3.2.1 Lifetime Electricity Generation

As mentioned, the carbon intensity of nuclear energy can be expressed in units of gCO$_2$e/kWh$_e$. If focusing on the embodied carbon of construction, the numerator is a fixed quantity determined upon practical completion, whilst the denominator is determined by what happens afterwards (i.e. how many hours the plant operates at full power over its lifetime). Therefore, it is important to establish the total lifetime performance of the project. The two variables essential for this assessment are the number of years of operation, and the average capacity factor during that time, defined here on a net basis, i.e. as the electricity *delivered* to the grid divided by the maximum amount that would be *generated* if the plant operated continuously at 100% capacity.

Various statements have been made about the operating life of EPRs in general and HPC in particular. The EPR brochure [48] states that the reactors are rated at 1.6 GW$_e$ and will operate with *availability* of up to 92% over the full 60-year life of the facility, implying total generation of 1.55 10^{12} kWh$_e$. EDF [49] states that HPC will have a capacity of 3.26 GW$_e$ with a *load factor* of at least 90%. These figures appear to refer to gross generation, not allowing for self-consumption by the plant, although this is not explicitly stated. Regarding longevity, no nuclear facility has yet achieved 60 years of operation, with 40 years being a more typical assumption. And regarding capacity factor, nuclear plants in the UK generally operate at well below 90%, as illustrated in Table 2. The figures represented in this table reflect the actual performance of the existing nuclear fleet, net of an allowance for the parasitic use of electricity generated on site for pumps, controls, etc. The average capacity factor across the period is 74.3%.

Table 2. Nuclear electricity generation in the UK: capacity (end of year), generation and capacity factor (CF). Source – DUKES tables 5.6 and 5.7 [50].

Year	2014	2015	2016	2017	2018
Capacity (MW)	9,937	9,487	9,497	9,361	9,314
Generation (GWh)	57,903	63,895	65,149	63,887	59,098
CF %	66.4	76.8	78.2	77.8	72.3

Using these figures from historic data to project generation for HPC, the total electricity delivered over 40 years with an average capacity factor of 74% would be 8.3 10^{11} kWh$_e$. The operators of HPC receive a fixed payment for each MWh of electricity generated in the first 35 years, known as the strike price: £92.50/MWh, inflation-linked to 2012 [51]. It might be argued that this incentive to maximise generation during the first 35 years is so high that a capacity factor of 74% is sure to be exceeded. However, (a) nuclear power plants do sometimes run into unexpected problems, and (b) the 92% proposed does not allow for electricity used on site (an average of 9.2% of UK nuclear electricity generated is 'used on works' according to DUKES [50], which would take the 92% capacity factor down to a net figure of about 84%). Also, the proposed 60-year life span is not fully supported by the financial incentives in place, which are currently just for the first 35 years. It has also been suggested that even 40 years at 74% might be optimistic, with most reactors having a projected life of 30-40 years, and exhibiting a decline in performance after only 24 years [16]. The analysis in this paper is therefore based on three scenarios, as follows:

A. A cautious scenario, based on existing UK facilities, that HPC will operate at 74% (net) for 40 years
B. HPC operating at 84% (net) for 60 years
C. The developers' view that HPC will operate at 92% for 60 years, with no allowance made for self-consumption.

3.2.2 Building a Life Cycle Inventory

An inventory for a nuclear plant likely exceeds millions of individual products and components, and designs are sensitive information. It is unlikely that a detailed inventory of a nuclear plant exists in the public domain, and it certainly does not for HPC. Thus, physical quantities of materials used are hard to find and it often requires using aggregated and generic information from secondary data. For instance from [16]:

> 'A typical nuclear plant usually contains some 50 miles of piping welded 25 thousand times, and 900 miles of electrical cables. Thousands of electric motors, conduits, batteries, relays, switches, operating boards, transformers, condensers, and fuses are needed for the system to operate. Cooling systems necessitate valves, seals, drains, vents, gauges, fittings, nuts, and bolts. Structural supports, firewalls, radiation shields, spent fuel storage facilities, and emergency backup generators must remain in excellent condition…'.

In light of this complexity, and the absence of publicly available bills of quantities for developments such as HPC, a relatively straightforward starting point for the life cycle inventory (LCI) is a review of the main construction materials required to build HPC.

Concrete and steel reinforcement are usually the first target for an LCI of a nuclear plant, as the quantities are so vast. EDF's own publicity on HPC is useful here [49], as it notes at least 3 million tonnes of concrete and 220,000 tonnes of reinforcement steel. Other sources do not suggest larger numbers (see supplementary information), so it seems justifiable to use the above figures for this assessment. An EPR brochure [48] provides descriptions and drawings of many aspects of an EPR, but these are only partially supported by numbers that can be used for an LCI. It is possible to make a crude estimation of concrete volumes from the reactor drawings in [48], but this excludes the very significant volumes of concrete used away from the nuclear island, and may also exclude significant volumes of below-ground concrete on the nuclear island.

Information in the brochure also permits an estimate of the upper limit of uranium mass (SI 1.3) to be made. The fuel rods can contain approximately 300 tonnes of UO_2, which corresponds to 264 tonnes of uranium, together with small quantities of Gadolinium (approximately 0.25% by mass). The level of uranium enrichment is an optimisation question for the operator, so the exact quantities of U-235, and therefore uranium ore required, cannot be precisely determined. Additionally, the brochure provides limited inventory information about the Rod Cluster Control Assemblies, which contain quantities of boron, silver, indium and cadmium, although a design life for these is not suggested: this is detailed in the supplementary material (Table A2), however the relative contribution to the LCA is negligible.

3.2.3 Uranium refuelling

When the U-235 in the fuel rods has been depleted beyond a certain point, the plant must be refuelled: this has been roughly estimated at 40 days every 18 months [52] although it depends upon variables such as the original level of fuel enrichment and the capacity factor of the plant.

An estimate for the uranium demand for HPC can be derived from previous calculations that around 30 tonnes of enriched U (at 3% U-235) is required for a 1 GW$_e$ station for a year, obtained from 165 tonnes of natural uranium [53]. Correcting for HPC's electrical output and efficiency, this would translate to around 80 tonnes of enriched U (at 3%) required per year by HPC. A similar treatment of figures presented elsewhere [28] suggest just over 60 tonnes of uranium enriched to 4% would be required per annum – which is similar in terms of U-235 content.

3.2.4 Capital Costs

The capital cost estimate associated with the HPC project has been increasing steadily over time. Press from autumn 2019 [54] reports EDF acknowledging that the cost has risen from £21.5 to £22.5 billion and with a delay of 15 months beyond the 2025 completion date. For the analysis here, we use the central figure of £22 billion. A WNA report [55] provides tools for understanding the breakdown of such costs. At 2015 prices, the full cost associated with EPR construction (including the cost of finance at 10% interest rate until the date of grid connection) is given as $\$7,202/\text{kW}_e$ (approximately \$23 bn for HPC, in total). Without the finance element, the cost (also known as 'overnight cost') is given as $\$5,067/\text{kW}_e$. It is easy to demonstrate the potential significance of delay in this context: a delay of just one year revealed towards the end of construction – for instance – would add nearly 10% to the total. The WNA report references a study [56] that shows how finance can be 30% of the total, rising to 40% if applied to a (longer) seven-year construction cycle. The WNA report suggests that 80% of overnight costs are engineering, procurement and construction costs (EPC), with 70% of these being direct costs (plant, materials, labour) and 30% indirect (supervisory engineering, support labour, etc.). In light of this, the 2015 figures for the EPR can be summarised as per Table 3 (scaled to 3.2 GW$_e$ in brackets).

Table 3 - Estimate of 2015 figures for the EPR. Values for HPC's nominal 3.2 GW$_e$ in brackets. Table is to be read left to right, and top to bottom, in the sense that each column shows how the figure on the left is divided into different categories.

$\$7,202/\text{kW}_e$: full capital cost (\$23.0 bn)	$\$5,067/\text{kW}_e$: overnight cost (\$16.2 bn)	$\$4,054/\text{kW}_e$: EPC cost (\$13.0 bn)	$\$2,838/\text{kW}_e$: direct (\$9.1 bn) $\$1,216/\text{kW}_e$: indirect (\$3.9 bn)
		$\$1,013/\text{kW}_e$: contingencies, testing, training, etc. (\$3.2 bn)	
	$\$2,135/\text{kW}_e$: finance cost (\$6.8 bn)		

As an estimate of how these costs would be applicable to HPC, they could all be scaled, linearly, to the acknowledged full capital cost (2019) of £22 billion. For the input-output analysis, more specific estimates of the various engineering and construction contracts are used. Approximate values of key work packages are available on the EDF website [57], and in some cases with further detail from additional sources. Where EDF has placed the costs within a range, we have assumed the mid-point of that range. For the costs greater than £1 billion (with no stated upper limit), estimates have been derived from other sources as follows, with a sectoral classification offered in Table 4.

- Framatome states that its contract is worth in excess of 5 billion Euros. This is interpreted as ‘approximately’ 5 billion Euros and hence £4 billion as a ‘round numbers’ estimate [58]
- The Bylor consortium contract value has been stated as £2.8 billion [59]
- No further information on the GE-Power contract was found, so we used benchmark costs for conventional power generators as a proxy. The mechanical and electrical capital costs associated with a combined cycle gas plant amount to \$0.524/kW [60], so approximately £1.5 billion for 3.2 GW.

Table 4. Estimates of the value of HPC contracts as identified on the EDF website. C – contracts allocated to the construction economic sector; E&M – Electrical and Machinery sector contracts. Criteria for inclusion: contract >£5m, and broadly applicable to one or both of the two economic sectors identified (so we exclude site operations for instance). The cost band £5-250m summarises the cost of contracts in four narrower bands.

Contract	Sector	EDF price band	Estimated value
Framatome ‘nuclear steam supply systems’	E&M	>£1bn	£4bn
Bylor consortium – civil engineering works	C	>£1bn	£2.8bn
GE-Power’s ‘conventional island’ package: turbines, generators, condensers	E&M	>£1bn	£1.5bn
Enabling works (earthworks) – Kier Bam JV	C	£250-500m	£375m
Marine works (re cooling water) – Balfour Beatty	C	£250-500m	£375m
BNI Mechanical erection on nuclear island – Cavendish Boccard Nuclear JV (preferred bidder)	C	£250-500m	£375m
Electrical and I&C works – Balfour Beatty Bailey JV	E&M	£250-500m	£375m
22 construction sector contracts	C	£5-250m	£1145m
46 E&M sector contracts	E&M	£5-250m	£1810m
TOTAL construction value	**C**		**£5070m**
TOTAL electrical & machinery value	**E&M**		**£7685m**

4. Results

As explained results in this paper have been obtained using process-based LCA, multipliers from input-output tables for the UK, and a simplified hybrid LCA. They will be now presented in turn.

4.1 Results using a process-based approach

Process analysis is well suited to the level of assessment involved with modelling construction and operation impacts, and process-based LCA has been recommended to investigate the sustainability of nuclear power [52]. Construction and operational emissions have been assessed through single point estimates due to the lack of a range of figures to allow for stochastic modelling, for instance. End of life impacts have instead been divided in two possible scenarios based on recurring figures found in the literature: 35% of construction impacts based on energy analysis, and other claims for higher costs for ‘environmentally responsible’ options [8], and 10% of construction impacts based on a report on nuclear decommissioning costs [61], which includes costs of actual decommissioning projects in the US. These average around $620 million (in 2013 USD), suggesting a cost in the region of 10% of initial capital investment. The values used in this scenario analysis are:

- EoL Scenario i: end of life impacts are 35% of construction impacts
- EoL Scenario ii: end of life impacts are 10% of construction impacts

Results of the detailed process analysis are given in Table 5. Data behind the modelling done in SimaPro based on Ecoinvent v.3 and with the IPCC GWP100 [62] as the impact assessment method are given in full in the Supplementary Information linked to this article.

Table 5 - Results of the process analysis for construction, operation and end of life (EoL). The three output options refer to the different scenarios considered for both service life and energy ouput. EC – embodied carbon.

EC construction		$1.66\ 10^{9}$ kgCO$_{2e}$		
Output Option		A [74% - 40 yrs]	B [84% - 60 yrs]	C [92% - 60 yrs]
Lifetime output	kWh$_{e}$	$8.30\ 10^{11}$	$1.41\ 10^{12}$	$1.55\ 10^{12}$
EC operation	kgCO$_{2}$e	$1.07\ 10^{10}$	$1.82\ 10^{10}$	$2.00\ 10^{10}$
EC thermal energy	kgCO$_{2}$e	$1.95\ 10^{9}$	$3.31\ 10^{9}$	$3.63\ 10^{9}$
EC EoL (i)	kgCO$_{2}$e	$5.81\ 10^{8}$	$5.81\ 10^{8}$	$5.81\ 10^{8}$
EC EoL (ii)	kgCO$_{2}$e	$8.30\ 10^{8}$	$8.30\ 10^{8}$	$8.30\ 10^{8}$
Carbon intensity (EoL i)	gCO$_{2}$e/kWh$_{e}$	17.936	16.825	16.681
Carbon intensity (EoL ii)	gCO$_{2}$e/kWh$_{e}$	18.236	16.531	16.414

It can be seen that variations in end-of-life scenarios do not significantly impact the overall results.

4.2 Results using an input-output approach

As a first step we extracted multipliers for total requirements (in terms of mass of CO$_{2e}$/USD) from the latest version of the Eora database [63] for 26 sectors of the UK economy in 2015. Eora is one of the most comprehensive MRIO databases available globally. It contains input-output tables for 187 countries and details the international trade links between more than 15,000 industries globally, all over a 20+ year timeseries. Eora documents >5 billion supply chains and covers >99.7% of the global GDP. Eora supported energy, carbon and water analyses with foci on tourism, biodiversity and international trade [64–66], to name but a few. Multipliers are shown in the SI (Table A4). These multipliers enabled estimates based on a scenario analysis. We developed and consider the four scenarios shown in Table 6. All costs are allocated to the following multipliers: construction; electrical and machinery; financial intermediation; and – for any costs that do not fit in those categories – the average value for the UK economy in Table A4 in the SI. It is worth noting that a weighted average (where the weights are represented by total value of each sector) would lead to an even higher value for the UK economy, thus making our assumption a conservative hypothesis. We retain the three output options (A, B, and C), defined in Section 3.2.1, for each of these scenarios.

Table 6. Four scenarios linking project value to emissions. These capture diverse possibilities for sectoral allocations of economic costs. Since environmentally-extended input-output analyses couple economic data with environmental repercussions, this diverse allocation accounts for the variability of environmental impacts that different economic sectors have. Full numerical details given in SI (Table A3).

Scenario	**Description**
S1	£12.8bn of construction costs and electrical & machinery costs (Table 5), estimated through the average carbon intensity of those sectors. Finance assumed to be 30% of the total.
S2	£22bn declared project value, coupled with World Nuclear data used on typical split between finance costs and overnight costs (Table 4), and the contribution of construction costs to the latter.
S3	Based on the strike price of £92.50/MWh scaled up to the total MWh generated; impacts are then estimated through the average from the multipliers in Table A4 in SI.
S4	Emissions linked to total project value estimated through the average carbon intensity of the UK economy.

Table 7 shows the normalised results for carbon intensity of the different scenarios. Results range from 8.06 gCO_2e/kWh_e in the case of S2 Option C with a partial cost approach to 64.22 gCO_2/kWh_e for S3 Option A. However, there are issues that justify such a significant discrepancy. For instance, S1 only accounts for 58% of the total project value. This lack of completeness is also present in S2. Conversely, S3 is based on the strike price [51] which arguably includes all life cycle impacts since it is EDF's revenue, which exceeds the costs. However, it assumes that all the energy demand will occur in a single year, neglecting the progressive decarbonisation of the UK economy, and hence the very high aggregated value. Further, for Scenarios 1, 2 and 4 additional issues are:

- No operational impacts are considered (e.g. regular refuelling over the lifetime of the plant)
- No end-of-life impacts are considered
- No fossil fuel consumption at the plant itself is considered[3].

Fixing the three issues above would require a detailed process analysis, for which primary and reliable data is unavailable. However, fixing the completeness issue for S1 and S2 is doable if carried out through a simplified calculation assuming that the excluded costs are evaluated through the carbon intensity of finance (where such costs are identifiable) with any remaining costs being evaluated through the average carbon intensity from all 26 sectors considered for the UK economy. The results of this calculation are labelled without the '-PC' extension in Table 7.

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[3] Literature reports 80 GWh_{th} for a plant of 1 GW. This should be scaled up to the 3.2 GW capacity of HPC, and an appropriate assumption made about the nature of the fuel (e.g. that it is primarily natural gas, although doubtless liquid fuels will form a part).

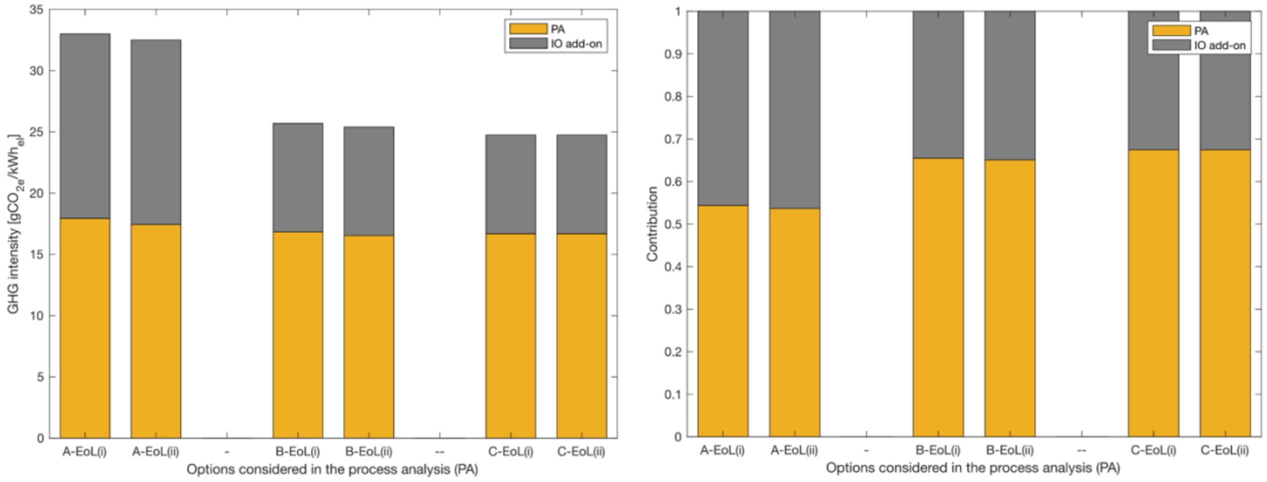
Table7 – Results obtained through input-output multipliers for total requirements for different sectors of the UK economy. The three options always refer to differences in the length of service life and overall energy output of the nuclear power plant. S1-PC and S2-PC are based on partial costs (PC) of construction and equipment elements where these are separately identifiable.

Scenario	Option A [74%-40yrs] EC [gCO$_2$e/kWh$_e$]	Option B [84%-60yrs] EC [gCO$_2$e/kWh$_e$]	Option C [92%-60yrs] EC [gCO$_2$e/kWh$_e$]	Notes
S1-PC	17.07	10.04	9.14	Partial cost
S1	29.87	17.58	15.99	Full cost
S2-PC	15.06	8.86	8.06	Partial cost
S2	28.11	16.55	15.05	Full cost
S3	64.22	37.80	34.39	Full cost
S4	18.40	10.83	9.85	Full cost
Mean	35.15	20.69	18.82	Full cost values only

These show a more interesting and complete picture. While S3 and S4 are, to an extent, outliers, the other numbers converge towards much more agreed values, and are close to the overall averages (mean values) for each scenario given in the bottom line of the table.

4.3 Results using a simplified hybrid approach

While the values from the process analysis (Table 5) are less spread and in general a little lower than those from the IO analysis (Table 7), it is worth stressing that they are different in nature and both suffer from issues either in terms of completeness or accuracy. As previously discussed, process-based results suffer from truncation error (completeness issue) and IO-based results and suffer from aggregation error (accuracy issue). A simplified hybrid approach was adopted, to produce estimates which are closer to a more comprehensive value, without truncation. These results are shown in Figure 1.



(a) (b)

Figure 1 – Results from simplified hybridisation. (a) Normalised carbon intensities using the three alternative EoL scenarios within the three project lifetime options. (b) Percentage breakdown between the process analysis and input-output add-on.

For this, we have assumed that, in addition to the £2.8 billion of the civil engineering contract covering the bulk of the concrete and reinforcing steel to be installed on site, a further £1.2 billion is allocated to nuclear fuel and other rare elements which we have accounted for in the process analysis. Using these assumptions, the process analysis only addresses £4 billion of the costs, leaving £18 billion unaccounted for. Without immediate and accurate knowledge on how this £18 billion is spent, we have used the average carbon intensity from Table A4 in the SI to estimate corresponding emissions. While this is a simplification as costs will come from both carbon-intensive and less-carbon intensive sectors of the UK economy, it should be noted that sectors like transport, construction, finance, electricity, and machinery (which are likely to make up a large share of the remaining costs) all have carbon intensities higher than the average value used for our analysis, which therefore suggests a conservative assumption.

Results show that normalised carbon intensities range from an average 32.74 gCO_2e/kWh_e for Option A, to 24.61 gCO_2e/kWh_e for Option C. It is worth noting that the average truncation error introduced by a process-analysis is 37.8% which is in line with average truncation errors previously demonstrated for process-based LCA [35,40]. To understand what process analysis leaves out, it might help to consider the product layer decomposition of the emissions completeness of the supply chain behind the UK construction sector (Figure 2). Process analysis typically covers direct impacts (Stage 0) and impacts occurring in the immediate upstream layer(s) of a sector's supply chain. Figure 2 shows that, for the UK construction sector, Stage 1 represents about 50% (so half of the impacts would be left out) and Stage 2 represents about 75% (25% left out). Since our average truncation error sits in between these two figures, it seems that values obtained through our process analysis are aligned with the general coverage offered by process-based LCA, and that our simplified hybridisation through IO multipliers helps convey a more complete picture of what the likely impacts are.

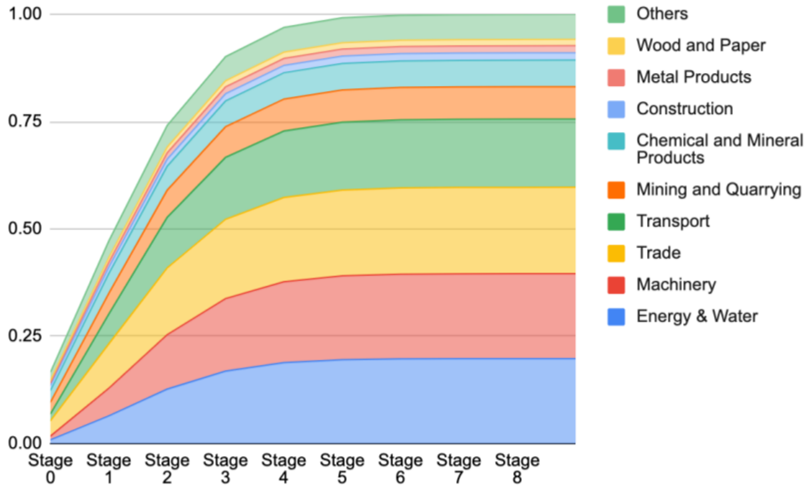


Figure 2 - Analysis of supply chain emission completeness for the UK Construction sector with values extracted from Eora (2015). The original 26 sectors have been grouped into larger groups for readability. Figure shows cumulative values at each upstream supply chain stage.

5. Discussion

We tested the sensitivity of our results to a number of variations: end of life impacts and total energy output for the process analysis, different breakdown of costs and approaches for the IO analysis, and a combination of both for the simplified hybrid approach. The overall variation of our results is captured in the box and whiskers plot in Figure 3. Interquartile ranges for PA, IO, and HLCA are 16.55—17.69 gCO_2e/kWh_e, 18.82—35.15 gCO_2e/kWh_e, 24.61—32.74 gCO_2e/kWh_e, respectively (Figure 3). The minimum value within interquartile ranges (16.55 gCO_2e/kWh_e) is unsurprisingly obtained with a process-based approach. This value relies on the very generous output declared by EDF for HPC, and yet it is triple the value publicly acknowledged by EDF. Further, it is the lower-bound of a process-based approach, which undeniably does not offer comprehensive impacts due to its truncation error.

All of these results are, depending on the scenario, either above or at the upper end of the range of possibilities (5 to 22 gCO$_2$e/kWh$_e$) stated in a report for the Committee on Climate Change [67], and comfortably higher than the median value of 12 gCO$_2$e/kWh$_e$ presented by the IPCC [68]. They are also higher than the values generally acknowledged by the nuclear industry, although not in every case. For instance, in their own meta-analysis the WNA [69] reports an average of 30 gCO$_2$/kWh$_e$ whilst acknowledging that the studies from the industry and associations produced averages of 13 gCO$_2$/kWh$_e$.

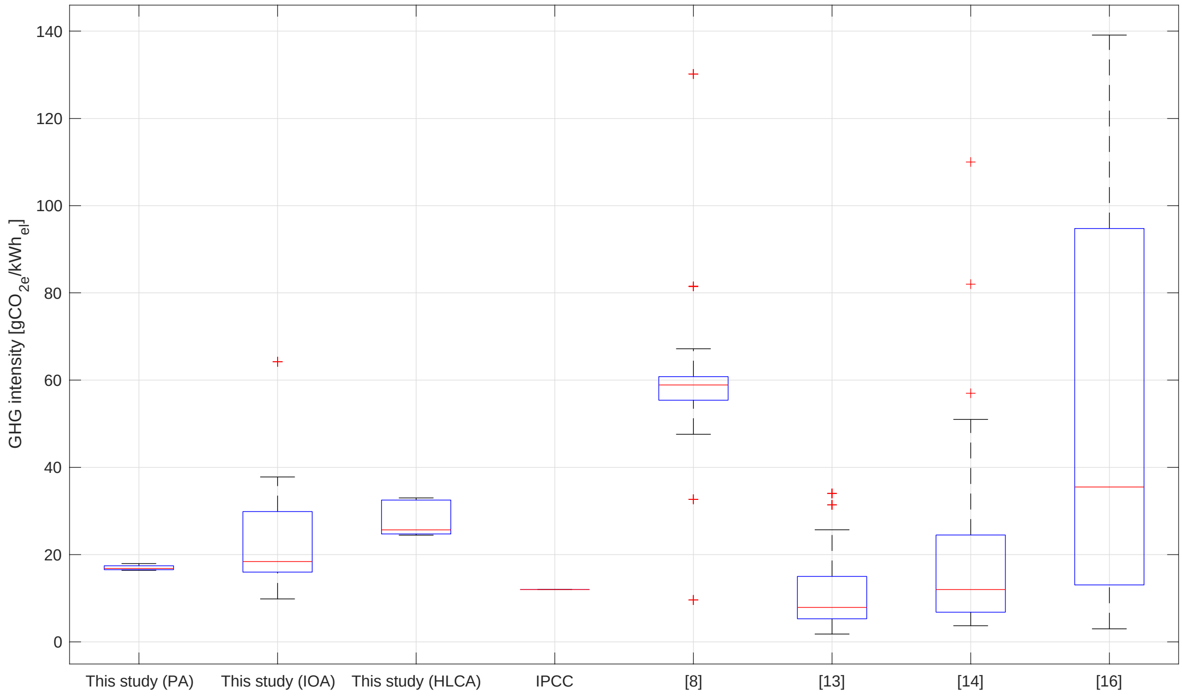


Figure 3 – Box and whiskers plot for the sensitivity of the results obtained with the three approaches used in this research compared against the single value used by the IPCC and the broad range of values reported in previous review papers that harmonised previous research findings to enable comparisons.

The results indicate carbon intensities that are substantially higher than many of the literature values mentioned in section 2, also. In several cases it is possible to isolate likely reasons for the discrepancy. For instance, in Wang [18] (~12 gCO$_2$e/kWh$_e$) construction materials are derived through secondary analysis and transformed into mass of material per unit energy output. They end up being two orders of magnitude lower (e.g. for concrete 0.0422g/kWh$_e$) than EDF's own declared figures (3 million tonnes of concrete/ 1.5 10^{12} kWh ≈ 2g/kWh$_e$). In those studies mentioned where intensities <10 gCO$_2$e/kWh$_e$ are reported, Koltun et al. [21] seem to draw system boundaries tightly around the construction of the basic infrastructure, with the declared input for concrete (400 000 t), an order of magnitude lower than EDF's own declared figures; from the four-line definition of system boundaries in Ding et al. [19] it seems that only the basic infrastructure is considered and that decommissioning and end of life activities are neglected; the construction data in Siddiqui and Dincer [22] is taken from a 1998 conference paper and used as input; and Serp et al. [24] (i) neither disclose input data nor overall quantities and (ii) is a paper authored by the French Nuclear Energy Association.

In general, our results are very much aligned with the range offered by previous studies as Figure 3 shows, and to further strengthen the confidence in our results, the analysis is based on conservative hypotheses. For instance, material inputs to the process-based LCA are taken directly from EDF's own declared figures (see SI Table A1). Secondly, the 17% increased efficiency reported by EDF has also been accounted for. Inputs of rare earth metals included in the PA have consistently been taken from conservative figures in the literature. Also, apart from estimates for piping and cables found in the literature, all other materials have been excluded. These are surely substantial and coming from complex carbon-intensive supply chains and would therefore add to the embodied carbon up to practical completion. Finally, with respect to total electricity generation over the project lifetime, the option that results in the lowest embodied carbon (Option C) may be unrealistic, as the 92% capacity factor is not a net figure. The option that results in the highest embodied carbon (Option A) is not at the other extreme end of possibilities, as it is chosen to represent an average level of performance for existing UK plants (and not an overly pessimistic scenario).

A final observation is that EDF states that the electricity generated at HPC will offset 9 Mt of CO_2 a year, or 600 Mt over its 60-year lifespan [70]. Using their predictions of capacity factor, this calculation is based on an offset of nearly 400 gCO_2/kWh_e, which corresponds approximately to the emissions from a Combined Cycle Gas Turbines station powered by natural gas, with no carbon capture and storage. As the use of such facilities are only compatible with the UK's carbon budgets for the first decade or two of HPC's lifetime, an alternative comparison needs to be made. As it is unlikely to be realistic to replace the existing fossil fuel and nuclear power stations with a single type of generator (such as offshore wind), a system-level LCA is called for, to compare alternative strategies (combining, in various proportions, offshore and onshore wind, energy storage, solar, nuclear, etc.) for meeting carbon budgets.

6. Conclusions

This article investigates the greenhouse gas emissions associated with nuclear energy generation in the UK through multiple lenses and assumptions and by using the three main approaches available in life cycle assessment: process-based, input-output, and a simplified hybrid analysis. Our analysis suggests that the GHG emissions associated with future nuclear power plants in general, and Hinkley Point C in the UK in particular, will be higher than is currently suggested by the industry. They will be more in line with what has previously been found by academics in other studies on the carbon intensity of nuclear energy. Our results range from 8 to 64 gCO_2e/kWh_e, with averages for the three approaches as 16.97, 24.89 and 27.63 gCO_2e/kWh_e, respectively.

The limitations of this research are linked to both data and methods. For the former, the data scarcity – only in part justified by commercial interests and sensitive information – on nuclear power generators makes it extremely hard to conduct detailed process-based analysis. For the latter, there are the well-known limitations of all life cycle assessment approaches. While input-output and hybrid life cycle assessments provide a fuller picture than can be achieved with process-based analysis alone, further research expanding on any of the three methods used in this article would increase the robustness of, and confidence in, our findings. However, any analysis would be heavily based on assumptions in the face of incomplete data.

Therefore, further sensitivity analysis would help to mitigate the limitation of incomplete input data and could be usefully augmented with uncertainty analysis.

In spite of the limitations of the present work, we demonstrate that regardless of the life cycle assessment approach used, and with extremely conservative hypotheses that favour nuclear energy generation, our values are two- to over ten-fold higher than what the nuclear industry declares. Only our absolute lowest value (an outlier, much as our absolute highest value is) is in line with numbers used in publications from the Intergovernmental Panel on Climate Change, and our average values are well above those of alternative low-carbon renewable energy technologies. At a time where the latest International Energy Agency publications still classify nuclear energy as low-carbon, this article shows the urgent need for further and deeper research into the topic to avoid an emissions lock-in in both ongoing and planned projects of nuclear generators. This would divert from, not drive towards, sustainable energy goals and the achievement of global carbon targets.

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Author Contributions

The authors contributed equally to the research.

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