Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era

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The Paris Agreement provides an international framework aimed at limiting average global temperature rise to well below 2°C, implemented through actions determined at the national level. As the Agreement necessitates a 'net-zero' emissions energy system prior to 2100, decarbonisation analyses in support of national climate policy should consider the post-2050 period. Focusing solely on mitigation objectives for 2030 or 2050 could lead to blindsiding of the challenge, inadequate ambition in the near term, and poor investment choices in energy infrastructure. Here we show, using the UK as an example, that even an ambitious climate policy is likely to fall short of the challenge of net-zero, and that analysis of the post-2050 period is therefore critical. We find that the analysis of detailed, longer term national pathways which achieve net-zero is important for future reassessment of ambition under Nationally Determined Contributions (NDCs).

Global ambition to limit anthropogenic warming to 2°C requires a radical transformation of the energy system to one that produces 'net-zero' GHG emissions before 2100 [1]. For a 1.5°C limit, action has to be even more rapid, with net-zero emissions achieved much earlier [2]. The goal of net-zero GHG emissions is expressed in the Paris Agreement as a system that achieves 'a balance between anthropogenic emissions by sources and removals by sinks'[3]. In this paper, we define net-zero as ‘reducing net CO_2 emissions from energy and industrial processes, after accounting for CCS, to zero’ [4]. However, analyses of current pledges by individual countries, Nationally Determined Contributions (NDCs), estimate that such action will result in warming of between 2.9 and 3.4°C (based on a 66% probability)[5]. This reveals a fundamental disjuncture between the aspiration for an equitable global transition to a net-zero future and the national policy planning being carried out. This disjuncture will only be addressed by countries fully exploring the ambition levels in the Agreement, and a subsequent ratcheting up of mitigation action. To date, however, government-backed national studies exploring net-zero transitions are limited to Bhutan [6], Costa Rica [7], Ethiopia [8], Norway [9], and Sweden [10], while no NDCs have assessed emissions reductions targets in the post-2050 period.

Furthermore, longer term planning horizons are needed to understand path dependencies[11]. Energy system investments are often into capital intensive assets with long lifetimes, raising the risk of technological ’lock-in‘ [12] to system configurations that will meet 2030 or 2050 targets but which are unsuitable for achieving net-zero positions thereafter. However, most NDCs only consider 2025 or 2030 as their target time horizon. The Paris Agreement encourages this reframing of NDCs; firstly, promoting a longer term perspective, with Article 4.19 stating that ‘Parties should strive to formulate and communicate long term low greenhouse gas emission development strategies’. Secondly, the pledge and review approach will allow for countries to periodically re-assess the strength of their ambition. Critical also to this reframing is the recognition that countries have divergent priorities and circumstances [13], as per the principle of ‘common but differentiated responsibilities and respective capabilities’[3].

Using the example of the UK, we explore the implications of 2°C-compliant carbon budgets on the national energy system, under a range of critical uncertainties. We find that the most stringent budget, named 590 Equity and constituting ambition 'well below 2°C', results in a net-zero system before 2050, and requires stronger mitigation efforts than those currently envisaged by UK policy. The central budget cases chosen (590 Inertia / 1240 Equity) result in net-zero emissions by 2070, and again requires higher ambition than under current UK climate legislation. We conclude that strategic national energy system planning, even in the short term, requires analysis with a post-2050 time horizon that appropriately reflects global climate ambition. Furthermore, such analyses need to capture policy-relevant uncertainties, which in the case of the UK include future bioenergy availability, CCS deployment, and consumer response, including societal acceptance of increasing mitigation costs.

Critical uncertainties under a net-zero emission transition

In exploring stronger ambition over the longer term, there are a range of key uncertainties that energy transitions must explore, to understand implications for technical, economic and socio-political feasibility. Four that are critical to consider in country-scale analyses include; i) the global carbon budget and its allocation; ii) commercial availability of key energy system technologies; iii) bioenergy resource, including its use for generating 'negative' emissions; and iv) demand levels for energy services. Their criticality is discussed below, with additional detail, including on the uncertainty ranges used, provided in Supplementary Note 1.

Concerning i), a key finding to emerge from climate modelling in the last decade is the near-linear relationship between cumulative CO_2 emissions since preindustrial times and the rise in global mean surface temperature over that same period [14,15]. The simplicity of this relationship has proven particularly attractive at the science-policy interface where a selected global warming threshold and probability of achieving said limit can be distilled into a global CO_2 emissions budget. In the latest review of carbon budget estimates, Rogelj et al. 2016 [16] recommend the use of a CO_2 budget range of 590-1240 Gt (from 2015 onwards) from the IPCC AR5 Synthesis Report [1], commensurate with limiting warming to 2°C with at least a 66%

chance. The sizeable budget range is largely driven by uncertainty in future non-CO_2 GHG emissions.

Furthermore, national level studies require an approach to share out a global emissions budget. An extensive literature exists that considers allocation of climate mitigation from different perspectives[17–19]. A recent approach is that proposed by Raupach et al. [20], also used in Peters et al. [21], which applies effort sharing principles of equity (per capita basis) and inertia (current total emissions basis, also known as grandfathering) to carbon budgets. For a developed country such as the UK, equity leads to the allocation of a much more stringent, lower budget, compared to what would be achieved under inertia, based on current emissions. Within this allocation framework we implicitly assume that other countries are also pushing toward commensurate levels of ambition. The implementation of these budgets is further described in the Methods section and Supplementary Note 1.

For ii), both nuclear power and the use of fossil fuels with large-scale carbon capture and sequestration (CCS) technology are often shown to play key roles in decarbonisation scenarios [22]. However, their effective deployment is beset by multiple uncertainties, relating to technical feasibility, commercialisation, and public acceptability [23]. The attraction of CCS lies mainly in the potential for delaying the shift away from fossil fuel use, reducing overall transition costs. However, there has been limited progress in moving to commercial-scale deployment, with few projects having implemented the full CCS chain at scale[24]. Nuclear power also appears as a cost effective option in energy modelling exercises, but faces significant uncertainties. Plants are complex to build and highly capital intensive, with a history of cost escalations and public resistance to deployment [25,26].

Concerning uncertainty iii), even in strongly decarbonised futures, residual emissions from hard-to-address sectors may require a negative emissions strategy to achieve a net-zero emissions position. 87% of global IPCC AR5 scenarios with a 66% chance of staying below 2°C deploy negative emissions technologies, with bioenergy CCS (BECCS) technology being most prevalent [27]. However, the practicality of negative emissions strategies remains contested [28]. Additionally, future bioenergy resources are likely to be constrained by biophysical and socio-economic factors, with a wide range of estimates reflecting uncertainties around food security and diets, land use dynamics, and water use [29].

Finally, concerning iv), uncertainty of future demands for energy services such as mobility, heating and lighting are important drivers of CO_2 emission levels. Reducing such demands can be achieved via a range of mechanisms, including pricing, regulation, and information provision to influence consumer choices. A number of modelling assessments have underlined the role of price-induced demand reductions in energy services, particularly in sectors where mitigation options are limited. However, the role and impact of such a mechanism is also highly uncertain, in large part due to a limited empirical basis [30].

CO_2 pathways and budget feasibility

Implications of a net-zero transition for the UK, subject to the above uncertainties, are modelled under the 2°C (66%) emission budget range (from 2015) of 590–1,240 $GtCO_2$, with the allocation of the global budget to the UK explored on equity and inertia principles. This results in four sets of model outputs, based on the combination of global budget and allocation principle e.g. 590 Equity. The 1240 Equity and 590 Inertia cases have very similar results, given their almost identical budgets. These cases are compared to the UK's current policy framework (Policy case), for which we assume the 2050 level of decarbonisation is maintained to 2100.Combinations of the uncertainties described above (16 in total) are explored for each budget case (see Supplementary Note 1). In addition, a further budget case, 915 Blend, was also investigated and is described in Supplementary Note 2.

The analysis shows that achieving a 2°C compatible net-zero position in both Equity cases requires stronger action before 2050 than is achieved under the current UK policy case. In Figure 1, cumulative emissions to 2050 under the 590 and 1240 Equity cases are at 33% and 64% of the Policy case total. In the 590 Equity case, extremely high average annual reductions of 9% per annum to 2030 are required to remain within the carbon budget, resulting in net-zero emissions by 2045. This compares to 4% per annum under 1240 Equity, which reaches net-zero emissions after 2050 and by 2070. CO_2 emissions have been reducing on average by 1% per annum since 1990, underlining the necessary but unprecedented increase in mitigation efforts.

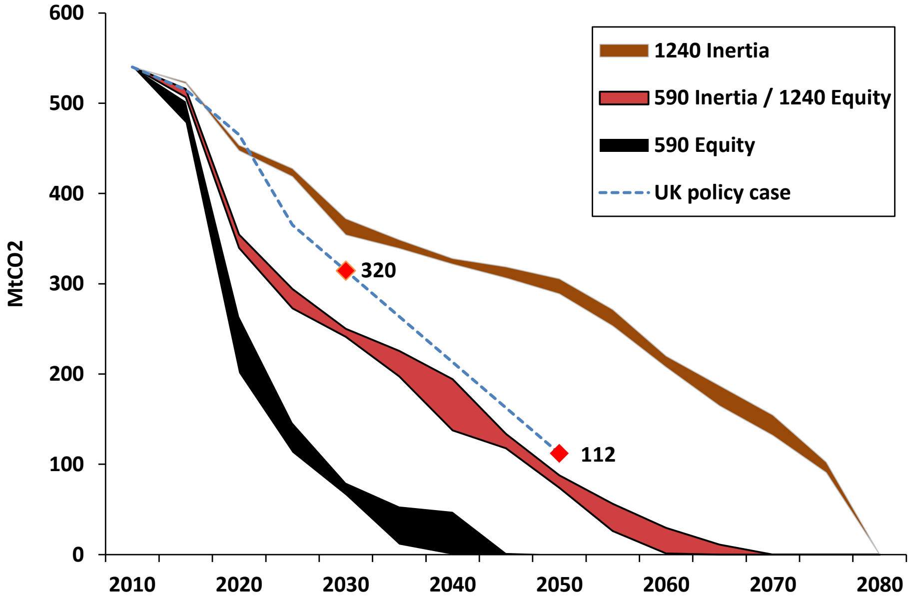

Figure 1. Net CO_2 emissions from the energy system under the 2 °C (66% probability) carbon budget range based on *Equity* and *Inertia* allocations. The emission trajectories represent the full range for all feasible runs, which are those that did not include the backstop option. Note that 590 Inertia has the same trajectory as 1240 Equity. In the policy reduction trajectory, the red markers show CO_2 emissions indicative of the UK Government's 5th carbon budget (2030) and the Climate Change Act 2008 (2050).

The 590 Equity case, however, is at the limits of feasibility. 70% of the runs for this case deploy a 'backstop' mitigation option by 2050, priced at £10,000 /tCO_2 (Supplementary Figure 4). Deployment of the backstop effectively means that the model has failed to find a solution. In the 590 Equity case, the use of the backstop technology results from limits on the model's ability to rapidly deploy low carbon technologies in the near-term. Deployment rates are restricted due to physical build rate constraints, a lack of commercial availability or underdeveloped supply chain capacity. In the other budget cases, infeasibilities are found only in those model runs that assume low bioenergy resource potential, meaning insufficient negative emissions can be generated to offset residual emissions in the post-2050 period, with resulting net emissions of 40-45 $MtCO_2$ (Supplementary Note 2). None of the model runs deploying the backstop option are included in Figure 1, or in subsequent results presented below.

Emission reduction options under transition pathways

The mitigation options under different transition pathways are strongly influenced by the uncertainties described earlier. The results demonstrate that staying within budget levels without CCS is extremely challenging, underlining the critical nature of this technology. Figure 2 shows the relative importance of CCS in each scenario, illustrating the cumulative level of emissions captured and sequestered relative to the overall budget in each case. Median cumulative emissions captured and stored (8.9 $GtCO_2$) are equal to the total carbon budget level in the 1240 Equity case, and almost three times the more stringent budget level in the 590 Equity case (11.2 $GtCO_2$) (Figure 2).

The importance of BECCS to the system is particularly evident, representing 62-67% of the CO_2 captured across all cases, and accounting for approximately 85% of the total bioenergy used. BECCS deployment is seen as key for addressing residual emissions from hard-to-address sectors, such as international transport, that lack alternative mitigation options (this is discussed in more detail below). Crucially, the results show that the Equity cases see much higher median CCS deployment relative to the Policy case, both prior to and post-2050 (Supplementary Figure 6).

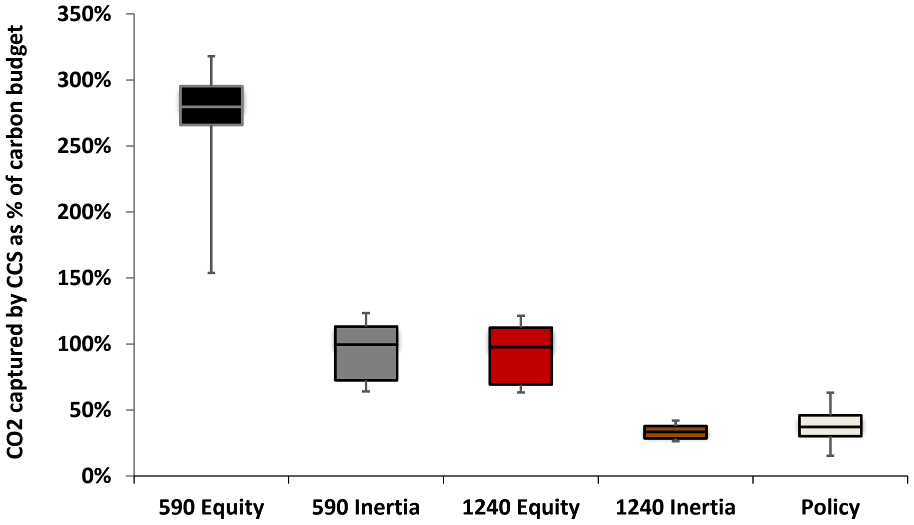

Figure 2. Cumulative CO_2 emissions captured and stored between 2025-2100 as a percentage of the overall carbon budget. A value of over 100% indicates that CCS is used to sequester a level of CO_2 at least equivalent to the carbon budget. The lower and upper extent of the boxes show the 25th to 75th percentile range, respectively, which is separated by the median level. The whiskers show the minimum and maximum of the plotted data.

Figure 3 compares oil consumption, electricity generation, and welfare losses for key scenarios. The broad picture that emerges from Figure 3 is one where net-zero ambition results in higher rates and increased absolute deployment of mitigation measures in the Equity cases, as compared to the Policy case. Oil consumption declines more rapidly, falling to 20% and 40% of current levels by 2030 in the 590 and 1240 case respectively (Figure 3a and 3b). A 'floor' level of 500 PJ of oil consumption is seen in all cases post-2070 primarily as a result of international transport having few technological alternatives to fossil-fuels (Supplementary Figure 5). A lower floor level resulting from lower transport demand or a switch to alternative fuels, would reduce the residual emissions in a net-zero system, and the corresponding need for CCS and BECCS deployment.

High growth in electricity generation, and the rapid reduction in its carbon intensity, reflects the importance of electrification in pre-2050 decarbonisation pathways (Figure 3d-3f). The particularly steep growth in generation under the 590 Equity case (3d) is largely met by onshore and offshore wind, growing at the assumed maximum build rates of at least 3 GW per annum. In both Equity cases (3d and 3e), the average investment rate is higher than that observed in the Policy case, while existing fossil capacity is utilised at very low rates after 2020, as highlighted by the reduction in carbon intensity.

Finally, consumer surplus losses express, in economic terms, the reduction in energy service demands resulting from high carbon prices (Figure 3g-3i). That is, higher prices for delivering energy services are inducing demand reductions, for example in the provision of private car mobility, aviation demand, or excess heating and lighting. Under the 590 Equity case in particular (3g), the importance of this mitigation option for the transition in the near term is obvious, as it can be affected rapidly without large scale investment or infrastructure build. These losses plateau post-2050, as supply-side solutions become more cost-effective, and can be scaled. Again, with the exception of the 1240 Inertia case (3i), levels of demand response are higher than observed in the Policy case.

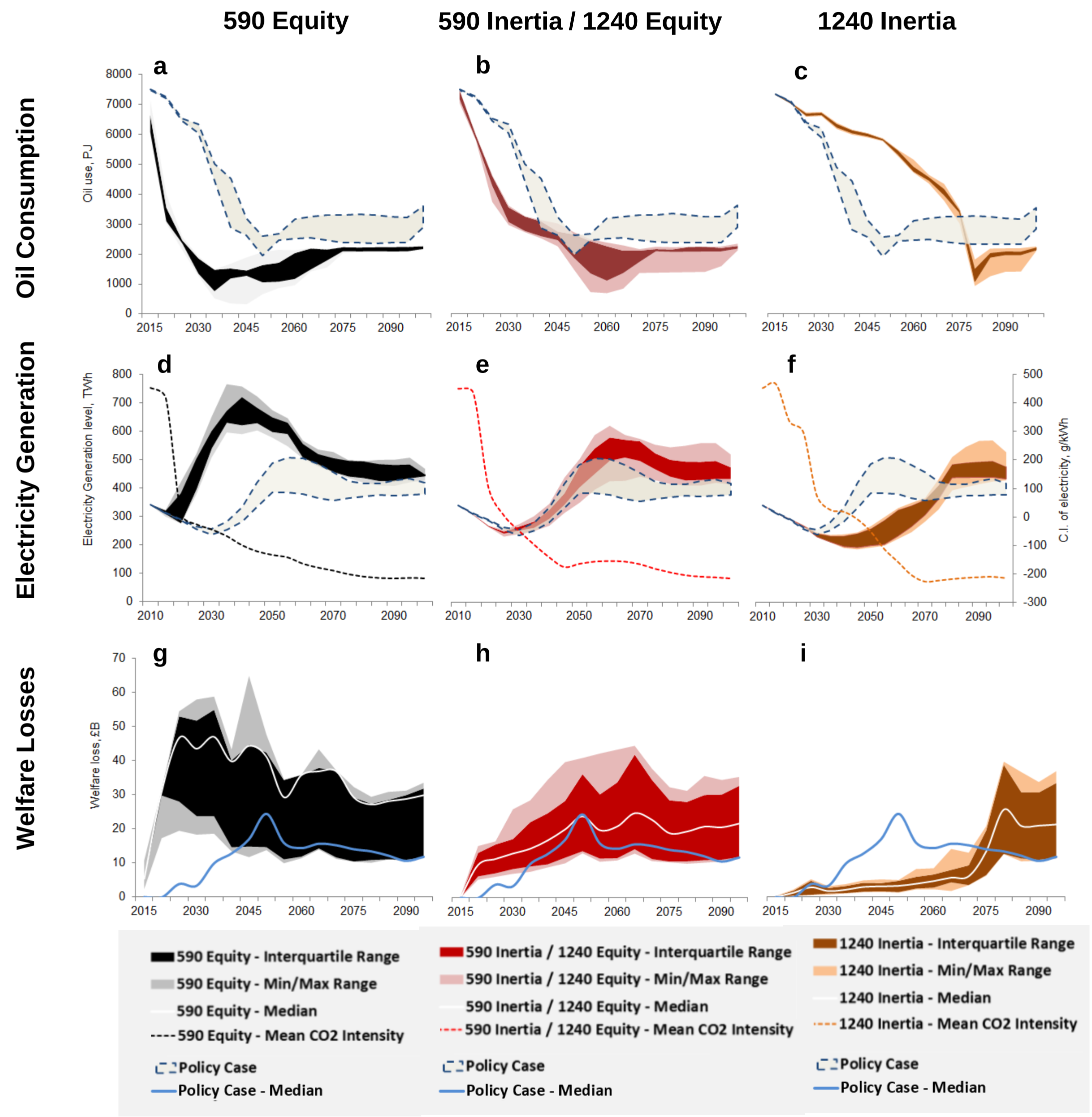

Figure 3. Selected decarbonisation transition indicators. From left to right, the columns represent the cases 590 Equity, 1240 Equity / 590 Inertia and 1240 Inertia. In each plot, the darker shade shows the 25th to 75th percentile range (interquartile range) while the lighter shade gives the minimum and maximum extent. **a –c. Oil consumption indicating a shift away from fossil fuels:** The budget range is compared to the Policy case, shown by the grey dashed area; **d-f. Electricity generation representing electrification as a key low carbon pathway:** The budget range is compared to the Policy case, shown by the grey dashed area. The dashed trend line shows mean carbon intensity of electricity of the budget case, against the secondary vertical axis; **g-i. Consumer surplus losses representing demand reduction in energy services:** The white trend line represents the budget case median while that for the Policy case is shown by the blue trend line.

Economic implications

Over the period 2020-2040, the costs of the system re-orientation under the 590 Equity case are between 20-30% higher than the Policy case, reaching an additional £100 billion by 2030. Achieving this would need a massive increase in investment flows into the energy sector, and a policy package that could put the relevant market and regulatory-based incentives in place.

To put this in context, the UK plans to spend £100 billion annually on all infrastructure by 2020-21, with an estimated share of 60% on energy infrastructure[31]. The marginal costs of achieving these reductions reflect the policy challenge, with a 2030 marginal abatement cost of CO_2 at around £1800 /tCO_2 (Supplementary Note 3, Supplementary Figure 7). The annual cost increase over the same period for 1240 Equity is 2-3% (or £10 billion in 2030), which, as seen across the other metrics, also implies a strengthening of action versus the Policy case.

By 2050, investment levels are broadly similar across all cases (£260-275 billion), with the Equity cases and 590 Inertia seeing marginal costs in the range of £400-550/tCO_2, falling by 2080 as low carbon technologies reduce in cost (Supplementary Figure 7). The costs of the transition are of course strongly dependent on the modelled uncertainties. The bioenergy resource potential has the largest impact on costs, with only the high resource cases providing model-feasible solutions across all budget cases. For the other three modelled uncertainties, the impact on costs is highest from restricting CCS availability, followed by the level of demand reduction possible and then the level of nuclear deployment achieved, as illustrated by the *1240* Equity case (Supplementary Figure 8).

Discussion

The analysis shows that pre-2050, national mitigation efforts needed to stay within Equity-based budgets (and 590 Inertia) are likely to be underestimated without a longer term perspective on the necessary emission reductions. Both Equity cases require higher rates of decarbonisation than those projected under the current UK policy framework, which is based around achieving ambitious (but not net-zero) decarbonisation targets by 2050. An important implication of this is that, given the relationship between cumulative CO_2 emissions and surface temperature rise, pre-2050 emission reduction targets should be informed by the overall long term objective of limiting warming to well below 2°C. If not, there is a real risk that insufficient action is taken out to mid-century to affect a transition that stays within the available carbon budget implied by the Paris Agreement's headline goals.

We observe that the current UK policy framework locks-in a strategy that underestimates the levels of low carbon technology deployment required to meet an Equity-based carbon budget. Specifically, the role of commercially-deployed CCS appears critical. The feasibility of scaling this type of technology depends on demonstrating its commercial viability. Therefore, the UK government's decision to scrap its CCS demonstration programme in 2015 for the second time in 5 years appears short-sighted[32]. Secondly, a quicker phase out of fossil-based generation, and higher deployment of wind and nuclear power is required in the power sector. Thirdly, there is a need for more rapid and earlier reductions in emissions from the transport and building sectors. In short, the results put into sharp focus the need for a more ambitious policy package if Equity-based budget cases are to be achieved.

Our analysis suggests that under the Equity allocation approach, the UK's legislated targets would need to be strengthened to include a net-zero target no later than 2070, thereby providing a clear policy direction[33], and to be founded on a carbon budget with at least a 66% probability of staying below 2 °C. This conclusion broadly holds for the budget case 915 Blend as described in the Supplementary Note 2 (see Supplementary Figure 3), which takes the central value from the global budget range and uses the hybrid allocation approach, Blend, from Raupach et al.[20]. For a developed country such as the UK, a net-zero target in line with the ambition level expected under the Paris Agreement would form a useful basis for evaluating the sufficiency of pre-2050 actions.

The question remains how far below a 2 °C-type budget countries can push? One could argue that our findings for the 590 Equity case gives some indication of the actions required to meet a 1.5 °C carbon budget, although the former is still somewhat higher. Our analysis for the UK shows that, barring an unprecedented fall in demand for energy or radical breakthroughs in sequestration technologies, realising a net-zero energy system prior to 2050 appears improbable. At the very best, this would require radical and immediate action across all sectors and a rapid shift away from fossil fuels, both of which are happening but at comparatively sedentary rates[34]. While such a target could be considered politically infeasible, this type of analysis helps bridge the gap between the international political rhetoric of what is desirable and an evidence-based national level assessment of what could be achieved. This analysis provides an insight into just how challenging the required action is and helps expand the evidence base, which in the UK context, is recognised to be lacking to date[35].

The broader findings here are wholly relevant for decision makers across the developed world in the post-Paris Agreement era. As countries are encouraged to revisit the ambition in their NDCs, the end goal of net-zero GHG emissions can be used to guide both near and longer term strategy. The longer term objective will be feasible only with the necessary action in the short term while the carbon budget still exists within which to manoeuvre. Crucially, therefore, national climate policy analyses will need to extend their time horizons, explore stronger ambition, and effectively assess the uncertainties that are most relevant to their national circumstances.

Methods

To explore the implications of emission reductions in line with the Paris Agreement level of ambition, we perform a scenario sensitivity analysis of the UK energy system. The UK is widely regarded as being amongst the group of advanced economies which have the most ambitious goals, legislating for a legally binding 2050 GHG target[36] that has, in recent years, appeared to engender broad cross-party political support[37]. Additionally, the setting of climate targets in the UK has been informed by an evidence based process using multiple model-based analyses [38,39]. This case study therefore explores whether a post-2050 net-zero target could necessitate a rethink of the current policy architecture, ambition level, and approach to modelling.

The UKTM model

For the analysis, we use the UK integrated energy system model, UKTM[40]. This model has been developed at the UCL Energy Institute over the last few years as a successor to the UK MARKAL model [41]. UK MARKAL was a major analytical framework used to underpin UK energy policy making and legislation from 2003 to 2013 [38,42,43]. A version of UKTM is now being utilised by the UK Department of Business, Energy and Industrial Strategy (formerly the UK Department of Energy and Climate Change) to inform their climate policy analysis, including the 5th Carbon Budget[44].

UKTM represents the technology and fuel choices across different energy-using sectors under decarbonisation objectives. These choices are made based on what is economically-optimal, subject to numerous constraints that reflect system characteristics. These include balancing of supply and demand across multiple diurnal and seasonal time periods, limits on technology build rates, and representation of available resources. A key strength of this approach is that it permits trade-offs between actions in one sector versus another, and allows for full emissions accounting. The model is divided into three supply (resources and trade; processing and infrastructure; and electricity generation) and five demand sectors (residential, services, industry, transport and agriculture). All sectors are calibrated to UK energy balances in the base year, 2010[45], for which the existing stock of energy technologies and their characteristics are taken into account.

The large variety of future supply and demand technologies are represented by techno-economic parameters such as the capacity factor, energy efficiency, lifetime, capital costs, O&M costs etc. For most technologies or technology groups, growth constraints between 5 to 15% per year are fixed to ensure realistic future technology deployment rates. With respect to future technology costs, exogenous learning rates are applied, especially in the case of less mature electricity and hydrogen technologies, assuming that the UK is a price taker for globally developing technologies. A global discount rate of 3.5% p.a. for the first 30 years and 3% afterwards is used based on Government guidance on economic appraisal [46]. In addition, sector-specific discount rates are included to reflect the varying private costs of capital by sector (10% for all energy supply sectors, industry, agriculture and service sectors, 7% for transport, and 5% for the residential sector[39]).

While UKTM has flexible time periods, and can be run for any time horizon up to 2100, our analysis uses two single-year time periods representing 2011 and 2012 and there-after five year periods from 2015 up to 2100. To represent changes in demand across seasons and hours of the day, it features a time resolution of 16 time-slices (four seasons and four intra-day time-slices). This allows for some representation of peak demand, system security via a peak reserve margin, and therefore key requirements for power system operation. In addition to representing energy flows, UKTM models both energy and non-energy related CO_2, CH_4, N_2O and HFC emissions, although non-CO_2 GHGs have not been explicitly considered in this analysis.

Table 1. UKTM sector descriptions

Sector	Description
Resources and trade (UPS)	Includes potentials and cost parameters for domestic resources and traded energy products. Fossil fuel prices are sourced from DECC projections [47], while the assumptions on bioenegy potentials are aligned with the CCC's Bioenergy Review [48].
Energy processing (PRC)	Covers all energy conversion processes apart from electricity generation, including oil refineries, coal processing, gas networks, hydrogen production, bioenergy processing as well as carbon capture and storage (CCS) infrastructure.
Power generation (ELC)	Represents a large variety of current and future electricity generation technologies as well as storage technologies, the transmission grid and interconnectors to continental Europe and Ireland. The technology assumptions are mostly aligned with DECC's Dynamic Dispatch Model (DDM[49]).
Residential (RES)	Domestic housing is divided into existing and new buildings with existing buildings being further differentiated along the categories of flats/houses and cavity-walls/solid-walls. In addition to a large portfolio of heating technologies for the two main energy service demands of space heating and hot water, other services like lighting, cooking and different electric appliances are represented. The technology data is mainly aligned with the National Household Model (NHM).
Services (SER)	As per the residential structure, but with the building stock divided into low- and high-consumption non-domestic buildings. The technology data is mainly aligned with the National Household Model (NHM).
Industry (IND)	Divided into 8 subsectors of which the most energy-intensive (iron & steel, cement, paper and parts of the chemicals industry) are modelled in a detailed process-oriented manner [50], while the remainder are represented by generic processes delivering the different energy services demands. Data are aligned with DECC assumptions[51].
Transport (TRA)	Nine distinct transport modes are included (cars, buses, 2-wheelers, light goods vehicles, heavy goods vehicles, passenger rail, freight rail, aviation and shipping). Technology parameters for road transport are mainly sourced from work by Ricardo-AEA[52].
Agricultural and land use (AGR)	Represents, in addition to processes for the comparatively small fuel consumption for energy services, land use and agricultural emissions as well as several mitigation options for these emissions based on work by Defra[53].

Sensitivity analysis approach

The scenario sensitivity analysis focuses on the key set of identified system uncertainties – carbon budget level, CCS deployment, role of nuclear, bioenergy resource level, resulting in 64 model runs (Supplementary Figure 1). For comparison, an illustrative UK policy case has also been modelled under the same uncertainty dimensions (16 model runs), based on the current policy framework but with 2050 ambition extended to 2100.

The global carbon budget range for 2°C (66% probability) is taken from the IPCC AR5 assessment. The low and high end of the budget range, 590-1240 $GtCO_2$, are used in the modelling. This is similar to the 1.5°C (33% probability) budget range [1]. The 1.5°C (50%

probability) budget range was not analysed due to its stringency (Supplementary Figure 2). To allocate a share of the global budget to the UK, we use two approaches [20] – i) equity, where allocation is on an equal per-capita basis, giving the UK a 0.8% share of the budget, and ii) inertia, determined by its 2010 share of global emissions, giving the UK a 1.5% allocation. These provide both a high and low allocation stringency respectively, and in combination with the global budget range, result in a wide spread of UK budgets for analysis, compliant with the 2°C climate objective. An additional sensitivity 915 Blend provides a central case for comparison, and is described further in Supplementary Note 2.

The budget is implemented between 2015-2100, leaving the model free to determine the timing of emissions, and the point at which net-zero is reached. To illustrate the requirement of the Paris Agreement requiring developed countries to achieve net-zero faster than other nations, we impose a constraint that net-zero must be achieved at least by 2080. The modelling approach does not however permit net negative accounting. This is so that negative emission technologies are deployed sparingly in order to deal with hard to mitigate sectors rather than at a larger scale to provide system wide flexibility and reduce the need for near term action (see Supplementary Note 2).

CO_2 offsets are not permitted, meaning that the UK has to ensure all reductions are accounted for domestically. This is broadly consistent with the UK's current approach, and the guidance provided by the statutory UK climate advisors, the Committee on Climate Change [44]. While offsetting could provide a degree of flexibility in the transition, it is assumed that other countries will also be aiming for net-zero, and therefore will have limited scope for supplying offsets, with those available likely to be at high market prices.

Uncertainty regarding the role of nuclear power and CCS technology is reflected in divergent high and low cases. The high case uses constraints that are in line with current UK government assumptions. Nuclear energy can contribute a maximum of 33 GW to electricity system capacity, while CCS technologies in electricity generation, industrial CCS and hydrogen production are commercially available from 2030 onwards, with permitted annual growth at 5-10%. In the low case, the nuclear capacity is capped at 15 GW (close to the currently installed 11 GW), reflecting constraints on financing and public acceptance. In the low case for CCS, commercial availability is delayed to 2040 and the growth constraint tightened, from 10% to 5% per year.

For the UK, bioenergy resources have been shown to be the most critical uncertainty for meeting decarbonisation goals cost-effectively [54]. A high and low case have been formulated based on published bioenergy scenarios (Supplementary Note 1). The high case reflects extending land use for bioenergy, allowing bioenergy to grow to four times the current level, while the low case reflects constraints on land use and restrictions on imports.

Demand reduction resulting from changes in the price of energy services completes the scenario sensitivity set. Providing a crucial policy mitigation option in those sectors where technology-based solutions are costly, limited or exhausted, reductions in demand are accounted for as welfare losses, allowing for a system cost trade-off with supply-side options. Low and high own-price elasticity assumptions have been used for the sensitivity range [30]. The absolute limits of demand reduction have been set at 15% per annum in the low case and 40% per annum in the high case, versus an inelastic counterfactual for each. Reductions in demand resulting from non-price factors, such as societal change, are not represented.

Data Availability Statement: The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

S.P. and B.F. set-up and undertook the energy modelling. All authors contributed to designing the research, analysing the results and writing the paper.

Competing financial interests

The authors declare no competing financial interests.