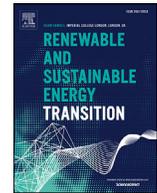


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# Renewable and Sustainable Energy Transition

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Perspective

## Which way to net zero? a comparative analysis of seven UK 2050 decarbonisation pathways

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### ABSTRACT

Since the UK's Net Zero greenhouse gas emissions target was set in 2019, organisations across the energy systems community have released pathways on how we might get there – which end-use technologies are deployed across each sector of demand, how our fossil fuel-based energy supply would be transferred to low carbon vectors and to what extent society must change the way it demands energy services. This paper presents a comparative analysis between seven published Net Zero pathways for the UK energy system, collected from Energy Systems Catapult, National Grid ESO, Centre for Alternative Technology and the Climate Change Committee. The key findings reported are that (i) pathways that rely on less stringent behavioural changes require more ambitious technology development (and vice versa); (ii) electricity generation will increase by 51–160% to facilitate large-scale fuel-switching in heating and transport, the vast majority of which is likely to be generated from variable renewable sources; (iii) hydrogen is an important energy vector in meeting Net Zero for all pathways, providing 100–591 TWh annually by 2050, though the growth in demand is heavily dependent on the extent to which it is used in supplying heating and transport demand. This paper also presents a re-visited analysis of the potential renewable electricity generation resource in the UK. It was found that the resource for renewable electricity generation outstrips the UK's projected 2050 electricity demand by a factor 12–20 depending on the pathway. As made clear in all seven pathways, large-scale deployment of flexibility and storage is required to match this abundant resource to our energy demand.

## 1. Introduction

### 1.1. Context

In 2019, the UK became the first major economy to legislate for greenhouse gas (GHG) emissions neutrality, enshrining Net Zero GHGs by 2050 [1]. In the same year, 79% of UK final energy demand was derived from burning fossil fuels [2]. While this is the lowest proportion it has been since the Industrial Revolution, it demonstrates the scale of the challenge ahead. UK GHG emissions in 2019, including the country's share of international aviation & shipping (IAS), were 539 MtCO<sub>2</sub>e [3].

Since the publication of the Net Zero target, several Net Zero pathways have been released from organisations across the energy systems community. These pathways, though differing in their specifics, all lay out a general pathway from the present day to a 2050 UK economy that emits no more GHGs than it sequesters. The pathways all include a projection of how energy demand will evolve across sectors (for example, heating/cooling, transport and electrical appliances) and how each one can be decarbonised through a mixture of technological substitu-

tion and behavioural changes. All pathways rely on significant portions of electricity generation from renewable resources.

### 1.2. Introduction to the pathways

Two of the pathways are from the Energy Systems Catapult (ESC), a part-publicly funded centre that, amongst other things, provides whole-systems modelling of the UK energy system for addressing innovation priorities in the decarbonisation of the sector. These pathways are named 'Clockwork' (ESC-C) and 'Patchwork' (ESC-P); both are from the ESC's 2019 *Innovating to Net Zero* report [4]. These scenarios are designed to explore the effect of (de-)centralisation of the energy system and the extent to which behavioural shifts might interact with technology change: ESC-C represents a scenario with minimal behaviour shift and large-scale, centralised changes to energy supply accompanying significant advances in technology; ESC-P represents a scenario where a higher level of behavioural change is offset by a weaker central policy framework and less ambitious advances in technology. The intended purpose of the ESC pathways is to investigate the combinations of

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options in supporting “innovation and scale-up across low carbon technology, land use and lifestyle”; the pathways were designed to show the “combinations, interactions and trade-offs of competing decarbonisation approaches” [4].

The next three analysed pathways are from the 2020 edition of National Grid ESO’s *Future Energy Scenarios* (FES) [5], an annual publication from the electricity system operator (ESO) and gas system operator of Great Britain (GB) that explores how projected changes in the energy sector can be met given varying levels of societal change and differing rates of decarbonisation. Out of the four scenarios presented in FES, three of them meet the 2050 Net Zero target. Those three are analysed in this paper: ‘Leading the Way’ (FES-LTW), ‘System Transformation’ (FES-ST) and ‘Consumer Transformation’ (FES-CT). FES-LTW is the most ambitious of the FES scenarios in terms of societal change, including large-scale shifts away from private car use and high uptake of flexible demand schemes such as time of use (ToU) tariffs and vehicle to grid (V2G); FES-ST represents a scenario with minimal behavioural change and large-scale centralised changes including the conversion of the existing gas grid to hydrogen for residential heating (allowing a less drastic program of energy efficiency retrofits); FES-CT represents a scenario whereby near-total electrification of demand accompanies high energy efficiency and moderate levels of behavioural change. The intended purpose of the FES pathways is to explore options for the investment in energy infrastructure, and how this interacts with changes in energy demand from now to 2050 [5].

The sixth scenario is from the Centre for Alternative Technology (CAT), an educational charity dedicated to researching and communicating positive solutions for environmental change. In their 2019 ‘Zero Carbon Britain’ pathway (CAT-ZCB) [6], a 100% renewable electricity system is accompanied by seasonal storage of synthetic hydrocarbon fuels produced with hydrogen from renewables and biomass gasification to smooth out supply and demand and provide energy for aviation & shipping. This scenario involves significant behavioural changes, including relatively ambitious reductions in meat & dairy consumption and to allow land currently used for rearing livestock to be re-purposed for CO<sub>2</sub> capture via afforestation. The intended purpose of the CAT-ZCB pathway is as a “research project that shows that a modern, zero-emissions society is possible using technology available today” [6].

The final scenario analysed is from the Climate Change Committee (CCC), the independent, statutory advisor on climate change to the UK government. Their ‘Balanced Pathway’ (CCC-B), released as part of the 2020 Sixth Carbon Budget recommendation [3], is (as the name suggests) a compromise between societal change and technological fixes, including limitations on car miles and aviation demand mixed with high rates of electrification and a supply of low-carbon hydrogen for long-term storage of renewable electricity and fuels for aviation and shipping. The intended purpose of the CCC-B pathway is as the basis for the CCC’s recommendation to the UK government as to how it can meet its sixth carbon budget (2033–2037) and the longer-term 2050 Net Zero target.

### 1.3. Previous work on pathways to decarbonisation and their analyses

As the number of countries mandating decarbonisation targets grows, there has been growing interest in the development of pathways that enable the realisation of low-carbon economies. From reviewing the literature, it is clear that the majority of these pathways in research circles have been focused on the electrical power sector. In [7], the authors model 100 scenarios of electricity generation, storage and transmission for decarbonisation pathways for Central Europe in realising a zero carbon electricity system by 2035. The study highlights the trade-offs between employing different technological options in minimising cost, maximising regional equality in distribution of these costs and maximising renewable generation; the paper highlights that the optimal pathway for each of these objectives is generally different. In [8], potential pathways are explored for the decarbonisation of the New England electricity mix. An overall ‘sustainability score’ is given to

each pathway based on a number of factors, including its contribution to reducing GHG emissions, improving air quality, as well as minimising water consumption and system cost. An approach is proposed in [9] for including human health indicators as input into planning an electricity generation mix, including health damage from GHG emissions and other pollutants (both are monetised in terms of \$/MWh). In [10], a graphical method called Carbon Emissions Pinch Analysis (CEPA) is used to examine alternative pathways for a Net Zero UK electricity system, considering constraints such as the current fleet of power stations, potential deployment of renewable generation and the availability of particular technologies. The method resembles the merit order by which bids and offers to supply and purchase electricity are made in the UK electricity market, starting with the lowest-cost means of generation first. A key conclusion from [10] is that significant bioenergy with carbon capture & storage (BECCS) capacity is required to meet Net Zero, given the residual emissions from the existing fleet of fossil-fuelled power stations. The authors in [11] use multiple capacity expansion and dispatch models to examine the differences in different pathways for a Net Zero electricity system. The study assumes fixed costs for each technology and a fixed annual electricity demand prediction, but employs 8 different scenarios, each with different technology mixes based on separate narrative storylines. The study concludes that systems with a high diversity in generation technologies lead to higher plant utilisation, which reduces system cost. Furthermore, the study emphasises the value of ‘firm clean’ power generation such as nuclear and combustion of low-carbon hydrogen in minimising system cost.

The electricity system certainly appears to be the best-represented part of the energy system in the development of decarbonisation trajectories; while [12] and [13] present studies concerned with decarbonisation pathways for industrial energy consumption, and [14] presents the development of pathways for the decarbonisation of the UK residential heating sector (including consideration of the supply of low-carbon hydrogen for a potential hydrogen-based heating system), such examples are scarce in comparison to studies in electrical systems. In [15], whole energy systems are considered in the development of decarbonisation pathways for several Latin American countries within a 1.5–2 °C warming framework. Unlike the works in [7–14], the study presented in [15] considers other parts of the economy, such as land use change, forestry and agriculture.

There have also been several works in the literature that have reviewed sets of decarbonisation pathways. In [16], 40 separate pathways across academic and government publications are reviewed as to the most prevalent technologies and system costs. A review of socio-technical energy system models is presented in [17], from which the authors present a taxonomy for such models. In [18], failure modes of a transition to Net Zero are identified (broadly defined as: failure to deploy infrastructure at pace, failure to mobilise capital, failure to keep the public on-side and failure to mitigate disruption in fossil fuel industry jobs) based on potential US decarbonisation pathways. A review of pathways is presented in [19] which, through numerical examination of 177 scenarios from the 1.5 °C scenario database hosted by the International Institute for Applied Systems Analysis (IIASA), presents analysis of the year of peak emissions and year of Net Zero achievement by region for the different scenarios.

While there have been many studies published on the development of Net Zero trajectories for the energy system (although usually for certain parts of the energy system, more often than not electricity), there exists a research gap in comparative analysis of post-Net Zero target (2019) trajectories for the UK energy system. Furthermore, to the authors’ knowledge, there has been no further systematic quantification of the UK’s total renewable electricity generation resources since David MacKay’s<sup>1</sup> *Sustainable Energy – Without the Hot Air* in 2008 [21]. Due

<sup>1</sup> MacKay was appointed as the first Chief Scientific Advisor to the Department of Energy & Climate Change (DECC), the precursor to the current Department for

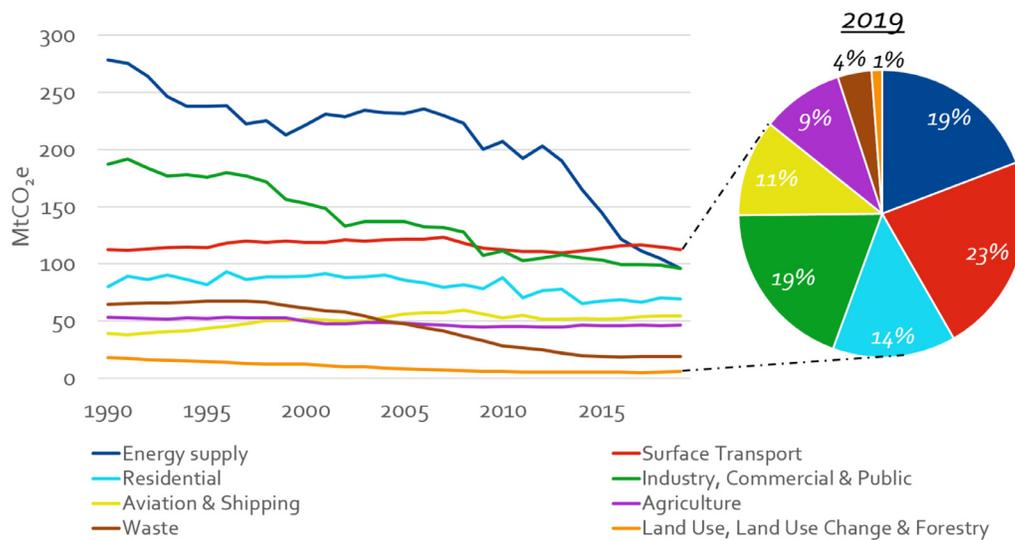


Fig. 1. UK emissions by sector (including the UK's share of international aviation & shipping), MtCO<sub>2</sub>e, 1990–2019, and percentage, 2019 – data from [22].

to the importance of having an abundant renewable electricity supply in all seven of the Net Zero pathways analysed in this paper, and the significant changes in technology since 2008, an upgrade to these numbers is due. This paper aims to fill these research gaps by addressing the research questions presented in Section 1.4.

#### 1.4. Research questions

This paper aims to shed light on energy systems transitions for a Net Zero UK energy system – with applicable lessons for comparable high-income countries – by addressing the following research questions:

1. How do these pathways compare in terms of i) how they assume energy demand will change, ii) what technologies will be used to facilitate drastic reduction or elimination of burning fossil fuels, and iii) how are decarbonisation efforts in different sectors likely to be traded off with one another in meeting Net Zero GHG emissions overall?
2. Given the significant increase in renewable electricity generation to follow these pathways, are we suitably resourced in the UK to allow this transition to happen?

The comparisons made can assist researchers and policymakers assess the most favoured pathways (combining technology change and societal change), and can enable the assessment of Government policy against pathways to a binding target.

The rest of this paper is organised as follows: Section 2 presents a discussion on progress in UK energy system decarbonisation; Section 3 presents a discussion on the key elements of energy system decarbonisation common to all pathways; Section 4 presents a comparative analysis of all seven pathways; 5 presents a re-visited analysis of total UK renewable resources; Section 6 presents a conclusion of the main findings from this analysis.

## 2. Taking stock: Progress in UK energy system decarbonisation

Fig. 1 shows UK emissions (MtCO<sub>2</sub>e) by sector from 1990 to 2019 inclusive (left), and a pie chart showing the proportion of each sector to total emissions in 2019, which were 539 MtCO<sub>2</sub>e [22]. Whereas some

sectors, such as industry, commercial & public, non-energy and particularly energy supply have seen significant reductions in emissions between 1990 and 2019, residential emissions have been stagnant and transport (both surface transport and aviation & shipping) emissions have increased over the period.

The change in emissions shown in Fig. 1 depend on the level of energy demand, which vectors are used to supply demand and the efficiency of end-use technologies. To allow comparison in energy terms, Fig. 2 shows UK energy flows in 1997 (top) and 2019 (bottom). Note that 1997 was chosen because it is the earliest UK energy balance available, included in the Digest of UK Energy Statistics (DUKES) for the year 2000 [23].

Aside from changes in energy demand, rates of progress in improving energy efficiency and fuel switching can be seen in Fig. 2. In terms of energy efficiency, while total residential energy demand has fallen by 8% against a 17% increase in the number of households between 1997 and 2019 [25] and total industrial energy demand has fallen 35% against a reduction of 4% in industrial production between the same years<sup>2</sup> [28], other sectors have remained stagnant, or worse – in the case of transport – increased in energy demand between 1997 and 2019. In terms of fuel switching, while notable progress has been made in the reduction of the use of coal (having reduced 86% between 1997 and 2019, driven primarily by the near-elimination in its use for electricity generation) and the expansion of biomass and wind, solar & hydro electricity (having increased their contribution to energy supply by 1580% and 890% respectively), fossil gas and petroleum have remained persistent vectors in the UK energy sector, between them comprising the majority share in all four end use categories for both years in Fig. 2.

The progress (and lack thereof) in the transition away from fossil fuels between 1997 and 2019 as highlighted in Fig. 2 illustrates the scale of the remaining challenge to which the Net Zero pathways analysed in this paper seek to meet.

Business, Energy & Industrial Strategy (BEIS). The MacKay Carbon Calculator [20] allows anyone visiting the web page to develop their own future energy scenarios, exploring the range of options available in meeting Net Zero by 2050. The publication is discussed further in Section 5.

<sup>2</sup> This is based on the Index of Production (IoP), which is calculated on a monthly basis by taking turnover and removing the impact of price changes or by using direct volume estimates. While there have been major improvements in sector-by-sector industrial energy intensity (unit energy consumption per unit industrial output) in the UK over the last few decades resulting from improvements in energy efficiency [26], the shift from traditional, energy intensive industries such as steel to high value manufacturing over a similar period [27] accounts for some of this change.

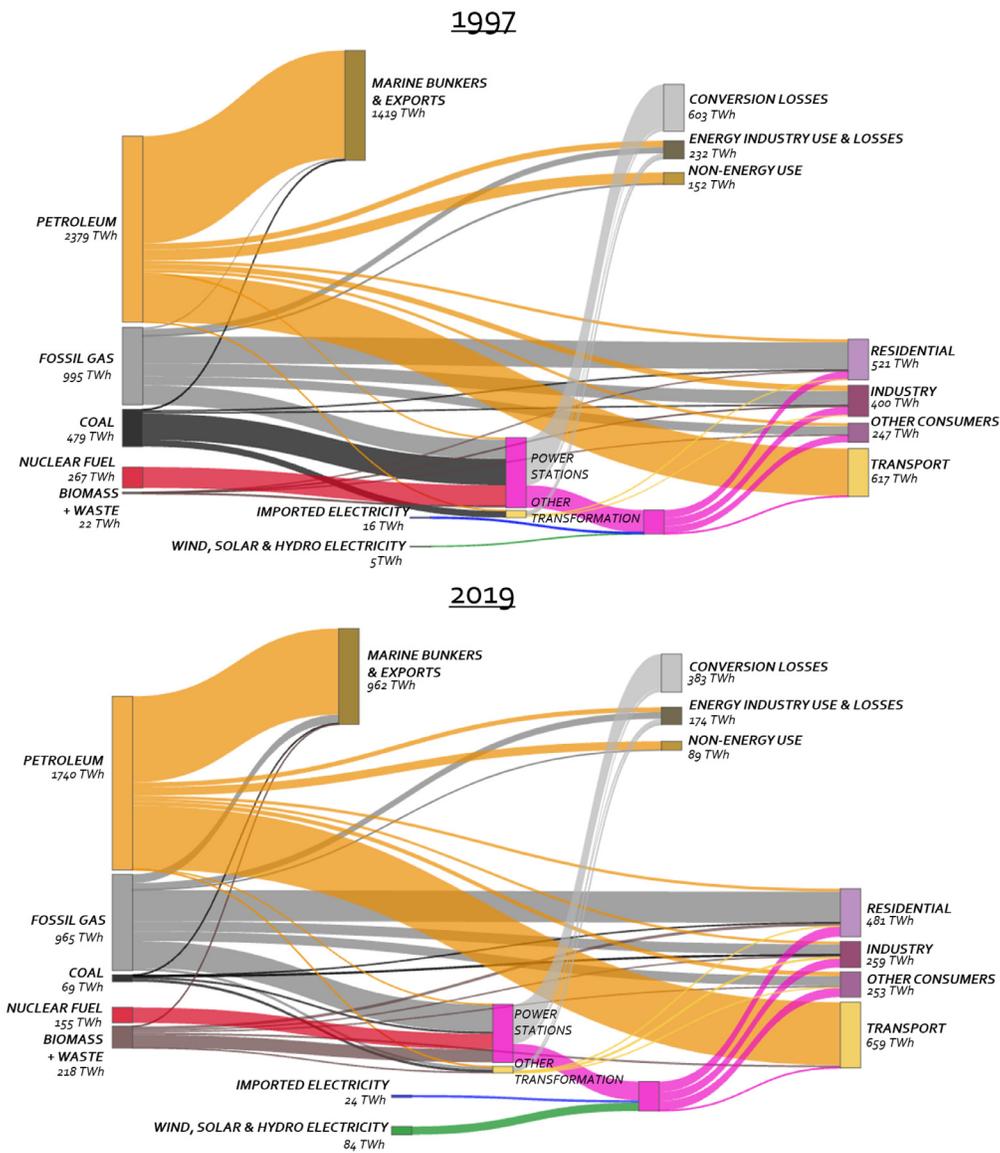


Fig. 2. UK energy flows, 1997 (top) and 2019 (bottom); created using Plotly [24] from data in [23] and [2].

### 3. Key elements of pathways to energy system decarbonisation

There are key elements in energy system decarbonisation scenarios, common to all seven published UK Net Zero pathways analysed in this paper: (i) low carbon energy vectors, end-use technologies and demand management; (ii) technological fixes and behavioural changes; (iii) greenhouse gas removals; (iv) emissions accounting and cross-sector interactions. In the following sections 3.1–3.4, each of these key elements is described in more detail across the seven pathways analysed. Section 3.5 presents a comparison of the modelling methods used in each pathway to allow fair comparison between the pathways.

#### 3.1. Low carbon energy vectors, end-use technologies and demand reduction

Replacing fossil-derived energy vectors for low carbon energy vectors involves transitioning to alternative means of converting energy from one form to another in satisfying our demand for energy services. In all seven pathways analysed in this paper, electricity and hydrogen are crucial low carbon energy vectors that are used in varying amounts. In all pathways, the vast majority of electricity generation is from low

carbon sources (renewables or nuclear) and the means to generate hydrogen varies between electrolysis of water using low carbon electricity, biomass gasification or chemical processing of natural gas (the latter two involving carbon capture & storage (CCS) to reduce process emissions).

Substitution of end-use technologies includes: the electrification of large parts of heating and transport; the substitution of battery electric and hydrogen fuel cell-powered surface transport; the derivation of low-carbon fuels (including ammonia and synthetic hydrocarbons) from hydrogen (produced from one of the methods described above) and carbon, captured either directly from the air – i.e. direct air CCS (DACCS) – or from biomass gasification for powering heavy transport including shipping and some aviation demand; the use of heat pumps (HPs), district heating and hydrogen boilers for domestic heating; transitioning industrial energy demand to electricity and low carbon hydrogen-derived fuels.

An important part of allowing the substitution of low-carbon energy vectors to effectively reduce emissions is by demand reduction. This can be divided into two broad categories. The first refers to demand reduction that can be brought about by technology switching, including the electrification of heating and transport, and the installation of energy efficiency measures. The second refers to demand reduction that

relies on changes in energy use practices, such as choosing active/public transport over private car use, eating less meat and choosing to fly less. These two categories have different levels of impact on people's everyday lives, and therefore require very different levels of social license to enact. However, coordinated technology and governance can make changes in energy use practices much more practical: [29] reports that UK energy demand could be reduced by 50% by 2050 relative to 2020 levels without negatively impacting quality of life.

### 3.2. Technological fixes and behavioural changes

Behavioural changes in energy consumption will play an increasing role in decarbonisation, particularly as the energy vectors used to supply heating and transport are shifted from fossil fuels to low carbon sources [30]. In their *Further Ambition* scenario, the first-published Net Zero scenario<sup>3</sup> from the CCC [31], 38% of emissions abatement would come from the substitution of low carbon technologies or fuels; 9% of emissions abatement would come from societal or behavioural changes; 53% of emissions abatement would come from a combination of technology and societal or behavioural change.

While some sources of emissions abatement are based purely on technology substitution (for example, most emissions abatement in the UK economy to date has been as a result of decarbonisation in the electricity sector by the phasing out of coal-fired generation and increasing installations of renewables [32]), others are based purely on behaviour change (for example, a transition towards plant-based diets as a means of emissions abatement – quantified by an increase in the amount of protein per unit of GHG emissions in [33]). Furthermore, the relationship between technology and behaviour is intertwined. As energy demand is decarbonised, behavioural change is going to be increasingly linked to technological substitution. For instance, the uptake of HPs – relied upon for the majority of emissions abatement in the domestic heating sector in six out of seven pathways analysed in this paper – has been found to require learning on the behalf of consumers [34] and, in some cases, a level of engagement (including possible upgrades to building efficiency, as is typically required for HP integration [35]) that serves as a barrier to the technology's adoption [36,37]. Similar behavioural changes are required for the adoption of other low carbon technologies, such as electric vehicles (EVs), relating to users' adjustment to the variety in location and type of charging infrastructure (versus petroleum refuelling infrastructure), and participation in electricity system flexibility, relating to consumers' uptake of variable tariffs and remotely controllable electrical appliances [38].

### 3.3. Greenhouse gas removals

There are residual emissions by 2050 in all seven pathways analysed in this paper, notably from 'hard to decarbonise' sectors such as aviation and agriculture. To offset these, varying degrees of engineered GHG removals<sup>4</sup> are used across all pathways. The methods by which GHGs are removed from the atmosphere differ by pathway, though bioenergy with CCS (BECCS) and DACCS feature prominently, contributing to GHG removals in five out of seven pathways. Nature-based solutions, such as afforestation and peatland restoration, also feature in three out of seven pathways. Aside from the methods of GHG removals listed, there are many more – the reader is directed to [41] for a comprehensive guide.

Another crucial application of CCS in six out of seven pathways is to capture emissions from heavy industrial processes that are not easy to

decarbonise, any remaining fossil-fuelled electricity generation or hydrogen production from chemical processing of fuels. An important assumption in the application of CCS is the capture rate, i.e. how much of the CO<sub>2</sub> in an exhaust can be captured. In the pathways analysed in this paper, the assumed capture rate varies in the range 95–99%. While this is theoretically possible, it requires advancement on what has been achieved to date: [42] states that modern CCS plants aim for 85–90% capture rates; while [43] states that the Petra Nova carbon capture & utilisation (CCU) plant in the US has achieved up to 95%, [44] reports capture rates from a variety of industries to be in a wide range from 8% to 94%.

### 3.4. Emissions accounting and cross-sector interactions

Emissions accounting sets which parts of whole-economy emissions are to be included in scope for decarbonisation. The ESC and FES pathways (i.e. ESC-C, ESC-P, FES-LTW, FES-ST and FES-CT) all follow territorial emissions accounting in line with the 2008 Kyoto Protocol [45], and what is reported annually by the UK government (for example in [46]). Notably, this excludes the UK's share of IAS and emissions associated with the production of goods consumed in the UK<sup>5</sup> While the ESC and FES pathways give numbers for changes in aviation and shipping demand, the emissions associated with IAS<sup>6</sup> are not accounted for in their overall GHG balance. The CAT and CCC pathways (i.e. CAT-ZCB and CCC-B) both include emissions from the UK's share of IAS (i.e. aircraft and ships that depart the UK and land somewhere else), but none of the seven pathways reviewed include emissions from the offshore production of goods for the UK<sup>7</sup>

Relative trade-offs of decarbonisation in – and interactions between – different sectors is key to any pathway. This can be seen, for example, in the CCC-B pathway: scaling up BECCS to remove 52 MtCO<sub>2</sub>/year by 2050 is stated to require (in addition to imports) 720,000 ha of land dedicated to cultivation of energy crops (approximately 3% of the UK's total land area). As this land is in direct competition with land already used for agriculture<sup>8</sup>, the CCC-B pathway includes a requirement to free up some of this agricultural land by reducing meat and dairy consumption by 34% and 19% respectively.

The analysis presented in Section 4 provides a visual representation of how trade-offs are made across sectors for all seven pathways.

### 3.5. Modelling and analysis techniques

Before comparing the results of each of the seven pathways, the modelling and analysis techniques in each scenario should first be compared. All pathways are centred on the development of one or a set of 'story-lines': narratives that build on a set of radical changes to the current UK energy system, comprised of the availability and costs of technologies that can reduce, or eliminate, reliance on fossil fuels, and, often to a lesser extent, of societal willingness to change demand of energy service.

The ESC pathways (ESC-C and ESC-P) are based on the Energy Systems Catapult's Energy Systems Modelling Environment (ESME), an optimisation model that returns the least-cost combination of energy resources and technologies that satisfy UK energy service demands from

<sup>5</sup> As of April 2021, the UK government will include its share of IAS in its sixth carbon budget (2033–2037) following CCC advice, which has consistently been to include IAS in UK carbon budgets [47].

<sup>6</sup> Of particular importance are emissions from international aviation, which made up 96% of aviation emissions and 70% of IAS emissions in 2019 [48].

<sup>7</sup> CAT estimates that UK emissions including all goods and services consumer in the UK (imports minus exports) was 784 MtCO<sub>2</sub>e in 2016, and up to 884 MtCO<sub>2</sub>e including land use change abroad attributed to UK food consumption [6]. For reference, domestic (excluding IAS) emissions in 2016 were 473 MtCO<sub>2</sub>e, and emissions including IAS were 515 MtCO<sub>2</sub>e.

<sup>8</sup> 70% of the UK's land is used for agriculture, the vast majority of which is used for feed and pasture of beef and lamb [49].

now to 2050. The constraints applied include emissions targets, resource availability and technology deployment rates. The model includes a multi-regional representation of the UK which can assess infrastructure needs to link supply to demand, including electricity, gas and CO<sub>2</sub> networks. ESME has the capability for a Monte Carlo approach, which may be used to explore many scenarios of technology deployment and infrastructure provision to identify low regret options that feature consistently across well-performing runs (this capability is demonstrated in [4]). The difference in the two ESC pathways is built on two distinct forecasts of the evolution of UK energy demand (for example, average indoor temperatures and air miles per person per year) and a distinction of which of a series of “speculative” measures are applied. These represent further technology innovation, behavioural shifts and land use changes (for example, increasing UK biomass imports, reducing meat consumption or increasing carbon capture rates for CCS applied to heavy industry). They are applied to the ESC modelling as changes to model constraints – for example, increasing the carbon capture rate of CCS plant from 95% to 99%.

The FES pathways (FES-LTW, FES-CT and FES-ST) are based on a framework of different modelling techniques to represent different parts of the UK energy system. Congruent with these pathways being developed by the system operator of the UK electricity and gas transmission networks, historical electricity and gas demand data are used with projections on economic output, energy prices and uptake rates of energy efficiency measures and end-use technologies to perform regression analyses to produce forecasts for energy demand across residential, commercial and industrial sectors of the UK economy. The outputs of these sector-based simulation models, which take in a wide variety of data to model annual electricity and gas demand, are input into UK TIMES [50], a cost-minimisation whole energy systems modelling tool used to direct the FES scenarios towards the Net Zero target. The modelling in UK Times is augmented by National Grid ESO’s modelling of energy storage, distributed generation and demand response. The three different FES scenarios are based on different changes in energy demand, different rates of uptake for various technologies and differing levels of flexibility in energy demand.

The CAT pathway (CAT-ZCB) is based on a Net Zero scenario that allows total decarbonisation of the UK energy system according to a set of principles (for instance, supplying demand by 100% renewable energy). Future demand is modelled, similarly to the other six pathways, on government projections of population, household size and demographic change. This is then assumed to shift from a baseline projection according to a set of assumptions pertaining to societal change, technology uptake and increasing energy efficiency. To test the suitability of the proposed Net Zero scenario, an energy model is used with historic weather data (that influences the availability of renewable supply and informs the necessary amount of energy storage at different timescales) to ensure that supply always meets demand. The model does not explicitly calculate the economic cost of meeting Net Zero.

The CCC pathway (CCC-B) is based on a synthesis of five pathways to Net Zero, consistent with the range of societal preferences for climate mitigation options as found from the deliberations of the UK Climate Assembly [51]. Out of these five exploratory scenarios based on varying levels of optimism regarding credible amounts of behavioural change and falling costs of key technologies, the Balanced pathway is intended to offer a compromise between reliance on technology change and behavioural change. These pathways build narratives in terms of behaviour change and technology costs as constraints into the CCC’s modelling: for example, 80% of total electricity generation by 2050 being from renewable generation, or 100% of private car sales being battery EVs by 2032. Demand projections are based on government datasets and research across the energy systems community, including modelling on energy demand reduction from the Centre for Research in Energy Demand Solutions (CREDS) and the ESME modelling framework used by the Energy Systems Catapult.

## 4. Comparative analysis of seven UK net zero pathways

### 4.1. Comparative analysis methodology

The seven pathways analysed in this paper were selected specifically as they represent a wide breadth of Net Zero scenarios for the UK energy system from reputable centres of energy systems modelling. Other scenarios do exist, and further comparison from the basis of this analysis would be a valuable piece of further work. Notable omissions from this analysis are the four other pathways released – aside from CCC-B – with the CCC’s Sixth Carbon Budget recommendation. These pathways, entitled Headwinds, Tailwinds, Widespread Innovation and Widespread Engagement, represent varying levels of technological and societal change. They have been purposely left out of this paper in the pursuit of clarity: it was Balanced pathway that was the basis for definition of the 6th Carbon Budget and of the UK’s Nationally Determined Contribution as part of the Paris agreement. However, in *Innovating to Net Zero* and *Future Energy Scenarios*, neither Energy Systems Catapult nor National Grid ESO recommend any particular one of their Net Zero pathways.

Each pathway was reviewed in detail, including the main modelling results and methodology documents. Where details were not clear, contact was made to each of the four organisations for points of clarification.

### 4.2. Limitations of this analysis

The limitations of the comparative analysis presented in this paper are as follows:

- This analysis is only able to compare results and descriptions of modelling methodologies, which vary in their depth of description between pathways. Ideally, all the modelling approaches would be open-source and validation runs could be conducted to compare models like-for-like.
- Some pathways are more prescriptive than others, which makes direct comparison difficult. For example, the CCC-B pathway prescribes that modal shift to public transport and active travel act to reduce car miles per person by 17% by 2050 compared to 2020. On the other hand, while the FES pathways have differing levels of modal shift between their pathways’ narratives, with FES-LTW seeing the largest shifts away from private car use, there is no quantified reduction in car miles given (there is, instead, a quantified reduction in car ownership). For a full breakdown of the comparison between pathways, see Annex A.
- Some pathways are intrinsically related to one another: for example, the FES and ESC pathways cite CCC advice on future aviation demand, and the CCC use ESME (the modelling environment used in the ESC pathways) for parts of their analysis. Therefore, there is a chance that pathways could be repeating results found in other pathways, which reduces the importance of a comparative analysis.

Bearing in mind the limitations of the study listed above, the results are presented in the following subsections.

### 4.3. Comparative analysis – overview

This section presents a comparative analysis of the Net Zero pathways analysed in this paper. Figs. 3, 4, 5 show, respectively:

- Key changes in energy demand, behavioural shifts and policy measures in each of the seven pathways, ranked in order to least to most drastic versus the current baseline (2019 or 2020, depending on the pathway)
- Key end-use technologies in each of the seven pathways, split into energy vector (electricity; hydrogen; fossil fuel)
- Supply of electricity and hydrogen for each of the seven pathways

Key changes in each sector of the UK economy are described in sections 4.4.1–4.4.10.

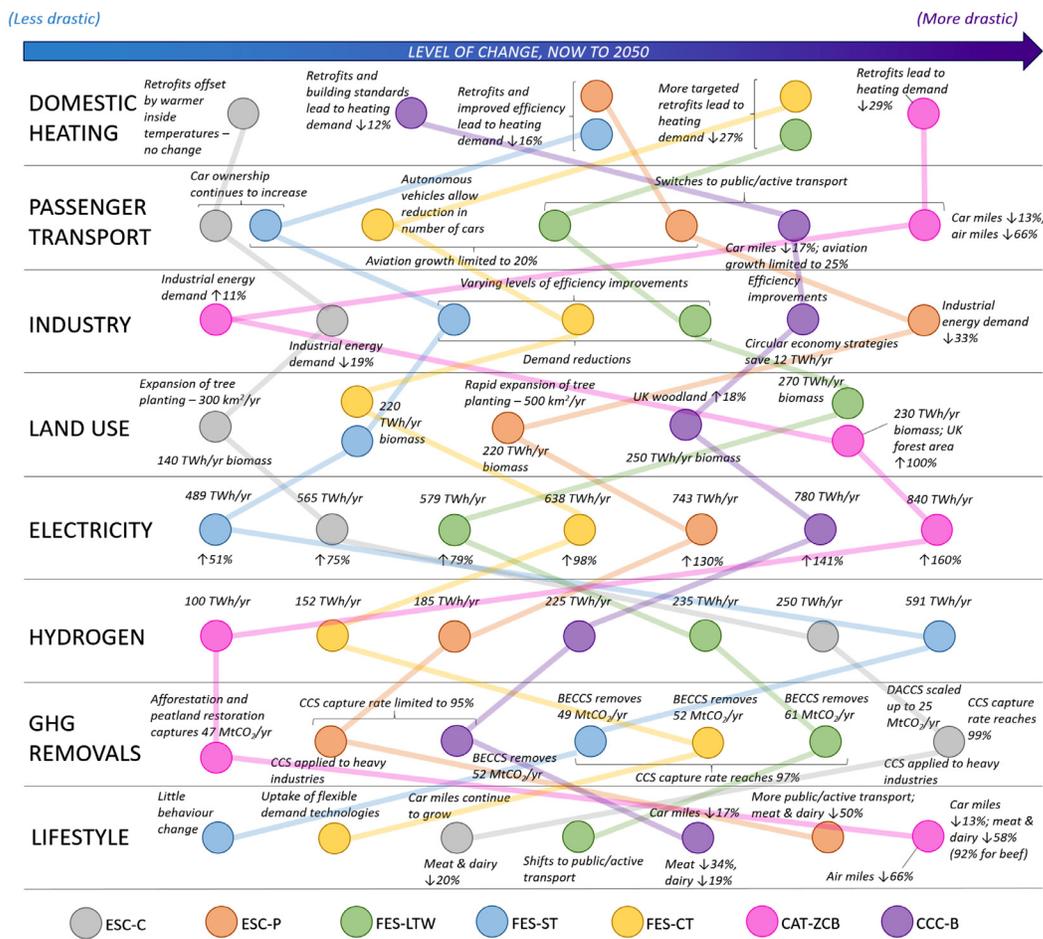


Fig. 3. Comparative level of demand change to 2050 for seven UK Net Zero pathways.

It should be noted that not all pathways are equal in their assessment for two reasons: firstly, as discussed in Section 3.4, only two of the seven pathways include IAS emissions in scope for decarbonisation; secondly, there are differences in the modelling and analysis techniques that underpin the scenario results, as discussed in Section 3.5. Ultimately, the ranking of how drastic one mitigation measure is over another – for example, whether reducing meat consumption or curbing private car use would be more of a stretch for societal habits – is a matter of opinion. Annotations are made for key values in Fig. 3, but for a complete set of results from each pathway the reader is directed to Tables 1, 2, 3, 4, 5, 6, 7.

#### 4.4. Comparative analysis – detail

##### 4.4.1. Residential heating

Energy demand for residential heating does not increase from today to 2050 in any pathway. In only one pathway, ESC-C, does heating demand remain static – this is as a result of efficiency improvements made to 10 million dwellings being offset by a move to higher indoor temperatures. In all other pathways, the effect of efficiency improvements outweighs any increase in thermal comfort; the reductions in energy demand range from 12% in CCC-B to 16% in ESC-P and FES-ST, to 27% in FES-LTW and FES-CT, to 29% in CAT-ZCB.

None of the seven pathways allow any domestic heating to be met by unabated burning of fossil fuels by 2050. Individual heat pumps in homes are an important technology in all pathways, varying from 27% of UK homes being fitted in FES-ST, the most hydrogen-reliant scenario,

to 74% of UK homes being fitted in FES-CT, a scenario with (comparatively) much higher rates of electrification. In all pathways, varying proportions of these heat pumps are hybrid heat pump/hydrogen boilers to provide winter peak heating demand. District heating (powered by large water- or sewage- source heat pumps or industrial waste heat) caters for urban population centres in all pathways, varying between 10% of UK homes in FES-ST and 42% of heating demand in CCC-B. Biomass heating is niche for all pathways except CAT-ZCB, in which 18% of heating demand is provided by burning biomass. Hydrogen is used for peak winter heating in less well-insulated housing stock as part of hybrid heat pump designs in six out of seven pathways (the exception being CAT-ZCB, which uses no hydrogen for heating); the only pathway that uses hydrogen as a major source for heating is FES-ST, which sees 53% of UK homes being fitted with a hydrogen boiler by 2050 (96% of the heat pumps that serve 27% of UK households are hybrid designs that burn hydrogen to meet the winter peak).

##### 4.4.2. Surface transport

Private car ownership continues to rise in line with historical patterns in ESC-C only; conversely, the rate of growth in private car ownership decreases in ESC-P, and private car ownership stagnates altogether at current levels or reduces to 2050 in all other pathways. In FES-CT and FES-ST, some private car ownership is displaced as a result of the development in shared electric autonomous vehicles (AVs). In FES-LTW, CAT-ZCB and CCC-B, changing travel habits resulting from increased usage of communication tools and modal shifts to cycling, walking and public transport lead to a reduction in car reliance. In the latter three

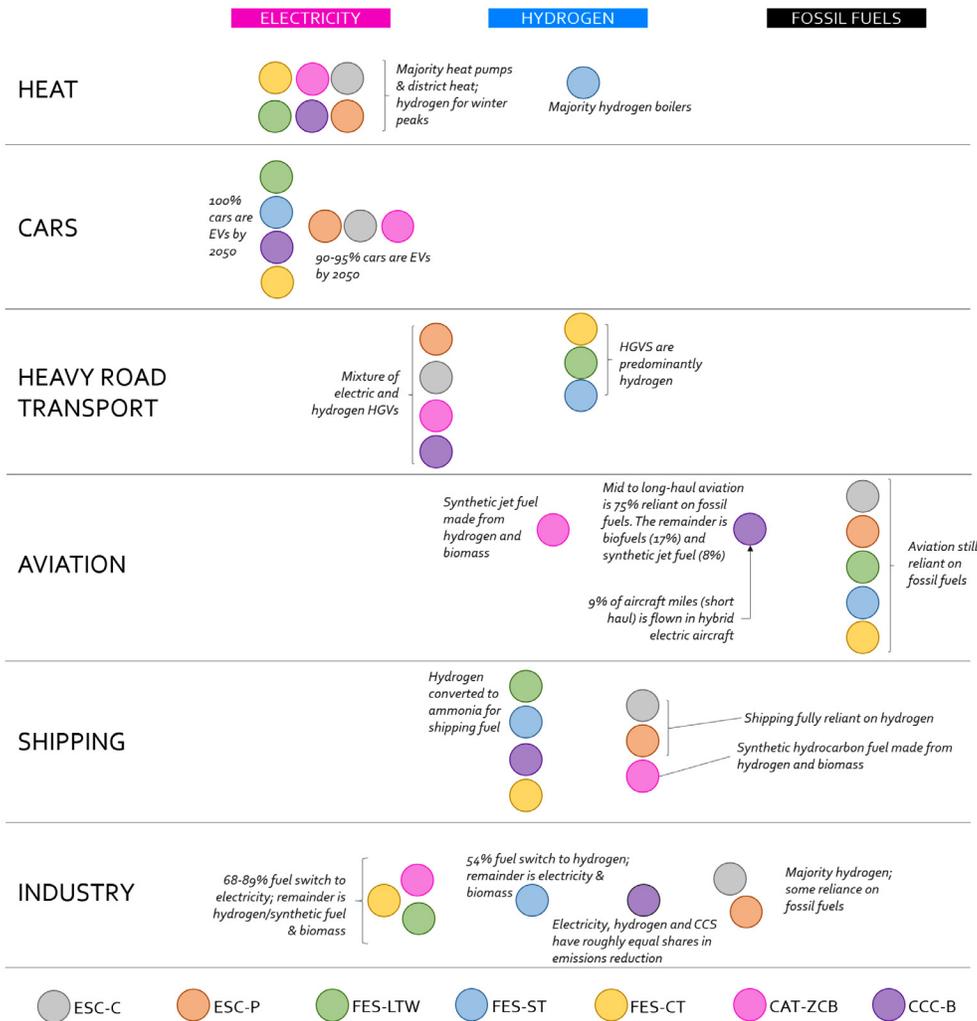


Fig. 4. Comparative analysis of technologies used to meet energy demand in 2050 for seven UK Net Zero pathways.

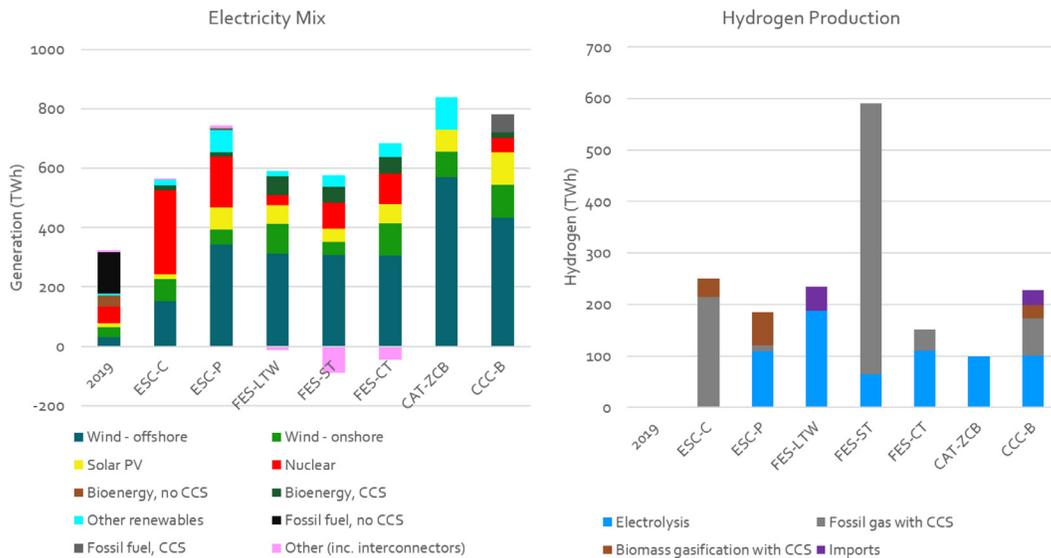


Fig. 5. Comparative analysis of technologies used to meet energy demand in 2050 for seven UK Net Zero pathways.

scenarios, these behavioural shifts lead to reductions in car driver distance: car miles per person reduce by 13% to 2050 in CAT-ZCB and by 17% in CCC-B.

Freight transport demand has risen in recent years, partly due to the growth of online shopping. The UK Department for Transport predicts that under a Business as Usual scenario, HGV transport will increase 7% from 2020 to 2050 [52]. Conversely, CAT-ZCB sees shifts to rail freight of up to 200% to 2050 (based on a feasibility study originally presented in [53]) offset the elimination of air freight for all but essential items and continued growth in demand for deliveries to lead to road freight demand to be roughly equal to what it is today in 2050. CCC-B sees a reduction of HGV miles of 10% to 2035 due to improved logistics.

To meet the energy demand for private road transport, 90–100% of cars in 2050 will be battery electric by 2050 in all scenarios; notably, no other low-carbon powertrains (for example, hydrogen fuel cell) constitute any of the passenger car stock in 2050. Heavy road transport, including buses, coaches and HGVs will be decarbonised by a mixture of electric and hydrogen fuel cell powertrains in ESC-C, ESC-P, CAT-ZCB and CCC-B; hydrogen is the predominant means of decarbonisation in FES-LTW, FES-ST and FES-CT.

#### 4.4.3. Aviation

As discussed in Section 3.4, the ESC and FES scenarios do not include international aviation emissions. Therefore, projections on changes in demand for aviation in these pathways (a 60% increase in ESC-C; a 20% increase in ESC-P, FES-LTW, FES-ST and FES-CT) represent only small proportions of the emissions that would be accounted for under territorial emissions accounting (see Section 3.4, given that only 4% of UK aviation emissions are currently associated with domestic flights [48]). That said, both ESC and FES pathway documents declare that CCC advice for future aviation demand should be followed, which at their time of publication referred to the CCC's 2019 Net Zero report [54]. This means limiting growth in aviation demand to 2050 to 25% relative to current levels. Note that this is the same constraint on aviation demand growth as used in the CCC-B pathway as shown in Fig. 3 (compared to a baseline growth rate of 73% to 2050 as forecast by the UK Department for Transport in 2020 [52]). The CAT-ZCB pathway, which also includes international aviation emissions, relies on a 66% reduction in aviation demand to 2050 as remote communications technologies and a concerned populace that prefers to holiday locally lead to a reduction in demand for flying.

Aviation is totally reliant on fossil fuels by 2050 in all ESC and FES pathways. In CAT-ZCB, synthetic hydrocarbons – manufactured from low-carbon hydrogen and carbon from biomass gasification – are used to supply a significantly reduced aviation demand (a third of today's aviation demand). In CCC-B, 9% of aircraft miles are flown by hybrid electric aircraft; the remainder is 75% reliant on fossil fuels and 25% reliant on low carbon fuels – biofuels (17%) and synthetic hydrocarbons (8%).

#### 4.4.4. Shipping

As the ESC and FES scenarios do not include international shipping emissions in their scope for decarbonisation, they do not explicitly model shipping demand but – like for aviation – refer to the CCC's advice for shipping. The shipping demand trajectory to 2050 in the CCC-B pathway – and therefore used across the ESC-C, ESC-P, FES-LTW, FES-ST and FES-CT pathways – is based on the Department for Transport's *Clean Maritime Plan* [55], which sees shipping energy demand increase by approximately 50% by 2050 as the UK expands international trade over the coming decades. Conversely, the shipping demand trajectory in CAT-ZCB sees shipping demand reduce by 50% to 2050 – a result of i) a reduction in the need for importing energy products (e.g. imported liquefied natural gas and petroleum) and ii) a reduction in the reliance on imports for food and consumer goods.

Shipping demand is met by burning hydrogen or hydrogen-derived fuels in new and retrofitted vessels in all pathways. In ESC-C and ESC-P,

hydrogen fuels shipping demand directly. In FES-LTW, FES-ST, FES-CT and CCC-B, hydrogen is combined with nitrogen (from air separation) to produce ammonia via air process to take advantage of its higher energy density per unit volume and ease of liquefaction compared to hydrogen. Some shipping demand in CCC-B is met by battery electrification for shorter routes. In CAT-ZCB, a combination of electricity and synthetic hydrocarbons (derived from hydrogen and carbon from biomass gasification) are used to power shipping.

#### 4.4.5. Industry

Industrial energy demand in the UK increases to 2050 only in the CAT-ZCB pathway, as a result of a decreasing reliance on imported goods (coupled with the reduction in shipping energy demand). In ESC-C, FES-LTW, FES-ST and FES-CT, growth in industrial output is offset by energy efficiency improvements and a move away from energy-intensive industries, leading to an overall reduction in industrial energy demand of 19–33%. The CCC-B pathway sees circular economy strategies play a role in reducing energy demand, though the pathway assumes the use of policies to prevent offshoring industrial emissions.

Decarbonisation of industrial demand is reliant on fuel switching and CCS, with a high degree of sensitivity on CCS capture rate. In FES-LTW, FES-CT and CAT-ZCB, electricity supplies the majority (68–89%) of industrial energy demand, with the remainder supplied by hydrogen, synthetic hydrocarbons and/or biomass. In FES-ST, hydrogen plays a more important role – supplying 54% of demand. In the other three pathways, CCC-B, ESC-C and ESC-P, there is still some reliance on fossil fuels in 2050 (particularly for hard-to-decarbonise sectors such as steel manufacturing). As a result, CCS applied to industry takes a major role in emissions reduction: annual industrial emissions removals are given in ESC-C, ESC-P and CCC-B as 28, 13 and 12 MtCO<sub>2</sub> respectively by 2050.

#### 4.4.6. Land use and bioenergy

Bioenergy is an important resource in all seven Net Zero pathways, though some rely on it more than others for electricity generation, hydrogen production and supply of heavy transport demand. UK bioenergy primary energy supply in 2019 was approximately 162 TWh, of which around 109 TWh was domestic production; around 60% of the total was burned to generate electricity [2]. The way in which bioenergy resource is defined varies across the pathways. ESC-C and ESC-P specify only domestic bioenergy resource, of 140 TWh/yr and 220 TWh/yr respectively. FES-LTW, FES-ST and FES-CT all specify total bioenergy resource (both domestic and imports) as 270 TWh/yr, 220 TWh/yr and 220 TWh/yr respectively. CAT-ZCB specifies a total bioenergy resource of 230 TWh/yr and CCC-B a total of 250 TWh/yr by 2050. For context, the CCC's high biomass scenario in [56] sets a sustainable limit for UK domestic bioenergy resource as 230 TWh/yr. (To be compliant with this sustainable limit, anything over and above 230 TWh/yr would be imported.)

Aside from actively capturing CO<sub>2</sub> from the atmosphere, afforestation and active management of those forests can contribute to bioenergy resource. Whilst the rate of afforestation is not specified in the FES scenarios, the other four pathways all specify how much UK forests will have to expand to 2050 to provide sufficient bioenergy resource. In ESC-C and ESC-P this is given as planting rates of 30,000 ha/yr and 50,000 ha/yr respectively from now until 2050. In CCC-B, it is specified that UK woodland will increase by 18% to 2050. In CAT-ZCB, woodland will have to increase by 100% to 2050. These changes in land use clearly rely on other sectors: in all pathways where a specific planting rate or forestry expansion is mentioned, there is also a reduction in UK meat & dairy consumption to allow the re-purposing of livestock grazing land for forestry and energy crops. This ranges from a 20% reduction in meat & dairy demand in ESC-C to a 34% meat reduction/19% dairy reduction in CCC-B to a 50% meat & dairy reduction in ESC-P to a 58% reduction in meat & dairy in CAT-ZCB (with 92% for beef).

#### 4.4.7. Emissions removals

Emissions removals are strongly linked to land use & bioenergy resource, with the addition of engineered removals in six out of seven pathways. Only CAT-ZCB has no mention of engineered removals and no reliance on BECCS for electricity generation, instead relying on significant afforestation and peatland restoration to capture the entire economy's residual 47 MtCO<sub>2</sub>/yr by 2050.

All other pathways rely on combinations of engineered removals, in addition to removals achieved by afforestation. BECCS is used for varying minorities of electricity generation across these pathways (Fig. 5), from 2% of annual electricity generation in ESC-P to 11% to FES-LTW and FES-ST. This results in emissions sinks of up to 61 MtCO<sub>2</sub>/yr by 2050. DACCS is scaled up in only two pathways – CCC-B and ESC-C, at sinks of 5 MtCO<sub>2</sub>/yr and 25 MtCO<sub>2</sub>/yr respectively by 2050. CCS is applied to heavy industry in all six of the pathways with engineered removals, capturing residual industrial emissions between 4 MtCO<sub>2</sub>/yr in FES-LTW, FES-ST and FES-CT to 8 MtCO<sub>2</sub>/yr in CCC-B, 13 MtCO<sub>2</sub>/yr in ESC-P and 28 MtCO<sub>2</sub>/yr in ESC-C. The assumed capture rate of CCS varies across the pathways, but no pathway allows for capture rates less than 95%. 95% is assumed in ESC-P and CCC-B; 97% is assumed in FES-LTW, FES-ST and FES-CT; 99% is assumed in ESC-C. The latter highlights how crucial a very high capture rate is for scenarios in which lifestyles are comparatively less changed (in terms of travel, eating and heating habits).

#### 4.4.8. Lifestyle

Two of the seven pathways are built on narratives of 'business as usual' lifestyle choices: ESC-C and FES-ST. These are also the scenarios with the highest hydrogen demand, following its contribution to residential heating without the same need for thermal efficiency improvements as required for HP uptake. That said, ESC-C includes a 20% reduction in meat & dairy demand to allow expansion of energy crop resource, and FES-LTW relies on aviation growth (in terms of passenger-kilometres) being capped at 20% to 2050 (relative to, as already mentioned, a baseline of 73% as forecast by the Department for Transport [52]).

The remaining five pathways are constructed around narratives of behavioural change accompanying technology change in meeting Net Zero. This covers not only peoples' decisions on how they travel and what they eat, but how they interact with new technologies. In FES-LTW, CAT-ZCB and CCC-B, emphasis is put on modal shift away from private cars to public and active transport. While FES-LTW only specifies that such a shift enables car ownership to reduce (resulting in around a third fewer cars on the road in 2050 than today), CAT-ZCB and CCC-B are more specific: reductions in car miles of 13% and 17% respectively from 2020 to 2050; CAT-ZCB sees a reduction in air miles of 66% to 2050 versus the present day and a four-fold increase in cycling as a means of transport. In FES-CT, emphasis is put on technology adoption: people are quick to take up V2G and ToU tariffs which enables a more flexible electricity system that can maximise the use of renewables, and adoption of autonomous EVs is able to reduce the number of private cars on the road by around 15% relative to today by 2050. Only the FES pathways do not discuss diet change. In all other pathways, demand for meat & dairy reduces to allow the repurposing of livestock grazing land for afforestation and growing bioenergy resources: this varies from a 20% reduction in meat & dairy in ESC-C to a 58% reduction in CAT-ZCB (with demand for the most land-intensive livestock, beef & lamb, reducing by 92% to 2050). CAT-ZCB and CCC-B are the only pathways that specify changes to dealing with household waste: in CAT-ZCB, emissions from landfill waste are reduced by 70% to 2050; in CCC-B, waste per person reduces by 39% to 2050.

#### 4.4.9. Electricity

Heavy electrification of surface transport, heating and industry leads to significant increases in electricity demand across all seven pathways – including the electricity required for hydrogen and/or low-carbon fuel

production via electrolysis. The change in total electricity demand between 2019/2020 and 2050 varies between a 51% increase in FES-ST to a 160% increase in CAT-ZCB.

The generation of electricity – as shown in Fig. 5 – is totally reliant on low-carbon sources; the only inclusion of fossil fuels is the possibility for up to 7.5% of generation from fossil fuels with CCS in the CCC-B pathway (though it is specified that this could be met by burning hydrogen as long-term chemical storage of surplus renewables, depending on costs of CCS vs. hydrogen production and storage). The largest share in six out of seven pathways comes from offshore wind (the exception being ESC-C, in which the largest share comes from nuclear); onshore wind, solar PV and other renewables (including wave & tidal) are contributors in all pathways.

Storage and flexibility in the electricity system is key in all pathways as variable renewables form large shares of the generation mix (Fig. 5). Long term storage is done via the production of hydrogen from electrolysis of water using surplus electricity, and the long-term storage of that hydrogen (or a hydrogen-derived low-carbon fuel) in geological storage (for example, ESC-C relies on geological hydrogen storage of 657 GWh, which can be delivered at a rate of 164 GW; ESC-P relies on 601 GWh, which can be delivered at 150 GW). Day-to-day flexibility and storage is provided by a mixture of uptake of flexible technologies (for example, FES-LTW relies on 83% of households adopting time of use tariffs and 45% of households adopting V2G) and electrical storage (for example, CCC-B relies on the installation of 18 GW of battery storage capacity and up to 10 GW of pumped hydro storage capacity by 2035).

#### 4.4.10. Hydrogen and low-carbon fuels

No matter the comparative roles of hydrogen and electricity in meeting energy demand in 2050 hydrogen plays a key role in all pathways. The range is significant, between 100 TWh/yr in CAT-ZCB and 591 TWh/yr in FES-ST. (Hydrogen and electricity generation are shown in Fig. 3 to be at an odds: the pathway with the highest electricity demand in 2050 has the lowest hydrogen demand, and vice versa.)

The hydrogen is produced via a mix of three sources: fossil gas with CCS, biomass gasification with CCS and electrolysis using low-carbon electricity (particularly surplus renewable generation). In five out of seven pathways, electrolysis constitutes the largest share by 2050. In the remaining two, ESC-C and FES-ST (the pathways with the highest hydrogen demands), the largest share is met by processing fossil gas with CCS.

Six out of seven pathways specify the volume of geological hydrogen storage required to enable surplus renewable electricity to be stored long-term, ranging from 601 GWh in ESC-P to 80 TWh of hydrogen-derived synthetic methane in CAT-ZCB. This significant range reflects the range of variable electricity generation in the pathways.

## 5. Renewable resources in the UK: A revisited analysis

Electricity is a crucially important energy vector for meeting Net Zero in all pathways analysed in this paper: between the seven pathways, electricity demand increases between 51–160% by 2050 versus 2019/2020 as i) large swathes of energy demand from heating, transport and industry are electrified and ii) hard to decarbonise sectors are fuelled by hydrogen or hydrogen-derived liquid fuel, of which (in five out of seven pathways) the majority is produced using electrolysis powered by low-carbon electricity.

David MacKay's *Sustainable Energy – Without the Hot Air* [21] was published in 2008 with the aim of finding out whether supplying the UK's energy demand could be made sustainable – mostly via electrification and the generation of low carbon electricity from renewable energy resources. The book goes through each renewable resource (onshore wind, solar etc.) and establishes the total viable contribution from each, given a set of assumed efficiencies, energy densities and feasible levels of coverage (e.g. 5% of the UK's total land area is given as an upper

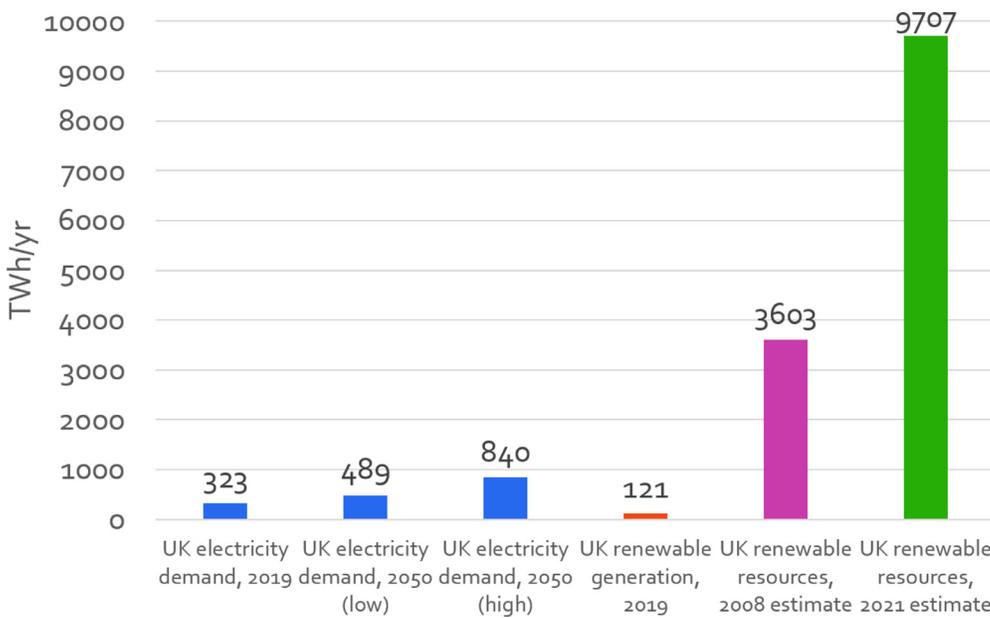


Fig. 6. Illustration of size of UK renewable resources for electricity generation compared to 2019 renewable generation, 2019 electricity demand and low/high cases for 2050 electricity demand (taken from the ESC-C and CAT-ZCB pathways respectively). Analysis and assumptions for production of this figure are detailed in Annex B.

limit of solar PV coverage). This paper revisits the analysis in that book, and provides a comparison between the established resource available and our current – and projected – demand for electricity based on the seven pathways.

There are three notable assumptions that have changed since 2008. The first surrounds the efficiency of solar PV cells: in [21] this was assumed as 10%; however, in line with improved manufacturing processes, the efficiency of solar PV panels has increased: in 2019, the average efficiency of crystalline silicon (representing 95% of global installations) solar PV cells was 18% [57]. The second surrounds floating offshore wind: whereas offshore wind resource in [21] was assumed as fixed to the seabed (and therefore constrained to water depths of 50 m or less), the potential growth of floating offshore wind in waters off the UK has since been identified [58]. Applying the same assumption used for fixed offshore wind (that up to one third of territorial waters of less than 50 m depth could theoretically be covered in wind turbines) for territorial waters over 50 m depth results in a significant resource from floating offshore wind – that dwarfs renewable resource from all other sources (Fig. 7). The third assumption surrounds bioenergy resource: in [21], it was assumed that up to 75% of the total UK land area could be dedicated to growing energy crops as an upper limit on what is plausible. However, in their 2018 *Biomass in a low-carbon economy* [56] report, the CCC set a sustainable upper limit of 7% of current UK agricultural land area for energy crop cultivation, corresponding to around 1.4 million ha. This upper limit has been adopted by the UK Government’s 2021 *Biomass Policy Statement* [59]. The resulting bioenergy resource is therefore somewhat lower than in [21]; detailed assumptions regarding this (and all other renewable energy resources presented in this section) are given in Annex B.

Fig. 6 shows the relative magnitudes of i) 2019 UK renewable electricity generation, ii) 2019 UK electricity demand, iii) the lowest 2050 UK electricity demand (from the ESC-C pathway), iv) the highest 2050 UK electricity demand (from the CAT-ZCB pathway), v) the total UK renewable electricity generation potential as estimated in [21] and vi) the total UK renewable electricity generation potential as per this revised estimate.

Fig. 7 shows the total potential resource split by each means of renewable generation for both the original estimates in [21] and the revised updates presented in this paper. For comparison, the total generation by each method is also shown. Further details of the assumptions used are provided in Annex B.

Fig. 6 shows that the total renewable resource in the UK outstrips the UK’s projected 2050 electricity demand by a factor of between 12 and 20, depending on the pathway. Fig. 7 shows that solar and wind (both offshore and onshore) are by far the biggest renewable electricity resources available to the UK, which is in line with the generation mixes shown in Fig. 5. The only resource that is being exploited closely to its theoretical maximum is bioenergy from plants: generation in 2019 was found to be 39% of the maximum available domestic resource. It should be noted that 33% of total 2019 bioenergy supply was from imports [2], so there is evidently scope for increasing total bioenergy supply by bringing in resource from overseas. However, the associated impacts of bioenergy (including competition with food supply and impacts on biodiversity) are of course a global issue and could have negative effects on the overseas countries from which the imported biomass would be sourced.

## 6. Conclusion

This paper has presented a comparative analysis of seven UK 2050 Net Zero pathways, which has shown that all scenarios involve various trade-offs between technology change – including switching from fossil fuels to zero-emission energy carriers and improvements in energy efficiency – and energy demand changes resulting from lifestyle shifts.

For example, ESC-C relies on little or no change in car ownership or use habits, and aviation demand continues to grow (though as already discussed, international aviation emissions are not in scope for this pathway). To counter for this, CCS is applied extensively to heavy industry and capture rates must reach 99% – which, as discussed, is higher than what has been achieved to date. Furthermore, DACCS is scaled up to 25 MtCO<sub>2</sub>/yr – its maximum permissible rate of emissions capture in the ESC scenarios. Even for the comparatively ‘business as usual’ narrative in the ESC-C pathway, there is one notable behavioural change: a reduction in meat & dairy demand by 20% allows livestock grazing land to be repurposed for afforestation and the cultivation of energy crops. CAT-ZCB is a pathway on the other end of the technology-behaviour spectrum, relying on significant behavioural change: car miles driven drop by 13%, aviation demand falls by 66% and demand for meat & dairy falls by 58% (with demand for beef and lamb falling 92%). As a result, the removal of residual emissions can be less drastic; this is achieved through mass afforestation and peatland restoration (achievable through the reduction in land requirement for livestock). As the

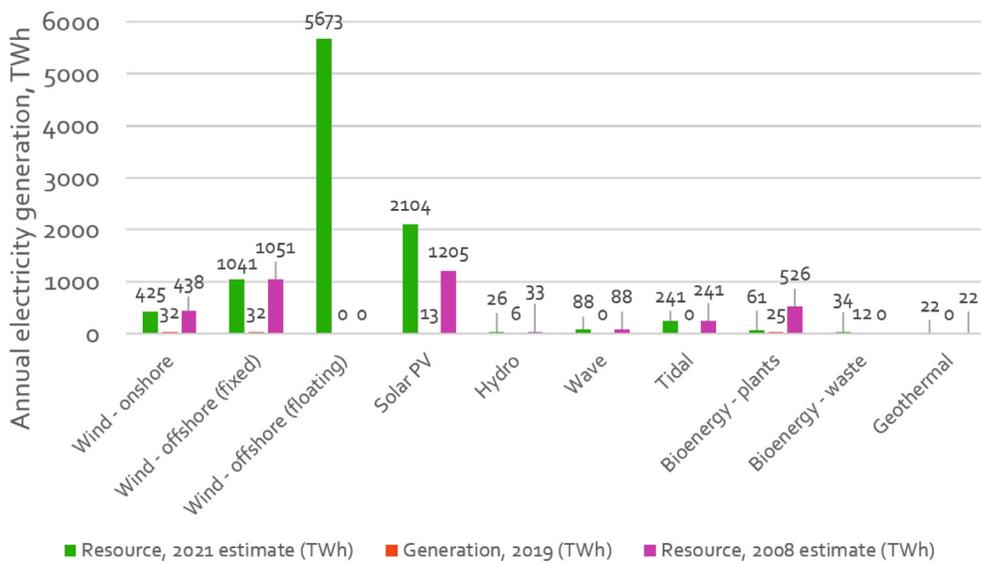


Fig. 7. Total UK renewable resources by source. Analysis and assumptions for production of this figure are detailed in Annex B.

name suggests, CCC-B is an example of a pathway that is balanced between this dichotomy: car miles are reduced and meat & dairy demand drops sharply, but the overall lifestyle shifts are not as ambitious as in CAT-ZCB. While the total emissions removals are greater in CCC-B than in CAT-ZCB, the capture rate of 95% is less ambitious than the 99% assumed in ESC-C.

Across all pathways, there is a significant contribution to emissions abatement from the management of demand growth. In five out of seven pathways, there is a reduction in car ownership and use from now to 2050. In the two pathways that account for IAS, aviation demand growth is constrained – at most to 25% above current levels by 2050 in CCC-B. This is against a baseline demand growth of 73% to 2050 as forecast by the UK Department for Transport in 2020 [52].

While the breadth of pathways analysed in this paper has shown that there are several possible routes to Net Zero, the transition to Net Zero is not based on ‘either or’ choices of decarbonisation in particular sections whilst others enjoy a relative status quo. Development of technologies to allow decarbonisation in some sectors appears to be riskier than in others: for instance, while electrified transport and heating are by now well-established, others are still a long way off where they have to be to achieve the Net Zero target. A prime example of this is CCS: while required capture rates in the seven pathways presented in this paper are at least 95% and up to 99%, [44] reports only one example worldwide that has achieved 90% based on post-combustion capture, with the majority being much lower. To mitigate the risk that these technologies fail to develop within the necessary timescales, Net Zero trajectories must spread their decarbonisation efforts across all sectors of the economy, making use of areas where technologies are already developed. Maximising the potential of energy demand reduction, which as shown in [29] can bring total UK energy demand down by 50% by 2050, will de-risk against shortcomings in technology development. In practice, this translates to many of the same things contained within the seven pathways in this paper: promoting active travel and public transport over private car use, transitioning to private car usership rather than ownership, encouraging employers to offer workers the flexibility to work from home, increasing targeted support for building heating efficiency measures and promoting more plant-based diets.

Based on the pathways reviewed in this paper, there are several themes that emerge amongst all pathways. A set of plausible outcomes for the decarbonisation of the UK energy system is hence established:

1. Heavy electrification of heating and transport will increase electricity system demand but reduce final energy demand.

2. Storage (short and long-term) and flexibility will be required to match demand to an electricity supply that has a large share of variable renewable generators (mostly wind and solar).
3. Liquid and gaseous fuels (hydrogen, ammonia, biofuels and synthetic hydrocarbons) will be required to provide energy for heavy transport (including aviation and shipping), some industrial demand and peak winter heating. The production of these fuels must be low-carbon, with a focus on hydrogen production from electrolysis being prevalent in most pathways.
4. A small amount of fossil fuels may still be in use by 2050, so long as the emissions produced from burning them are either captured at the point of combustion or offset elsewhere in the system. This may include burning natural gas with CCS for backup electricity generation, the production of hydrogen from fossil gas with CCS, or the use of petroleum-derived jet fuels for aviation.
5. Any residual emissions will need to be offset by negative emissions elsewhere in the system. This is likely to include engineered GHG removals, including CCS applied to heavy industry and electricity generation, and DACCS.
6. Transformation of energy use practices and lifestyles – and the associated reduction in energy demand – will mitigate the risks of the Net Zero target not being met through failure of technologies to develop sufficiently, or be distributed adequately, in the required timescales.

All pathways rely on significant increases in electricity generation, with large proportions (in six out of seven pathways, the majority) generated from renewable sources. By updating key assumptions in analysis originally presented in [21], it was shown that the magnitude of potential UK renewable resources far exceeds projected 2050 electricity demand in any of the pathways by a factor between 12 and 20, depending on the Net Zero pathway. The potential available resource from floating offshore wind is particularly significant, representing over 58% of the total UK resource based on the assumptions in this analysis (see Annex B for details). This result highlights the importance of floating offshore wind as a technology for continued research and development if this potential is to be realised.

**Annex A: Details on the seven Net Zero pathways for 2050**

In this section, key details from each pathway are provided. Because of the modelling methods behind each pathway, they are not always directly comparable (for instance, some pathways quantify HP uptake in terms of number of households, whereas others quantify it in terms of energy demand served). All details in Tables 1–7 are taken from the publications themselves.

**Table 1**  
Key details of Energy Systems Catapult – Clockwork (ESC-C) Net Zero pathway.

Sector	Description
Heating demand	Residential heating demand in 2050 remains similar to today (~370 TWh). Efficiency improvements from retrofitting 10 million homes are countered by increased indoor temperatures.
Heating supply	58% of UK's 2050 residential heat demand is supplied by heat pumps; large district heating networks are rolled out across large population centres to provide 18% of heating demand. While parts of the gas network are decommissioned, some areas with poorly insulated housing stock retain gas networks for conversion to hydrogen to provide winter peak heating demand. This results in around 17% of heating demand being provided by hydrogen.
Transport demand	Car travel and private car ownership continues to rise to 45 million private cars by 2050. International aviation demand continues to increase to 7,500 km/year on average by 2050.
Transport supply	Less than 10% of 2050 transport demand is met by fossil fuels (compared to 97% today). 93% of cars on the road by 2050 are EVs, with the remainder being hybrids. As a result of mass electrification, road transport energy demand in 2050 is a third of what it is today. Hydrogen serves a niche role for heavy-duty transport including shipping. Aviation is still reliant on fossil fuels in 2050.
Industrial demand	Growth in industrial output to 2050 is offset by energy efficiency improvements and a shift away from energy-intensive industries: industrial demand in 2050 is 19% less than it is today.
Industrial supply	Industries switch fuels from fossil fuels to biomass, hydrogen and electricity. Industrial emissions are 12 MtCO <sub>2</sub> e in 2050, down from 100 MtCO <sub>2</sub> e today.
Land use & biomass	1.4 million hectares of UK-grown biomass and 30,000 hectares of forest provides 140 TWh of domestic biomass by 2050.
Emissions removals	Early innovation in CCS pushes capture rates to 99%. CCS is applied to heavy industries, and 28 MtCO <sub>2</sub> e/year is captured directly from industry by 2050. DACCS scaled up to remove 25 MtCO <sub>2</sub> e/year by 2050; BECCS provides around 15 TWh/year of electricity and 34 TWh/year of hydrogen production by 2050.
Hydrogen & low carbon fuels	~250 TWh/year hydrogen needed by 2050 to supply industry, peak heating, electricity storage and heavy-duty transport (including shipping). 86% of this is to be made from steam reformation of methane with CCS (99% capture rate). The remaining 14% is produced by biomass gasification with CCS.
Electricity demand	Electrification of road transport, heating and industry leads to a 75% increase in electricity system demand from today to 2050. Total electricity generation in 2050 is 565 TWh/year.
Electricity mix	40% of generation is wind (27% offshore, 13% onshore), 50% is nuclear. The remainder is solar PV, biomass and flexible generation: 6 GW of gas with CCS and 22 GW of hydrogen turbines are required to smooth out gaps in supply and demand.
Storage & Flexibility	Geological storage of 660 GWh of hydrogen is needed by 2050 to provide peak winter heating demand and electricity generation for flexibility. 8 GW of grid-level electricity storage with a capacity of 35 GWh smooths out peaks and troughs in supply.
Lifestyle & behaviour	High levels of technology change allow Net Zero with little impact on peoples' lives. Car travel and aviation demand continues to rise, and indoor temperatures rise to an average of 21 °C compared to 18 °C today. However, a shift towards plant-based diets leads to a 20% reduction in meat and dairy demand by 2050.

**Table 2**  
Key details of Energy Systems Catapult – Patchwork (ESC-P) Net Zero pathway.

Sector	Description
Heating demand	Residential heating demand reduces by 16% to ~310 TWh by 2050, driven by efficiency improvements from retrofits in 11.5 million homes and lifestyle shifts (wearing more layers).
Heating supply	61% of UK's 2050 residential heating is provided by heat pumps. District heating is rolled out in major cities - powered by large heat pumps, geothermal resource or nuclear small modular reactors, this provides 19% of heating demand by 2050. Hydrogen boilers are used more sparingly than in the Clockwork scenario, providing around 6% of heating demand.
Transport demand	Car ownership becomes less important due to a combination of urbanisation, different working habits and a perceived need for climate action. As a result, the number of private cars rises less than in Clockwork, to 38 million by 2050. Demand for international aviation falls away from 2035 due to the 'flight shame' movement; average distance flown is 5,000 km per year by 2050 (2 trips to Europe each year).
Transport supply	Improvements in access to public transport and cycling & walking infrastructure allow a slower uptake in car ownership. 95% of cars in 2050 are EVs. Shipping is completely decarbonised by a switch to hydrogen; aviation is still reliant on fossil fuels.
Industrial demand	A shift towards less energy-intensive industries leads to a fall in industrial energy demand by one third relative to today.
Industrial supply	Industry goes part way to decarbonising its supply; 68% of demand is met by hydrogen, electricity and biomass. Gas continues to play a significant role, with CCS. Industrial emissions fall to 10 MtCO <sub>2</sub> e in 2050.
Land use & biomass	UK biomass supply is constrained to 80 TWh by 2050 due to a disjointed policy framework. Tree planting enjoys public support, and 50,000 hectares of new forest are planted per year by 2050 - much of this is on land previously used for animals.
Emissions removals	A failure to innovate CCS limits capture rates to 95%. CCS is applied to industry to capture 13 MtCO <sub>2</sub> e of industrial emissions. Emissions are captured by rapid increases in tree planting. BECCS provides around 15 TWh/year electricity and 65 TWh/year of hydrogen production by 2050.
Hydrogen & low carbon fuels	~185 TWh/year hydrogen needed by 2050 to supply industry, peak heating, electricity storage and heavy duty transport (including shipping). 59% of this is produced from electrolysis provided by renewables; 35% is produced from biomass gasification with CCS; the remaining 6% is produced from steam reformation of methane, which is limited by the 95% CO <sub>2</sub> capture rate.
Electricity demand	Heavy electrification of road transport, heating and industry leads to a 130% increase in electricity system demand from today to 2050. Total electricity generation in 2050 is 743 TWh/year.
Electricity mix	53% of generation is wind (46% offshore, 7% onshore), 21% is from other renewables - solar PV, tidal stream and geothermal. While a programme for large-scale nuclear fails to materialise, nuclear still supplies 23% of electricity by 2050. 20 GW of gas with CCS and 30 GW of hydrogen turbines are required to smooth out gaps in supply and demand.
Storage & Flexibility	Geological storage of 600 GWh of hydrogen is needed by 2050 to provide long-term electricity storage and winter peak heating demand. 4 GW of grid-level electricity storage with a capacity of 29 GWh smooths out peaks and troughs in supply.
Lifestyle & behaviour	A fairly active society seeks low-carbon ways of living, including reducing car use in favour of public & active transport and constraining flight. Warm layers are sought instead of turning up thermostats (average room temperatures reach 19.5°C). Meat and dairy demand falls by 50% by 2050.

**Table 3**  
Key details of National Grid ESO Future Energy Scenarios – Leading the Way (FES-LTW) Net Zero pathway.

Sector	Description
Heating demand	60% of UK homes are EPC C or higher by 2035, leading to reduction in heating demand by 27% to ~270 TWh by 2050.
Heating supply	By 2050, 74% of UK homes are fitted with heat pumps, 56% of which are hybrid HP/ hydrogen boilers to supply winter peak heating. District heating rollout in urban centres leads to 13% of UK homes being connected to district heating. Hydrogen boilers (without heat pumps) are not used in this scenario. The remainder is met by biomass boilers and electric storage heaters.
Transport demand	Car ownership reduces due to improved public transport, changing travel habits and rapid development in autonomous vehicles (AVs): by 2050, 1.8 million electric shared AVs are driving an average of 90,500 miles each per year. There are 20 million cars in total in the UK by 2050, a 35% reduction from today. Aviation demand increase is limited to 20% higher in 2050 than it is today.
Transport supply	All passenger cars are battery electric by 2050 at the latest. HGVs predominantly run on hydrogen. Shipping is decarbonised via hydrogen (converted to ammonia). Aviation is still reliant on fossil fuels; Net Zero is achieved by limiting demand and offsetting in other sectors.
Industrial demand	Rising energy (electricity and gas) prices in the early 2020s trigger energy efficiency drives across industry earlier than in the other two NG ESO scenarios. Industrial demand follows positive trajectory based on growing GDP.
Industrial supply	Industries switch fuels to electricity (68%), hydrogen (31%) and biomass (1%). Gas demand is completely phased out, and residual industrial emissions are 4 MtCO <sub>2</sub> e in 2050.
Land use & biomass	The UK imports biomass from overseas and makes full use of its domestic resource to give a resource of around 270 TWh/year by 2050.
Emissions removals	CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 MtCO <sub>2</sub> e/year by 2050). BECCS provides around 64 TWh/year electricity by 2050, but is not used for hydrogen production. Removals from BECCS are 61 MtCO <sub>2</sub> e/year by 2050.
Hydrogen & low carbon fuels	235 TWh/year hydrogen needed by 2050 to supply industry, peak winter heating, electricity storage and heavy duty transport (including shipping). 80% of this is produced from electrolysis powered by renewables, the remaining 20% is supplied by imports.
Electricity demand	Heavy electrification of road transport, heating and industry leads to a 79% increase in electricity system demand from today to 2050. Total electricity generation in 2050 is 579 TWh/year.
Electricity mix	71% of generation is wind (54% offshore, 17% onshore), 11% is solar, 11% is BECCS and 3% is other renewables including wave & tidal and hydro. 6% of generation is met by nuclear. Britain becomes a net exporter of electricity, which amounts to -4% of demand per year by 2050. Hydrogen-powered generators offer flexible generation, providing 1% of annual energy demand. There are no fossil fuel plants by 2050.
Storage & Flexibility	16 TWh of hydrogen storage (including geological and pipeline) is needed by 2050 to provide long term electricity storage and winter peak heating demand. Widespread adoption of time of use tariffs (83% of households by 2050) and V2G (45% of households by 2050) results in considerable domestic demand flexibility. 203 GWh of pumped hydro, battery and compressed air electricity storage systems provide day-to-day flexibility.
Lifestyle & behaviour	Fairly significant lifestyle changes, including reduced car ownership in favour of public/active transport and car sharing. Highest uptake of flexible demand schemes such as time of use tariffs and V2G.

**Table 4**  
Key details of National Grid ESO Future Energy Scenarios – System Transformation (FES-ST) Net Zero pathway.

Sector	Description
Heating demand	Less drastic program of retrofits than FES-LTW or FES-CT due to lower reliance on heat pumps and higher reliance on hydrogen. Heating demand falls by 16% to ~310 TWh by 2050.
Heating supply	By 2050 27% of UK homes are fitted with heat pumps, 96% of which are hybrid HP/hydrogen boilers to supply winter peak heating. District heating rollout in urban centres leads to 10% of UK homes being connected to district heating. Hydrogen boilers (without heat pumps) are used extensively due to a mains gas network switchover to hydrogen: 53% of homes are fitted with one by 2050. The remainder is met by biomass boilers and electric storage heaters.
Transport demand	Development of shared electric AVs is able to displace some private car ownership, but most AVs are privately owned. By 2050, 5.9 million electric AVs are driving an average of 14,800 miles each per year. There are 31 million cars on the road by 2050, roughly equal to today. Aviation demand increase is limited to 20% higher in 2050 than it is today.
Transport supply	All passenger cars are battery electric by 2050 at the latest. HGVs predominantly run on hydrogen. Shipping is decarbonised via hydrogen (converted to ammonia). Aviation is still reliant on fossil fuels; Net Zero is achieved by limiting demand and offsetting in other sectors.
Industrial demand	Energy efficiency improvements are encouraged with strong carbon pricing. Industrial demand follows positive trajectory based on growing GDP.
Industrial supply	Industries switch fuels to electricity (45%), hydrogen (54%) and biomass (1%). Gas demand is very small (0.1% of demand) and CCS is applied to remove emissions. Industrial emissions are 4 MtCO <sub>2</sub> e in 2050.
Land use & biomass	Strategically managed land use and waste products leads to a UK domestic biomass resource of around 220 TWh/year by 2050.
Emissions removals	CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 MtCO <sub>2</sub> e/year by 2050). BECCS provides around 52 TWh/year electricity by 2050 and 8 TWh/year of hydrogen production by 2050. Removals from BECCS are 49 MtCO <sub>2</sub> e/year by 2050.
Hydrogen & low carbon fuels	591 TWh/year hydrogen needed by 2050 to supply widespread domestic heating, industry, electricity storage and heavy duty transport (including shipping). 89% of this is produced from methane reformation with CCS (97% capture rate), the remaining 11% is from electrolysis powered by renewables.
Electricity demand	Heavy electrification of road transport, heating and industry leads to a 51% increase in electricity system demand from today to 2050. Total electricity generation in 2050 is 489 TWh/year.
Electricity mix	72% of generation is wind (63% offshore, 9% onshore), 9% is solar, 11% is BECCS and 8% is other renewables including wave & tidal and hydro. 18% of generation is met by nuclear. Britain becomes a net exporter of electricity, which amounts to -20% of demand per year by 2050. Hydrogen-powered generators offer flexible generation, providing 3% of annual energy demand. Gas with CCS provides some peaking plant, contributing 0.01% of electricity generation by 2050.
Storage & Flexibility	18 TWh of hydrogen storage (including geological and pipeline) is needed by 2050 to provide long term electricity storage and winter peak heating demand. Widespread adoption of time of use tariffs (60% of households by 2050) and V2G (11% of households by 2050) results in considerable domestic demand flexibility. 146 GWh of pumped hydro, battery and compressed air electricity storage systems provide day-to-day flexibility.
Lifestyle & behaviour	Consumers are less willing to change their behaviours, and uptake of flexible demand-enabling technologies remain fairly low outside of an engaged few. Private car ownership remains high.

**Table 5**  
Key details of National Grid ESO Future Energy Scenarios – Consumer Transformation (FES-CT) Net Zero pathway.

Sector	Description
Heating demand	60% of UK homes are EPC C or higher by 2035, leading to reduction in heating demand by 27% to ~270 TWh by 2050.
Heating supply	By 2050 74% of UK homes are fitted with heat pumps, 16% of which are hybrid HP/ hydrogen boilers to supply winter peak heating. District heating rollout in urban centres leads to 16% of UK homes being connected to district heating. Hydrogen boilers (without heat pumps) are not used in this scenario. The remainder is met by biomass boilers and electric storage heaters.
Transport demand	Car ownership reduces due to AV development, but personal travel habits do not change much. A higher proportion of AVs are privately owned than in the LTS scenario. By 2050, 6.3 million electric shared AVs are driving an average of 17,000 miles each per year. There are 28 million cars in total in the UK by 2050, a 10% reduction from today. Aviation demand increase is limited to 20% higher in 2050 than it is today.
Transport supply	All passenger cars are battery electric by 2050 at the latest. HGVs predominantly run on hydrogen. Shipping is decarbonised via hydrogen (converted to ammonia). Aviation is still reliant on fossil fuels; Net Zero is achieved by limiting demand and offsetting in other sectors.
Industrial demand	Energy efficiency improvements are pursued due to effective carbon pricing. Industrial demand follows positive trajectory based on growing GDP
Industrial supply	Industries switch fuels to electricity (89%), hydrogen (5%) and biomass (1%). Gas demand lingers for 5% of demand and CCS is applied to remove emissions. Industrial emissions are 4 MtCO <sub>2</sub> e in 2050.
Land use & biomass	Strategically managed land use and waste products leads to a UK domestic biomass resource of around 220 TWh/year by 2050.
Emissions removals	CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 MtCO <sub>2</sub> e/year by 2050). BECCS provides around 55 TWh/year electricity by 2050, but is not used for hydrogen production. Removals from BECCS are 52 MtCO <sub>2</sub> e/year by 2050.
Hydrogen & low carbon fuels	152 TWh/year hydrogen needed by 2050 to supply industry, peak winter heating, electricity storage and heavy duty transport (including shipping). 72% of this is produced from electrolysis powered by renewables, the remaining 28% is produced from methane reformation with CCS (97% capture rate).
Electricity demand	Heavy electrification of road transport, heating and industry leads to a 98% increase in electricity system demand from today to 2050. Total electricity generation in 2050 is 638 TWh/year.
Electricity mix	65% of generation is wind (48% offshore, 17% onshore), 10% is solar, 9% is BECCS and 7% is other renewables including wave & tidal and hydro. 16% of generation is met by nuclear. Britain becomes a net exporter of electricity, which amounts to -8% of demand per year by 2050. Hydrogen-powered generators offer flexible generation, providing 1% of annual energy demand. There are no fossil fuel plants by 2050.
Storage & Flexibility	18 TWh of hydrogen storage (including geological and pipeline) is needed by 2050 to provide long term electricity storage and winter peak heating demand. Widespread adoption of time of use tariffs (73% of households by 2050) and V2G (26% of households by 2050) results in considerable domestic demand flexibility. 194 GWh of pumped hydro, battery and compressed air electricity storage systems provide day-to-day flexibility.
Lifestyle & behaviour	Consumers are somewhat willing to change their behaviours, and uptake of flexible demand-enabling technologies is moderate. Some two car households become one car households because of the advent of autonomous vehicles, but their travel habits do not change much.

**Table 6**  
Key details of Centre for Alternative Technology – Zero Carbon Britain (CAT-ZCB) Net Zero pathway.

Sector	Description
Heating demand	Residential heating demand reduces by 29% to 264 TWh by 2050, as a result of targeted retrofits and efficiency improvements without people seeking increased indoor temperatures relative to today.
Heating supply	63% of UK's 2050 heating demand is provided by heat pumps, some of which are large-scale heat pumps attached to district heating networks. 12% of heating demand is provided by solar thermal, 7% is provided by geothermal heating and 18% is provided by biomass.
Transport demand	Car distance driven per person decreases by around 13% by 2050, as better communication tools replace the need for some journeys and urbanisation reduces many other journey times. People cycle and walk more often, and public transport increases from a share of 14% to 28% of domestic travel. Average car occupancy increases from 1.6 to 2. International aviation demand falls by two thirds.
Transport supply	90% of road passenger vehicles in 2050 are electric. There is zero demand for fossil fuels across the transport sector by 2050. Aviation and shipping are decarbonised using synthetic fuels made from hydrogen from electrolysis and biomass.
Industrial demand	Growth in industry leads to a 11% growth in industrial energy demand by 2050.
Industrial supply	Total industrial fuel switch to 68% electricity, 18% synthetic methane, 5% synthetic liquid fuels and 9% biomass. Industrial emissions are Net Zero.
Land use & biomass	75% of current livestock land is repurposed, freeing up space for other purposes including afforestation and growing energy crops for biomass. As such, UK biomass resource is increased to 230 TWh/year. Forest area is doubled to 24% of the UK's land area, and 50% of UK peatland is restored.
Emissions removals	Afforestation and peatland restoration leads to capture of 47 MtCO <sub>2</sub> e/year by 2050.
Hydrogen & low carbon fuels	~100 TWh/year hydrogen needed by 2050. Only ~10% of this hydrogen is used as hydrogen (in hydrogen vehicles); the remainder is used to produce synthetic fuels for shipping, aviation and industry. Hydrogen is 100% produced by electrolysis using excess renewable electricity.
Electricity demand	Heavy electrification of road transport, heating and industry leads to a 160% increase in electricity system demand from today to 2050. Total electricity generation in 2050 is 840 TWh/year.
Electricity mix	78% of generation is wind (68% offshore, 10% onshore), 9% is wave & tidal, 9% is solar PV, 3% is geothermal electricity and 1% is hydro. Large-scale renewable power generators use their excess electricity to manufacture synthetic fuels (gaseous and liquid) through electrolysis of water (for hydrogen) and combining with biomass. These synthetic fuels enable decarbonisation of shipping & aviation, and provide fuel for gas plants for when demand outstrips supply.
Storage & Flexibility	Geological storage of 80 TWh of synthetic methane is needed by 2050. The synthetic methane is made from hydrogen (from electrolysis, using surplus renewable energy) and biomass. 200 GWh of pumped hydro and battery storage provide day-to-day flexibility between supply of renewable power and demand.
Lifestyle & behaviour	People seek no rise in indoor temperature relative to today. Transport behaviour changes significantly: average car mileage per person reduces to ~4,400 miles in 2050 relative to ~6,500 miles today, offset by a four-fold increase in cycling and two-fold increase in bus usage. Demand for beef and lamb falls by 92%; other meat demand falls by 58%; dairy demand falls by 59%.

**Table 7**  
Key details of Climate Change Committee – Balanced (CCC-B) Net Zero pathway.

Sector	Description
Heating demand	Residential heating demand reduces by 12% to 2050, as a result of energy efficiency and behavioural measures. All rented UK homes are EPC C by 2028, all homes with mortgages achieve EPC C by 2033 and no home can be sold below EPC C past 2028. All new builds are zero-carbon (i.e. high levels of energy efficiency and low carbon heating) as of 2025.
Heating supply	By 2050 UK heat demand is met by 52% heat pumps, 42% district heat, 5% hydrogen boilers and 1% direct electric heating. The heat pumps include hydrogen hybrid designs for provision of the winter peak, enabled by rapid gas grid conversion to hydrogen from 2030 onwards. District heating sources are dominated by water- and sewage-source heat pumps and waste heat from industry.
Transport demand	Car distance driven per person decreases by 17% from 2019 to 2050, as modal shares of cycling, walking and public transport increase. Aviation travel demand increases by 25% from 2018 to 2050, but this is offset by 1.4% efficiency improvements year-on year (resulting in a net 18% reduction in aviation energy demand to 2050). By 2035, there are 28 million EVs (3 million of which are plug-in hybrids) whose charging is supported by 390,000 public charge points. Total HGV miles decrease by 10% by 2035 as a result of improved logistics such as expanded use of consolidation centres, extended delivery windows and higher loading.
Transport supply	100% of cars in 2050 are electric; 100% of buses in 2050 are zero-emission (either battery electric or hydrogen). 100% of HGVs are zero-emission (either battery electric or hydrogen) by 2050. 9% of aircraft distance is flown by hybrid electric aircraft in 2050; the remainder is still reliant on liquid jet fuels. Of this, 75% is fossil fuels. The remainder is 'sustainable aviation fuels', split two-thirds biofuels and one-third synthetic kerosene produced from low-carbon hydrogen and carbon captured from the air. Shipping is decarbonised primarily by burning ammonia in combustion engines (meaning that the vast majority of existing ship types and sizes can be retrofitted to burn it), made from low carbon hydrogen. 75% of the ammonia for shipping propulsion is made in the UK, the remainder is made abroad from low-carbon hydrogen. A small minority of shipping energy demand is electrified.
Industrial demand	Industry is decarbonised by policies that ensure manufacturing is not moved offshore. Energy efficiency improvements lead to savings of 12 TWh/year by 2050 (compared to an industrial final energy demand of 259 TWh in 2019). Additional energy reductions are acquired through circular economy strategies.
Industrial supply	Large-scale fuel switches to electricity and hydrogen which, expressed in terms of GHG abatement, provide 14 MtCO <sub>2</sub> e/year of abatement each in 2050. Significant industrial emissions remain from processes by which no decarbonisation routes have been found: around 15 MtCO <sub>2</sub> e/year is residual before CCS and BECCS are applied to industrial processes to reduce residual emissions to around 3 MtCO <sub>2</sub> e/year by 2050.
Land use & biomass	UK woodland area increases by 18%; peat areas restored increases from 25% in 2019 to 89% in 2050. 720,000 hectares of dedicated energy crops provide 200 TWh of bioenergy resource.
Emissions removals	CCS capture rates reach 95% by 2050. Carbon capture and storage from industry reaches 8 MtCO <sub>2</sub> /year by 2050. Engineered emissions removals reach 58 MtCO <sub>2</sub> /year by 2050 (BECCS provides 52 MtCO <sub>2</sub> /year of removals across power, energy-from waste, industry and hydrogen production by 2050; DACCS provides 5 MtCO <sub>2</sub> /year; LULUCF provides 1 MtCO <sub>2</sub> /year) in addition to nature-based sinks of 39 MtCO <sub>2</sub> /year.
Hydrogen & low carbon fuels	225 TWh/year hydrogen needed by 2050 to supply demands for which electrification remains difficult - mostly shipping, industry, some heating and seasonal storage of surplus renewable electricity. 45% of hydrogen supply comes from electrolysis using surplus renewable energy by 2050, 32% is from fossil gas with CCS, 11% is from biomass gasification and 13% is from imports produced from excess renewable electricity abroad. Around 31% (70 TWh/year) of the hydrogen supply in 2050 is used for ammonia production for shipping; around 13% is used for synthetic jet fuel production.
Electricity demand	Heavy electrification of road transport, heating and industry leads to a 141% increase in electricity system demand from today to 2050. Total electricity generation in 2050 is 780 TWh/year.
Electricity mix	70% of generation is from wind (of which, by installed capacity, is 75% offshore and the remainder onshore) and 14% is from solar PV. Gas with CCS and BECCS contribute around 10% of generation, and the remainder is met with nuclear. Uncertainty exists for the future of i) carbon prices and ii) carbon capture rates. If the price of carbon and/or capture rates are not significantly high, the role of hydrogen will increase as fuel for flexible electricity generation.
Storage & Flexibility	Additional flexibility is met with 18 GW of battery storage capacity by 2035 and expansion of interconnector capacity 4.5x from current levels to 18 GW by 2050. Around 13% of electricity demand is for hydrogen production to allow for seasonal energy storage.
Lifestyle & behaviour	Transport patterns change, in that growth in aviation demand is limited and car mileage per person reduces to ~7,300 miles in 2050. Waste per person, after prevention and recycling, reduces by 39% by 2050 compared to 2019 levels. Demands for meat and dairy reduce by 34% and 19% respectively.

## Annex B: Analysis and assumptions for the calculation of UK renewable resources

Assumptions relating to renewable resources in the UK are detailed below:

- Wind (onshore):** average power intensity of wind farms = 2 W/m<sup>2</sup>, as derived in [21] from average onshore wind speeds of 6 m/s. Covering 10% of UK land surface in wind farms is taken as the upper limit (as in [21]) which gives 2 W/m<sup>2</sup> × 0.1 × 2.42 × 10<sup>11</sup> m<sup>2</sup> [UK land area] × 8766 h [hours in a year, including leap years] = 425 TWh/yr.
- Wind (offshore):** average power intensity of offshore wind farms = 3 W/m<sup>2</sup>, as assumed in [21]. UK territorial waters are 7.74 × 10<sup>11</sup> m<sup>2</sup>, of which 1.2 × 10<sup>11</sup> m<sup>2</sup> are less than 50 m deep (taken as the limit of fixed offshore wind installations in [21]). If one third of these waters are covered in offshore wind farms, leaving two thirds to allow shipping channels and fishing areas, the available resource is 3 W/m<sup>2</sup> × 0.33 × 1.2 × 10<sup>11</sup> m<sup>2</sup> × 8766 h = 1040 TWh/yr if constrained to fixed offshore wind. If floating wind installations are to be included, and one third of the UK's territorial waters were covered in offshore wind farms, the resource would be 3 W/m<sup>2</sup> × 0.33 × 7.74 × 10<sup>11</sup> m<sup>2</sup> × 8766 h = 6710 TWh/yr.
- Solar PV:** average insolation (over a year, including night-time and cloud cover) in the UK is 110 W/m<sup>2</sup> [21]. In 2019, average efficiency of crystalline silicon (representing 95% of global installations) solar PV cells was 18% [57]; therefore, the average power density of solar PV is taken as 0.18 × 110 W/m<sup>2</sup> = 19.6 W/m<sup>2</sup>. If 5% of the UK's land area (including rooftop space) were covered in solar cells (as per the assumption in [21]) the total resource would be 19.6 W/m<sup>2</sup> × 0.05 × 2.42 × 10<sup>11</sup> × 8766 h = 2100 TWh/yr.
- Hydro:** average power density of hydro in the UK 'highlands' (land of at least 200 m elevation) with average rainfalls of around 2000 mm/year is 0.24 W/m<sup>2</sup>; the area of the highlands is 6.07 × 10<sup>10</sup> m<sup>2</sup>. If 20% of the highlands' valleys and rivers were dammed to harness the power of the rainfall as it makes its way back to the sea (the same assumption for maximum possible resource as used in [21]), this would correspond to a total resource of 0.24 W/m<sup>2</sup> × 0.2 × 6.07 × 10<sup>10</sup> × 8766 h = 26 TWh/yr.
- Wave:** average power density of Atlantic waves has been measured to be around 40,000 W/m of exposed Atlantic coastline [21]. If the efficiency of wave energy generators is taken to be 50%, and 50% of the UK's Atlantic coastline (10,000 km) is covered in wave generation, the total resource would be 40,000 W/m × 0.5 × 0.5 × 10,000 × 10<sup>3</sup> m × 8766 h = 88 TWh/yr. This can be compared to the 2012

- estimate of maximum wave resource of 69 TWh/yr from the Crown Estate [60].
- Tidal*: it is derived in [21] that, through a combination of tidal barrages, lagoons and stream generators placed in Britain's largest tidal resources, that 11 kWh per person per day could be generated from tidal. Based on a UK population (2008) of 60 million, this corresponds to a maximum resource of 241 TWh/yr. This can be compared to the maximum tidal resource (also from barrages, lagoons and stream generators) of 216 TWh/yr from the Crown Estate [60].
  - Bioenergy (plants)*: It is stated in [21] that high-performance energy crops capable of being grown in Northern European climates carry an energy density of around 0.7 W/m<sup>2</sup>. The Climate Change Committee recommends an upper bound of 7% of UK agricultural land (around 1.4 million ha) to be covered in energy crops for plant biomass in their 2018 biomass report [56], which is repeated by the UK government in their 2021 Biomass Policy Statement [59]. The maximum energy resource for bioenergy from domestically grown energy plants on this basis would be 0.7 W/m<sup>2</sup> × 1.4 × 10<sup>10</sup> m<sup>2</sup> × 8766 h = 86 TWh/yr. Assuming a 40% efficient power plant for electricity generation, the resulting resource would be 0.4 × 86 = 34 TWh. In the 2018 CCC report on biomass, the total UK resource from plants (energy crops, forestry residue and agricultural residue) is around 75% that of resource from energy crops. Therefore, the total UK bioenergy resource from plants is approximately 61 TWh/yr.
  - Bioenergy (waste)*: the power resource from waste depends, obviously, on how much waste is produced (something in itself that should be minimised). The 2018 Climate Change Committee report on biomass [56] implies that the primary energy resource from waste is roughly 85 TWh/yr. Therefore, if burned in a 40% efficient power plant, this translates to a renewable electricity resource of approximately 34 TWh/yr.
  - Geothermal*: it is derived in [21] that sustainable geothermal power extraction (by which the rate of heat extraction is less than or equal to the rate of heat transfer from the Earth's core to the hot rocks reachable by a geothermal power station) could provide 2 kWh per person per day. Based on a UK population (2008) of 60 million, this corresponds to a maximum resource of 22 TWh/yr.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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