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Comparative analysis of UK net-zero scenarios: The role of energy demand reduction

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ABSTRACT

Final energy demand in the UK has remained relatively constant since the 1970s. However, most of the scenarios that model pathways to achieve the UK's net-zero greenhouse gas emissions by 2050 indicate that energy demand reduction (EDR) will be an important pillar of climate change mitigation. Despite this, the UK Government has no clearly defined strategy to reduce demand. This comparative analysis explores the role of EDR across twelve UK-based climate scenarios from four organisations that estimate changes in carbon emission and energy consumption from 2020 to 2050. We focus on changes in final demand across the economy, assessing the scale of ambition and the implications for the rest of the energy system in the context of net-zero. All the pathways explored achieve reductions of at least 32.8% in total final energy demand from 2020 to 2050, suggesting that this is the minimum level of demand reduction required to achieve the development and rollout of the supply side technologies necessary to decarbonise the energy system. Reductions in total final demand of up to 52% are demonstrated. We find that pathways with higher levels of EDR mitigate against technological challenges, such as scaling up renewable energy capacities, are less reliant on carbon-dioxide removal technologies and require less investment – but are characterised by higher levels of social change.

1. Introduction

1.1. Low energy demand scenarios

Demand-side climate change mitigation strategies aim to reduce demand for carbon intensive goods and services through targeting behaviours and technology adoption via a variety of means, such as choice infrastructures and service provision (Creutzig et al., 2018). These strategies have been an oft-overlooked mitigation lever (Roy et al., 2018). Whilst supply-side technologies are represented in significant detail in Integrated Assessment Models (IAMs), demand-side options beyond price-induced efficiency improvements are largely neglected (Pye et al., 2021; Roy et al., 2018), artificially narrowing the mitigation levers available. The full basket of demand-side mitigation options includes a variety of technical improvements (more efficient provision of energy services, e.g. electric vehicles, heat pumps etc.) and social change (e.g. reducing the number of miles travelled by car). Additionally, IAMs use marginal abatement cost curves (MACCs) as a mitigation decision tool, which compare the cost-effectiveness of various abatement measures. However, MACCs only consider technology abatement costs, excluding non-monetized mitigation options or those unrelated to the adoption of technologies (Kesicki and Ekins, 2012), thus also excluding some demand-side options.

This study considers the role that energy demand reduction (EDR), referring to reductions in final demand over a given period, plays in a variety of net-zero scenarios for the UK. We ask: to what extent does EDR play a role in UK net-zero scenario modelling? Given that there is currently no cohesive EDR strategy for the UK, understanding how significant its role is expected to play on route to net-zero emissions is important. Given that we find that EDR makes significant contributions to all net-zero pathways assessed, policymakers must recognise this and develop an EDR strategy. Furthermore, by drawing on the similarities between scenarios with comparable levels of EDR, we offer new insights into the implications of EDR for the rest of the energy system that may be overlooked when looking at scenarios in isolation. Whilst most energy analysis focusses on primary energy (i.e. the energy used before being transformed and distributed), this study assesses demand at the final energy stage. A focus on primary demand can potentially be misleading due to differences in accounting methods (Kraan et al., 2019), and reductions in primary demand can potentially mask increases in final

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energy demand due to smaller intermediary losses. Thus, we are considering final demand – energy consumption at the point of end use (e.g. the amount of electricity being used to power a vehicle drivetrain).

Recent modelling has shown that without strong demand-side action, supported by comprehensive policy programs, low carbon supply-side technologies are unlikely to meet energy service demands whilst achieving national climate targets (Barrett et al., 2022). In recent years, the role that EDR can play in mitigation efforts has been investigated in scenario modelling. Grubler et al. (2018) explores a global low energy demand scenario and estimates reductions in total final demand of 54.9% in the Global North from 2020 to 2050 – largely via an efficiency-focused pathway. As found by Barrett et al. (2022), they evidence that ambitious EDR can achieve net-zero without large-scale application of engineered emission removal technologies, such as BECCS and DAC (Grubler et al., 2018; Barrett et al., 2022), which are unproven at scale and have the potential to lock-in emissions for decades to come (Anderson and Peters, 2016). Similarly, Napp et al. (2019) showed how innovative end-use technologies in conjunction with behavioural changes, can reduce reliance on BECCS by 18%. Others have developed global scenarios that demonstrate how demand-side mechanisms can achieve short-term emissions reductions and avoid temperature overshoot (van Vuuren et al., 2018; Riahi et al., 2021).

Some scenario exercises explore an increased role for demand reduction through social change (sometimes referred to as behavioural- or lifestyle-change mechanisms), going beyond efficiency measures and looking at how changes to consumption and social practices can influence final energy demand. The Social Transformation Scenario (Kuhnhenn et al., 2020) demonstrates considerable absolute EDR in the global north, reducing by approximately 68% from 2017 to 2050, whilst allowing for increases in total final energy demand in the Global South to support adequate development.

In addition to global energy scenarios, national pathways have been developed exploring the potential of EDR in Western European countries. These scenarios showed reductions in total final energy demand of 52% by 2050 compared to 2020 in France (Association négaWatt, 2022), and 50% in Germany (Umweltbundesamt, 2019) – demonstrating that a consensus around the potential for energy demand reduction in developed economies is beginning to emerge.

A growing number of international studies and scenarios have started to evidence the benefits of pursuing EDR as a mitigation strategy, in addition to the reduced reliance on CDR technologies as cited above. Firstly, EDR can reduce costs, requiring moderate investment in the energy system compared to higher demand pathways (Barrett et al., 2022). The less energy that is consumed, the less low-carbon infrastructure is needed to meet that demand, requiring less capital expenditure. Furthermore, reducing overall demand will likely reduce peak demand. This limits intra-day discrepancies between variable renewable sources and energy consumption, reducing the need for more expensive forms of firm low-carbon electricity provision, such as nuclear power generation (see Price et al., 2023). Finally, EDR can produce near-term emissions reductions (Barrett et al., 2022). Given the reductions in cumulative emissions that are possible, temperature overshoot is less likely under demand-led transitions.

1.2. UK net-zero scenarios

The UK case study is chosen for two reasons. First, scenario modelling is relatively mature in the UK, yielding a number modelling exercises to be assessed. Secondly, final energy demand in the UK was at a remarkably similar level in 2019, before the Covid-19 pandemic, as it was in 1970. UK final demand increased by 10.2% from 1970 to its peak in 2001, before reducing by 8.6% from 2001 to 2019. Excluding the anomalous years of 2020 and 2021, which reflected the impact of Covid-19 restrictions, energy demand has increased by 0.8% compared to 1970 (Department for BusinessEnergy and Industrial Strategy, 2022). Whilst demand reductions of 64% in industry and 1% average annual improvements to end use energy efficiency – providing the same or better energy service for less final energy use – since 1989 have reduced final energy demand, growth in final demand in transport (101% increase) and residential housing (11% increase) have counter-acted these reductions (Lees and Eyre, 2021). However, the 1% figure stated above does not differentiate between final demand reductions from technological efficiency improvements or structural changes in the economy, such as the off-shoring of industry. Government projections, based on known and planned policies, project a decrease in total final demand of 1.8% from 2021 to 2040 (Department for BusinessEnergy and Industrial Strategy, 2021b). Given that Barrett et al. (2022) found that the UK's energy demand can be reduced by 43% over that same period, there is a clear gap between potential and action.

Various net-zero scenarios for the UK explore differing social, political and technological narratives culminating in net-zero emissions by 2050. These scenarios outline different potential pathways to net-zero emissions for subsectors of the economy, different pathways for final energy demand, and differing implications for the energy system.

The Committee on Climate Change (CCC), an independent body that advises the UK Government, explores four pathways characterised by varying levels of technological and social change. These four pathways inform a central *Balanced Pathway*, which keeps a variety of options in play up to 2050 (Climate Change Committee, 2020b). The Centre for Research into Energy Demand Solutions (CREDS) created two low energy demand scenarios named *Positive Low Energy futures* (*PLEF*), exploring the potential for EDR in each end use sector, alongside another scenario that kept energy service demands constant up to 2050 (Barrett et al., 2021, 2022). The National Grid Energy Service Operator produced three net-zero pathways with varying speeds of change. One focuses on technical, supply-side changes, another is social change-led, and a final pathway explores socio-technical complementarities to decarbonise more quickly (National Grid, 2021). Zero Carbon Britain produce an ambitious scenario whereby net-zero emissions are reached as early as possible without relying on speculative technologies. They argue the UK's responsibility to decarbonise is greater due to the share of the global carbon budget the UK has historically used as an early-to-industrialise nation (Centre for Alternative Technology, 2019). Finally, the UK government published three pathways as part of their *Net-zero Strategy* (Department for BusinessEnergy and Industrial Strategy, 2021a), examining the implications of a highly electrified economy, an increased role for hydrogen and natural carbon sinks, as well as greater technological innovation. The most notable of which is carbon dioxide removal (CDR) technologies, such as carbon capture at the point of emission (e.g. bioenergy with carbon capture, fossil fuel combustion with carbon capture) or direct air carbon capture, which removes carbon directly from the atmosphere post-combustion. However, changes to final demand were not reported in the UK Government's pathways, with a greater emphasis on the role of supply-side transitions and energy efficiency options.

Whilst each scenario infers a significantly different pathway, a review of the academic literature found only one comparative analysis of UK net-zero scenarios. Dixon et al. (2022) compare seven 2050 decarbonisation pathways, assessing the scale and diversity of technologies necessary to meet energy demand, finding that (a) pathways with limited behavioural changes require more intensive technological development and (b) hydrogen plays a large role in all the pathways.

However, the focus of Dixon et al. (2022) on supply-side technologies, means a comprehensive comparative analysis of the role of changes to final energy demand in UK net-zero scenarios is unexplored, which is a significant omission from the academic literature. The following analysis finds reductions in total final energy demand play a key role in all the comparable decarbonisation pathways explored that reach net-zero (ranging from 33 to 52% in 2050, relative to 2020). Additionally, scenarios with lower levels of final EDR (~30% from 2020 to 2050) potentially face significant difficulties in the scale of supply-side technological rollout necessary to decarbonise the energy system. Without further EDR, pathways are over-reliant on carbon removal technologies, such as BECCS and direct air capture, which are unproven at scale and come with significant risks (Anderson and Peters, 2016). EDR of around 40% reduces the reliance on CDR technologies. Beyond this, the potential of EDR as a mitigation option is much higher, with over 50% EDR found in several scenarios. Pursuing these further reduces the risks associated with the supply-side transition. Our findings reinforce those of Dixon et al. (2022) in that pathways with less social change have less final demand reduction and require a greater scale of technological rollout on the supply side to meet that demand. We conclude that governments must fully integrate demand-side action into energy policy to realise the net-zero transition.

2. Methods

2.1. Comparative analysis

This study adopts a comparative analysis, exploring the role of reductions in final demand in reaching net-zero emissions in UK mitigation scenarios. All the scenarios analysed explore the same timeframe, with estimates running from 2020 to 2050. An aggregated comparison of total final energy demand is drawn between twelve scenarios. However, the availability, comparability and transparency of data was found lacking in National Grid and Zero Carbon Britain pathways, thus a more detailed comparison is exclusively drawn between the five pathways in the Sixth Carbon Budget (Climate Change Committee, 2020a) and the two *PLEF* scenarios that reach net zero emissions (Barrett et al., 2021). Quantitative comparisons were drawn where possible, such as total final energy demand, energy system costs and cumulative carbon removals. When modelling frameworks did not quantitatively align, a qualitative comparison of suitable variables was considered.

2.2. Scenario descriptions

Table 1 outlines each scenario, their shorthand and a narrative description. Whilst a detailed comparison of the first eight scenarios is explored, the only variable explored across the *National Grid* and *Centre for Alternative Technologies* scenarios is final energy demand – due to limited availability transparency and comparability of modelling data.

2.3. Sector mapping

More detailed comparisons of demand in each end-use sector (residential buildings, non-domestic buildings, transport, industry and agriculture) are also presented for the CCC and PLEF scenarios. Some sectors did not align perfectly across organisations and had to be mapped onto one another. Table 2 presents how these sectors translate.

2.4. Creating an 'AMBITIOUS' scenario

An 'AMBITIOUS' scenario is also generated in Section 3.1.3, which combines the most radical aspects of each scenario into one pathway in order to explore what the maximum EDR potential might be. This was rather simply produced by choosing each sectoral demand pathway with the greatest demand reduction from the seven available scenarios and summing each sectoral pathway to produce an economy wide vision. For example, in the residential sector, *CCC-Widespread Engagement* has the greatest EDR, and thus was chosen for that sector. However, the extent to which this is possible using a whole-systems approach is not clear. It may be that there are trade-offs that make such a strategy implausible.

3. Results

This section explores the key differences in both economy-wide and sectoral final demand metrics and the most important variables that influence demand, before exploring the implications for other energy

Table 1
Overview of the scenarios.

Organisation	Title	Shorthand	Description
PLEF	Steer	PLEF-ST	Maintains energy service demands but has the goal of reducing emissions to net-zero by 2050. However, there is an emissions gap in 2050.
	Shift	PLEF-SH	Significant shift in the attention given to energy demand strategies providing ambitious interventions across the whole economy, achieved with existing technologies and current social and political framings.
	Transform	PLEF-T	Considers transformative change in technologies, social practices, infrastructure and institutions to deliver reductions in energy and numerous co-benefits
CCC	Balanced Pathway	CCC-BP	Keeps in play a range of ways of reaching that target
	Headwinds	CCC-H	Policies only manage to bring forward societal and behavioural change and innovation at the lesser end of the scale, which does not reduce the cost of green technologies.
	Widespread Innovation	CCC-WI	Successes in cost-reduction of technologies facilitates widespread electrification, high levels of efficiency and cost-effective methods of greenhouse gas removal.
	Widespread Engagement	CCC-WE	There are high levels of societal and behavioural changes, which reduce demand for the most carbon intensive activities. However, substantial cost reductions are not realised.
	Tailwinds	CCC-T	Assumes successes in both innovative and societal mitigation measures. Goes further than *CCC-Balanced Pathway* in reaching net-zero prior to 2050.
CAT	Zero Carbon Britain	CAT-ZCB	Explores the possibility of reaching net-zero emissions as soon as possible using currently available technologies without relying on future developments (i.e. carbon capture technologies).
National Grid	System Transformation	NG-ST	Consumers are willing to modify their behaviours, high energy efficiency, electrification for heating and demand flexibility
	Consumer Transformation	NG-CT	Consumers less inclined to change behaviour, lower energy efficiency and more supply-side flexibility
	Leading the Way	NG-LTW	Fastest credible decarbonisation pathway with high levels of consumer lifestyle change, hydrogen and electrification

Table 2
Sector mapping for detailed comparisons.

Mapped end-use sector	CCC equivalent(s)	PLEF equivalent
Non-domestic buildings	Non-residential buildings (commercial only) Non-residential buildings (public only)	Non-domestic
Residential buildings	Residential buildings	Shelter
Industry	Manufacturing & Construction Waste Removals F-Gases	Materials & products
Transport	Surface transport Aviation + Shipping (incl. international)	Mobility

system variables (e.g., carbon dioxide removal technologies, growth of the power sector and energy system costs).

3.1. Final demand across scenarios and sectors

3.1.1. Total final demand in 2050 across all pathways

Changes in total final demand varies greatly across all pathways (Fig. 1), ranging from 30.2 to 57% from 2020 to 2050 (excluding agriculture). However, the pathway with the least reduction, *PLEF-Steer*, has an emissions gap in 2050, and does not reach net-zero emissions within the UK Government's legally binding target timeframe. Additionally, the three National Grid pathways, two of which show the greatest demand reductions relative to 2020 (*NG-CT* and *NG-LTW*, with reductions of 57% and 54.9% respectively), do not include important end-user sectors – namely rail, aviation and shipping. Aviation and shipping both have limited EDR potential and rail demand would likely increase in a net-zero transition, thus artificially over-estimating the demand reduction potential of both the transport sector and the pathway overall. Therefore, a meaningful comparison with National Grid scenarios cannot be made.

Of the remaining scenarios that are considered (i.e., that reach net-zero emissions and have comparable end-user sectors; left of the dashed line in Fig. 1), the scenario with the greatest change in total final demand is *PLEF-Transform*, with reductions of 51.5% in 2050 relative to a 2020 baseline, closely followed by *CCC-Widespread Engagement* (48.1%) and *CCC-Tailwinds* (43.2%). Across these scenarios, relative changes in final demand vary from 32.1 to 51.5%.

Crucially, Fig. 1 demonstrates the variety in reporting across scenario exercises – both in terms of end-use sector inclusion and classification. The National Grid scenarios omit key end-use sectors, whilst the Zero Carbon Britain scenario reports the buildings sectors' final demand according to the energy-using processes involved. Such variability in reporting methods highlights the difficulties in comparing final demand

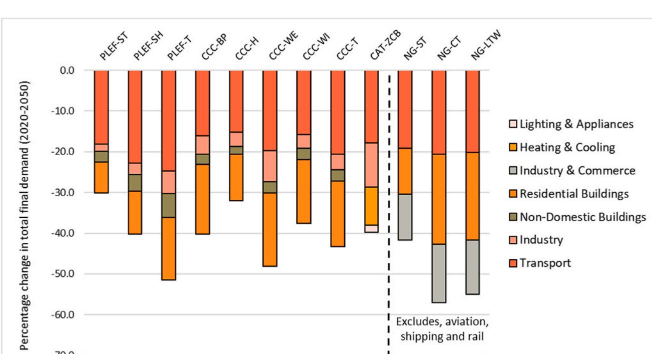

Fig. 1. Comparison of relative changes in total final demand (2020–2050, agriculture is excluded).

across several scenario exercises, despite it being an important component in each mitigation pathway. The following comparisons exclude the National Grid and Zero Carbon Britain scenarios on this basis.

Comparing a time-series of final demand between PLEF and CCC (Fig. 2), PLEF-T*ransform* shows the earliest and most consistent relative and absolute demand reductions. The CCC scenarios show final demand increasing in 2021 (driven by increases in transport and non-domestic buildings) before declining. PLEF-T*ransform* achieves reductions of over 50%, based on a broad suite of social changes that are supported by comprehensive energy demand policy. The demand time-series in the CCC scenarios are reverse S-shaped, plateauing after 2040. Furthermore, neither set of scenarios represents many of the changes in final demand (the exception being the transport sector) as a result of the Covid-19 pandemic. Thus, it may be possible that demand reductions will begin from a much lower baseline moving forwards. Contrastingly, whilst uncertain in their size, rebounds may occur in successive years, with the potential to cause a reversion to baseline levels or higher for some interventions. As historical data shows (see Department for BusinessEnergy and Industrial Strategy, 2022), it is unlikely that energy demand changes will be linear and will be dependent on policy success, failure and scale of ambition.

3.1.2. Sector-level comparisons

Fig. 3 shows a sector-specific comparison of final demand across *CCC* and *PLEF* scenarios. Looking at residential buildings, most of the *CCC* scenarios contain more ambitious EDR than *PLEF* pathways. *PLEF-Shift* shows the least reduction in demand, followed by *CCC-Headwinds*. Meanwhile, *CCC-Widespread Engagement* shows the greatest demand reductions of 60.7% compared to *PLEF-Transform's* 52.3% reduction. Differences in the resolution of retrofit adoption made comparing the thermal efficiency of residential buildings unachievable. Regarding heat electrification, the *CCC's* scenarios had a quicker rollout of higher energy-efficient heat pumps (particularly air-source) than both *PLEF* scenarios. Given that ASHPs have a lower up-front cost and are less disruptive to homeowners, they were adopted more widely throughout the scenarios. However, these trends are counter-balanced by lower levels of housebuilding in *PLEF* scenarios, especially in *PLEF-Transform*, which explored maximising the utility of the existing housing stock by reversing trends of decreasing occupancy.

The *PLEF* scenarios show greater EDRs in the non-domestic buildings sector than the *CCC* analysis. The *CCC* pathways show reductions of 22–25%, except for *CCC-Headwinds*, which achieves a reduction of 16.2%. The *PLEF-Shift* achieves a 34.1% drop in final energy demand, whilst *PLEF-Transform* shows reductions of 48.5% and is the only pathway with sustained reductions up to 2050, with the rest showing upticks in demand post 2045. Beyond these high-level comparisons, it is difficult to draw any concrete conclusions. Table 3 illustrates that none of the non-domestic energy demand levers were modelled in a comparable way, limiting our ability to evaluate different demand pathways for the sector.

Transport is a sector with high EDR potential. This sector has the greatest difference in EDR between both sets of scenarios, with *PLEF-Shift* and *PLEF-Transform* achieving reductions of 63% and 68% in total final demand (2020–2050). Significant demand reductions are also present in the CCC's scenarios (ranging from 43 to 58%). However, total final demand for transport in the most ambitious *CCC* scenario, *CCC-Tailwinds*, is 32% higher in 2050 than *PLEF-Transform* and is 73% higher in *CCC-Balanced Pathway*. As demonstrated by Table 3, this is because of a far greater transition away from energy intensive modes of passenger transport, such as cars and aviation, towards shared public transit, micro-mobility and active travel *PLEF* scenarios, partially countered by greater efficiency improvements in CCC scenarios.

EDR in industry and construction follow a similar profile across all seven scenarios, sharply falling until 2035 before plateauing, with six scenarios increasing in the last ten years up to 2050, with only *CCC-Widespread Engagement* continuing to fall to a reduction of 35.6%

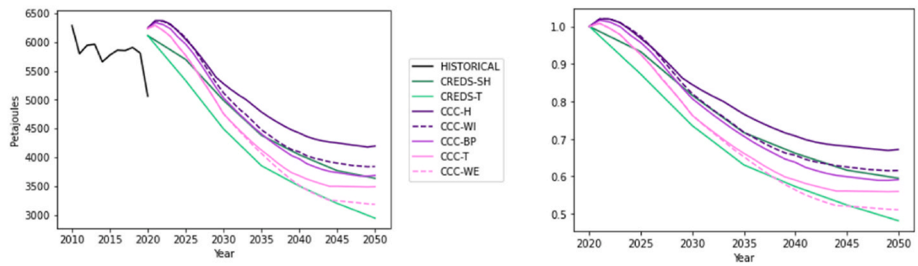

Fig. 2. Changes in historical (black line) and projected total final energy demand across the CCC and PLEF pathways. Changes are shown in absolute terms (left) and relative terms, with 2020 values indexed to 1 (right).

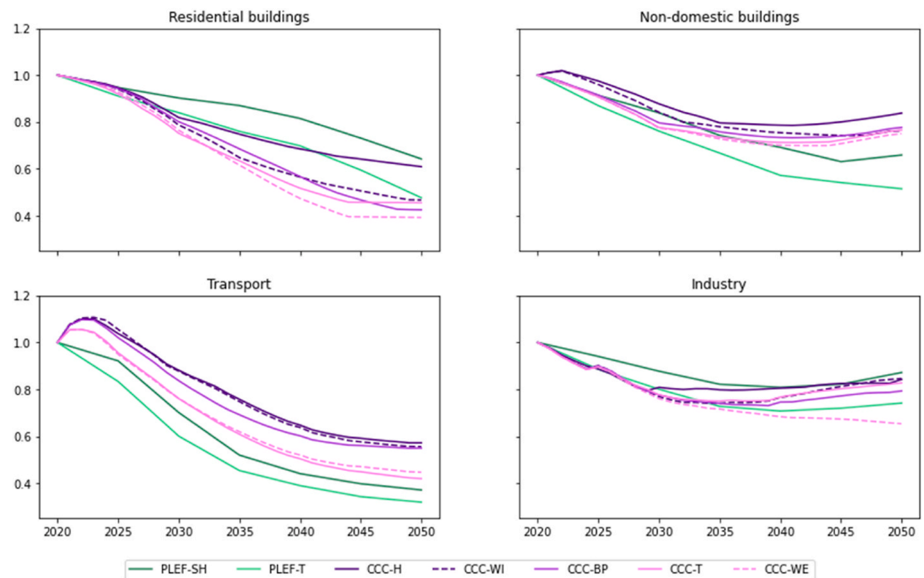

Fig. 3. Changes in total final energy demand of each major end-use sector. Index = 2020.

compared to 2020. *PLEF-Transform* shows EDR of 25.8% in 2050. The remaining scenarios find reductions of 12.8%–20.7%, with *PLEF-Shift* demonstrating the highest level of energy consumption in 2050. Many of the energy and emissions reductions in both modelling exercises were taken from a range of resource efficiency measures, also known as material efficiency, which refers to using less materials to provide the same service or more (e.g. light weighting in the car manufacturing process). There are three resource efficiency pathways (Low, Medium and High, taken from Scott et al., 2018), with varying degrees of material use. Four scenarios adopted the 'High' resource efficiency pathway and produced the greatest energy demand reduction, highlighting the central role of resource efficiency in industrial decarbonisation and demand reduction. Beyond resource efficiency, variation in construction and energy efficiency measures resulted in different levels of EDR, however these modelling frameworks could not be compared. Interestingly, final demand reductions in *PLEF-Transform* did not keep pace with *CCC-Widespread Engagement,* despite exploring the impact of radical policy levers, such as a substantial drop in housebuilding and road infrastructure projects.

Comparing the four predominant end use sectors presents two outcomes. First, comparing key demand-side mechanisms between scenario modelling projects is severely hindered by a diversity of modelling methods across both sets of scenarios, making it difficult to ascertain the key sectoral drivers of demand reduction. Of the 25 demand-side indicators assessed, only 15 could be adequately compared across both modelling exercises (see Table 3), with just 8 available for all seven scenarios. Modelling differences in the non-domestic buildings, industry and construction sectors were particularly difficult to overcome. Given the prevalence of this issue, ensuring modelling inputs and outputs are transparent and easily translatable into policy goals would support future cross comparison of pathways.

Second, applying the avoid-shift-improve (ASI) framework to the scenarios' assumptions (see Table 4) enables the characterisation of *PLEF* scenarios as led more by social change (more ambitious avoid and shift mechanisms) whereas the *CCC* scenarios are driven by technological change (more ambitious improve mechanisms). Table 3 characterises each variable according to the ASI framework. The *CCC* had greater values for two of the four 'improve' mechanisms (i.e., changes to the efficiency of energy service provision) that were presented in comparable terms, namely air-source heat-pump and combustion engine vehicle efficiency. The other two variables, resource efficiency ambition and ground-source heat-pump efficiency, showed similar ranges. For variables categorised as 'shift', which incorporate transitioning towards the use of low-energy or low-carbon forms of energy service provision, *CCC* scenarios performed better in housing (shifting to heat pumps at a greater rate), whereas the *PLEF* scenarios performed better in transport (more ambitious shifting to lower energy forms of passenger-kilometre provision). The only notable exception being the assumed date where electric vehicles reached 100% of sales, whereby four of the five *CCC* scenarios reached this date between three and five years earlier than the 2035 date in *PLEF*. The change in 'shift' mechanisms across both sets of scenarios is reflected in the scale of energy demand reduction across transport and residential housing. There were no comparable 'shift' variables in either non-domestic buildings or industry and construction.

Of the four 'avoid' mechanisms (i.e., measures aimed at avoiding the use of energy intensive services) that could be compared across the

Table 3
Key demand variables for each end use sector across the seven scenarios explored in detail in relation to the ASI (avoid, shift, improve) framework. Green rows indicates where an appropriate comparison could be made (at least one per PLEF and CCC). Red rows indicate where this was not possible. Values with a "+/−" indicate a change from 2020 to 2050. "-" = data was not available. "NA" = the variable was not modelled. "x" = the variable was modelled across all scenarios but not presented in comparable terms. Resource efficiency strategies are taken from Scott et al. (2018). Agriculture is excluded due to its relative size. This is not an exhaustive list of modelled variables, rather the ones which were deemed to have the most impact on energy demand.

Sector	Demand Variable	Scenario						
		PLEF-SH	PLEF-T	CCC-BP	CCC-HEAD	CCC-WI	CCC-WE	CCC-TAIL
Residential Buildings	Avg. HP installations pa (S)	752,741	619,625	856,795	-	-	-	-
	Max. HP installations pa (year achieved) (S)	1,613,589 (2045)	1,480, 659 (2037)	1,432,406 (2041)	-	-	-	-
	Avg. # houses-built pa (A)	190k	26.5k	232.2k	232.2k	232.2k	232.2k	232.2k
	ASHP CoP (I)	2.51/2.89	2.51/2.89	3.0	-	-	-	-
	GSHP CoP (I)	3.04/3.5	3.04/3.5	3.26	-	-	-	-
	Internal temperature setpoint (A)	19.5°C	18°C	NA	NA	NA	NA	NA
	Thermal insulation (I)	x	x	x	x	x	x	x
Non-Domestic Buildings	Efficiency measures (I)	x	x	x	x	x	x	x
	Floorspace change (A)	+26.7%	+2.0%	NA	NA	NA	NA	NA
	Electrification rate (S)	x	x	x	x	x	x	x
Transport	EVs 100% of car sales (S)	2035	2035	2032	2035	2030	2030	2030
	ICEV efficiency (I)	+7%	+7%	+30%	+30%	+30%	+30%	+30%
	Car use (vkm) (A/S)	-51%	-69%	+11%	+28%	+41%	-11%	-11%
	Bus use (vkm) (S)	+261%	+318%	0%	0%	0%	0%	0%
	Motorised two-wheel use (bvkm) (S)	29.81	35.25	13.1	13.1	24.6	18.5	18.8
	Rail use (vkm) (S)	+74%	+84%	+37%	+37%	+37%	+45%	+37%
	Aviation demand (pkm)* (A/S)	-17%	-39%	+53%	+53%	+70%	-1%	-5%
	Change in walking/cycling (bvkm) (S)	+20.2	+19.9	+5.8	+5.8	+5.8	+7.6	+7.6
Industry & Construction	Resource efficiency scenario (I)	Medium	High	High	Medium	Medium/High	High	High
	Energy efficiency (I)	x	x	x	x	x	x	x
	Avg. # houses-built pa (A)	190k	26.5k	232.2k	-	-	-	-
	Material demand: Iron & Steel (NA)	-26%	-47%	NA	NA	NA	NA	NA
	Material demand: Non-ferrous metals (NA)	-48%	-52%	NA	NA	NA	NA	NA
	Material demand: Cement (NA)	+39%	-24%	NA	NA	NA	NA	NA
	Material demand: Non-metallic minerals (NA)	+20%	-48%	NA	NA	NA	NA	NA

Table 4
The avoid-shift-improve framework with examples for each end-use sector. Adapted from Creutzig et al. (2018).

	Avoid	Shift	Improve
Explanation	Measures aimed at preventing the use of a carbon/energy intensive service	Shifting to alternative, low-carbon/low-energy ways of fulfilling an energy service	Making existing energy service provision more efficient
Sector:			
Buildings	Insulation measures Temperature setpoint	Heat pumps Electric boilers	Condensing boilers Energy efficient appliances
Transport	Compact cities Teleworking	Cycling/walking Public transport	Electric vehicles Smaller, lightweight vehicles
Industry	Long-lasting fabrics	Recycled materials	More efficient equipment
	Sharing economy	Low carbon materials for construction	Improving manufacturing processes
Food	Reducing calorific intake	Consuming alternative protein sources	Smaller, more efficient refrigerators
	Food waste reduction		Reuse food waste

scenarios, the *PLEF* scenarios performed markedly better across them all. Furthermore, there were two more additional 'avoid' mechanisms (floorspace change and reductions in residential temperature setpoints) that were modelled by *PLEF* but not *CCC*, suggesting that the *PLEF* pathways pursued a greater range of ambitious EDR options through changes to energy service demand via social change.

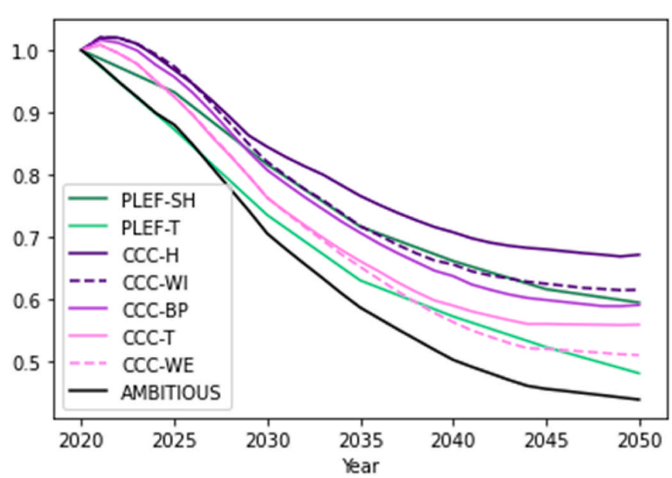

Fig. 4. Total final energy demand across all scenarios. An 'ambitious' pathway is added in black, which is the sum of the most ambitious scenario in each sector. Index = 2020.

3.1.3. An 'AMBITIOUS' energy demand pathway

In an *AMBITIOUS* scenario (Fig. 4), which considers the most radical aspects of each strategy, total final energy demand drops by 56.1%, reaching approximately 2729 PJ by 2050. This suggests the technical potential of EDR in the UK is even greater than established in the scenarios assessed in this study. There is an argument to be made that energy modelling should show the extremes of what is possible to account for 'unforeseen circumstances' (McCollum et al., 2020). It is highly likely that there will be disruptive drivers, such as rebound effects, policy and technology failures that may necessitate that demand reduction plays a more significant role.

3.2. Economy-wide implications

3.2.1. Carbon dioxide removals (CDRs)

All seven net-zero scenarios reduce energy demand by at least 32%, indicating a minimum level that demand must be reduced by in order to reach net-zero emissions. This implies that a greater level of attention needs to be paid to EDR by policymakers. However, reductions of just 30% implies greater levels of risk, with substantial carbon removal technologies being required (see Table 5), such as BECCS, which does not currently exist at scale. In this context, CDR refers only to negative emissions technologies and nature-based solutions, excluding fossil fuel carbon capture and storage.

EDR levels of approximately 40% diminish this risk by limiting the extent of emissions remaining in 2050. *CCC-Tailwinds* is the exception to this. Despite being characterised by relatively high levels of EDR (44.1%), *CCC-Tailwinds* still features a substantial amount of engineered CDRs (1188 MtCO2 cumulatively). This is because this pathway assumes successes in reducing the costs of these technologies, as well as requiring more energy demand for CDRs in order to meet net-zero earlier than the other pathways, in 2045. It is also noted that the scenario with the greatest EDR (PLEF-T*ransform*) achieves net-zero emissions without the need for CDR technologies, such as DACCS or BECCS, which carry significant risks.

The range of cumulative engineered CDRs in the CCC estimates range from 530 to 1184 MtCO2, with CCC- *Balanced Pathway* requiring 714.9 MtCO2 removal by 2050. Both the *PLEF* net-zero scenarios require substantially less engineered removals than CCC scenarios, with *PLEF-Shift* requiring 554 MtCO2 and *PLEF-Transform* requiring just 3 MtCO2 to reach net-zero. However, the *PLEF* scenario that shows no reductions in energy service demands, *PLEF-Steer*, still has significant levels of engineered carbon removals at 647.6 MtCO2 by 2050. Significantly, the two net-zero scenarios with the greatest EDR and social change (*PLEF-Transform* and CCC-*Widespread Engagement*) estimate the smallest amount of both engineered and nature-based removals.

Whilst avoiding the need for engineered removals, *PLEF-Transform* also deploys less nature-based solutions (i.e., afforestation, soil sequestration and peat sinks) than CCC-T*ailwinds* and *CCC-Widespread Innovation*. This is despite *PLEF-Transform* having more restrictive assumptions on potential tree planting rates. It is worth noting that *PLEF-Steer* scenario (excluded from Fig. 5) achieves reductions of 30.1% compared to 2020, but still not does reach the target of net-zero emissions by 2050. Under the assumptions taken, we suggest that a 30% reduction in energy demand leaves too much effort from either supply side decarbonisation or CDR. Pathways failing to adequately reduce demand require more ambitious (and potentially infeasible) assumptions regarding the development of carbon removal technologies if they were to meet net-zero, such as greater capacity and deployment rates, increased capture rates or availability of land.

Table 5
Level of EDR (from most to least) and cumulative carbon removals. Only includes negative emissions technologies, excludes fossil fuel CCS. * = reaches net zero emissions earlier, by 2045. ** = does not reach net zero emissions by 2050.

Scenario	Reduction in final energy demand 2020–2050 (%)	Cumulative Engineered GHG removal 2020–2050 ($MtCO_2$)	Cumulative total carbon removal 2020–2050 ($MtCO_2$)
PLEF-T	51.9	3	907
CCC-WE	48.0	529.8	1294.7
*CCC-T**	44.1	1188.4	2191.8
CCC-BP	40.9	714.9	1493.1
PLEF-SH	40.5	554.6	1089.9
CCC-WI	38.5	741.8	1685.2
CCC-H	32.8	945.3	1669.9
*PLEF-ST***	30.1	647.6	813.6

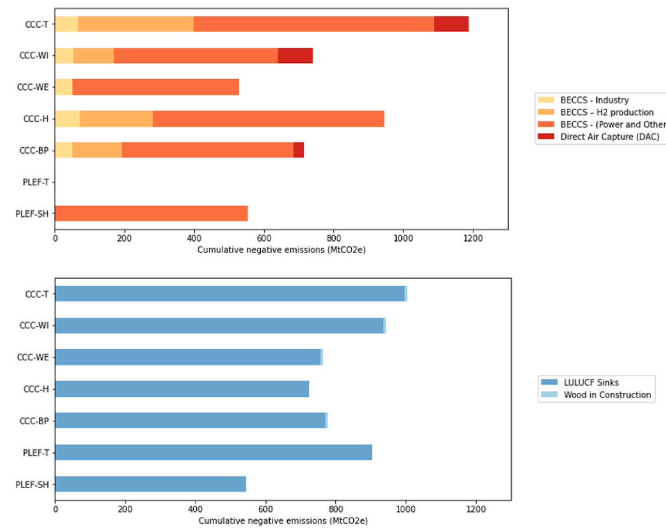

Fig. 5. Cumulative engineered carbon removal (top) and nature-based solutions (bottom), 2020–2050.

However, demand is not the only influential factor here. The technological options adopted across the scenarios are also important. For example, two pathways with the same level of demand could have varying levels of carbon removal (e.g. *PLEF-Shift* and *CCC-Balanced Pathway*) due to varying proportions of hydrogen produced from steam methane reforming, as opposed to production via electrolysis. A comparison on this basis could not be made in full as the *CCC* did not have data available for the split between hydrogen produced using different methods in their scenarios. However, *PLEF-Shift* and *PLEF-Transform* both estimated a similar proportion of hydrogen production from both SMR and electrolysis in 2050 (45:55 in favour production via SMR), with the latter requiring substantially less carbon removal.

There is evidently a relationship between EDR and the amount of carbon removal required. EDR strategies can induce early emissions reductions, thus limiting cumulative emissions and the need for carbon dioxide removals as we approach the UK's 2050 net-zero target.

3.2.2. Interplays between electricity demand, generation and system costs

Given the importance of electrification in decarbonisation, demand for electricity increases in all pathways (Fig. 6), with the greatest increases in the *CCC* scenarios (by a factor of 1.8–2.2 compared with 2020), and more modest increases in *PLEF-Transform* and *PLEF-Shift* (1.2 and 1.6 respectively). This increase is driven by the electrification of transport fleets, heating (e.g. heat pumps) and some industrial processes (boilers, arc furnaces, machinery etc.).

Although electricity demand is comparably smaller across all sectors of the *PLEF* scenarios, this is not necessarily always the most appropriate comparison. Smaller increases in final electricity demand may conceal larger increases in electricity generation for the purpose of hydrogen production via electrolysis. For example, *CCC-Balanced Pathway, CCC-Widespread Engagement* and *CCC-Tailwinds* all have similar levels of total final electricity demand in 2050, ranging from 595.2 to 599.1 TWh.

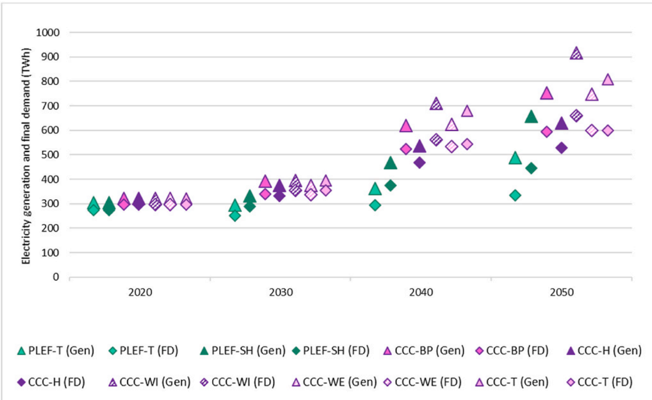

Fig. 6. Final electricity demand (FD; excluding agriculture) and generation (Gen). Index = 2020.

However, they have greater variation in the levels of total power generation, ranging from 748.3 (*CCC-Widespread Engagement*) to 809.2 (*CCC-Tailwinds*) TWh – largely owing to the 237 TWh of electricity curtailed from hydrogen production in the latter, compared with 161 TWh in the former.

Despite these nuances, the scenarios with the lowest electricity demand also tend to have lower amounts of power generation. The only notable exception being *PLEF-Shift* and *CCC-Headwinds*, wherein *PLEF-Shift* has a lesser electricity demand but a greater amount of electricity generation. Again, this is largely attributable to the differences in hydrogen production via electricity. Although, *CCC-Headwinds* does have a greater total demand, in part owing to high overall hydrogen demand (Climate Change Committee, 2020b). A larger share of this is produced via steam methane reforming – thus necessitating further use of greenhouse has removals.

The caveats stated above notwithstanding, reduced growth in electricity demand (and overall energy demand) requires less renewable infrastructure. Although electricity generation capacity was not available for the *CCC* scenarios, *PLEF-Transform* did have 21% less installed capacity than *PLEF-Shift* in 2050, suggesting that less demand would also require less energy infrastructure overall. Thus, minimising the proliferation of electricity demand (and demand more generally) can potentially reduce the energy systems' embodied energy and emissions whilst minimising investment costs.

Both sets of scenarios estimate the associated costs associated with their respective transitions. However, the datasets are not presented in comparable terms and the accounting method is not reported for the *PLEF* pathways. Both sets of scenarios include capital and operating costs (operation and maintenance, fuels), whilst the *CCC* also includes the cost of financing capital investment. *PLEF* scenarios also include non-energy costs associated with mitigation levers in the agricultural sector, whereas the *CCC* does not state this. *PLEF* costs are reported as undiscounted and in 2010 prices, in contrast to *CCC* reporting, which has a discount rate of 3.5% and is in 2019 prices. Furthermore, the CCC reports their costs relative to a baseline scenario, whilst the *PLEF* baseline is an uncosted estimate that was not an output from UKTM. Finally, neither set of scenarios reported the assumed technology prices, which could drastically skew the estimates for energy system investment. Policy costs are also excluded from both scenarios.

Therefore, we must assess each group of pathways in isolation. Looking at the *PLEF* scenarios, *PLEF-Transform* requires reduced investment than *PLEF-Shift*, reflecting less need for supply-side infrastructure. Undiscounted annual investment increases by 29.8% from 2020 to 2050 in *PLEF-Shift*, whereas it remains almost the same in *PLEF-Transform* (<-0.01%), suggesting that demand reduction can moderate against investment costs in the transition to net zero emissions.

The *CCC* pathways show a similar, but more muddled picture. Like the *PLEF* analysis, the pathway with the greatest EDR, *CCC-Widespread Engagement*, has the lowest cumulative annualised resource costs (£279bn by 2050). The link between demand reduction and costs is particularly acute when you consider other scenarios, such as Widespread Innovation (£368bn by 2050), assume greater reductions in the cost of low-carbon technologies and carbon removal. However, *CCC-Tailwinds*, which has the next lowest energy demand, requires the most energy investment costs (£513bn). This reflects the high levels of technological development characterising this pathway and the increased mitigation ambition in reaching net zero emissions in 2045. Despite containing the least electrification, *CCC-Headwinds* entails significant investment (£454bn). This is due to the associated costs of high levels of CDR technologies and large-scale hydrogen production.

4. Discussion

4.1. Demand reduction, risks and uncertainties in UK net-zero scenarios

The UK net-zero scenarios analysed indicate that reductions of 30% – at the very least – are necessary to reach net-zero emissions. However, pathways with 30% EDR are largely reliant on efficiency improvements, rather than broader societal change. They risk the need for higher capacity levels and deployment rates of supply-side infrastructure to meet demand and potentially unrealistic removals of carbon dioxide to achieve net-zero. Reductions of around 40% imply an active role for energy demand policy beyond energy efficiency policies, requiring considerable changes to social practices and patterns of consumption, supported by comprehensive and cohesive government policy. Scenarios reducing demand by 50% or more extend the changes described above, requiring a radical departure from current dominant thinking on energy and climate policy, from infrastructure and construction to diets and mobility. Table 6 identifies the different characteristics associated with varying degrees of final demand reduction.

The technological uncertainties associated with an overreliance on the development and scaling of supply-side and CDR technologies in pathways with lower levels of EDR, adds weight to the need for a much greater focus on demand-led mitigation. As found in this study, substantial near-term EDR moderates the extent of electrification, reducing the amounts of renewable capacity required to displace fossil fuels (Barrett et al., 2022). To add to this, the smaller the demand, the lesser residual emissions, diminishing the reliance on CDR technologies (Barrett et al., 2022; Grubler et al., 2018; Pye et al., 2021), which echoes the findings of non-UK based scenario exercises (Umweltbundesamt, 2019; Association négaWatt, 2022).

Decarbonisation strategies that are heavily reliant on the use of

Table 6
Broad trends identified across PLEF and CCC pathways.

Demand Reduction	Scenarios	Technological Risk Level	Characteristics
~30%	*PLEF-ST*	High	Emphasis on EE measures rather than social change
	CCC-H		Greater reliance on CDR technologies (BECCS/DAC)
~40%	*PLEF-SH* *CCC-BP* *CCC-WI*	Medium	Increased role for EDR policies beyond just EE measures CDR plays a more limited role (DAC likely not needed)
	CCC-T *CAT-ZCB*		Less risk of supply-side technologies not meeting demand
~50%	*PLEF-T*	Low	Can potentially achieve net-zero emissions without engineered CDR technologies
	CCC-WE		Greater levels of social change required Requires less energy infrastructure costs

BECCS and other CDR technologies pose considerable questions around the feasibility of the scale of removals required in some scenarios (Vaughan and Gough, 2016; Mander et al., 2017; Grant et al., 2021a). This uncertainty is underpinned by a) the feasibility of required investment levels and high costs (Rogelj et al., 2013; Riahi et al., 2015; Smith et al., 2016; Fuss et al., 2018; Hansen and Kharecha, 2018; Bednar et al., 2019); b) the significant consumption of land use required by oft-relied on technologies such as BECCS and the potential for negative climate related side-effects (Smith et al., 2016; Fuss et al., 2018); and c) the potential for the promotion or reliance on CDR to negate incentives to decarbonise, locking in near term emissions (Rogelj et al., 2019; McLaren, 2020; Pye and McKane, 2000; Grant et al., 2021b). This has resulted in some authors proclaiming the risks of relying on negative emissions technologies to be "an unjust and high stakes gamble" when compared with strong mitigation in the near term (Anderson and Peters, 2016, p. 183).

Whilst the uncertainty and risk associated with a high reliance on technological CDR options is high, it is also the case that EDR led mitigation faces barriers and risks. One flaw in the modelling of EDR across the scenarios assessed here is the limited exploration of rebound effects, which could reduce the achievable level of demand reduction. Only the *CCC* pathways consider rebound effects, assuming an increase in electric vehicle miles due to the lower fuel costs associated with their operation. However, quantified estimates of rebound effects in the literature are diverse, often depending on the particular intervention and the nature of rebound effect captured (Brockway and Dickinson, 2021). However, estimates for rebound effects are often excluded to a single specific intervention and reflect a likely response given present day economic conditions. Given the breadth of socio-economic change implied by pathways pursuing significant EDR, estimates for rebound are difficult to apply. In fact, given that many of the high-rebound estimates in the literature regard the positive impact of energy efficiency measures on economic growth (Brockway et al., 2021; Barrett et al., 2022; Bruns et al., 2021), a greater focus on social changes to unlock those higher levels of EDR may limit the size of rebound effect involved. Understanding the potential rebound effects of EDR scenarios as a whole and integrating these into scenario modelling is a necessary area for future research.

Another possible risk to high EDR is that, in present political contexts, pathways with high levels of social change cause a tension in policymakers' reluctance to encourage social change to reduce demand. Many demand-side mitigation options require fundamental shifts in individual lifestyle consumption choices; however, the mainstream political view is that public support for these actions is weak (Carmichael, 2019), and therefore not worth pursuing. In this view, social change to unlock higher levels of EDR is more difficult given it may require changing attitudes or values of individuals, who whilst supportive of climate change mitigation, do not want to fundamentally change their lives or consumption habits, resulting in it being difficult to realise EDRs (Dubois et al., 2019).

Given present conditions, it is true that energy intensive needs satisfaction is often incentivised, making social-led change difficult, or require individuals to be 'forced' to change (Dubois et al., 2019). However, this need not be conceived as paternalist changes to individual lifestyles, but as providing the policy and infrastructure required to foster low-energy societies and increase public participation in the transition. A first step is recognising that current hegemonic approaches in the UK induce demand growth, foster policy inertia, and lock in emissions by perpetuating energy intensive patterns of energy service provision, such as significant ongoing investments in road infrastructure projects (Department for Transport, 2020; Marsden et al., 2014), reductions in air passenger duty on domestic flights (H. M. Revenue and Customs, 2022) and the steady removal of regulations and funding to improve thermal efficiency (Eyre and Killip, 2019). Some research has shown that historical social transitions operate on a smaller timeframe than technological transitions, despite governments tending to be less proactive actors than in the former. However, after a certain level of public acceptance in social change is reached, policy implementation acts as a tipping point for fast-paced behavioural change (Nelson and Allwood, 2021). Given the urgency and scale of change required over the next few decades, governments must seize this capability in conjunction with technological development to reach net-zero targets.

4.2. *Transparency in UK net-zero modelling and beyond*

Transparency in scenario modelling is essential to enable their use in policymaking. We generally found demand assumptions to be unreported, opaque, or vaguely described across UK scenarios – hence the limited scope of this analysis and exclusion of certain scenarios. This is also a problem for the reporting of energy demand output data, where a lack of consistent reporting (e.g., classification of end-use sectors and variables) meant comparisons could not be drawn. Furthermore, the *PLEF* pathways only publicly reported assumptions for three of the five end-use sectors. Similarly, the *CCC* pathways did not publicly report final demand or key demand variables (Table 3). These data were only acquired after extensive communication with the respective organisations, which was not possible with the others.

A central benefit of modelling decarbonisation pathways is their ability to evidence and describe the scale of change necessary, or to form milestones or targets that progress can be checked against. They inform us of the range of heat pump installations likely to be needed over a given period, or the market share of electric vehicles required to adequately decarbonise the transport sector in a timely manner. They identify key priorities for decarbonisation, and important system-wide implications of different policy choices. However, the non-transparent way that assumptions are currently reported ensures that this important function cannot be realised. Greater transparency, clarity and openness in the reporting of model inputs will increase the potential for external energy modelling to influence government thinking.

Beyond providing greater transparency in modelling assumptions, improved reporting of the impact of decarbonisation scenarios on demand-side metrics is crucial to ensure necessary government policy is pursued. Whilst we were able to access demand-side data behind the *Sixth Carbon Budget* report by engaging with the *CCC*, the public reporting of the impact of their scenarios on final energy demand at a sectoral or economy wide scale was lacking, with only primary energy demand being published (i.e. the total energy demand in its raw energy source, including the energy that is lost in extraction, refining, conversion and transportation), which can mask the inefficiencies associated with losses and distribution. Failing to report key demand metrics associated with various net-zero scenarios undermines EDR as a crucial and necessary mitigation mechanism in public and policy debates. These actions obscure the need for policy to actively reduce energy demand to achieve net-zero. A greater level of reporting, and consistency between how energy demand metrics are reported in modelling exercises can help support necessary policy development and allow consensus to emerge. Thus, further research in this area could develop common frameworks for the reporting of key modelling assumptions and outputs beyond a UK context.

The need for transparency is also crucial in government-published modelling, whereby the modelled pathway represents an intended strategy to achieve legally binding decarbonisation targets (e.g., the UK Government's Net-zero Strategy (Department for BusinessEnergy and Industrial Strategy, 2021a). National strategies on climate change mitigation must be led by science, and maintaining transparency and openness to scientific scrutiny of proposed pathways are essential to ensuring this. The published material in the UK's Net-zero Strategy (Department for BusinessEnergy and Industrial Strategy, 2021a) does not offer this level of transparency. It does not publicly report the level of anticipated final demand, nor the underlying modelling assumptions and timelines of important variables, such as energy service demands or the rollout of key end-use technologies. Due to the vagueness in the reporting of decarbonisation measures in this government strategy, the UK's High Court of Justice found the Net Zero Strategy to be unlawful (Good Law Project, 2022). This lack of transparency in public office has significant implications for energy demand policy.

Based on limited publicly available data, the UK Government's *Net Zero Strategy* (and its implied policies) fail to explore energy demand options that independent scenarios suggest are essential to achieve net-zero. There is little mention of energy demand beyond the adoption of energy efficiency measures and efficient end-use technologies. This is reflected in the report's foreword, wherein the then Prime Minister writes that "we will still be driving cars, flying planes and heating our homes, but our cars will be electric …, our planes will be zero emission allowing us to fly guilt-free" (Department for BusinessEnergy and Industrial Strategy, 2021a, p. 9) – suggesting that shifting patterns of consumption and avoiding unnecessary energy demand will not be required. Whilst the reporting of final demand in the *Net-Zero Strategy* is lacking, assessing these priorities against those in Table 3, indicates an affinity with high final demand scenarios. This kind of scenario has implications for energy policy, the rollout of supply-side and CDR infrastructure and the investment costs of a net-zero transition. If this is the case, then it is imperative that the underlying assumptions are necessarily transparent so that it can be interrogated by academics, civil society actors and the public. The UK Government's failure to publish its' climate plan in an open or transparent manner has meant that a comparison of the UK's *Net Zero Strategy* could not be conducted in this analysis. Without a more detailed understanding, it is unclear whether the trajectories outlined by the UK Government are either practical, feasible or socially acceptable.

This research necessarily has a national perspective, as mitigation and EDR strategies and targets largely occur at this level. Progressing the understanding of EDR at the national level provides opportunity for others, outside of a UK context, to learn from. This analysis provides a framework for comparison that can be replicated across different countries and geographical contexts to assess the relative contribution of energy demand reduction to national mitigation strategies and pathways. Further comparisons across geographical scopes, such as cross-country or cross-regional comparisons are also possible but would likely be most suitable on a per capita basis and need to consider the idiosyncrasies of various national energy systems.

4.3. Limitations and further work

As outlined above, direct comparisons between key variables were not always possible (e.g., levels of insulation, construction mitigation measures etc.) due to varying modelling methods across scenario sets. This prevented a more detailed understanding of EDR ambition across the net-zero scenarios analysed.

A further key limitation of this analysis is that two sets of pathways (National Grid's Future Energy Scenarios and the Centre for Alternative Technology's Zero Carbon Britain) are excluded from the more detailed analysis that follows due to data availability, transparency and reporting. National Grid pathways have been excluded as their modelling exercises exclude key end-use subsectors (rail, aviation and shipping). The Zero Carbon Britain pathway was excluded because their end-use sectors could not be mapped onto corresponding sectors for the CCC and PLEF reporting. We also wanted to include a comparison with the UK Government's Net Zero Strategy but were unable to do so. The Net Zero Strategy pathways significantly lack transparency and fail to publish basic time series and sectoral data for final energy demand.

There is variation between each scenario in terms of the level of ambition in each sector. For example, *CCC-Widespread Engagement* shows greater demand reductions in domestic buildings, whereas *PLEF-Transform* shows greater reductions in transport. Therefore, there may be further potential for total overall EDR that isn't explored in these scenarios. Future scenario exercises could incorporate the most ambitious elements of each scenario into a consistent modelling framework to create a pathway with greater overall energy demand reduction.

Additionally, further work should attempt to quantify the co-benefits of various scenarios. It is often the case that co-benefits and improved wellbeing are an implicit by-product of energy demand reduction (Creutzig et al., 2022), as is argued in this analysis. However, the actual quantifiable impacts – specific to each scenario – of EDR are rarely interrogated in a quantifiable manner (Finn and Brockway, 2023). Being able to compare the associated improvements to wellbeing could aid policymakers in decision-making. Furthermore, we would implore that these issues are not viewed through a narrow, economic lens, as previous work on co-benefits has tended to be (e.g. Pye and McKane, 2000; Jakob, 2006; Bleyl et al., 2019, amongst others). Understanding improvements to wellbeing in monetary terms leads to many co-benefits being excluded from analyses if they are less tangible (Finn and Brockway, 2023), such as comfort, and the over-prioritisation of benefits that are easily transformed into monetary units, such as health outcomes.

5. Conclusion and policy implications

It is clear from this analysis that EDR will be imperative in the transition to net-zero emissions in the UK. All the scenarios assessed show substantial reductions in energy demand. The pathways with the least demand reduction leave the door open to substantial technological risk, relying on the rapid development and large-scale rollout of CDR technologies, such as BECCS and DAC – which risk being unable to achieve climate targets. These pathways tend to be the most expensive option. Vice versa, the pathways with the highest levels of demand reduction had a smaller (and almost non-existent in one case) reliance on CDR technologies and tended to require less investment in supply-side infrastructure relative to their counterparts.

Achieving higher levels of EDR requires a drastic reframing of energy demand policy. It cannot be assumed that these reductions in demand will occur organically. It requires a broad and cohesive suite of policies and regulatory changes (Eyre et al., 2022) to develop less energy-intense energy service provision and modifications to patterns of consumption. To do so, greater transparency in net-zero modelling done by policymakers, academics and other research groups is necessary to inform policy. But currently, it is almost impossible to (a) accurately scrutinize the UK Government's approach to energy demand, (b) measure progress on energy demand against government pathways and (c) wholly understand the implications of the UK Government's net-zero strategy for the energy system. Conducting comparative analyses of possible net-zero pathways holds significant value in this respect, allowing for a more public debate on the potential advantages and pitfalls of each strategy, as well as identifying key points of consensus to inform policy making. Further research developing standards for transparency and accessibility of energy modelling, to enable clearer scrutiny of net-zero pathways would make a valuable contribution in supporting effective policies to achieve net-zero.

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Declaration of competing interest

No conflict of interest statement.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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