Energy demand reduction options for meeting national zero emission targets

John Barrett (✉ j.r.barrett@leeds.ac.uk)

University of Leeds <https://orcid.org/0000-0002-4285-6849>

Steve Pye

UCL <https://orcid.org/0000-0003-1793-2552>

Sam Betts-Davies

University of Leeds <https://orcid.org/0000-0001-5682-4103>

Oliver Broad

University College London <https://orcid.org/0000-0002-6179-927X>

James Price

UCL

Nick Eyre

ECI - University of Oxford

Jillian Anable

University of Leeds

Christian Brand

University of Oxford

George Bennett

University College London

Rachel Carr-Whitworth

University of Leeds

Alice Garvey

University of Leeds

Jannik Gieseke

Strathclyde University <https://orcid.org/0000-0003-2915-1323>

Greg Marsden

University of Leeds

Jonathan Norman

University of Leeds

Tadj Oreszczyn

University College London

Paul Ruyssevelt

University College London

Kate Scott

University of Manchester <https://orcid.org/0000-0001-7952-0348>

Article

Keywords:

Posted Date: January 26th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1070886/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Abstract

Energy Demand Reduction (EDR) refers to lowering the amount of energy required to provide energy services across mobility, shelter, nutrition or the production of goods and services, among others, with the goal of reducing greenhouse gas emissions. In recent years, global studies have attempted to understand the contribution EDR could make to climate mitigation efforts. Whilst these studies are important to build a global picture, climate targets and policy are necessarily devised at the national level. To address this disconnect, we develop a bottom-up, whole system framework that comprehensively estimates the potential for energy demand reduction at a country level. Replicable for other countries, our framework is applied to the case of the UK where we find that reductions in energy demand of 52% by 2050 compared with 2020 levels are possible without compromising on citizens' quality of life. This translates to annual energy demands of 40GJ per person, compared to the current OECD average of 55GJ. Our findings show that EDR can reduce reliance on high-risk carbon dioxide removals, moderate investment requirements, and allow space for ratcheting up climate ambition. We conclude that national climate policy should increasingly develop and integrate EDR measures to both articulate national ambition and feeding into international pledges through Nationally Determined Contributions.

Full Text

Since the Paris Agreement was signed, global assessments have shown the important role that reducing energy demand can play in meeting international climate targets by easing pressure on the decarbonisation of energy supply and reducing the need for carbon dioxide removal (CDR)²⁻⁴. Yet, global final energy demand continues to grow; since 2000, it has increased at an average annual rate of 1.9%⁵. This growth continues to be met, in part, by fossil fuels. New low carbon energy, particularly renewable generation, is not keeping pace with increasing demand^{6,7}. Whilst the carbon intensity of the global energy system is falling, at its current rate it would take 150 years to fully decarbonise⁸. This highlights the importance of actions that reduce energy demand for meeting stringent targets.

The bottom-up framing of the Paris Agreement means that the responsibility for reducing GHG emissions and delivering climate action is at the country level. Many countries have revisited their initial Nationally Determined Contributions (NDCs) assessments, and have developed long-term Low Emissions Development Strategies⁹, including net-zero emission targets. Despite this, current pledges by countries continue to fall short of the 1.5°C target¹⁰. A stronger focus on energy demand reduction in national mitigation plans could reduce this shortfall by realising the potential identified in global assessments, particularly in nations with disproportionately high energy use.

Recognising this gap, we develop a framework to comprehensively estimate the potential for energy demand reduction at a country level. This framework, replicable for other countries, is applied here to a case study of the United Kingdom, providing the most comprehensive assessment to date of the potential for energy demand reduction at the national level. We show that, for a developed country such as the UK, it is possible to halve energy demand by 2050 without negatively affecting citizens' quality of life. This results in a per capita energy use in the UK, in 2050, of around 40 GJ compared to the present global average of 55 GJ/capita.

We also find that the role of Carbon Dioxide Removal (CDR) technologies, which have yet to be proven at scale, is substantially reduced or eliminated, reducing the risk of failing to achieve climate objectives should such technologies not materialise in a timely manner. Further, the required annual investment to expand the electricity generation system is reduced by up to 40% by 2050. Finally, the option for additional ratcheting of climate ambition becomes possible due to the smaller energy system, its associated lower emissions, and the potential for faster implementation of demand side measures. Crucially, such a strategy does not compromise quality of life but rather realises strong co-benefits of climate action, such as healthier active lifestyles, lower urban airborne pollution and improved work-life balance. With policy implemented at the national level, a stronger focus on the potential for energy demand reduction at this level, is critical to the delivery of GHG emission reductions and the many associated benefits.

The potential role for energy demand reduction

Global energy demand increases are being driven by economic growth and the rising demand for energy services. Between 1971 and 2018 on average, every 1% of additional global Gross Domestic Product (GDP) has increased energy demand by 0.68%¹¹. This growth in demand has occurred despite a period of substantial energy efficiency improvement across all sectors¹². Notwithstanding, modelling assessments have highlighted the contribution energy demand reduction could make to meeting climate goals. Grubler et al. construct a scenario that reduces global energy demand by 40%, negating the need for CDR, with different pathways for global north and south regions². The IEA's *Sustainable Development Scenario*¹³ and *Net Zero by 2050*³ roadmap focus on the potential of energy efficiency improvements from investment in new technologies, arguing that these measures are crucial to the decarbonisation of energy systems. Kikstra et al. highlight that an energy efficiency focused recovery from the COVID-19 pandemic would reduce the cost of meeting the Paris Agreement¹⁴. The literature also includes scenarios on how energy demand could be reduced through changes to how society consumes energy services. There are various terms used to describe this mechanism, such as 'lifestyle change'¹⁵⁻¹⁷, 'behaviour change'^{3,13,18} or 'social change'^{19,20}.

To date, comprehensive energy demand reduction scenarios have focused at a multi-national or global level. While global analysis provides useful framing, mitigation targets and climate policies are necessarily devised at the national level. This presents a gap in the national scenarios literature that has direct policy relevance, namely the potential for energy demand reduction to help deliver stringent mitigation targets²¹ (see SI section 2). We use the UK as a case study to explore this potential, given its legally binding targets for short and long term GHG emissions^{22,23} (see SI section 1) and extensive development and use of scenario analysis of decarbonisation pathways²³. This case study develops a modelling framework that brings together sector level energy demand modelling with a whole systems energy model to determine the role of energy demand reduction in achieving ambitious climate targets²⁴.

A national modelling framework for energy demand reduction

As argued in Pye et al.²⁵, most energy modelling approaches focus on representing the energy supply system to meet a set of exogenous energy service demand projections. Energy services refer to the utility we derive from energy, such as lighting, thermal comfort, leisure, mobility and food. While energy efficiency gains are often represented to some extent, solutions that help avoid energy service demand altogether, or that shift to cleaner forms of demand provision, are often missing¹.

We propose a modelling framework for national analysis which identifies and integrates essential steps to better understand and quantify the contribution of energy demand reduction to climate targets (see Figure 1). First, it allows for assessment of how energy demand reductions can contribute to achieving net-zero emissions through near- and medium-term emission reductions. These changes are developed in step with a corresponding supply side system and its necessary technology change. Second, it goes beyond options to ‘improve’ energy efficiency and considers solutions for energy demand reduction that ‘avoid’ energy use and ‘shift’ to more efficient energy demand provision¹. This recognises the need for a stronger focus on the socio-technical dimension of transitions. It identifies that reducing energy demand is not just a matter for energy policy but extends to other policy areas and stakeholders. Thirdly, it provides simultaneous and consistent whole economy and sector level perspectives. This captures the detail required at the sector level, and reflects the diverse strategies that are applied across different sectors. The whole system perspective is crucial to capture the linkages and trade-offs between sectors, helping ensure consistency based on the chosen scenario narrative. This also facilitates dialogue between sector experts, and a shared understanding of different aspects of the narrative.

Our modelling framework builds on and extends past advances in energy demand modelling outlined by Grubler et al.² and demonstrates how these can be transferred into a national modelling framework to assess the potential for energy demand reduction (Figure 1). We start by developing narratives based on known drivers of future energy demand (Step 1). These included similar trends to those considered by Grubler et al.² covering digitalisation, sharing and circular economy, energy efficiency, healthy society, environmental awareness, globalisation and work, and automation (see SI section 4).

These narratives are then implemented in sector models to derive detailed energy service demands and their evolution over time (Step 2), highlighting differences in the role for energy demand reduction. In parallel with step 2, an iterative process is undertaken to map the dependencies to ensure consistency between sectors (Step 3)^[1]. The resulting energy service demands and other demand sector assumptions are then fed into a whole-systems modelling framework, in which scenarios are assessed (Step 4). This allows us to assess supply side implications that reflect demand side changes across all sectors. Finally, the outputs from the whole systems model are used to describe a set of coherent scenarios (Step 5). This approach is further elaborated in the Methods, with additional detail in Supplementary sections 3 and 4.

The potential for energy demand reduction in the UK

To demonstrate the application of our framework to the UK context of getting to net-zero GHG emissions by 2050, we consider four scenarios, each with differing levels of energy demand reduction.

Table 1. Scenarios considered

Scenario name	Description
Ignore demand	Identifies levels of energy demand up to 2050 assuming only existing UK Government climate policy instruments are implemented (as of 2018). This includes existing policy for delivery of emission reductions, but not climate targets or ambition.
Steer demand	Adopts the more ambitious legislated target of net-zero GHG emissions by 2050, but falls just short of meeting it. Uses the same energy service demand projections as the Ignore scenario but implements a wide range of energy efficiency options.
Shift demand	Similarly to Steer, adopts the net-zero GHG emissions target. Significant shift in the attention given to energy demand strategies providing an ambitious programme of interventions across the whole economy describing what could possibly be achieved with currently available technologies under current social and political framings.
Transform demand	Similarly to Shift, this scenario adopts the net-zero GHG emissions target. Considers transformative change in technologies, social practices, infrastructure and institutions to deliver both reductions in energy but also numerous co-benefits such as health, improved local environments, improved work practices, reduced investment needs, and lower cumulative GHG emissions.

The key insights from these energy demand scenarios highlight the benefits of the proposed framework when analysing stringent emission targets. Firstly, energy demand reduction options that stretch beyond energy efficiency measures can lead to considerably higher levels of energy demand reduction in all energy service sectors. Secondly, these reductions can significantly curb the need for deploying large scale engineered CDR options such as bioenergy with carbon capture and storage (BECCS) or Direct Air Capture (DAC). Thirdly, a reduction in energy demand can substantially reduce the investment requirements across the energy system. Finally, energy demand reductions offer earlier mitigation opportunities and a greater reduction in cumulative emissions, allowing for ratcheting of climate ambition.

The most ambitious energy demand scenario, *Transform*, represents a 52% reduction in final energy consumption by 2050 compared to 2020. In comparison, energy efficiency measures alone deliver savings of 31% under the Steer scenario. The difference highlights the significant role that shifting and avoiding demand can play in reducing energy use. It is the use of this additional potential that means that both low energy demand scenarios, *Transform* and *Shift*, meet the UK's net-zero target, while *Steer* comes up short by 27 MtCO₂e.

The reductions observed in our scenarios imply that strict changes are required across all sectors. For example, *Transform* sees reductions of over 50% in energy demand across all sectors, except industry, which the transport sector compensates for with reductions of over 60%.

For the *Transform* scenario, this is equivalent to per capita energy use of 39.6 GJ, compared to the current global average of 54.9 GJ. The analysis in Grubler et al.² suggests the global North could reduce energy demand to 49 GJ / per capita by 2050. However, it is worth noting that the UK's energy demand is currently below the average of the global North (See SI section 1), one reason being the reliance of the UK on overseas industrial production and the net imports of embodied energy to satisfy its consumption²⁶.

Effects of energy demand reduction on the energy system and climate targets

There are significant risks around decarbonisation strategies that rely heavily on the scale up of CDR^{25,27}. Figure 3a and b shows that strong demand-side action can significantly reduce the reliance on such engineering solutions by reducing energy demand across the economy, and lowering associated emissions. Removals through BECCS and DAC, shown in figure 3a, total 49 MtCO₂e in 2050 for the *Steer* scenario, which increases to 76 MtCO₂e if we infer that the identified emissions gap to net-zero also requires removals. For context, residual emissions of 76MtCO₂e represents around 17% of 2019 day territorial emissions in the UK²⁸. This level can be more than halved to 37 MtCO₂e in *Shift* or removed completely under *Transform* where no engineered removals are required. The *Transform* scenario deploys more nature-based removal options (figure 3b), reaching up to 60 MtCO₂e by 2050. However, the system could still achieve net-zero with less than 30 MtCO₂e of nature-based removals and no engineered solutions, highlighting lower dependency on removals more broadly.

Under a net-zero target, the energy supply system needs to be transformed to decarbonise the wider economy. This challenge is significant, given the need for high levels of societal acceptance of new technologies, and overcoming the sizable challenge around building out a new infrastructure in a short period of time. The smaller energy system in the lower energy demand scenarios helps to moderate this challenge. For instance, while in all three scenarios electricity needs to be both decarbonised and scaled up, this scaling is lower under *Shift* and *Transform* at a 94% and 44% increase respectively relative to 2020, compared to 150% under *Steer*. When considering the implications for specific technologies, this means that significant capacity expansion in complex nuclear or BECCS for power technologies is either reduced, or not required. This is also the case for other sectors, reflected in overall system costs being 20%-40% lower in 2050 under the *Shift* and *Transform* cases respectively, relative to *Steer*.

Finally, on emission reduction targets, there have been calls to further strengthen climate ambition in the UK, to reflect a more equitable allocation of global efforts to reduce emissions^{29,30}. Anderson et al.²⁹ have called for the adoption of more stringent targets, translating to lower cumulative emissions (of around 23%) that better reflects an equitable apportionment of the remaining global carbon budget, in a way that is consistent with the Paris Agreement. To understand whether demand reduction enables a ratcheting of the UK's climate ambition, we modelled our transform scenario using a tighter cumulative carbon budget derived by Anderson et al.²⁹ (*Transform CB see SI section 5*)[2]. Our analysis finds that many energy demand reduction options can occur in the short-term, allowing for stronger near-term emissions reductions, and an overall lower level of

cumulative emissions (see *Transform CB* in Figure 4). This allows time for time-intensive infrastructure to be built, whilst still reducing emissions in the short term. By 2030, *Transform CB* sees a 47% emissions reduction relative to 2020, compared to a 41% reduction under *Transform* and 37% under *Steer*. Crucially, this earlier action keeps the window open for further strengthening the climate ambition, and reducing cumulative emissions further.

[1] See methods figure 5 for a graphical representation of sectoral interlinkages.

[2] We use a value of 3.87 GtCO₂e, differing slightly from Anderson et al to reintroduce process emissions from cement for cross comparison.

Discussion And Conclusion

This research shows substantial unexplored potential to reduce energy demand in developed countries that can make a significant contribution to near-term emission reductions, and long-term national and international climate goals. The analysis demonstrates that it is possible to operationalise the scale of reduction identified by Grubler et al.² that suggested a 56% reduction in energy demand in developed countries, with our results suggesting a reduction of 52%. Without energy demand reduction, short-term climate targets are unlikely to be reached and long-term net zero ambitions will need to rely on expensive and unproven CDR technologies, increasing the risk of failing to achieve the global goals of the Paris Agreement. The UK case study presented here suggests that there is significant potential for developed countries to reduce energy demand, reducing pressure on the decarbonisation of supply and deployment of CDR. At a national level, this potential is currently under explored and is often limited to a range of energy demand technologies as opposed to taking a broader approach that encompasses societal change to shift and avoid energy service demand. With the rapid cuts in global carbon emissions required over the next 10 years, particularly where energy use is high in the global north, energy demand reductions are essential.

Deep reductions in energy demand involve both rapid shifts to more energy efficient technologies alongside broader societal transformations that maintain quality of life while reducing energy service demands. The first are truly global opportunities, while the second currently have greater potential in the global north, where they can be pursued across most sectors without compromising quality of life. This significant potential for energy demand reduction, particularly in countries of the global north such as the UK, calls for the integration of explicit energy demand reduction strategies into national climate mitigation pathways.

Methods

The description of our methods is organised around the steps outlined in our framework diagram in Figure 1.

Step 1: Development of scenario narratives

Some modelling approaches are designed to provide a “prediction” or “forecast” of the future. That is not the case with our analysis; rather we are creating “simulations” of potential futures based on a well-developed narrative, written by experts across a range of disciplines and fields. This narrative is used to inform a bottom-up analysis of energy service demands in each sector, which are subsequently used in an economy-wide model to construct “net-zero” scenarios for the UK. Overall, our scenario approach is designed to give insights into the scale of change in energy demand and GHG emissions that is possible under certain circumstances.

Step 1 of our approach is the development of a scenario narrative that is underpinned by seven observable underlying trends that have impacted energy demand, and/or are likely to continue to do so throughout the scenario timescale. Our list of underlying trends is not exhaustive as various other observable societal, political, economic, and scientific or philosophical trends may impact on energy demand, such as demographic changes. We also recognise that there is considerable crossover between the various trends, and that some could have the potential to increase as well as further reduce energy demand³¹. Nevertheless, developing this narrative gives the sectoral scenarios a consistent underpinning. The underlying trends are listed below, and described in further detail in the SI section 4. Supplementary Table 1 in SI section 5 provides a mapping between the different energy services demands and the underlying trends listed below.

- Digitalisation – The integration of digital systems and ICT into the energy system is already driving significant changes in the energy sector and is likely to accelerate change in the future, from promoting new energy business models through to changing how consumers interact with energy services.
- Sharing and circular economy - The ‘sharing economy’ is an approach that aims to decrease the number of under-utilised ‘owned’ assets in an economy, by creating new business models that offer a service in its place². The ‘circular economy’ is a concept that explores resource efficiency strategies to extend the time that resources are retained in the economy, to reduce material throughput and environmental impacts^{32–34}.

- Energy efficiency – Energy efficiency has steadily improved by 1% annually over the past 30 years, with no indication that the potential for further energy efficiency improvements is saturated³⁵.
- Healthy society – The context of the COVID-19 pandemic has increased global focus on health, wellbeing and quality of life, at the policy level and by individuals.
- Environmental awareness - As climate and ecological breakdown accelerate and significant climate impacts of events such as wildfires and flooding gain global attention, public concern for the environment grows across the globe.
- Globalisation - Increasing globalisation in the form of international production networks and global value chains has a wide range of impacts on national final energy demand in different countries.
- Work and automation - This trend considers the distinct impact that automation may have on working patterns in the UK, and how this may change the demand for energy services.

Step 2: Sector level modelling

The options for delivering energy demand reduction vary considerably across different sectors. The technologies and embedded social practices are entirely different for different energy service demands. We therefore employ specific sector models to determine the energy demand for each sector before combining this information into a central whole-system energy modelling framework. A detailed description of each model and the underlying assumptions can be found in the Supplementary Information section 4.

Table 2. Sector level models

Sector	Models used	Modelling approach
Mobility	TEAM-UK (Transport Energy Air pollution Model for the UK) ³⁶	TEAM-UK is a transport-energy-environment system modelling framework that simulates passenger demand as a function of key travel indicators, built around detailed travel demand data from the UK National Travel Survey.
Nutrition (incl. agriculture)	Hybrid UK MRIO (Multi-Regional Input Output Model) ³⁷	The hybrid UK MRIO utilised for nutrition modelling is a Leontief physical input-output food system model, constructed from observed economic data of intermediate and final demand.
Shelter (domestic buildings)	UK National Household Model (NHM) ³⁸	The NHM is a micro-simulation model that utilises national housing survey data to explore the future of energy demand in the domestic building stock.
Non-domestic buildings	Bespoke Model	A bespoke sectoral model for non-domestic buildings was developed for this analysis and built around the UK Building Energy Efficiency Survey (BEES) dataset ³⁹ to explore different rates of energy efficiency uptake.
Materials and products (industry)	Hybrid UK MRIO (Multi-Regional Input Output Model) ³⁴	A hybrid UK MRIO model was used to determine the supply chain impacts and the ultimate impact on production requirements from UK industry

Step 3: Identification of individual linkages

A critical part of the sectoral modelling process is to map the dependencies between sectors, to ensure consistency so that key aspects of the narrative represented in one sector are also reflected in others. This is an important part of the approach to ensure that the scenarios are internally consistent.

Figure 5 shows the main dependencies between sectors. Many linkages relate to the shelter analysis highlighting dependencies (shown by the blue arrows), where shifts in working patterns fundamentally change the type and patterns of mobility demand, and the use of non-domestic buildings. Differences in house building assumptions are also reflected in the demands for construction materials. Choices about transport infrastructure impact on the demand for construction materials, while changes in vehicle sales impact on manufacturing. Changes to diet impact the level of

land take, which feeds into land availability for forestry, as well as the level of output in specific food and drink subsectors, impacting energy demand in that sector. A more detailed description of these inter-linkages can be found in supplementary information section 4.9.

Step 4: Integration into a central modelling system

The next step of the approach is to combine the sector analyses into an integrating framework, primarily to explore the system wide implications of lower energy demand requirements on energy supply, and the role of CDR. For this we use UKTM, a technology-explicit, whole system, partial equilibrium model which relies on the TIMES model generator framework⁴⁰. The model optimises future energy system evolution using linear programming, optimising future investment choices to meet energy service demands at least-cost (based on minimising the discounted NPV for the whole system). The model has been used across a wide range of energy scenario studies^{41–45}. In recent years, it has been co-developed with the UK's energy ministry (BEIS), who have used it extensively to inform their energy strategies^{46–48}.

The model represents the existing energy system in 2010, including the existing infrastructure assets (power generation plants, vehicle stock etc.) and flows of energy both between and across sectors. This is graphically represented using a systems network diagram, or Reference Energy System (see figure 6). In UKTM, the whole system is represented, from resource extraction, through to primary and secondary fuel production (electricity, hydrogen, biofuels), and finally consumption in the residential, industrial, service, transport and agricultural sectors. This final consumption is used to meet the wide range of final energy service demands needed across the economy, such as mobility, heating, and industrial production.

For scenario exercises, projected energy service demands are exogenous inputs into the model. Their change over time are the main drivers for investment and system development in the model which solves by exploring least cost supply-side solutions to meet these future service demands^[1]. The whole system representation allows for explicit trade-offs between sectors in respect of resource allocation. Demands for energy vectors, such as electricity and hydrogen, are endogenous to the model, and sensitive to changing prices driven by the dynamics of balancing demand and supply. The other benefit of the whole system representation is that it allows for comprehensive and internally consistent accounting of both energy- and key non-energy related greenhouse gases, including e.g. agriculture and land use. This means the model can be used for exploring energy systems that meet climate and energy policy goals.

Under each scenario, the sectoral modelling (steps 2 and 3) provides estimates of energy reduction through 'improve, shift, and avoid' measures. Two types of information relevant to energy demand are passed for use in UKTM:

- Energy service demand projections (blue arrows in Figure 6). These projections inform how energy services will change over time, based on 'avoid' measures and some 'shift' measures in transport. They are exogenous inputs to the whole-system model and are based directly on sector model projected energy service demands.
- Technology efficiency measures (orange arrows in Figure 6). The sectoral analyses takes account of opportunities for 'improving' the efficiency of energy use, and shifting to cleaner energy use. Such measures include improved efficiency of technologies, switching to electricity using appliances, and building retrofits. Such measures are typically considered endogenously by UKTM; therefore, we have not hardwired efficiency-related energy demand reductions in to UKTM from the sectoral modelling. Rather we have tried to align input assumptions on technology efficiency, and deployment rates, followed by an iterative process of checking model outputs with sector teams.^[2]

The linkages between sector models and UKTM are described in turn below. Further information on specific UKTM assumptions across sectors can be found in the Supplementary Information section 4.

- **Mobility:** The sectoral modelling approach for mobility includes the development of energy service demands based on in depth assessment of a range of behavioural levers, which are then fed into the UK Transport Energy and Air Pollution Model (TEAM)³⁶ to explore journey distance by purpose, mode choices, vehicle choices and rates of deployment. International aviation was restricted to an assessment of energy service demands influenced mainly by socio-economic, demographic and policy (e.g. changes in the cost of air travel via pricing such as frequent flier levy) drivers. Shipping was not included in the TEAM analysis and was considered separately by the UKTM team.

UKTM received energy service demand projections for all transport subsectors, except shipping. On energy technology assumptions, the key alignment was on vehicle efficiency factors to those in TEAM. The modelling teams also iterated on UKTM constraints, including rates of technology deployment.

- **Shelter:** This analysis uses the UK's National Household Model (NHM), focusing on heating requirements under different scenarios, which factor in varying levels of new house building, retrofitting, and other behavioural changes.

For this sector, UKTM received the energy service demands for space and water heating. Given that these energy service demands already include heat demand savings from energy efficiency measures, building retrofit options were switched off in UKTM to avoid double counting. The NHM already underpins energy technology assumptions in the UKTM residential sector meaning that further alignment was only required around elements adjusted for this analysis e.g. heat pump deployment rate and Coefficient of Performance (COP) as they differ between scenarios.

- **Non-domestic:** The sectoral modelling for non-domestic buildings was built around the UK Building Energy Efficiency Survey (BEES) dataset ⁴⁹ and is used to explore different rates of energy efficiency uptake across the three modelled scenarios. By reviewing the current and future expected building stock for each of the main sub-sectors, including main commercial, leisure, and public service building uses, this approach estimates the full technical savings potential across the sector and translates different levels of ambition into varying growth rates for corresponding energy efficiency options.

The results from this model provided direct input into UKTM by informing the total energy efficiency gains from building retrofit and management measures that are not related to technology replacement. These include fabric, building instrumentation and control, and carbon and energy management systems. Their roll out was then limited in UKTM according to the levels of ambition relevant to each scenario. Efficiency gains from technology switching (primarily through electrification) are estimated endogenously in UKTM.

In parallel, different growth trajectories for future building stock number – proxied through total floor space requirements - were developed for each scenario. These were built specifically for this sector but were developed in consultation with experts across the project to mirror changing pressures on e.g. storage space requirements in line with changes in retail shopping and home delivery. These floor space requirements then provided the main energy driver input into UKTM as their change over time was used to inform future growth in energy service demand in the model.

- **Materials and products:** The input to the industry sector of UKTM was from the sector analysis of resource efficiency gains as estimated in UK MRIO. The approach was to first apply resource efficiency percentage gains to the UKTM growth drivers; these growth drivers are largely taken from the UK Government econometric energy demand model, EDM ⁵⁰. In addition, further adjustment factors to account for changes in infrastructure construction in other sectors e.g. buildings, transport were applied to key sectors producing construction materials e.g. iron and steel, cement.
- **Nutrition:** The integration into UKTM of the sector analysis of nutrition covers the resulting on-farm agricultural changes, in terms of emissions and land availability, due to changes in the overall national diet as well as scenarios for the reduction of food waste throughout the supply chain. Because of the low level of detail in the UKTM agriculture sector, the link was made through the emissions of CH₄ and N₂O relating to crops and livestock which were updated to follow the trends seen in the sectoral modelling for each scenario. The resulting land freed up by a shift to a more plant-based diet was used to define new limiting constraints on the planting of forests within UKTM (both for biodiversity and energy crops) such that the more ambitious the nutrition scenario, the more land that becomes available for forests out to 2050. Finally, the assessment of food waste generation from the sector analysis for each scenario were used to adjust the trends shaping the scale of food waste production in UKTM.

Step 5 – Construction of scenarios

We have developed four scenarios, shown in table 3.

Scenario	Description	Climate ambition*
Ignore demand	Identifies levels of energy demand up to 2050 based on UK Government climate policy instruments as of 2018, as described in the Climate Change Committee's (CCC) 2018 Progress Report to Parliament ⁵¹ .	Based on achieving reductions as estimated in CCC 2018 progress report, including medium risk policies ⁵¹ . This is a 12% reduction in 2032 rel. to 2020 (or 50% rel. to 1990). This leads to GHG emissions of 390Mt by 2050, from 2020 emissions of 470 MtCO _{2e} .
Steer demand	This is considerably more ambitious than the ignore demand scenario. Maintains energy service demands (as per the Ignore scenario) but has the goal of reducing emissions to net-zero by 2050	Net-zero GHG target in 2050 pursued (27 MtCO₂ deficit), plus Carbon Budget 1-6
Shift demand	Significant shift in the attention given to energy demand strategies providing an ambitious programme of interventions across the whole economy describing what could possibly be achieved with existing technologies and current social and political framings.	Net-zero GHG target in 2050, plus Carbon Budget 1-6; cumulative emissions equiv. to 4.95 GtCO ₂ .
Transform demand	Consider transformative change in technologies, social practices, infrastructure and institutions to deliver both reductions in energy but also numerous co-benefits such as health, improved local environments, improved work practices, reduced investment needs, and lower cumulative GHG emissions.	Net-zero GHG target in 2050, plus Carbon Budget 1-6; cumulative emissions equiv. to 4.95 GtCO ₂ .

Table 3. Implementation of scenarios in UKTM

* All scenarios except Ignore demand have also been run with the cumulative carbon budget of 3.87 GtCO₂, described below.

Our “Shift” and “Transform” scenarios are our so called “Low Energy Demand” (LED) scenarios. They assume a national attempt to rapidly reduce energy demand in the UK to increase the likelihood of meeting ambitious climate outcomes in the short and long term. Our scenarios provide an analysis of the total final energy demand in the UK and are also broken down into the five high level categories of mobility, residential buildings, non-domestic buildings, nutrition and materials and products.

In addition to the LED scenarios, two additional scenarios were considered at the system level in the UKTM analysis for comparative purposes. These include a scenario called “Ignore Demand”, based on achieving reductions as estimated in CCC 2018 progress report, including medium risk policies⁵². The second scenario is called Steer demand, which aims for net-zero GHG emissions by 2050, based on all the UK's legislated carbon budgets, including the sixth carbon budget. However, the scenario fails to achieve the 2050 target, falling short by 27 MtCO₂ despite high levels of removals. It relies on improved energy efficiency and supply side options only, with no consideration of measures for avoiding energy use or shifting to options that supply energy services with less energy e.g. private cars to public transport. Energy service demands used for this scenario reflect those used in UKTM analysis, and sourced from UK Government analyses.

[1] ‘Supply-side’ refers to any part of the system used to supply energy to meet energy service demands. This includes transformation / conversion processes e.g. electricity generation, and all of the technologies used in end use sectors e.g. gas boilers, cars, cement kilns etc. It also includes some explicit energy saving measures in the buildings sector, such as fabric retrofit.”

[2] The approach to endogenise sectoral assumptions in UKTM means that there are some differences between the sectoral and UKTM outputs. Differences have been tolerated where these are not significant, particularly as the key insights from UKTM relate to implications for energy supply to end use sectors.

References

- Creutzig, F. *et al.* Towards demand-side solutions for mitigating climate change. *Nature Climate Change* vol. 8 268–271 (2018).
- Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515– 527 (2018).
- IEA. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. <https://iea.blob.core.windows.net/assets/4482cac7-edd6-4c03-b6a2-8e79792d16d9/NetZeroBy2050-ARoadmapfortheGlobalEnergySector.pdf> (2021).
- IPCC. Summary for Policymakers. in *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*, 1–24 (In Press, 2018). doi:10.1016/j.oneear.2019.10.025.
- IEA. *Key World Energy Statistics 2020*. <https://www.iea.org/reports/key-world-energy-statistics-2020> (2020).

6. IEA. World total final consumption by source, 1973-2018. *IEA* <https://www.iea.org/data-and-statistics/charts/world-total-final-consumption-by-source-1973-2018> (2020).
7. BP. *Statistical Review of World Energy 2021*. (2021).
8. Romanello, M. *et al.* The 2021 report of the Lancet Countdown on health and climate change: code red for a healthy future. *Lancet* **398**, 1619–1662 (2021).
9. UNFCCC. Communication of long-term strategies | UNFCCC. <https://unfccc.int/process/the-paris-agreement/long-term-strategies> (2021).
10. Ou, Y. *et al.* Can updated climate pledges limit warming well below 2°C? *Science* (80-.). **374**, 693–695 (2021).
11. Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K. & Court, V. Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renewable and Sustainable Energy Reviews* vol. 141 (2021).
12. IPCC. *Climate Change 2014: Synthesis Report Summary for Policymakers Summary for Policymakers*. https://www.ipcc.ch/site/assets/uploads/2018/06/AR5_SYR_FINAL_SPM.pdf (2014).
13. International Energy Agency. *Energy Technology Perspectives 2020. Energy Technology Perspectives 2020* www.iea.org/t&c/ (2020) doi:10.1787/ab43a9a5-en.
14. Kikstra, J. S. *et al.* Climate mitigation scenarios with persistent COVID-19-related energy demand changes. *Nat. Energy* **2021** 1–10 (2021) doi:10.1038/s41560-021-00904-8.
15. Eyre, N., Brand, C., Layberry, R., Anable, J. & Strachan, N. Energy Lifestyles. in *ENERGY 2050: Making the transition to a secure and low-carbon energy system: Synthesis report* (eds. Ekins, P. & Skea, J.) 103–118 (UKERC, 2009).
16. Van Vuuren, D. P. *et al.* Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies. *Nat. Clim. Chang.* **8**, 391–397 (2018).
17. Institute for Global Environmental Strategies, Aalto University, and D. Ltd. 2019. *1.5-Degree Lifestyles: Targets and options for reducing lifestyle carbon footprints*. (2019).
18. Niamir, L., Ivanova, O. & Filatova, T. Economy-wide impacts of behavioral climate change mitigation: Linking agent-based and computable general equilibrium models. *Environ. Model. Softw.* **134**, 104839 (2020).
19. Kuhnhen, K., Costa, L., Mahnke, E., Schneider, L. & Lange, S. *A Societal Transformation Scenario for Staying Below 1.5°C*. <https://www.boell.de/en/2020/12/09/societal-transformation-scenario-staying-below-15degc> (2020).
20. Ivanova, D. *et al.* Quantifying the potential for climate change mitigation of consumption options. *Environmental Research Letters* vol. 15 093001 (2020).
21. Lepault, C. & Lecocq, F. Mapping forward-looking mitigation studies at country level. *Environ. Res. Lett.* **16**, 083001 (2021).
22. BEIS. *Energy Consumption in the UK 1970 to 2019*. <https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes> (2020).
23. Pye, S., Li, F. G. N., Price, J. & Fais, B. Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era. *Nat. Energy* **2017 23** **2**, 1–7 (2017).
24. CCC. *Sixth Carbon Budget: The UK's Path to Net Zero*. <https://www.theccc.org.uk/publication/sixth-carbon-budget/> (2020).
25. Pye, S. *et al.* Modelling net-zero emissions energy systems requires a change in approach. *Clim. Policy* **21**, 222–231 (2020).
26. DEFRA. *UK's carbon footprint 1997-2018*. <https://www.gov.uk/government/statistics/uks-carbon-footprint> (2021).
27. Anderson, K. & Peters, G. P. The trouble with negative emissions. *Science* (80-.). **354**, 182–183 (2016).
28. BEIS. *Final UK greenhouse gas emissions national statistics: 1990 to 2019*. <https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2019> (2021).
29. Anderson, K., Broderick, J. F. & Stoddard, I. A factor of two: how the mitigation plans of 'climate progressive' nations fall far short of Paris-compliant pathways. *Clim. Policy* 1–15 (2020) doi:10.1080/14693062.2020.1728209.
30. Jackson Tim. Zero Carbon Sooner - The case for an early zero carbon target for the UK. *CUSP Work. Pap.* 12 (2019).

31. Brugger, H., Eichhammer, W., Mikova, N. & Dönitz, E. Energy Efficiency Vision 2050: How will new societal trends influence future energy demand in the European countries? *Energy Policy* **152**, (2021).
32. Cooper, S. J. G. *et al.* Thermodynamic insights and assessment of the 'circular economy'. *J. Clean. Prod.* **162**, 1356–1367 (2017).
33. Hahladakis, J. N., Iacovidou, E. & Gerassimidou, S. Plastic waste in a circular economy. in *Plastic Waste and Recycling* 481–512 (Elsevier, 2020). doi:10.1016/b978-0-12-817880-5.00019-0.
34. Scott, K., Gieseckam, J., Barrett, J. & Owen, A. Bridging the climate mitigation gap with economy-wide material productivity. *J. Ind. Ecol.* **23**, 918–931 (2019).
35. Lees, E. & Eyre, N. Thirty years of climate mitigation: lessons from the 1989 options appraisal for the UK. *Energy Effic.* **14**, (2021).
36. Brand, C., Anable, J., Philips, I. & Morton, C. *Transport energy air pollution model (TEAM): methodology guide*. . https://d2e1qxpsswcpgz.cloudfront.net/uploads/2020/03/ukerc_wp_team_guide.pdf (2019).
37. Garvey, A., Norman, J. B., Owen, A. & Barrett, J. Towards net zero nutrition: The contribution of demand-side change to mitigating UK food emissions. *J. Clean. Prod.* **290**, 125672 (2021).
38. Centre for Sustainable Energy. National Household Model | Centre for Sustainable Energy. <https://www.cse.org.uk/projects/view/1233> (2014).
39. BEIS. Building Energy Efficiency Survey (BEES) - GOV.UK. *Building Energy Efficiency Survey* <https://www.gov.uk/government/publications/building-energy-efficiency-survey-bees> (2016).
40. Loulou, R., Lehtilä, A., Kanudia, A., Remme, U. & Goldstein, G. *Energy Technology Systems Analysis Programme*. <http://www.iea-etsap.org/web/Documentation.asp> (2016).
41. Fais, B., Keppo, I., Zeyringer, M., Usher, W. & Daly, H. Impact of technology uncertainty on future low-carbon pathways in the UK. *Energy Strateg. Rev.* **13–14**, 154–168 (2016).
42. Pye, S., Li, F. G. N., Price, J. & Fais, B. Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era. *Nat. Energy* **2**, 17024 (2017).
43. Fuso Nerini, F., Keppo, I. & Strachan, N. Myopic decision making in energy system decarbonisation pathways. A UK case study. *Energy Strateg. Rev.* **17**, 19–26 (2017).
44. Zeyringer, M., Price, J., Fais, B., Li, P. H. & Sharp, E. Designing low-carbon power systems for Great Britain in 2050 that are robust to the spatiotemporal and inter-annual variability of weather. *Nat. Energy* **3**, 395–403 (2018).
45. Broad, O., Hawker, G. & Dodds, P. E. Decarbonising the UK residential sector: The dependence of national abatement on flexible and local views of the future. *Energy Policy* **140**, 111321 (2020).
46. DECC. *Impact Assessment for the level of the fifth carbon budget*. (2016).
47. HM Government. *Building our industrial strategy*. (2017).
48. HM Government. *Net Zero Strategy: Build Back Greener - October 2021*. www.gov.uk/official-documents. (2021).
49. BEIS. *Building energy efficiency survey, 2014–15: Overarching Report*. . https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565748/BEES_overarching_report_FINAL.pdf (2016).
50. BEIS. *ENERGY AND EMISSIONS PROJECTIONS Methodology overview*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/794741/energy-emissions-projections-methodology-overview.pdf (2019).
51. CCC. *Reducing UK emissions - 2018 Progress Report to Parliament - Climate Change Committee*. <https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/> (2018).
52. CCC. *Reducing UK emissions: 2018 Progress Report to Parliament*. (2018).

Declarations

Acknowledgements

The contributions of all authors was supported by the Centre for Research into Energy Demand Solutions, award EP/R035288/1. In addition, the contribution of Kate Scott was supported by the NERC Fellowship Scheme, award NE/R012881/2.

Author contributions

JB designed, coordinated and wrote the paper with SP and SBD. SP also undertook the UK TIMES modelling with input from OB and JP. OB and JP also wrote and edited the paper. NE contributed to writing the paper. JA, CB, GM lead the transport modelling, contributed to paper writing and editing. GB with TO and PR undertook all the building modelling (domestic and non-domestic) while also editing the paper. JN with JG and KS undertook the industry, materials and product modelling while also providing edits to the paper. AG undertook the nutrition modelling with JN while also editing the paper. RCW undertook the modelling of appliances and edited the paper.

Competing Interest Declaration

The authors declare no competing interests

Data and code availability

All data and modelling available on request

Figures

Figure 1

Assessment framework for low energy demand scenarios

Figure 2

Reduction in final energy demand associated with scenarios. a) trend in total final energy consumption across the UK economy; b) relative percentage reductions (from 2020) across energy using sectors.

Figure 3

a) CO sequestration under net-zero scenarios, including CCS, CDR b) and Nature-based Solutions (NBS), 2020-50; c) Electricity generation by type under net-zero scenarios, 2010-50.

Figure 4

Cumulative GHG emissions budgets associated with the scenarios

Figure 5

Sector analysis and cross-sectoral linkages

Figure 6

Integration of sectoral analysis with UKTM [1]

[1] Appliances included within domestic and non-domestic sectors

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInformationTable1.docx](#)

- [SupplementaryInformation.docx](#)