CREDS

The role of energy demand reduction in achieving net-zero in the UK

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Our study

This study, undertaken by the Centre for Research into Energy Demand Solutions (CREDS), provides the most comprehensive assessment to date of the role of reducing energy demand to meet the UK's net-zero climate target. The study brings together 17 energy demand modelling experts from within CREDS to provide extensive detail on the possibilities to reduce energy demand in every sector. These sectoral reductions in energy demand are brought together into a whole-system modelling approach, to understand the potential contribution of energy demand reduction to support climate action in the UK.

CREDS was established as part of the UK Research and Innovation's Energy Programme in April 2018, with funding of £19.5M over five years. Its mission is to make the UK a leader in understanding the changes in energy demand needed for the transition to a secure and affordable, net-zero society.

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Glossary

ASHP	Air source heat pump
BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business, Energy & Industrial Strategy
BEV	Battery electric vehicle
CCC	Climate Change Committee
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CHP	Combined heat and power
DAC	Direct air capture
Defra	Department for Environment, Food & Rural Affairs
EV	Electric vehicle
GHG	Greenhouse gas
GSHP	Ground source heat pump
HEV	Hybrid electric vehicle
HP	Heat pump
ICE	Internal combustion engine
LED	Low energy demand
MRIO	Multi-Regional Input Output model
NDCs	Nationally Determined Contributions
NHM	National Household Model
ONS	Office for National Statistics
PHEV	Plug-in hybrid electric vehicle
TEAM-UK	Transport Energy Air pollution Model for the UK
TIMES	The Integrated MARKAL-EFOM System
UKTM	UK TIMES Model
ULEV	Ultra-low emission vehicle
WSHP	Water source heat pump
ZEV	Zero-emission vehicle

Executive summary

Our study

This study, undertaken by the Centre for Research into Energy Demand Solutions (CREDS), provides the most comprehensive assessment to date of the role of reducing energy demand to meet the UK's net-zero climate target. The study brings together 17 energy demand modelling experts from within CREDS to provide extensive detail on the possibilities to reduce energy demand in every sector. These sectoral reductions in energy demand are brought together into a whole-system modelling approach, to understand the potential contribution of energy demand reduction to support climate action in the UK.

Key findings

1. Without substantial reductions in energy demand, meeting climate targets becomes extremely expensive due to the substantial increases in the size of the energy system and the installation of expensive Carbon Dioxide Removal (CDR) technologies. Energy demand reduction is a significant enabler of a cost effective, timely and de-risked net-zero target.
2. Meeting carbon budgets aligned with net-zero by 2050 without substantial reductions in energy demand is extremely difficult and undesirable. Without reducing energy demand all greenhouse gas (GHG) emission reductions would need to be delivered through decarbonisation of energy supply and engineered CDR technologies.
3. The UK could more than halve its energy demand by 2050, making a substantial contribution to global and UK climate goals. Existing policy instruments would only reduce energy demand by 5% by 2050. We recognise there are a number of recent proposals reflecting increasing ambition but many of these have not translated into fixed policy instruments to date. Our focus is on policies actually implemented, not pledges of ambition, commitments or strategies.
4. Without a stronger role for energy demand reduction, the electricity system needs to be four times the size that it is today. Substantial energy demand reduction will moderate the expansion of the electricity system to double its current size. This makes system expansion more achievable in the coming decades. This is not only true of the electricity system but also in demand sectors that drive its growth, where the system will be much smaller when compared to our reference scenarios e.g. transport.
5. There are numerous co-benefits that could improve quality of life while reducing energy demand. People can still have access to local services, leisure and holiday activities, and diverse employment opportunities etc. Co-benefits to pursuing energy demand reduction include improved air quality, warmer homes, healthier diets and increased opportunities for exercise.

6. Energy demand reductions are possible across all sectors. Reducing energy service demand is particularly useful in "hard to mitigate" sectors such as steel production, aviation and agriculture. The response is different for each energy service and must include strategies to protect and enhance quality of life while reducing energy services as well as more traditional policy areas related to energy efficiency.
7. Some energy demand reduction measures offer earlier mitigation opportunities and a greater reduction in cumulative emissions. This would allow the UK to increase its climate ambition further in the next decade, establishing a role as a key leader in addressing the climate crisis.

Key conclusions

Without energy demand reduction we will not achieve the UK's Sixth Carbon Budget target in 2035 of 78% below 1990 levels, or our 2050 net-zero target. The UK Government has yet to define how energy demand will contribute to achieving our climate ambitions. Given the evidence presented in this report, it is imperative that the UK Government outline a detailed strategy and supporting policies to enable energy demand reduction to fulfil its necessary role in achieving rapid emissions reductions in the UK.

The limited government focus on energy demand has mostly been on improving technology efficiency with little attention to the other mechanisms that involve reducing the need for energy service demands. Reducing energy demand to the extent, and at the speed, that is needed requires both an acceleration in energy efficiency improvement and shifts in the consumption patterns of products and services, travel and diets to avoid the consumption of energy services. None of our Low Energy Demand (LED) scenarios compromise our quality of life. Instead, they seek to enhance it with numerous co-benefits associated with healthier diets, active living, clean air, safe communities, warm homes, rebalancing work and driving down inequality. All this is possible while halving the UK's energy demand.

There are clear advantages associated with energy demand reduction in achieving our path to net-zero compared to other options. Lowering energy demand has five important effects:

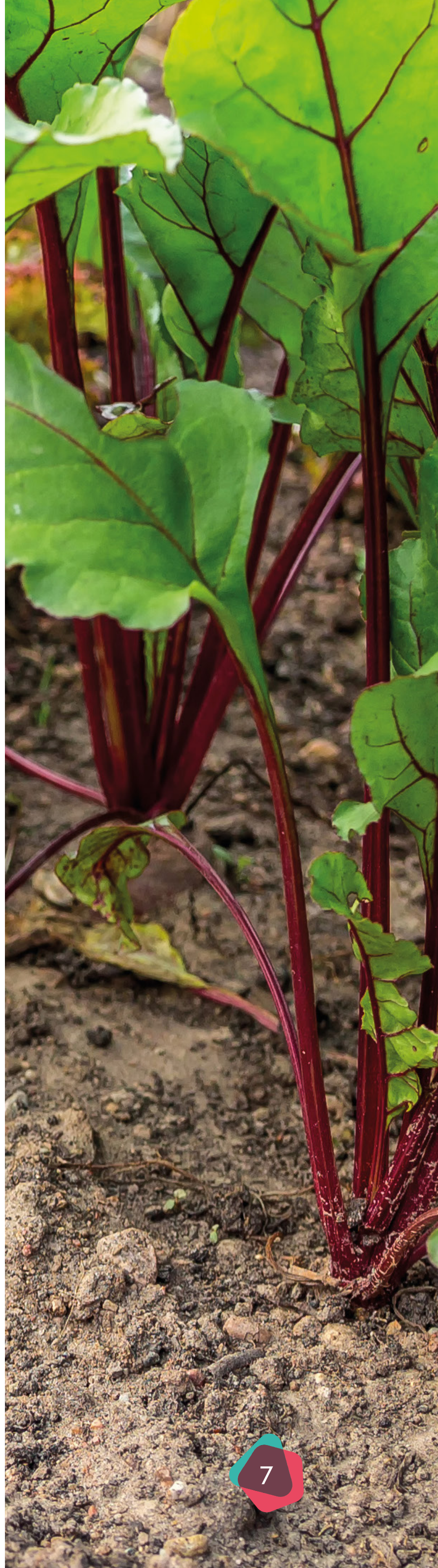
1. It accelerates transitions to a low carbon energy supply in the short-term by directly reducing our need for fossil-fuel energy production.
2. It reduces the technical challenges associated with building out larger low carbon energy supply systems that other futures require.
3. As a result, it reduces the overall investment requirements to achieve net-zero GHG emissions; these costs could potentially be passed on to consumers.
4. It provides flexibility to ratchet up climate ambition further.
5. It reduces reliance on risky CDR technologies.

Pursuing energy demand reductions lowers the risks of failing to achieve the UK's climate ambitions.

Broader implications

Our scenarios demonstrate that there is a significant gap between our current trajectory and the pathway necessary to achieve our net-zero goal. Here we outline five broader implications of our analysis.

1. Changes are required in the way we live, move and consume. The majority of changes needed to deliver the UK's 2035 and 2050 targets will have an impact on both technology and the way the way we live. To reach 2035 targets, early action to deploy both clean technologies and support lower-carbon lifestyles is urgently needed.
2. The challenge is truly systemic in nature and therefore requires oversight of the role of different actors to ensure system change. This leadership must be undertaken by Governments so that it can be overseen by democratically elected representatives. It is only possible if the UK Government has a clear vision outlining the role of different agents in achieving the goal of improving quality of life within net-zero aligned carbon budgets. Much of this change will stem from devolved, regional and local activities, and require a coordinated approach between different levels of government, communities, businesses and other stakeholders. Delivery is not solely undertaken by Government but roles are clearly defined and all agents are moving in the same direction.
3. The response to reducing our energy demand does not mean a collection of energy policies alone but aligned policies in all areas. The system is interconnected in that demands in certain sectors relate to practices and behaviours in others. This intrinsic link implies that some policies necessarily bridge any traditional divide. . Examples of this would be infrastructure development, innovation funds, recovery packages, procurement, planning and public health. It is policy coherency that delivers the scale of change required, not the piecemeal introduction of new energy policies alone.
4. This analysis raises questions on the measurement of progress and the tools applied to assess policy options inside Government. All UK Government policies are assessed for their "economic efficiency", rather than their broader value to both society and net-zero goals. While adjustments are made in economic analysis to try and address these exclusions, these are done using approaches that monetise social and environmental gains. An alternative approach is to create a strong vision of the UK that aligns improvements to the quality of life of citizens, whilst meeting net-zero targets. This involves monitoring and modelling a range of quality of life indicators and relevant Sustainable Development Goals (SDGs), and aligning these with net-zero goals. All policies, whether climate-related or not, need to be assessed against these broader objectives.
5. Social legitimacy is critical to delivering change. The changes required to deliver ambitious climate goals will have impacts on peoples' lives. The speed and scale of change will make the strategies and policies needed challenging to implement. As highlighted already, this can improve quality of life while reducing energy demand. However, even where there will be significant benefits to society, it requires public understanding and an honest public discussion, to give governments at all levels the social legitimacy to act. This will require deliberative methods such as those used in the UK Climate Assembly and similar exercises undertaken in several localities.



Key recommendations

To achieve this vision, we look to Government to provide the strategies and policies, and therefore recommend the creation of an **Energy Demand Reduction Delivery Plan** to be created as soon as feasibly possible, recognising the need for cross-departmental collaboration. This must include a quantitative assessment on the role of energy demand reduction in achieving short term carbon budgets and the long term goal of net-zero by 2050, feeding into Government planning on net-zero strategy. The plan must consider the role of energy efficiency improvements and technologies but also extend the analysis to societal changes that shift consumption and avoid unnecessary energy services.

The plan must also consider whether an energy demand target is required to support other important targets. For example, there is a target for the electricity generated by renewables in the UK but not a target on the level of energy demand.

The plan is required to consider whether non-energy policies are aligned with reducing energy demand, or are in fact making the challenge more difficult by increasing energy demand. This is particularly important in the area of infrastructure development, where it is essential to avoid the lock-in of high energy lifestyles. The plan must outline the role of different actors in achieving the reduction in energy demand, including the role of public and private actors for each sector. It is essential that UK citizens are fully engaged and this transition is not seen as a top-down approach to climate policy.

For specific sectors, any assessment considering how to reduce energy demand should consider:

- For agriculture and food, the promotion of healthy diets is essential to ensure that a significantly greater proportion of meals are plant-based and overall calorific intake is reduced in line with health guidelines;
- For industry, with limited energy efficiency improvements in energy intensive industrial processes available, reducing material consumption is essential through the introduction of a targeted resource efficiency strategy;
- For buildings, a triple approach of the rapid roll-out of heat pumps, retrofit of existing building stock and addressing the inefficiency of occupancy rates is required;
- For mobility, the scale of reduction required cannot be achieved with electric vehicles alone but requires a reduction in distance travelled delivered through investment in active travel and not the further expansion of road networks.

1. Introduction

Energy demand is the outcome of demands for energy services (such as thermal comfort, nutrition, and mobility), some of which are essential to life and most of which are widely accepted as important in a modern society. The scale of these energy service demands and the efficiency with which they are delivered together determine the size of the energy system. Because current global energy supply is dominated by fossil fuels, the size of the energy system determines the scale of decarbonisation or carbon removal required to mitigate climate change.

Global scenarios that deliver a 1.5°C target include energy supply changes and/or the rapid roll out of CDR technologies along with energy demand reductions through improved energy efficiency (IPCC, 2018). According to Brockway et al. (2021), energy efficiency improvements are projected to provide 40% of the planned global reductions in GHG emissions over the next 20 years. The International Energy Agency's net-zero analysis suggests a global reduction of 17% in energy demand between 2020 and 2050 while increasing energy service demands (IEA, 2021).

At present, change is not occurring at the speed required. Globally, renewable energy supply increased by 75 million tonnes of oil equivalent (Mtoe) in 2019. At the same time, energy demand grew by 120 Mtoe (IEA, 2019). Therefore, the current increase in renewable energy did not meet growing demand for energy, let alone replace the existing use of fossil fuels. In the UK, energy demand was at its high point in 2001. Since then there has been a decline with 2018 being 11% lower than in 2001. However, in recent years these reductions have ceased, with no notable reduction in UK energy demand for the past 6 years. This has allowed the expansion of renewable deployment to contribute to declining fossil fuel use and lower emissions.

However, current rates of displacement of fossil fuels are not at a pace consistent with the UK's 2035 emission reduction target. To ensure that reductions in use of fossil fuels occur at the pace required to meet the UK's climate ambition, both increased rates of renewable energy deployment and faster absolute reductions in energy demand are required.

At present, the UK Government has no comprehensive plan to reduce the UK's energy demand.[1] This report, undertaken by the Centre for Research into Energy Demand Solutions (CREDS),[2] provides the most detailed assessment to date on the potential to reduce the UK's energy demand by 2050. It brings together experienced modelling teams in the UK to construct a number of scenarios that demonstrate the contribution of energy demand reduction to achieving net-zero by 2050 and more importantly, a 78% reduction by 2035. More broadly, the report considers how reducing energy demand changes the need for emission reductions through the decarbonisation of energy supply and CDR.

This is achieved by undertaking the following steps.

1. Sectoral analysis of final energy demand up to 2050 for all the major energy service demands (mobility, shelter, services, nutrition, materials and products) for two energy demand reduction scenarios.
2. Use of the TIMES modelling framework to provide a comprehensive net-zero scenario for the UK based on our two energy demand reduction scenarios considering the changing contribution of energy supply decarbonisation and CDR.
3. Consideration of the social, cost and economic implications of the two low energy demand scenarios.
4. Discussion of the broader implications of achieving energy demand reduction in the UK.

1 There are a number of sector level strategies that define an important role for energy efficiency. An example is in the Industrial Decarbonisation Strategy. However, there is no economy-wide description of the role of energy efficiency in GHG mitigation.

2 For more information on CREDS, please visit www.creds.ac.uk

The overall aim of the report is to fill an important gap in the UK's net-zero transition by defining the role of reducing energy demand. Section 2 establishes the background to the report, outlining the need for energy demand reduction at the global and national level. It also establishes the importance of energy services to be maintained where necessary and identifies studies that have explored the potential mitigation contribution of energy demand reduction at a global scale. Section 3 outlines the scenario building and modelling approach used to construct our low energy demand scenarios. Section 4 discusses some key findings from our scenario analysis, and section 5 builds upon these to discuss the key implications, broader recommendations and opportunities for further research.

2. Background

2.1 The need for global energy demand reduction

Globally, energy demand is increasing, driven by economic growth and the rising demand for energy services. For every 1% of additional Gross Domestic Product (GDP), energy demand increases by 0.68% (Brockway et al., 2021). This is a long running trend dating back to 1971. Therefore, under current trends and given the ambition of every country to increase its GDP, energy demand is set to continue to increase.

This increase in global energy demand has occurred during a period of substantial energy efficiency improvements in all sectors. Efficiency of vehicles has improved year on year, improved insulation and better appliances continue to improve energy efficiency in buildings and industry continues to exploit energy efficiency options to reduce production costs. In a fossil fuel dominated energy system, improved energy efficiency has been the only significant downward pressure on global emissions (IPCC, 2014), but its effect has been more than offset by rising population, incomes and energy demand increases from productivity improvements.

The importance of energy demand for the global energy system is clear. The higher the energy demand, the larger the size of the energy system and the slower the transition to carbon-free energy production. With growth in global energy demand, any additional renewable energy supply first has to meet new demand before it can displace fossil fuel production.

Energy demand also has major implications for assumptions about the reliance on CDR to achieve global climate goals. All but one of the scenarios presented in the IPCC's 1.5°C report rely on the use of large amounts (100 to 1,000 $GtCO_2$) of CDR over the 21st century to achieve a 1.5°C target with limited or no overshoot (Rogelj et al., 2018). The exception relies on rapid and deep reductions in energy demand (Grubler et al., 2018). Concerns about the feasibility and adverse impacts of the rapid roll out of CDR are well documented (Rogelj et al., 2015; Anderson and Peters, 2016; Smith et al., 2016). In addition, it is not only the end point of net-zero emissions that matters but also the cumulative emissions on the pathway to it, as this determines the global temperature rise. Near term reductions in GHG emissions are therefore essential, and if CDR options do not materialise, earlier emissions are locked in, making climate goals unattainable.

Energy demand can be reduced in a number of ways: through energy efficiency improvements at the device level (e.g. vehicles, appliances), through delivering the same energy services for less energy (e.g. through modal shift from car to bus and increasing the use of recycled materials) and reducing the demand for energy services (e.g. by reducing the need to travel through local provision of services). Analysis has been undertaken at the global level on the potential contribution of lowering energy demand to achieve the global target of 1.5 degrees.

Grubler et al. (2018) provides one of the most comprehensive assessments to date, constructing a scenario that would negate the use of CDR by transforming energy demand at the global level. The analysis shows that two world regions (global north and global south) will take different pathways to achieve the global target. However, the paper does not present the low energy demand scenario at the national level. Global scenarios provide a valuable framing, but not an operational plan to reducing energy demand to achieve global targets. National level action on energy demand reduction is essential as this is where most strategies and policies will need to be implemented. Key policies relating to travel demand, efficiency of appliances, retrofitting of buildings, resource efficiency and food waste reduction will all be implemented nationally, making it essential to understand how global potentials outlined in Grubler et al. (2018) will be delivered.

We have categorised three ways to reduce energy demand.

- **Avoid – Reducing the need for energy services**: where this improves the quality of life. For example, this includes reducing unnecessary calorie intake, provision of local services to reduce the need to travel, food waste and lighting waste.
- **Shift – Providing the same energy service differently**: shifting calorie intake from meat to grain, shifting mobility from car to bus, shifting the purchasing of products to the services they provide.
- **Improve – Reducing energy demand through energy efficiency**: reducing the losses in converting delivered energy to useful energy. For example, adding more insulation to a wall or window, improving the efficiency of an electric transmission system, shifting heating from gas boiler to electric heat pump.

We recognise that there is considerable crossover between all three categories. For example, is a switch from a boiler to a heat pump an efficiency improvement or shift in technology? In reality, it is both. Our categorisation shown above is consistent with the approach described by Creutzig et al (2018) and commonly applied in the literature. The categorisation was used to ensure all options were considered, not to place different options within a fixed category.

2.2 The need for energy services

Whilst present levels of global energy demand are incompatible with limiting global temperature rises to less than 1.5°C (without relying on speculative CDR technologies) (Grubler et al., 2018; IPCC, 2018), it is also important to recognise that many essential societal needs rely on the consumption of energy. It would be impossible to heat our homes, provide food, mobility and communication, recreation and leisure activities to name a few. Thus, the consumption of energy is essential to the satisfaction of important human needs. However, there is agreement in the literature that this relationship hits a saturation point, where increased energy consumption no longer leads to the further satisfaction of these needs (Steinberger and Roberts, 2010; Burke, 2020). This indicates that countries with low energy use and low human needs satisfaction (often in the global south) should be allowed to increase their energy use to fulfil these. But further, this relationship suggests that in high energy consuming nations that have surpassed this saturation point, like the UK, the potential exists to reduce energy consumption, whilst maintaining the satisfaction of human needs and quality of life (Vogel et al., 2021).

Fortunately, there are numerous additional benefits to reducing the UK's energy demand that would improve or enhance quality of life while maintaining the services provided by energy. It is still possible to travel using alternative lower energy mobility (Brand et al., 2019; Brand et al., 2020). An active lifestyle is a healthy one while walking and cycling require negligible energy inputs in comparison to car travel (Brand et al., 2021). Reducing travel demand where most people live improves air quality and creates safer neighbourhoods. A healthy diet can also be a low energy diet with additional benefits of reducing non-GHG emissions from livestock (Garvey et al., 2021). A healthy diet can require less land area freeing up land for improving biodiversity while increasing recreational activities. Improving the fabric of a house to increase its efficiency results in warmer homes that use less energy. In addition, there are many new heating technologies that can reduce the operational costs for households. Businesses don't want to consume energy but want the service it provides. Energy and resource productivity improvements in industry reduce costs and increase competitiveness.

While there could be negative implications of reducing energy demand, this clearly does not have to be the case. However, there are some intensive energy demand activities that would need to be addressed. Aviation is a good example of this. Fortunately, the energy demand associated with flights is concentrated in a relatively small high-income group meaning that most of the population would not be affected by any strategies to reduce travel demand for aviation. Research by Buchs and Mattioli (2021) suggest that between 2006 and 2017, 75% of flights were taken by 20% of the UK population and in a typical year around 50% will not fly at all. At the global level, 1% of the population causes 50% of the GHG emissions associated with aviation (Gössling and Humpe, 2020).

Car travel is also highly unequal, particularly in cities and towns where more than 30% of households do not own a car and car ownership is highly correlated with income (Brand et al., 2013).

Figure 1 shows the distribution of energy demand across income groups in the UK, taken from Owen and Barrett (2020).

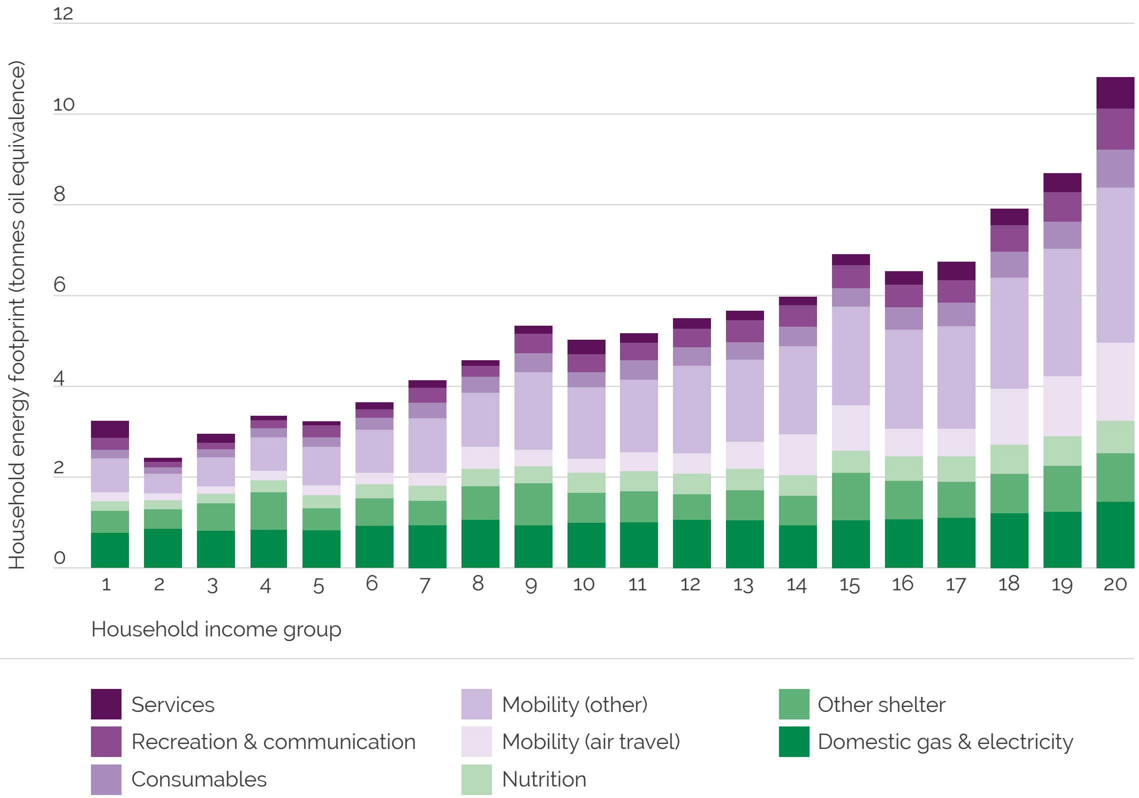


Figure 1: Distribution of final energy demand by income groups in the UK. Source: Owen and Barrett, 2020.

The analysis shows that the higher the level of income, the greater the energy demand. The difference between the lowest and highest energy using income group, is a factor of 4.5. This shows that it is possible to reduce energy demand in a way that does not increase levels of inequality. In fact, there is an opportunity to formulate a response to reducing energy demand while improving equality. One potential exception relates to household energy use for heating and power. The energy demand associated with home heat and power makes up a considerable proportion of low income energy demand. Any policies to reduce energy demand in this area will also need to reduce fuel poverty. Historically we have increased internal temperatures while reducing energy demand in our homes.

In summary, there are numerous co-benefits associated with reducing energy demand. Our low energy demand scenarios are designed to maximise these co-benefits, with one of our scenarios directly focusing on this issue.

2.3 UK energy demand

The UK Government currently has no comprehensive plan on how to reduce the UK's energy demand. A comprehensive plan would include a clear projection of energy demand and a sense on how individual strategies and policies would reduce this demand over time. Without a reduction in energy demand, the burden is placed on an even more rapid roll out of renewables to meet high levels of energy demand as well as the reliance on technologies yet to be fully demonstrated e.g. carbon capture and storage.

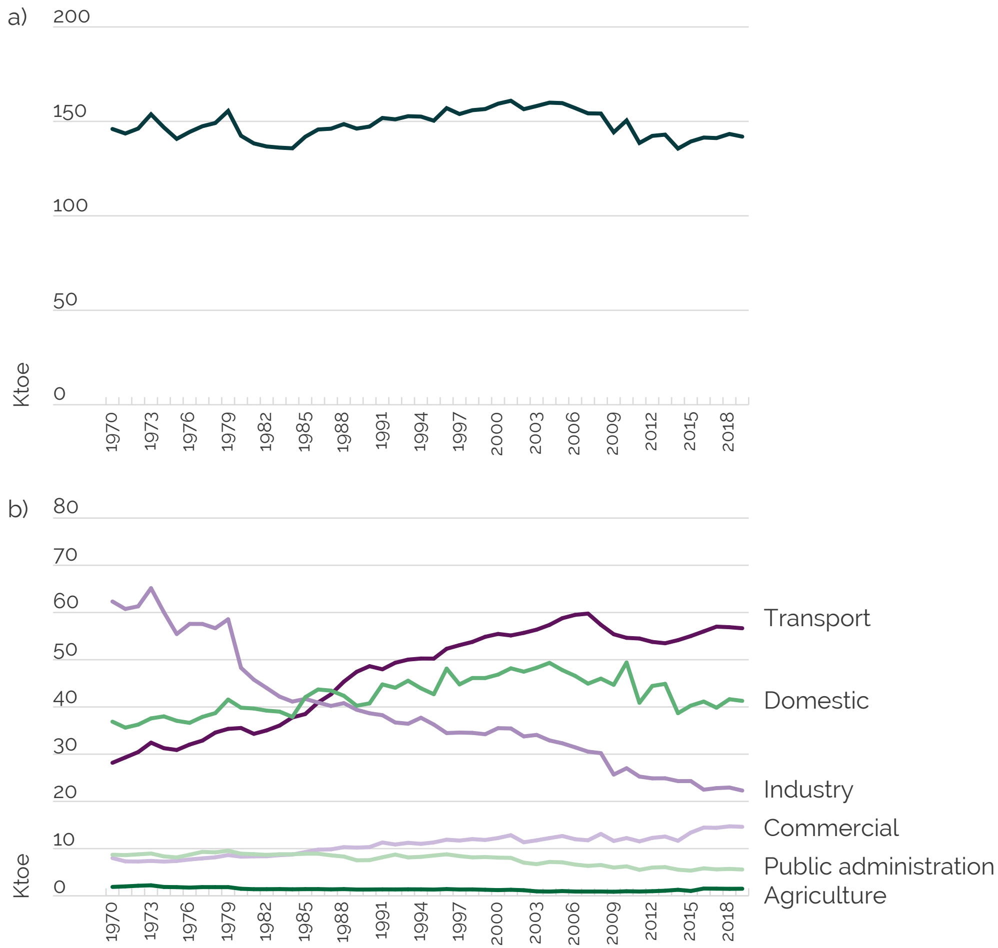


Figure 2: a) Total energy demand and b) by sector in the UK (1970–2018). Source: BEIS, 2020

In the last 50 years, the UK's energy demand has reduced by 2% (BEIS, 2020b). In reality, there has been virtually no reduction in energy demand in the UK for 50 years. As can be seen in Figure 2, there have been increases and falls in the total energy demand over this time period. Energy demand was at its high point in 2001 (10% higher than 1971), since then there has been a decline with 2018 being 11% lower than in 2001. However, in recent years these reductions have ceased, with no notable reduction in UK energy demand for the past six years.

This has been driven by opposing effects in the demand for energy services and the efficiency with which they are delivered. In the last 30 years, energy efficiency improvements have made the largest contribution to reducing UK emissions, exceeding the combined effects of renewable energy and fuel switching from coal to gas (Lees and Eyre, 2021).

The limited changes in total UK energy demand hide some significant changes in its sectoral composition. Energy demand for transport has doubled in the last 50 years while the population has only increased by 20%. Residential energy demand has increased by 11% over the same period while the number of households has increased by 47%, although this hides the fact that residential energy demand has reduced by 16% from its highest point in 2004. However, the reductions in residential energy demand have also slowed in recent years as energy efficiency programmes have weakened.

Energy demand for industry has reduced by 64% over the past 50 years. While some of this reduction can be attributed to energy efficiency improvements, the key driving factor is the shift in the UK towards a service-based economy (Hardt et al., 2018).

Data provided by the University of Leeds to the Department for Environment, Food & Rural Affairs (Defra) demonstrates that the UK's demand for energy to satisfy UK consumption has increased, not reduced.[3] However, the energy demand now occurs predominately outside the UK and is imported in the form of materials and products.

Future projections of UK energy demand undertaken by the Department for Business, Energy & Industrial Strategy (BEIS) suggest that energy demand will remain reasonably constant up to 2040, with their reference scenario showing a 2% decline over the next 20 years (BEIS, 2020c). The BEIS analysis also suggests that known policies will have no significant effect on the overall level of UK energy demand. The analysis by BEIS refers to known policies, rather than future policy aims or targets.

2.4 Relevant analysis of energy demand scenarios at international and global levels

This section identifies studies that have explored the potential mitigation contribution of reducing energy demand. The following literature review highlights that whilst there is a good understanding of mechanisms through which energy demand can be reduced and the potential range of impact this could have upon future global cumulative GHG emissions, there remains a limited picture of how energy demand reduction could be implemented at the national level, or the contribution it could make towards meeting national climate targets.

3 Data available from GOV.UK: UK's carbon footprint.

2.4.1 Energy efficiency-led scenarios

The low energy demand (LED) scenario developed by Grubler et al. (2018) is a frequently cited study that explores the potential contribution of global reductions in energy demand to GHG mitigation. Operating at the global level, it projects that energy demand could be 40% lower than today by 2050, based on a bottom-up analyses of changes in activity levels, energy intensity and final demand of end-use energy services. Its inclusion in the IPCC's (2018) Special Report on 1.5°C offered a contrasting perspective to other 1.5°C aligned scenarios, as the only scenario that did not increase energy demand. By reducing global energy demand, the reliance on speculative CDR measures to achieve ambitious carbon budgets was diminished (Rogelj et al., 2018). Furthermore, Grubler et al. (2018) evidence that reducing the size of the global energy system makes the task of transitioning to a low carbon supply much easier to achieve, as low carbon energy technologies can assume a larger share of the total energy mix.

The IEA's (2020) Energy Technology Perspectives 2020 report, included energy demand reducing measures within its Sustainable Development Scenario, in the form of exploiting energy efficiency improvements present in technologies. Broadly speaking, the scenario covers two groups of efficiency improvements, both of which are included in our UK focused LED scenario, adopting technologies that carry with them reductions in energy intensity, and material efficiency that aims to reduce energy service demand by reducing the material inputs needed to produce goods and services. Similarly to Grubler et al. (2018), it argued that energy efficiency measures that reduce overall energy use are crucial to decarbonisation of energy systems, as it reduces the 'resource constraint' problem with the roll out of low carbon technology (IEA, 2020).

Brugger et al. (2021) assess the potential for overarching societal trends to have an impact on energy efficiency and final energy demand at the EU level. They identify 12 societal trends that may have a future impact on the success of energy efficiency policies and future energy demand, both positive and negative. These societal trends relate to digitalisation, new social and economic models, industrial transformation, and changes in quality of life. In a best-case scenario, trends such as increased consumer awareness, urbanisation and smaller space living reduce energy demand by 67% compared with an EU baseline projection of final energy demand. Conversely, their worst-case scenario sees new societal trends contributing to a 40% increase in energy consumption through increased efficiency rebounds. They suggest this wide range of impacts displays that energy efficiency gains do not by themselves lead to energy demand reduction, highlighting the need for strong policy frameworks that ensure energy efficiency gains have the desired effect (Brugger et al., 2021).

2.4.2 Changes to social practices, lifestyles, and behaviour

The literature also includes scenarios that explore the extent that energy demand could be reduced through changes to how society consumes energy services. There are various terms used to describe this mechanism for demand reduction, such as 'lifestyle change' (Eyre et al., 2009; van Sluisveld et al., 2016; Van Vuuren et al., 2018; Institute for Global Environmental Strategies & Aalto University, 2019), 'behaviour change' (IEA, 2020; Niamir et al., 2020) or social change (Grubler et al., 2018; Kuhnhenn et al., 2020; Ivanova et al., 2020).

Van Vuuren et al. (2018) explore global scenarios consistent with limiting warming to 1.5°C that minimise the reliance on CDR strategies. Their scenario includes significant energy demand reduction through 'lifestyle change' including reduced meat consumption, modal shift in mobility service provision, changes in heating preferences and the avoidance of consumption of household appliances. Whilst on their own, these changes are found to be unable to match the pace of mitigation required, as part of a broader mitigation pathway including energy efficiency measures and shifts to low carbon energy production, demand reduction measures significantly reduce the need for CDR in limiting warming to 1.5°C.

Eyre et al. (2009) develop a scenario of lifestyle change in the UK built upon increasing concerns about energy use and its environmental implications. They suggest that lifestyle change impacts service demands mostly in residential and transportation energy services and have the potential to reduce national energy use and carbon emissions by 35% and 30% respectively.

They conclude that such a shift would reduce the cost of transitioning the energy supply to low carbon alternatives by £70 billion, concurring with others in the literature (Grubler et al., 2018; IEA, 2020) that energy demand reduction helps to facilitate supply-side transitions.

The Social Transformation Scenario developed by Kuhnhenn et al. (2020) is the most transformative scenario in terms of reducing energy demand. It does so by reducing the demand for high carbon goods and services, focusing on high carbon freight and passenger transport, heating, energy consuming appliances, and food. Energy demand in countries in the global north is significantly reduced through a strong decline in overall consumption levels, creating room for increased necessary consumption in the global south, whilst reducing global energy demand and staying within a global carbon budget consistent with 1.5°C of warming. They argue that the global north has a responsibility to dramatically reduce its consumption of high carbon goods and services, and abandon the pursuit of economic growth, to facilitate the dual aim of redistributing wealth within nations and internationally, whilst achieving mitigation rates consistent with limiting warming to 1.5°C.

Keyßer and Lenzen (2021) assess global 1.5°C scenarios that include a general reduction in economic output in the global north, due to strong climate mitigation. They compare these 'degrowth' mitigation scenarios to IPCC 'archetype scenarios' that assume ever expanding growth in economic output and energy demand. Whilst the political feasibility of degrowth is questioned, they suggest a reduction in final demand levels reduces the reliance on decoupling GDP from energy use at unprecedented rates, the development of unpredictable CDR technologies, and the unmatched speed of technological change necessary to decarbonise the current the energy supply.

Ivanova et al. (2020) evaluate the extent that various sustainable energy service consumption options led to genuine GHG mitigation, across food, housing, transport, and other consumption. They find that their top 10 most effective consumption options have the potential to mitigate 9.2 tCO_2eq/cap, compared to the high carbon alternative consumption option. They suggest this indicates an untapped area of mitigation that goes beyond discussions of the efficiency of production, to consider the nature of and scale of consumption in relation to planetary boundaries and satisfying human needs.

Modelling social change using integrated assessment models is a key challenge discussed widely in the literature, with various approaches being taken (van Sluisveld et al., 2016; Niamir et al., 2020; Sharmina et al., 2021). Van Sluisveld et al. (2016) insert 'lifestyle change' measures into an integrated assessment model, by changing key model parameters based on estimates established in the literature. Whilst this simple method does not directly capture agent decision making in the model, it facilitates a quick estimation of the scale of reductions given lifestyle changes could facilitate. Niamir et al. (2020) address this flaw, integrating an agent-based modelling framework into a computable general equilibrium model. This facilitates the scaling up of agent-based models of heterogeneous individuals to a larger level, capturing regional, social-demographic, and structural differences in individual's decision making when adopting low carbon decision making. Whilst these modelling approaches and methods used throughout the literature represent significant improvements in the methodologies to model social change-led energy demand reduction and GHG mitigation, the need for further model development is a key suggestion for further research throughout the literature.

2.4.3 Sectoral energy demand reduction

Some of the literature explores energy demand reduction scenarios in individual sectors with significantly high embodied energy such as construction (Mata et al., 2020), agriculture (Poore and Nemecek, 2018; Garvey et al., 2021), transport (Khalili et al., 2019) and other hard to mitigate sectors such as aviation, shipping, freight, and industry (Sharmina et al., 2021). Mata et al. (2020) investigate energy demand reduction in the building sector, through an exploration of sector roadmaps for net-zero around the world. They find that most roadmaps are focused on efficiency measures and technology-based upgrades to the housing stock, with limited focus on 'lifestyle' or 'behavioural' changes (Mata et al., 2020). Brand et al. (2019) explore four contrasting futures that compare transport-related 'lifestyle' changes and socio-cultural factors against a transition pathway focusing on transport electrification and the phasing out of conventionally fuelled vehicles. They find that lifestyle change alone can have a comparable and earlier effect on transport carbon and air quality emissions than a transition to electric vehicles with no lifestyle change.

Sharmina et al. (2021) identify key demand reduction options in four critical 'hard to reach' sectors: aviation, shipping, road freight and industry. They highlight that currently, integrated assessment models are unable to capture many demand side mitigation opportunities within their price elasticity demand mechanisms, such as modal shift for aviation, slow stemming for shipping, localised production reducing demand for freight transport, and circular economy measures in industry. Khalili et al. (2019) investigate scenarios of future global transport energy demand, mapping the shift away from fossil fuelled transport.

They suggest that the efficiency improvements accompanying low carbon fuel switching and electrification could offset the projected increase in global demand for passenger and freight transport, and this increased demand can be managed by a stable final energy demand in 2050, compared to 2015.

The literature that centres reductions in energy demand to support transitions to low carbon energy supply offers a crucially important alternative to those dominant scenarios relying solely on a supply-side transition and CDR. Given the pace and urgency needed to successfully mitigate the worst impacts of the climate crisis and the uncertain capacity of CDR measures to mop up remaining emissions, reducing final energy demand in countries where it is high is likely to be crucial to achieve the goals of the Paris Agreement.

However, to date, energy demand reduction scenarios have operated at a multi-national or global level, whilst mitigation targets and climate policies are devised at a national level, through Nationally Determined Contributions (NDCs) and net-zero commitments. This presents a gap in the energy demand reduction scenario literature that has direct policy relevance. This demand for tailored national-level evidence highlighting the capacity of energy demand reductions as a mitigation solution, is present in the Climate Change Committee's Sixth Carbon Budget (2020b), including energy and material efficiency measures, as well as changes to social practices including diet switching and modal shifting in transport. To further support national demand side climate mitigation policy, research is needed to develop cohesive frameworks for nations to put into operation energy demand reduction measures given unique national contexts. This research aims to fill this gap by developing a tailor-made low energy demand scenario for the UK.

3. Our approach

This section outlines the scenario and modelling approach that we adopted to construct our low energy demand (LED) scenarios. Each of these stages is summarised below and further information is given in each section.

1. Co-create a scenario narrative – see section 3.1
2. Devise coherent scenarios – see section 3.2
3. Bottom-up energy service demand modelling for two low energy demand scenarios – see section 3.3
4. Comprehensive economy wide scenarios developed in UK TIMES Model (UKTM) – see section 3.4

Figure 3 provides a visual representation of the modelling approach employed to develop our scenarios.

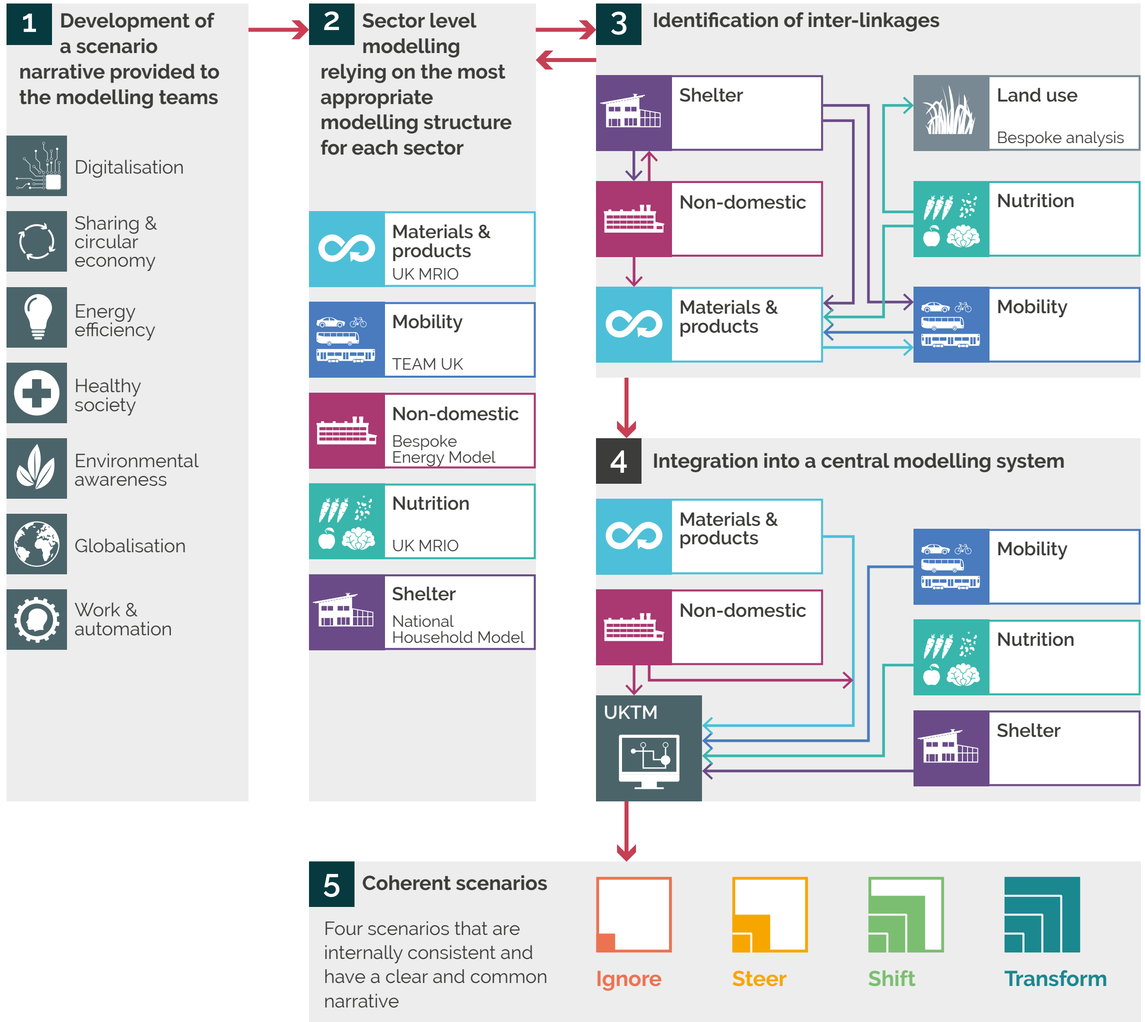


Figure 3: Our modelling framework

3.1 Scenario approach

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 then used to inform a bottom-up analysis of energy service demands in each sector, which are then used in an economy-wide model to construct "net-zero" scenarios for the UK. Our scenario approach is attempting to give insights into the possible scale of change in energy demand and GHG emissions under certain circumstances. Considerable effort has been made to ensure that the scenarios are internally consistent (see section 3.3.6).

We have developed four scenarios:

- **S1 – Ignore demand** Identifies levels of energy demand up to 2050 based on current known and planned UK Government policy instruments
- **S2 – Steer demand** Maintains energy service demands but has the goal of reducing emissions to net-zero by 2050
- **S3 – 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.
- **S4 – Transform demand** 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.

Scenario 3 and 4 assume a national effort to rapidly reduce energy demand in the UK to increase the opportunity 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. For nutrition, the analysis has been extended beyond energy demand to consider the non-CO_2 GHG emissions associated with livestock. This allows us to give a more comprehensive assessment of the GHG emissions associated with our scenario. Descriptions of definitions of the sectors are given in section 3.3.

Historically, strategies to reduce energy demand have focused largely on improving energy efficiency over options to reduce demand for energy services or to change the way that services are delivered. This unnecessarily limits options whilst also failing to consider the underlying drivers of energy demand and the connection between energy efficiency and the economy. Rebound effects created by energy efficiency improvements have been shown to occur a) directly, with lower prices allowing for increased energy consumption, b) indirectly, with increased consumption of other energy services, and c) on an economy-wide scale, by stimulating economic growth (Sakai et al., 2019). As there are also limits to the technical potential of efficiency improvements, particularly in energy intensive industrial processes (Cooper et al., 2017), it is important to consider other demand side strategies alongside energy efficiency.

Creutzig et al.'s demand-side assessment framework (Creutzig et al., 2018), adopted by the IPCC, can be used to identify a broader range of strategies to reduce energy demand.

Through this framework, we can avoid unnecessary energy services (e.g. reducing the need to travel), shift to the lowest intensity mode to deliver a service (e.g. modal shift from car to public or active transport), and improve energy efficiency. Each of these strategies can be applied to a range of energy services.

Before quantifying the energy demand for the individual sectors, we developed a scenario narrative to ensure consistency across our two LED scenarios, similar to the approach adopted in Grubler et al., (2018). This shared vision is applied across all of the different energy using sectors. They include a number of principles that ensure that our scenario is both transformative but also within the realms of possibility. What is "possible" is, of course, very difficult if not impossible to define. Therefore, the set of principles are broad enough to take into account that predicting technologies, social practices and behaviours in 2050 is highly problematic. It is important to remember that we are creating possible futures in the form of scenarios and not a prediction of the future.

3.2 Low energy demand scenario narratives

Whilst there are many observable societal, political, economic, scientific or philosophical trends that may impact transitions to low carbon societies, this section identifies seven observable underlying trends that have impacted upon energy demand, and/or are likely to continue to do so throughout the scenario timescale. This list is not exhaustive, as various other trends may impact on energy demand, such as demographic changes. These seven trends are captured in Figure 4. We recognise that there is considerable crossover between the various trends. We also recognise that some of these trends have the potential to both increase and reduce further energy demand (Brugger et al., 2021).

3.2.1 Digitalisation

In the context of our scenario, digitalisation is the integration of digital systems and information and communications technology (ICT) into the energy system. It is already driving significant changes in the energy sector and is likely to accelerate change in the future by promoting new energy business models through to changing how consumers interact with energy services (Rhodes, 2020). Integrating ICT into the household and workplace energy systems and supply infrastructures will improve the capturing and use of energy system data. This will enable energy service providers to better understand consumption patterns, and more efficiently meet user's needs (Grubler et al., 2018). The benefits of digitalisation also extend to consumers. Increased use of smartphones in managing energy services extend control and interactivity to the consumer, opening the potential for increased efficiency of consumption of energy in the household. Further, digitalisation has the potential to substitute material goods with digital equivalents, such as books or music (Court and Sorrell, 2020).

However, it is worth noting that increased digitalisation will not necessarily bring about a reduction in energy demand. Lange et al. (2020) identify four impacts of digitalisation on energy demand. Whilst digitalisation was found to facilitate efficiency increases with the potential to reduce energy demand, they highlight the potential for rebound effects. These include the potential to foster economic growth and the embodied energy within the production of ICT, that may both bring about increases in demand (Lange et al., 2020). This potential rebound effect is reiterated by others in the literature (Court and Sorrell, 2020; Noussan and Tagliapietra, 2020). In the mobility services context, Noussan & Tagliapietra (2020) suggest that avoiding increased energy demand due to rebound effects requires policies that ensure optimised and shared use of energy services and technologies.

Figure 4: Seven underlying trends impacting on energy demand

Thus, whilst digitalisation has the potential to improve user information and control, find efficiency savings in the supply and use of energy, support sustainable sharing business models, and improve quality of life, active policy is likely needed to ensure these amount to a reduction in energy demand.

In the LED scenarios developed in this study, digitalisation is applied to a range of energy services to reduce demand, such as energy management systems to extend control and avoid unnecessary consumption and mobility services to promote shared travel and reduce private consumption.

3.2.2 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 place (Grubler et al., 2018). Decreasing the overall demand for under-utilised products reduces the energy demanded for their production. A prominent example of the potential of the shared economy is in mobility. Shared vehicles such as car clubs or cycle hire offer the ability to rent vehicles as and when they are needed, replacing private ownership (Marsden et al., 2019). For example, car clubs have been found to reduce the private ownership of vehicles by 10.5 cars for every car club car in use (Carplus, 2016). A second strategy, shared trips, increases utilisation by filling empty seats with passengers who would otherwise have travelled alone (such as those facilitated by ride sharing websites such as Liftshare or BlaBlaCar) (Marsden et al., 2019). Sharing or use-based strategies that increase utilisation can be applied to other areas such as use of office buildings or shared use of consumer goods (Grubler et al., 2018).

Mobility sharing platforms, office sharing and hot-desking, and shared consumer electronics and appliances are all areas where shared economy approaches are applied in the LED scenarios developed in this study. It is worth noting that in some sectors there are trends towards less sharing, for example increased life expectancy and divorce rates have resulted in lower building occupancy, increasing heating and appliance use per person.

The sharing economy is closely linked to the concept of "circular economy". 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 (Cooper et al., 2017; Scott et al., 2019; Hahladakis et al., 2020). The term has become popular in policy discourses, with the European Commission and UK Government exploring legislation that promote circular economy strategies (Defra, 2013; European Commission, 2015). Circular economy approaches aim to reduce the flows of virgin material entering the system. These include a broad scope of strategies including: eco-design and production (ensuring waste materials can be recovered throughout the lifecycle), circular consumption (repairing and reuse aimed at increasing the use life of products), and developing new business models that increase the utilisation of products (Cooper et al., 2017; Grubler et al., 2018). These circular economy approaches have the potential to reduce the energy demanded to extract and produce virgin material, and lower the demand for new products through increased use-life.

3.2.3 Energy efficiency

Despite an improvement of 1% annually in energy efficiency over the last 30 years (Lees and Eyre, 2021), there is no indication that the potential for energy efficiency is anywhere near saturated. Globally, the overall conversion efficiency of primary energy into useful services is estimated to be approximately 15% (Cullen et al., 2011; TWI2050, 2018). Whilst the economic potential is lower, historically innovation has tended to increase the cost effective potential at a similar rate to its uptake, so that a 20-30% economic potential has existed for many decades (National Academy of Sciences et al., 2010).

The LED scenarios assume realistic levels of continued energy efficiency gains. For example, we assume further efficiency gains in many appliances, but also recognise this requires a substantial shift in technology in some cases. In other cases, notably building retrofit, the potential is large with existing technology. The principal constraints are usually supply chain practices and consumer engagement rather than technological innovation. We recognise the role of information technology as an enabler of reduced energy demand and the continuing innovation of such a fast-moving industry. The increased digitalisation of society offers new opportunities to control energy demand through increased functionality (sensors, wireless controls, etc.) in buildings, transport and industry.

The most important driver of future energy efficiency improvement is likely to be the wider energy transition. As energy supply shifts progressively from fossil fuels to primary electricity, not only are the conversion losses in thermal electricity generation avoided, but more efficient end use is enabled. In particular, there are huge potential benefits in the electrification of the two largest end uses of energy – building heating and light vehicles.

In each case, a factor of three in energy efficiency improvement can be achieved relatively straightforwardly, through replacing boilers with heat pumps and internal combustion engine vehicles with electric vehicles. In the longer term, similar effects are likely in a number of industrial processes, including steel and ammonia. These effects alone can reduce UK final energy demand by 30% (Eyre, 2019) and constitute the main driver of energy demand reduction in our scenarios.

3.2.4 Healthy society

It has been estimated that a scenario which meets the Paris Agreement and explicitly takes steps to benefit health via reduced air pollution, improved diet and active travel can result in 144,312 avoided UK deaths in 2040 compared to existing NDCs (Hamilton et al., 2021). For comparison, 20,830 deaths with Covid-19 mentioned on the death certificate occurred in 2020 in England and Wales (Appleby, 2021).

The scenarios developed in this study build upon an underlying trend of an increasing focus on health, wellbeing and quality of life, at the policy level and by individuals. The context of the Covid-19 pandemic brings this attention on healthy environments and lifestyles into sharp focus. As a result, both of the LED scenarios developed ensure there is not a reduction in health, wellbeing or quality of life. This is possible because there is a significant overlap and interdependence between policy and behavioural trends that both seek to improve health and reduce demand. In the case of nutrition, almost half of those switching to less energy intensive, plant-based diets, cite health reasons as their primary motivation for doing so (Waitrose & Partners, 2019).

Similarly, reducing average calorific intake would also improve national health, given the high prevalence of being overweight and obesity amongst UK citizens (NHS Digital, 2019). With regards to mobility services, significantly increasing the amount of active travel (cycling, walking) used to make shorter journeys, both reduces energy demand and improves physical and mental health (Public Health England, 2016). Moreover, shifting private car journeys to shared and active transport helps to reduce negative health impacts associated with inactive lifestyles and exposure to toxic air pollution in cities (WHO, 2016; WHO, 2018; Bull et al., 2020). For homes, providing well-insulated dwellings reduce the costs for the millions of families living in the poverty in the UK to achieve an appropriate internal temperature. This is strongly linked to healthy living. Reduced nitrogen oxides (NOx) and particulate emissions associated with electric vehicles (EVs) and heat pumps (HPs) also have health benefits (Watts et al., 2021). The scenarios developed here thus assume that health and wellbeing will become increasingly important to both individuals and policymakers in light of the global pandemic. This societal priority is reflected in the significant wellbeing benefits of the scenarios developed.

3.2.5 Increasing environmental awareness

As climate and ecological breakdown accelerates and significant climate impacts of events such as wildfires and flooding gain global attention, public concern for the environment grows across the globe. In the UK context, in January 2020 (before the Covid-19 pandemic), the environment ranked in the top three issues facing the country for over 30% of the British public (YouGov, 2021). This high point of environmental awareness largely correlates with the notable rise in high profile climate activism during 2019 (YouGov, 2021). Whilst during the Covid-19 pandemic, public concern relative to other issues has fallen, a quarter of views captured still suggest the environment is a significant issue.

As captured by opinion polling and academic studies, at the beginning of the last decade environmental awareness and concern about the climate was relatively low, suggesting increasing environmental concern is a significant trend (Pidgeon, 2012; YouGov, 2021).

Increasing environmental awareness and concern about the climate crisis is already having impacts on the demand for energy services. For example, in nutrition, there is a significant trend towards reducing meat consumption in diets. Whilst the empirical data on national spread of diets is poor, several market surveys have suggested the number of vegetarians has vastly increased in the last five years (YouGov, 2017; Waitrose & Partners, 2019; Finder UK, 2021). Some estimate that up to 33.5% of the population are reducing or cutting out meat from their diets (Waitrose & Partners, 2019), although this has yet to materialise in reduced UK meat consumption (Norton, 2020). Further, Waitrose (2019) report that for 38% of those going vegan or vegetarian, concern for the environment is the most significant motivation. There is further evidence that this trend may continue into the future. Bryant (2019) highlights that even amongst meat-eaters, over 70% have a positive view of the environmental benefits of a plant-based diet. This evidence suggests that increasing environmental concern can lead to significant changes in social practices and demand for energy services.

In our LED scenarios it is assumed that concern over the environment and promotion of appropriate actions to reduce energy demand, as well as concerns regarding health, quality of life and energy use continue to drive social change. Given the inevitable worsening impacts of the climate crisis, and the already increasing trend of environmental awareness, social norms are assumed to shift to favour sustainable consumption of energy services.

3.2.6 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 (Shahbaz et al., 2018). Studies focusing on the environmental impacts of globalisation have indicated that around 25% of global CO_2 emissions are embodied in global trade flows (Andrew and Peters, 2013). The energy intensity of globalised supply chains highlights a potential conflict between increased globalisation in this sense, and reductions in global energy demand. Of these emissions transferred between countries in trade flows, most are embodied in products consumed by 'developed' countries (Davis and Caldeira, 2010; Davis et al., 2011; Meng et al., 2018). This indicates that most developed countries, such as the UK, are net-importers of emissions and embodied energy in the products they consume, a trend that is growing over time (Meng et al., 2018).

In the UK context, final energy consumption declined by 11% between 2001 and 2013 (Hardt et al., 2018). However, Hardt et al. (2018) contextualise this trend with respect to the ongoing structural change occurring in the UK economy. They suggest that the most significant contributor to energy savings made through structural change are as a result of offshoring energy intensive production, available due to cost-effective global production networks and value chains (Hardt et al., 2018). This finding presents a distinction between reductions in domestic final energy demand (and territorial GHG emissions) that make a genuine contribution to mitigating climate change, and instances where reductions in domestic final energy demand (and territorial emissions) are caused by offshoring emissions to other regions, thus failing to contribute to climate change mitigation.

Understanding how globalisation can impact upon domestic and global energy demand is therefore important to ensure energy demand and emissions are not exported elsewhere. While our analysis of energy demand is from a territorial perspective, the LED scenarios developed here reflect genuine energy demand reductions that do not increase reliance on imports of highly energy-intensive products from abroad.

3.2.7 Work and automation

There are many overlaps between trends involving the increased digitalisation, as discussed previously, and automation of social and economic activity, such as the integration of machine learning and artificial intelligence into energy service provision (Rhodes, 2020). However, 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. As Graeber (2013) recounts, in 1930, John Maynard Keynes predicted that early industrialised wealthy countries such as the UK or USA would be working 10–15 hours in an average working week by the beginning of the 21st century due to significant advances in the productive capacity of technology. Technologically speaking, this prediction is not too far removed from reality. Several studies have aimed to assess how many jobs could be replaced by automation. Frey and Osborne, 2013 indicate that 47% of jobs in the US are at a high risk of being displaced by automation. In the UK context, several studies have suggested that 30% of UK jobs were vulnerable to automation, whilst the Office for National Statistics (ONS) suggests 7.4% of jobs are at high risk of automation, with 65% of jobs at a medium risk (ONS, 2017; BEIS Parliamentary Committee, 2019).

So whilst the productive capacity of autonomous technology can reduce the need for labour, the average full time working week over the past 20 years remains stable at around 38 hours per week (ONS, 2021). The stability of working time suggests that increasing integration of autonomous technology is not having a significant impact on working time. Whilst the stability of average hours worked is the result of multiple factors, it is partially explained by the need for increasing labour productivity to underpin growth-based business and economic models (Schor, 1992). This indicates that if prioritised, it is feasible that working less could be supported by increasing automation (Stronge and Harper, 2019).

3.2.8 Summary of key assumptions

The following tables map scenario drivers across sectors.

	Digitalisation
Nutrition	• New technologies would allow optimisation within the UK food supply chain to reduce food waste and deliver goods more efficiently. • Increased online shopping improves sector efficiency. • Nutrition tracking technologies at the consumer end also have a role in moderating calorie intake. • Apps and other IT-enabled services currently allow redistribution of excess food, reducing food waste.

	Digitalisation
Mobility	• Increased use of digitalised technology improves logistics for freight transport. • Greater use of video conferencing. • Greater integration of urban transport networks, including through digitalised timetabling and ticketing. • Lower car ownership and lower levels of car license holding because of reductions in the need to travel.
Residential buildings	• Increased use of smart meters. • Increased access to digitalised lighting controls, enabling energy savings whilst out of the house. • Increased integration of other 'smart' technology, extending greater control over domestic energy use to consumers.
Non-domestic buildings	• Implementation of digital building system control systems.
Materials and products	• Increased use of online second-hand market platforms in clothing and textiles, packaging, vehicles, electronics, appliances and machinery and furniture. • Digital industrial symbiosis programs to enable the exchange of materials between industries. • Increased use of digital tools enabling design optimisation to reduce life cycle impacts of construction.

Sharing and circular economy

Nutrition

- Reduction in food wasted by businesses and households.

Mobility

- Willingness for car-sharing to reduce single occupancy car use.
- Lower car ownership and lower levels of car license holding because of reductions in the need to travel.

Residential buildings

- Increased household occupancy reduces the need for new home construction.
- Expansion of co-housing.

Non-domestic buildings

- Office sharing and hot-desking reduces the need for new non-domestic buildings.

Materials and products (Industry)

- Increased use of online second-hand market platforms in clothing and textiles, packaging, vehicles, electronics, appliances and machinery and furniture.
- Increased car sharing reduces the consumption of new vehicles and the demand for the respective manufacturing materials.
- Waste reduction across key impact sectors through extension of lifetimes, material substitution in clothing and construction and increased ability of products to be repaired.

Energy efficiency

Nutrition

- Centralised retail and distribution (i.e. warehouse retailing and home delivery, without supermarkets) lead to efficiency improvements.

Mobility

- Switch of all non-HGV road transport to electric, yielding significant energy efficiency improvements.

Residential buildings

- Retrofitting of electric heat pumps, and improved insulation yield significant energy efficiency improvements.
- Energy efficiency improvements from mandatory use of light emitting diode (LED) lighting.

Non-domestic buildings

- Increased implementation of energy management systems, building retrofit, building system control, ventilation and cooling, and more efficient energy using technologies.
- Energy efficiency improvements from mandatory use of light emitting diode (LED) lighting.

Materials and products (Industry)

- Implement remaining energy efficiency options across UK industry.
- Replacement of inefficient technologies to facilitate low carbon fuel switching.

Healthy society

Nutrition	• Reductions in calorific intake improve health related issues associated with obesity. • A reduction in the number of omnivores as a result of an increased consciousness of the health issues around excessive meat consumption. • Nutrition tracking technologies at the consumer end also have a role in moderating calorie intake and promoting healthier diets.
Mobility	• Expansion of public and active travel networks facilitating increased exercise levels and reducing urban air pollution. • Improvement in local air quality through implementation of low-traffic neighbourhoods.
Residential buildings	• Reducing fuel poverty creates a healthier living environment, while improving ventilation.
Non-domestic buildings	• Improved ventilation and cooling systems allow for a well-regulated working environment, limiting the spread of airborne viruses in the workplace.
Materials and products (Industry)	• Reduced levels of industrial pollution because of fuel switching.

Environmental awareness

Nutrition	• A reduction in the number of meat eaters as a result of an increased awareness of the environmental impact.
Mobility	• Public opinion allows limits to be placed on investments in aviation and road infrastructure. • Less demand for aviation and road transport driven by an increased public awareness of the environmental damage. • Public mandate to implement a taxation framework to reduce excessive travel demand, including multiple car ownership.
Residential buildings	• Increased environmental awareness and the greater amount of control over domestic energy use afforded by the integration of smart technology, facilitates a reduction in energy use. • Households are more proactive in reducing energy use across the home, including in reducing heat.
Non-domestic buildings	• Net-zero commitments are made by an increasing number of companies, leading to greater uptake of energy efficiency improvements.
Materials and products (Industry)	• Increased environmental awareness helps to bridge the gap between the psychological obsolescence and technological obsolescence in clothing and textiles, vehicles, electronics, appliances, and furniture.

Globalisation

Nutrition

- Optimisation of international food supply chains reducing food waste.

Mobility

- Vertical integration across companies improves load factors for long and medium distance freight.
- Renewed push for consolidation centres around big cities and towns, reduces HGV miles travelled.
- Reduction in global aviation demand from UK passengers.

Materials and products (Industry)

- Optimisation of global supply chains for products that ensure consistent global standards.

Work and automation

Nutrition

- Increased availability of plant-based meals and reduction of meals containing meat in workplaces.
- Reduced domestic food waste as more people are eating at home as a result of home working.
- Apps and other IT-enabled services currently allow redistribution of excess food, reducing food waste.

Mobility

- Following the Covid-19 pandemic, new patterns of working are continued including increased working from home or teleworking, a greater use of video conferencing and a four-day working week.

Residential buildings

- Increased domestic energy use from higher levels of home working and the four-day working week are considered.

Non-domestic buildings

- Workplaces optimise work environments to reduce energy use.
- Office sharing and hot-desking reduces the need for new non-domestic buildings.
- Increased homeworking and teleworking reduce the need for office space.
- Increased use of video conferencing reduces the size of office space needed for large meetings or conferences.

3.3 Sectoral modelling of low energy demand scenarios

We outline in more detail how the above underlying trends translate into the two LED scenarios (scenarios 3 and 4) for the UK. These are labelled **Shift demand** and **Transform demand**. The **Shift demand** scenario describes a significant shift in the attention given to energy demand strategies providing an ambitious programme of interventions across all of our five sectors. It describes what could possibly be achieved with existing technologies and current social and political framings. At the same time the scenario still considers changing social-economic factors such as the changing nature of retail, businesses becoming increasingly accountable for their emissions, localisation and increased public acceptance to pay for environmental costs.

The **Transform demand** scenario reflects a much more transformative future, where more significant reductions are realised but under which quality of life is enhanced. To achieve substantial reductions in energy demand, decisions should be made by recognising the need for social-technical transitions. Energy efficiency alone is not the only driver available to affect energy demand. Our scenarios reinforce the Climate Change Committee's (CCC) Sixth Carbon Budget, that suggests 'behavioural' and 'technical' solutions are imperative to meeting the UK's climate ambition (CCC, 2020b). Relying on technical solutions alone is insufficiently rapid and risky, and policies influencing the demand for energy services (e.g. transport) should have a more prominent role.

Energy demand is shaped by cultural norms, values, preferences and structural factors (Creutzig et al., 2018). These practices are malleable and change over time leading to very different outcomes in relation to the UK's demand for energy. Recent shifts in attitudes related to climate change and the declaration of climate emergencies demonstrate the possibility for rapid change meaning that there is a danger that scenarios constrained by current thinking can be outdated and irrelevant. To overcome this problem, this scenario attempts to consider transformative change in technologies, social practices, infrastructure and institutions to achieve a greater level of energy demand reduction beyond the **Shift demand** scenario.

A particular focus of the two LED scenarios is to consider strategies that both reduce energy demand but also maximise other social and economic benefits. These include healthy diets, active living, improved local air quality, quality housing and lowering the costs of the net-zero transition. The scenario sets out to demonstrate the benefits of recognising the many co-benefits associated with role of energy demand reduction.

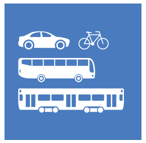
In the rest of this section, we outline how we have considered the different narrative drivers in both LED scenarios.[4] The modelling approaches used for each of the sector analyses are listed in Table 1.

4 For lists of modelling assumptions in each sector refer to the appendix.

Table 1: Modelling approaches used for each of the sectors[5]

Sector	Modelling approach
Mobility	TEAM-UK (Transport Energy Air pollution Model for the UK)
Nutrition (including agriculture)	Hybrid UK MRIO (Multi-Regional Input Output model)
Shelter (domestic buildings)	UK National Household Model (NHM)
Non-domestic buildings	Bespoke model
Materials and products (industry)	Hybrid UK MRIO (Multi-Regional Input Output model)

Please see the supplementary information that provides a separate report explaining in detail the modelling assumptions and approach used for each sector.



3.3.1 Mobility

In the UK, road transport accounted for just under three quarters of transport energy consumption in the UK in 2019, with the remainder almost entirely from air travel (24%). Energy use in railways (2%) and shipping (2%) were relatively minor. Of the road component, energy use from cars accounts for more than half (61%), with most of the remainder coming from 'light duty vehicles' (vans) (17%), heavy goods vehicles (HGVs) (18%) and buses (3%).

Energy use from transport has increased by 16% since 1990 (6% since 2013) against a UK economy-wide decrease of 4% and remains 98% dependent on fossil fuels.

There has been little to no focus on reducing distance travelled; instead the focus has been first to ultra low emission vehicles (ULEVs), and then to zero-emission vehicles (ZEVs), primarily through electrification. However, the energy efficiency improvements have been more than lost mainly due to a continued swing towards larger passenger cars. This almost universal focus on improving energy consumption per passenger-km or tonne-km travelled ignores the other two core elements of the Avoid-Shift-Improve hierarchy.

The focus of the LED scenarios is to reduce energy demand for transport. This will be achieved through the three-pronged approach of reducing the need for energy services at the same time as improving efficiency (e.g. speed limits, EVs) and using an efficient decarbonised supply of energy. The need to travel will be reduced through better land-use planning, restrictions on car use in central, residential, and environmentally sensitive locations, and facilitating transfer of car trips to public transport, walking and cycling by reallocation of expenditures, street design, pricing and regulation. This allows for a policy perspective where reduced energy use does not run counter to quality of life but arises from measures designed to enhance it. Evidence suggests a lower rate of demand for passenger mobility is a necessary and a credible future, but that this would require a different policy package to 'scale up' and 'lock in' the new demand patterns, alongside new vehicle technology (Brand et al., 2019).

5 Descriptions of sector level modelling approaches are available in the sector level evidence reports that accompany this report.

Key assumptions for both LED scenarios include (see sector summary for details):

- No more substantial new road building or airport capacity expansion; some roads repurposed for shared, public and active mobility. No more development on greenfield sites.
- Integrated transport authorities in all urban/city regions (One network; one timetable; one ticket).
- Doubling investment in public transport, walking and cycling with the construction of high-quality cycling networks of segregated cycleways in all urban areas.
- Single occupancy car use becoming socially unacceptable and parking charges and infrastructure designed to encourage vehicle sharing. High taxation on more than one car per household.
- Eco-levy applied to the whole system – the more you travel and the more polluting modes you use, the more you pay – includes air travel (frequent flier levy).
- Car fleet is reduced substantially as driving licence uptake is down with transition to 'car usership'.
- But taxi and shared fleets increase – all electric by 2030.
- Increase in light commercial vehicle (LCV) (van) fleet due to more online shopping – electric only sold from 2030.
- Large and heavy internal combustion engine (ICE), plug-in hybrid electric vehicle (PHEV) and hybrid electric vehicle (HEV) cars gradually phased out by 2030 and a substantially expanded bus fleet will be largely electric. Big investment in and standardisation of charging infrastructure across the nation.
- HGV – renewed push for consolidation centres around big cities and towns – reduced miles travelled.
- Road freight – much improved logistics, vertical integration e.g. Amazon – improves load factors for long and medium distance freight.
- No significant shift from road to rail freight, as rail capacity is largely taken up by net passenger rail increases (rail use for leisure rises, commuting and business use goes down).

Additional assumptions specific to the **Transform demand** scenario include (see sector summary for details):

- The phase out of ICE, PHEV and HEV cars is brought forward to 2025.
- Less demand for aviation driven by an increased public awareness of the environmental damage, higher costs for frequent flying, and increased fuel costs through taxation.
- Introduction of a four-day working week due to a greater focus on quality of life resulting in a 10% reduction in commuting trips per person by 2030 and further reductions by 2050.
- Increased reduction in commuting due to working at home or teleworking where industrial restructuring allows greater flexibility.
- Greater reliance on video-conferencing in businesses improving work-life balance.
- Lower car ownership levels, particularly in urban areas, in line with the "mobility" assumptions reducing the need to travel and a shift towards public transport, e-micro mobility and shared mobility.

3.3.2 Nutrition

The CCC estimates that 11% of UK GHG emissions are attributable to agriculture and land use, and predicts that the sector will become a major emitter in 2050 (CCC, 2018c). The food and drink industry also represents 7% of the UK's industrial GHG emissions (Hammond, 2018). As the ultimate driver of agricultural and related emissions, we consider how changes to the quantity and type of food demand could contribute to a UK low energy demand pathway by 2050.

We consider three key options for constraining energy demand in the sector, which cover each stage of the UK food system, and address the major current sources of inefficiency and emissions-intensity. The food system presents particular challenges in considering energy demand, given that non-energy emissions relating to land use change (LUC) and livestock (ruminant enteric fermentation) are more significant in the sector.

We consider the effect of calorific intakes being brought in line with Government Dietary Recommendations (i.e. healthy levels), and in reducing supply chain food waste. Calorific intake is the determinant of the volume of food demand per capita. The UK is challenged by overconsumption, with approximately 65% of the population of England estimated to be in 'overweight' or 'obese' BMI groups as of 2017 (NHS Digital, 2017).

We also consider the role of reducing food waste and losses across the supply chain; this is a key public policy target, as cited in the recent Resources and Waste Strategy (HM Government, 2018). It is also a means of avoiding additional food demand, by making more efficient use of the food that is currently delivered through the UK food system. As indicated by Bajželj et al., (2014), food waste reduction is more effective downstream (i.e. closer to households) given the embodied energy demand of the product by that stage. This is therefore one of our core energy demand reduction strategies in the analysis.

We consider the role of dietary transitions to more sustainable food products. Approximately 18% of global GHG emissions are attributable to livestock production, with ruminants posing the largest single anthropogenic methane source, and occupying 25% of global land for grazing (Stehfest et al., 2009). This scenario envisages a shift to plant-based diets as an extension of the recent trend for reduced meat consumption. From 2014 to 2018, the number of vegans in the UK is reported to have increased by 450,000. Of this number, 42% of vegans were reported to have switched to this diet during 2018 (The Vegan Society, 2019). Finally, we consider the potential for greater agricultural and industrial efficiency, primarily through new or best practice technologies.

Our analysis is based on the detailed assessment provided by Garvey et al (2021) (see sector summary for details).

Key assumptions for the **Shift demand** scenario include:

- Calorific intake reduces from the current average of 3,154 calories for a UK adult to 2686 calories by 2050 thus improving health related issues associated with obesity.
- A reduction in the number of omnivores in the UK population from 66.5% today to 17% by 2050.
- An increase in the number of people adopting our "healthy diet" (see appendix for description) from 21% to 27% of the UK population.
- Percentage of vegetarians increases from 9.5% today to 36% by 2050.
- Percentage of the UK population adopting a plant-based diet increases from 3% to 20%.
- An annual reduction in avoidable food waste of 2.5% a year up to 2050.

Additional assumptions specific to the **Transform demand** scenario include:

- Further reduction in calorific intake to ensure that a healthy diet is taken up by all UK adults giving an average daily calorific intake of 2,500 calories as recommend by Public Health England.
- An increase in vegetarians by 2050 where they represent 42% of the UK population.
- An increase in plant-based diets by 2050 where they represent 25% of the UK population.
- An increase in the annual reduction of food waste to 3.33% per annum.

Key drivers of these scenarios:

- New technologies would allow optimisation within the UK food supply chain to reduce food waste and deliver goods more efficiently. Trends towards centralised retail and distribution (i.e. warehouse retailing and home delivery, without supermarkets) could contribute to energy demand reduction in the food sector, whilst creating new business structures for food retail.
- Nutrition tracking technologies at the consumer end also have a role in moderating calorie intake and promoting healthier diets. Information provision around embodied energy/ emissions in food could also stimulate behaviour change in food buying.
- Apps and other IT-enabled services currently allow redistribution of excess food, reducing food waste.
- Greater demand for plant-based goods and vegetable proteins would create a market space and potential lower price for such products.

3.3.3 Heat in domestic buildings

Residential buildings in the UK rely predominantly on heat produced from burning natural gas in boiler-based systems that are popular because they are well-known, considered responsive, reliable quiet and relatively cheap. As a result, in 2019, this sector was responsible for 69.2 Mt of direct carbon dioxide emissions (BEIS, 2020a). This represented 15.2% of total national GHG emissions in that year, a share which has been increasing steadily since the 1990s – a relative increase due largely to the faster rates of decarbonisation seen in the power and industrial sectors as compared to residential buildings.

In parallel, the relatively poor thermal state of the housing stock in the UK has been the focus of frequent commentary with some stating that the country houses some of the worst performing buildings in Europe in efficiency terms (Maclean et al., 2016). As a result, 84% of all the energy used in the residential sector goes to producing space and water heat, a share which has only decreased by two percent points since 1990 in part because the level and volume of homes heated has increased. Three quarters of this energy is used for space heating alone.

Reducing energy use in this sector has been the focus of national policy since 1970. Successful strategies have included regulating the use of efficient boilers and windows as well as new buildings, incentivising cavity and roof insulation, and efficient appliances (particularly lighting) plus rolling out supplier obligations to reduce the carbon content of services delivered, particularly to vulnerable households.

While these have incentivised energy efficiency, the rate has not always kept pace with increased demand for domestic energy services in part because this sector has been particularly impacted by stop-start policies which have demotivated the domestic energy efficiency refurbishment sector and not encouraged economies of scale. A recent report by the UK Energy Research Centre (UKERC) put this in starker terms noting that the UK needed to upgrade around 19,000 homes per week, compared to 3,800 seen in 2018–19; at current rates, this report suggests that the target, set out by the CCC, would take more than 700 years to reach. (Rosenow et al., 2019). The UK Government has set a goal of installing 600,000 heat pumps per annum by 2028 from the current base of 30,000 (HM Government, 2020). However, the policy instruments to deliver this have yet to be defined.

To include the residential sector, the LED scenarios use the UK National Household Model (NHM) to develop a detailed analysis of how the current and future housing stock can develop and what they can achieve. The NHM was developed and is currently still run by the Department for Business, Energy and Industrial Strategy (BEIS) and is an open source housing stock model that simulates the energy performance of buildings under different sets of technical and building use assumptions.

The measures included in each of the LED scenarios explore incremental levels of technical ambition applied across the housing stock. They look at faster, deeper, and more widespread roll-out of building fabric retrofits; consider more ambitious heat pump, hybrid heat, and solar hot water programmes; and assume different requirement levels for new build housing apply as energy and infrastructure use in other sectors change.

By simulating these changes the NHM derives energy requirements across the building stock for space heating and hot water. These are aggregated to into building categories that fit the descriptions used in the whole systems model. Their change over time then form the basis for the annual growth rates that define the change in energy demand that the whole energy system model sees.

Key assumptions include:

- Fabric efficiency sees accelerated roll-out of building retrofits for existing stock reaching 250 k and 1 m measures per year in the **Shift demand** and **Transform demand** cases respectively.
- These changes are combined with increasing numbers of clean and highly efficient air and ground-source heat pumps. Hybrid systems forgo natural gas and rely instead on cleaner hydrogen or syngas. Gas boilers are phased out of existing buildings and excluded from new dwellings.
- As the scenarios explore deeper changes to society, the way in which we interact with and consider our residential buildings changes, for example:
  - The share of households practicing homeworking increases at a low, but steady pace. The **Transform demand** future goes further and considers a corresponding increase in a 4-day working week practice.
  - New build dwelling construction, while maintained in the **Shift demand** future, is reduced and replaced by repurposing non-domestic building space freed up by lower retail and office space needs.
  - Finally, smart systems help to change our building heating habits, maintaining quality of life while delivering heat only where and when it is needed.

3.3.4 Non-domestic buildings

The non-domestic sector includes a complex mix of buildings with a wide variety of different uses, from purpose built retail and commercial spaces, through to storage and refrigeration, hospitality health, education, or public services. Over time, this patchwork sector has shifted, in emissions terms, in both importance and composition. Total GHG emissions have grown from 26 Mt CO_2e (3.2% of UK territorial emissions) in 1990 to 30 Mt CO_2e (6.7% of total) in 2019 (BEIS, 2021a). In composition terms, the share of hydrofluorocarbon (HFC) emissions from cooling and refrigeration has progressed to represent 36% of the sector total; while a 40% reduction in public sector building emissions has left commercial and business buildings responsible for about 74% of total emissions in 2019.

In both the LED scenarios, the energy demand reductions take a two-pronged approach. On the one hand, they result from varying levels of ambition in rolling out energy efficiency measures detailed across the existing and future sector building stock. On the other, they rely on changes to the overall growth in non-domestic stock itself. The latter results from changes in the wider economy, e.g. reduced retail and office space requirements due to a move to online retail and homeworking, and leads to changes in growth expectations in non-domestic floor space.

The energy efficiency measure role out is based on assessing overall technical potential, using data from the Building Energy Efficiency Survey (BEES) (BEIS, 2016b). This approach considers sector requirements in both electrical and natural gas, and assesses the potential for 13 measures to reduce overall sector demand when applied across the relevant building stock at a sub-sector level. These measures include energy management systems, building retrofit, building system control, ventilation and cooling, and more efficient appliances.

On floor space, the **Transform demand** scenario sees growth in storage counteracted by a reduction in office space leading total floor space to remain constant. Some of the reduction in office space assumes that a proportion of commercial units are retrofitted to flats for residential occupancy. Most other non-domestic building types remain flat, apart from limited growth in education and health in line with population. The **Shift demand** scenario sees almost a 40% increase in floorspace; despite some reductions in office, storage growth is much more pronounced, leading to an overall increase. This compares to just over 50% growth in the **Ignore demand** scenario.

Key assumptions include:

- Varying speeds in BEES measure implementation with rapid, and very rapid, uptakes for both LED scenarios, relative to slower adoption in the **Ignore demand** scenario.
- This means full deployment of all efficiency potential across most measures by 2040, with rapid roll-out during the 2020s.
- Building fabric assumed to realise full potential by 2050, with stronger roll out across the 2020s and 2030s.
- Switching to improved energy using devices for heating means large-scale switching to electricity, with the use of heat pumps (determined in UKTM).
- Floor space increases by only 2% in 2050, relative to 2020 in the most ambitious low energy case. This is largely due to reduction in office space counteracting an increase in storage facilities.

3.3.5 Lighting and appliances in domestic and non-domestic settings

Electrical appliances, cooking and lighting account for 19% of energy consumption in UK homes (CCC, 2019b). While efficiency improvements in lighting and appliances have led to a fall in electricity demand in recent years, this is expected to be counteracted by increasing electrification, particularly of heat (CCC, 2019a). Most existing research focuses on efficiency improvements as the main method of energy demand reduction in appliances. Scenarios tend to assume that the variety and usage of appliances will increase to 2050, however, in our **Transform demand** scenario, we consider the possibilities to reduce energy service demands where there is no reduction in quality of life.

Therefore, as well as considering energy efficiency we also considered the impacts of behavioural change to use appliances more efficiently and less often, and the potential to reduce the number of appliances per household without compromising quality of life. In some areas like cooking and refrigeration there is limited capacity to avoid energy consumption as these appliances deliver an essential service and most households only own one of each type of appliance. However, in other areas like lighting and consumer electronics, it is possible to reduce the amount an appliance is used without impacting quality of life.

New technologies such as smart meters and disaggregated electricity consumption data can also play a role in helping individuals reduce unnecessary consumption (Kelly and Knottenbelt, 2016; BEIS, 2019c).

Energy efficiency improvements in appliances have had the largest impact on energy demand in recent decades. Without efficiency improvements, energy consumption in buildings would be 12% higher than current levels (IEA, 2018). However, there is still a large potential for further efficiency savings which have not been realised. Therefore, to 'improve' consumption, we considered the impact of widespread adoption of the best available technologies in new appliances, and the potential for future technological advancements.

Key assumptions include:

- Gas hobs and ovens are phased out by 2035, replaced with electrical appliances. 10% efficiency saving are available in electric hobs and ovens, which are achieved by 2030 (IEA, 2012).
- In lighting, incandescent sales are phased out by 2025, and are out of use by 2027. Fluorescent sales are phased out by 2030, and are out of use by 2035. We also assume that there are 5% efficiency improvements still available in light emitting diode technology, which are achieved by 2025 (Paoli and Cullen, 2020).
- Best available technologies are adopted across other appliances, resulting in efficiency savings of 45-60% in cold and wet appliances, 65% in consumer electronics, and 50% in air conditioning units (Grubler et al., 2018; IEA, 2018).

Additional assumptions specific to the **Transform demand** scenario include:

- The widespread adoption of smart meters with disaggregated and normative electricity consumption feedback reduces household electricity consumption by 5%, excluding cold appliances.
- A 5% reduction is achieved in air-conditioning units from improved cleaning of coils (McKinsey Global Institute, 2011).
- A 20% reduction in energy use from ICT and other appliances through replacing manual with automated building management controls (Grubler et al., 2018).
- The total number of appliances per household is reduced by 20% in lighting and 10% in ICT and consumer electronics due to demand saturation, cloud computing and increased sharing.

3.3.6 Materials & products

This energy service category refers to strategies that aim to reduce the energy demand embodied in the production of materials and products by UK industry. We focus on the material input and demand for clothing and textiles, packaging, vehicles, electronics, appliances and machinery, furniture and buildings and infrastructure. In 2019, emissions attributed to UK industry total 102 $MtCO_2e$, representing 22% of UK GHG emissions (CCC, 2020a). GHG emissions from UK industry have declined significantly, falling by 53% when compared with levels in 1990 (CCC, 2020a).

Some of these savings can be attributed to reductions in industrial energy use resulting from energy efficiency savings, however, most of these reductions are explained by the offshoring of the production of goods previously made in the UK (Hardt et al., 2018). The energy demand reductions in this scenario look to reduce industrial energy use embodied in the production of materials and goods without offshoring this to other countries. The analysis focuses on UK action. Due to the international trade of materials and products additional reductions would be seen if similar strategies were followed by overseas consumers of UK manufactured materials and products.

We consider three key options for reducing the energy demanded in the production of materials and goods: resource efficiency, energy efficiency, and changes to construction's demand for materials. Resource efficiency strategies reduce the required output of materials and products. Energy efficiency strategies reduce the energy demand to produce each unit of output. Additionally, changes in construction demand are an important driver of material production and associated energy demand.

Resource efficiency options were based on an existing review of opportunities for the UK (Scott et al., 2019). This is the widest existing assessment of such options for the UK and has been used extensively by (amongst others) the Climate Change Committee in informing the potential for resource efficiency within their carbon budget analysis (CCC, 2020b) and the UK Government's recent Industrial Decarbonisation Strategy (BEIS, 2021b). The resource efficiency opportunities related to construction and nutrition from the earlier analysis of Scott et al. (2019) were not included in the current assessment as each is analysed independently here.

Energy efficiency measures in the LED scenarios are based on the existing technology options within the UKTM model (see Appendix), which are based upon a review of technological options at the level of industrial subsectors in the UK Energy Research Centre Usable Energy Database (Griffin et al., 2013). The sectors represented in UKTM, covered by this analysis are iron and steel, non-ferrous metals, cement, non-metallic minerals, chemicals (ammonia), chemicals (high value chemicals), chemicals (other), paper and others. UKTM was used to select efficiency measures for each sector in a cost optimal manner to reach the emissions targets of each scenario.

The construction sector is the largest user of materials and the largest producer of waste by tonnage in the UK (CLC and GCB, 2020). The sector is the principal consumer of a sizeable proportion of industrial output, particularly of key highly energy intensive materials, such as cement and steel. There is potential to reduce demand for production of these materials (and the corresponding energy demand) by changing national demand for new buildings and infrastructure; and how these assets are designed and delivered. In this analysis we derive future estimates of demand for key construction materials based upon scenarios of future demand for buildings and infrastructure; and the uptake of a range of mitigation measures that may reduce the quantity of new materials needed to service this demand. Whilst many of the measures undertaken to reduce demand in the construction sector fall into the categories of resource and energy efficiency, they were treated separately given the significant contribution of construction to total energy demand, and construction's interrelationships with other sectors. To do so, a literature review of over 60 academic publications and industrial case studies was undertaken to identify mitigation options, which were then analysed using a construction-specific dedicated model. The bespoke model considers 36 specific applications of key materials across 17 different built asset categories.

Key assumptions include (see sector summary for further details):

Energy efficiency

- Improvements to current processes and replacement technologies (including fuel switching) are selected at the UKTM subsector level, to meet emissions targets in a cost optimal manner.

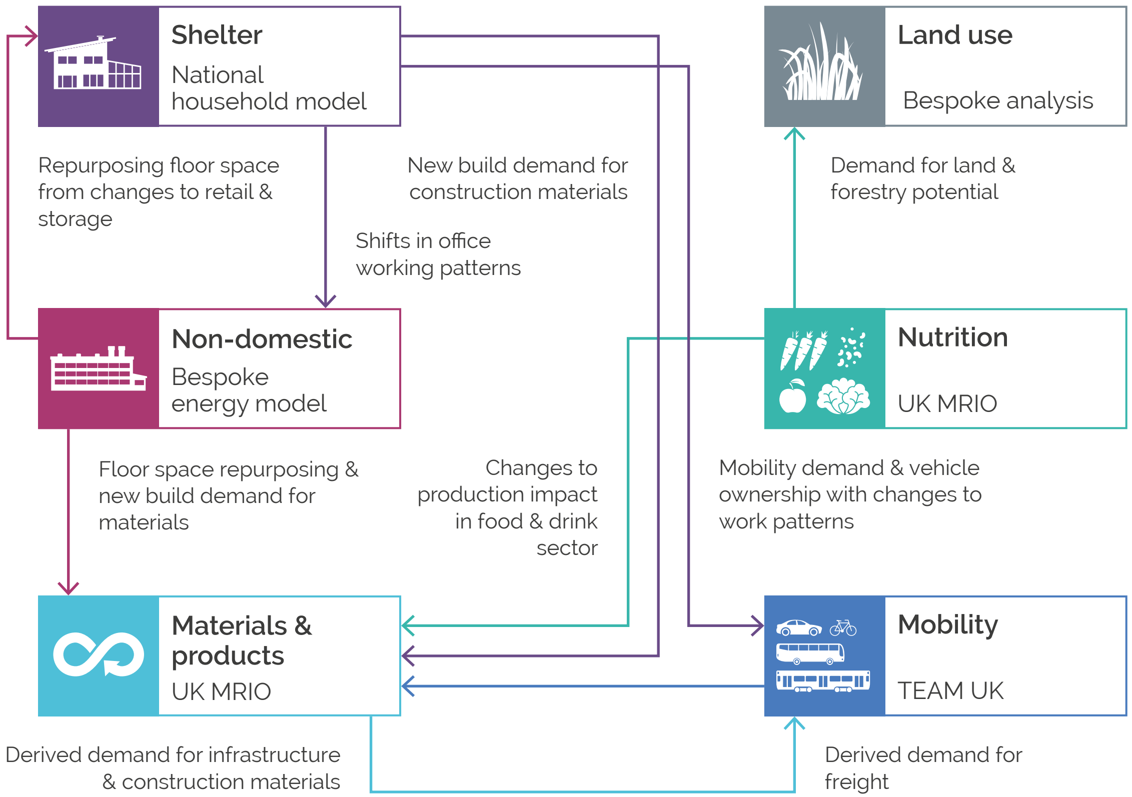
Resource efficiency

- In the reference case industrial output was taken from UKTM (which is aligned with the BEIS Industrial Pathways Model, 2017).
- Forty four resource efficiency strategies were applied across clothing and textiles, packaging, vehicles, electronics, appliances and machinery and furniture. The **Transform demand** scenario sees the adoption of maximum technical potential of these strategies in 2032, the **Shift demand** scenario represents a 66% adoption over the same time period. This aligns with the medium and high scenarios of Scott et al. (2019).
- The full supply chain impacts of these strategies, applied within the UK, on the industrial subsectors of UKTM was determined using a multi-regional input-output modelling approach. A logistic model was used to extrapolate these impacts to other time periods.

Construction

- Baseline future demand for new infrastructure construction to 2050 was taken from projections within the Green Construction Board's Low Carbon Route map for the Built Environment.
- Demand for new construction under the **Shift** and **Transform demand** scenarios was primarily determined by assumptions developed within the analyses of other energy service sectors (e.g. under the **Transform demand** scenario for Transport it is assumed that no new road building takes place, therefore output for the asset sub-category of 'Roads' is set to zero in the corresponding construction sector model scenario).
- 21 additional mitigation options to reduce material demand from construction were adopted across specific applications and asset categories based on the maximum practically achievable deployment in 2050, with a linear trajectory to this year.

Figure 5: Sector analysis and cross-sectoral linkages



3.3.7 Mapping dependencies between sectors

A critical part of the sectoral modelling process was to map the dependencies between sectors, to ensure consistency so that key aspects of the narrative represented in one sector were also reflected in others. Figure 5 shows the main dependencies between sectors. Many flow from the shelter analysis (shown by the blue arrows), where shifts in working patterns fundamentally change type and patterns of mobility demand, and the use of non-domestic buildings. Differences in house build assumptions are also reflected in the demands for construction materials. Choices about transport infrastructure also impact on the demand for construction materials, while changes in vehicle sales impact on manufacturing. Changes to diet also impact the level of land take, which feeds into land availability for forestry. It also changes the level of output in specific food and drink subsectors, impacting energy demand in that sector.

3.4 Modelling whole system net-zero scenarios

The final step of the analysis was to integrate 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. The model, which uses the TIMES modelling framework (Loulou et al., 2016), optimises future energy system evolution using linear programming, and future investment choices to meet energy service demands at least-cost (based on minimising the discounted net present value for the whole system). The model has been used across a wide range of energy scenario studies (Fais et al., 2016; Pye et al., 2017; Fuso Nerini et al., 2017; Zeyringer et al., 2018; Broad et al., 2020). 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 (DECC, 2016; HM Government, 2017).

The model represents the existing energy system in 2010, including the existing infrastructure assets (power generation plants, vehicle stock etc.) across sectors, and flows of energy. This is graphically represented using a systems network diagram, or Reference Energy System. 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 energy consumption is used to meet the wide range of 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. The model then solves by exploring least cost supply-side solutions to meet those future service demands.[6] The whole system representation allows for the 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 accounting of energy-related GHGs, plus other key non-energy sources, such as agriculture and land use. This means the model can be used for exploring energy systems that meet climate and energy policy goals.

6 '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.

This section describes the linkages between the sector modelling and the whole system modelling using UKTM. These are illustrated in Figure 6 below. The sector analyses, based on the agreed scenario narratives, were undertaken using a variety of modelling approaches (see Table 2). Under each scenario, the sectoral modelling provided estimates of energy reduction through 'improve, shift, and avoid' measures. Two types of information relevant to energy demand were passed to UKTM for integration:

- Energy service demand projections (grey arrows in Figure 6). These inform how energy services will change over time, based on 'avoid' measures and some 'shift' measures in transport, and are exogenous inputs to UKTM. Based on the projected energy service demands, UKTM is used to construct an energy supply system to meet those demands (as described earlier).
- Technology efficiency measures (dark grey arrows in Figure 6). The sectoral analyses also took 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 considered endogenously by UKTM; therefore, we have not hardwired associated final 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.[7]

7 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.

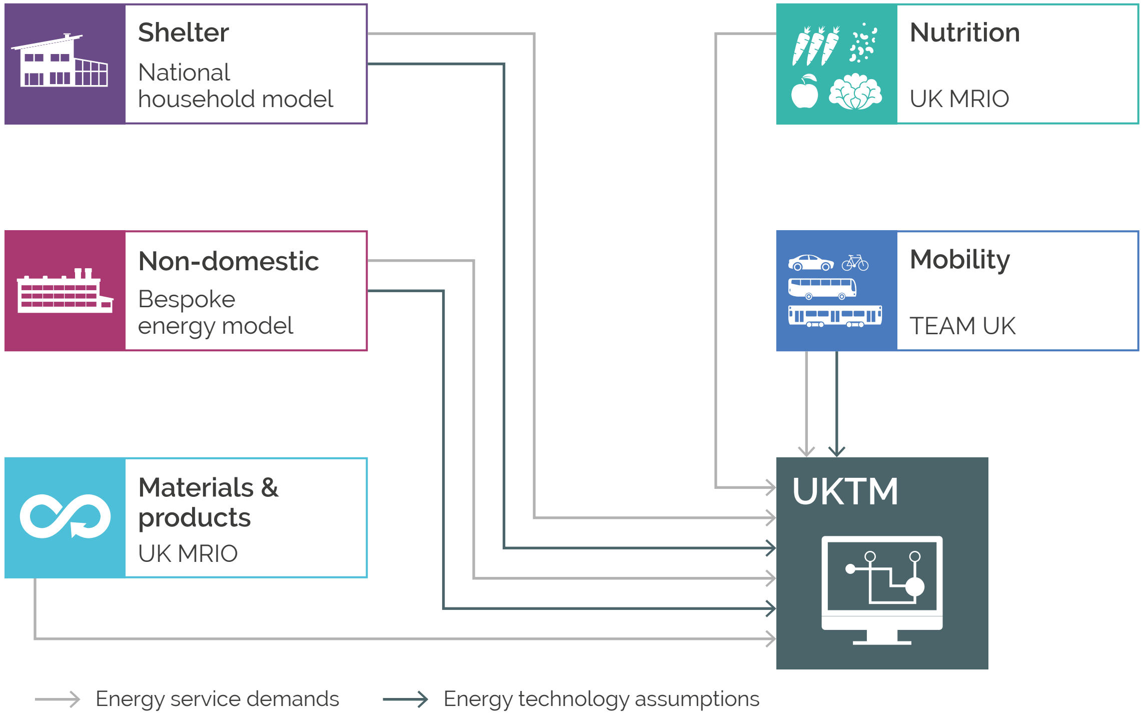


Figure 6: Integration of sectoral analysis with UKTM.[8]

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 Appendix.

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) (Brand et al., 2019) to explore vehicle choices and rates of deployment. 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.

8 Appliances included within domestic and non-domestic sectors.

UKTM received energy service demand projections for all transport subsectors, except shipping, which was considered separately by the UKTM team. 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. In respect of energy technology assumptions, the assumptions are already aligned to the NHM; further alignment on heat pump deployment was undertaken to differentiate between scenarios.

Non-domestic: The sectoral modelling for non-domestic buildings was built around the UK Building Energy Efficiency Survey (BEES) dataset (BEIS, 2016a) and used to explore different rates of energy efficiency uptake across the 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 floorspace 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, for example, storage space requirements in line with changes in retail shopping and home delivery. These floorspace 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 & 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 (BEIS, 2019b). 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. To achieve this, the emissions of methane and nitrous oxide relating to crops and livestock in UKTM were updated to follow the trends 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.

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 policies (CCC, 2018b). The second scenario is called **Steer demand**, which aims for net-zero GHG emissions by 2050, based on all legislated carbon budgets including Carbon Budget Six. However, the scenario fails to achieve the 2050 target, falling short by 27 $MtCO_2$ 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. All scenarios modelled in UKTM are described in Table 2.

Table 2: Implementation of scenarios in UKTM

Scenario	Demand narrative 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 CCC 2018 progress report.	Based on achieving reductions as estimated in CCC 2018 progress report, including medium risk policies. This is a 12% reduction in 2032 relative to 2020 (or 50% relative 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 $MtCO_2$ 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 equivalent to 4.95 $GtCO_2$.
Transform demand	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.	Net-zero GHG target in 2050, plus Carbon Budget 1–6; cumulative emissions equivalent to 4.95 $GtCO_2$.

* All scenarios except Ignore demand have also been run with the cumulative carbon budget of 3.87 $GtCO_2$, described below.

3.4.1 Carbon budget modelling assumptions

In addition to those scenarios listed, the **Steer demand** and two LED cases, **Shift** and **Transform**, were also run with a cumulative carbon budget consistent with the targeted temperature rise and responsibility sharing justice principles of the Paris Agreement. Determining a single national carbon budget that can be defined as the UK's obligation to the Paris Agreement is not possible. When dividing a global carbon budget between countries there are a number of assumptions that could be taken based on historical contribution to GHG emissions, capacity to change, per capita allocations and other equitable considerations. Added to this, deriving Paris Agreement compliant national carbon budgets comes with significant scientific uncertainty ranges.

This enables a wide range of UK carbon budgets to be considered 'aligned' with the Paris Agreement. We have estimated that the UK carbon budgets and net-zero target results in cumulative emissions of 4.95 $GtCO_2$ for the period 2020–2050. This cumulative estimate, derived from the UK targets, can be considered to be the overall carbon budget to 2050.

Given the uncertainty in what constitutes a Paris Agreement-aligned target, we have also considered an alternative budget. The value of this is to ascertain whether the two LED scenarios offer the opportunity to increase the climate ambition of the UK.

The additional carbon budget chosen in this study was derived using a resource sharing approach as developed by Anderson et al. (2020). It allocates larger shares in remaining carbon emissions to 'developing' countries to facilitate necessary economic development, before apportioning the remaining budget to developed nations using a grandfathering method. The UK's budget, derived by this method is 3.87 $GtCO_2$.[9] Our additional carbon budget is 22% lower than the budget derived from the UK's current planned budgets. This budget is an ambitious carbon budget for the UK. It was chosen based on its robust internalisation of the principle of common but differentiated responsibility and respective capacity at the heart of the Paris Agreement. This assigns the UK, and other wealthy early-industrialised nations emissions sooner and faster than those who have contributed less to the climate crisis. In the modelled scenarios, this CO_2 budget was implemented from 2020–2050, with net-zero GHG emissions also having to be met by 2050.

9 For a detailed description of the method used to derive this UK remaining carbon budget see Anderson et al. (2020). The budget here differs slightly to the one presented by Anderson et al. (2020), as the UK's share of global cement process emissions are included.

4. Results and discussion

This section provides an overview of some of the key insights building on our four scenarios, based on eight key findings from our analysis.

4.1 Securing net-zero GHG emissions will require ambitious energy demand reductions

The **Ignore demand** scenario describes the effect of existing policies as established by the UK Government in 2018, rather than their stated future ambition of recent months. As a result GHG emissions of 390Mt remain in 2050 demonstrating that there is a clear policy implementation gap to get anywhere near the net-zero target. Comparatively, the **Steer demand** scenario is constrained to reach net-zero by 2050 while maintaining current energy service demands and accounting for limits to sustainable biomass availability and reasonable bounds on the use of Direct Air Capture (DAC). It does include considerable energy efficiency improvements along with substantial decarbonisation of supply and a range of CDR technologies. Notwithstanding, the **Steer demand** scenario does not meet the UK net-zero GHG target in 2050 and results in an emissions gap of 27 $MtCO_2e$, as shown by the pink bar in Figure 7. This is largely due to residual emissions in agriculture (24 $MtCO_2e$) and international aviation (37 $MtCO_2e$) that exceed our assumed capacity for CO_2 removals. While alternative assumptions could arguably allow for higher levels of removals, incremental reliance on these options comes with additional risk that scenarios presented here seek to mitigate.

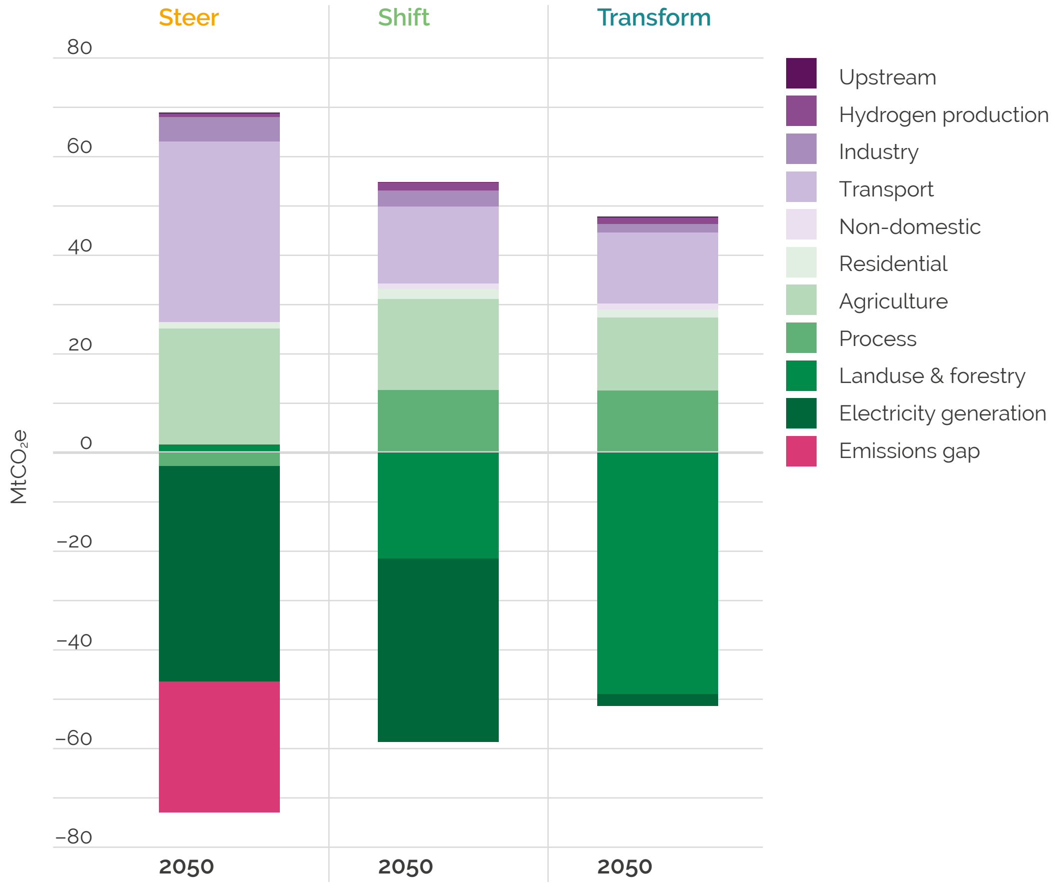


Figure 7: Net GHG emissions by sector, 2050. The transport sector includes emissions from international aviation and shipping. The pink shaded bar under the Steer demand scenario represents the additional emissions removal (or 'Emissions gap') required for net-zero emissions to be achieved in 2050.

Dealing with these residual emissions can be achieved through reductions in energy demand that go beyond energy efficiency and offer a more robust approach, by reducing reliance on CDR, whilst ensuring that the net-zero target can be achieved. These deeper reductions in energy service demands are applied here across all sectors of the economy and are shown to reduce the energy and carbon pressures on the overall system, meeting climate targets with less reliance on higher risk technologies. This is highlighted in both LED cases, where neither have an emissions gap. The **Shift demand** scenario reduces GHG emissions to 55Mt while the **Transform demand** scenario reduces GHG emissions to 47Mt by 2050. This compares to the **Steer demand** scenario with GHG emissions of 69 Mt in 2050 which can't be offset. The **Ignore demand** scenario, by stark contrast, would lower emissions by just 50% compared to 1990.

4.2 The UK can halve energy demand relative to current levels.

The **Ignore demand** scenario shows that the UK Government's existing policies fail to reduce energy demand by any notable level. Energy demand in this scenario reduces by 5% between 2020 and 2050. The **Steer demand** scenario maintains energy service demands but implements a wide range of energy efficiency measures. This scenario shows a 31% reduction in final energy demand between 2020 and 2050. It is important to remember, however, that this scenario fails to reach the net-zero target.

The two LED scenarios show that the potential for energy demand reductions, necessary to help meet net-zero GHG targets, is extremely high. Under the two low energy demand cases, reductions in energy service demands combined with strong and sustained energy efficiency action can reduce final energy consumption by 41–52% in 2050, relative to 2020 levels (Figure 8).

Crucially, the changes in energy consumption that occur over the next 30 years in the LED cases do not see corresponding drops in the activities that the use of energy supports: low energy demand does not come at the expense of activities that support a good quality of life, such as mobility services, warm homes, strong industrial production, or healthy diets.

Under the **Ignore demand** case, established UK policies help to achieve a 50% GHG reduction in 2050 (relative to 1990) with energy consumption levels remaining similar to those seen today. This highlights that under lower levels of ambition, mitigation can occur largely through fuel decarbonisation, a notable feature of the gains made in the UK to date. This is not the case if we are to reach net-zero GHG targets, we need both strong supply and demand side action in order to achieve the pace of change required.

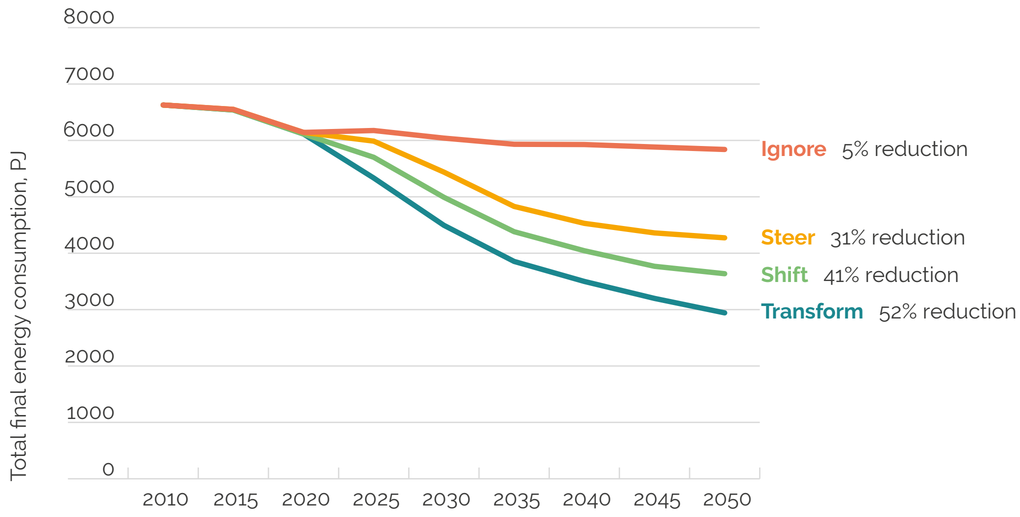


Figure 8: Total final energy consumption by scenario, 2010–2050.

4.3 Energy demand reduction is possible and required across all sectors

The breakdown of energy demand reductions by sector is shown in Figure 9. By design, this reduction will necessarily reach across all sectors of the economy, but interestingly this reach is unequal. Under the most ambitious low energy demand case, **Transform**, all sectors except industry have reductions exceeding 50% (relative to 2020). The transport sector compensates for the lower reduction in industry, allowing the economy as a whole to more than halve energy consumption by 2050. The relative difference in building sector energy consumption between the reference and the low-demand cases in 2050 highlight the comparatively deeper efforts required to support net-zero in this sector. While the agriculture sector has the highest relative reductions, this is also a very low energy consuming sector when compared to other parts of the economy.

The smaller relative reductions seen in industry can be explained by several effects. Firstly, this analysis focused on UK actions to reduce energy demand. The industrial sector supplies materials and products to consumers within the UK, and also overseas. Therefore, additional reductions may be seen if overseas consumers were to follow similar resource efficiency strategies as UK consumers did in our scenarios. Secondly, carbon capture and storage (CCS) is utilised in some industrial subsectors to reach challenging decarbonisation targets. This causes an increase in energy demand. Finally, energy-intensive subsectors of industry are starting from an efficient baseline (as energy forms a significant part of their operating costs these subsectors have been historically driven to reduce their energy demand), and therefore further demand reduction is more challenging than in other sectors.

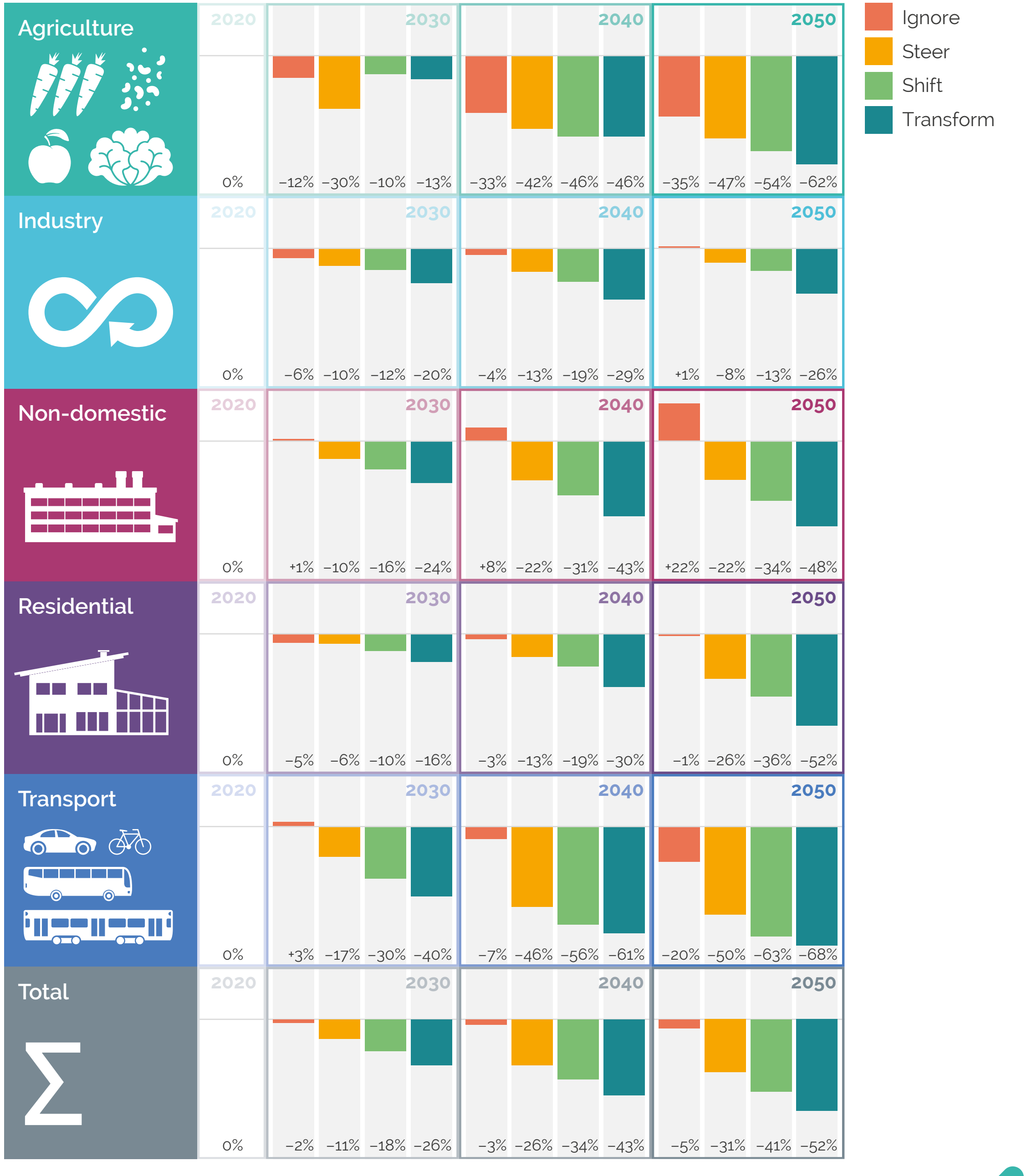


Figure 9: Change in final energy consumption by sector and scenario, relative to 2020 levels.

4.4 Reaching net-zero requires both energy efficiency and societal change

Energy efficiency improvements from heat pumps, electric vehicles and home retrofit, for example, are not the only options to reduce energy demand. In fact, our scenario analysis shows that by implementing energy efficiency alone without considering broader shifts in consumption patterns and reduction in energy service demands, net-zero is very difficult to achieve.

Figures 10a and 10b show the proportion of the reduction in energy demand associated with either efficiency improvements or broader societal changes in patterns of consumption. This analysis follows a similar framework first developed in Germany in the early 1990s (Transformative Urban Mobility Initiative, 2019) and later adopted by Creutzig et al., (2018), namely the "Avoid, Shift, Improve" framework. Dividing our reductions by these three categories proved difficult due to the nature of the modelling exercise (bottom up approach) and the fact that there is considerable crossover between the categories. Therefore, for each of the two LED scenarios we consider Improve to be "efficiency" that maintains energy service demands and "Avoid / Shift" that represents a reduction in energy service demand. Here we compare the difference in 2050 between scenario 1 (**Ignore demand**) and scenario 3 and 4 (**Shift** and **Transform demand**).

There is a reasonable variation across the different sectors as to whether the reduction is derived from an efficiency improvement or a shift or reduction in energy service demand. In our **Shift demand** scenario, the majority of the reduction relates to efficiency (86% for non-domestic buildings and 57% for domestic buildings). In contrast, the majority of the reductions in nutrition and materials and products derive from broader societal changes in shifting consumption patterns and reducing the need for energy services.

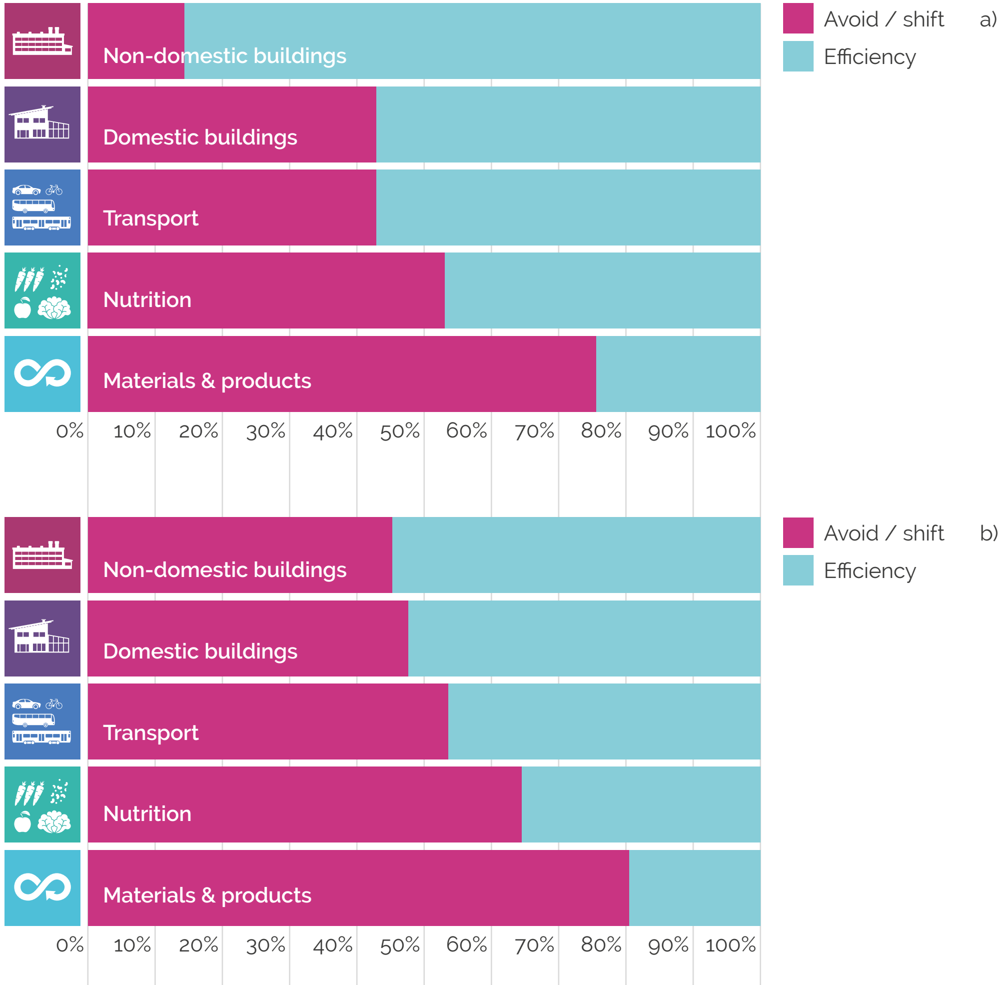
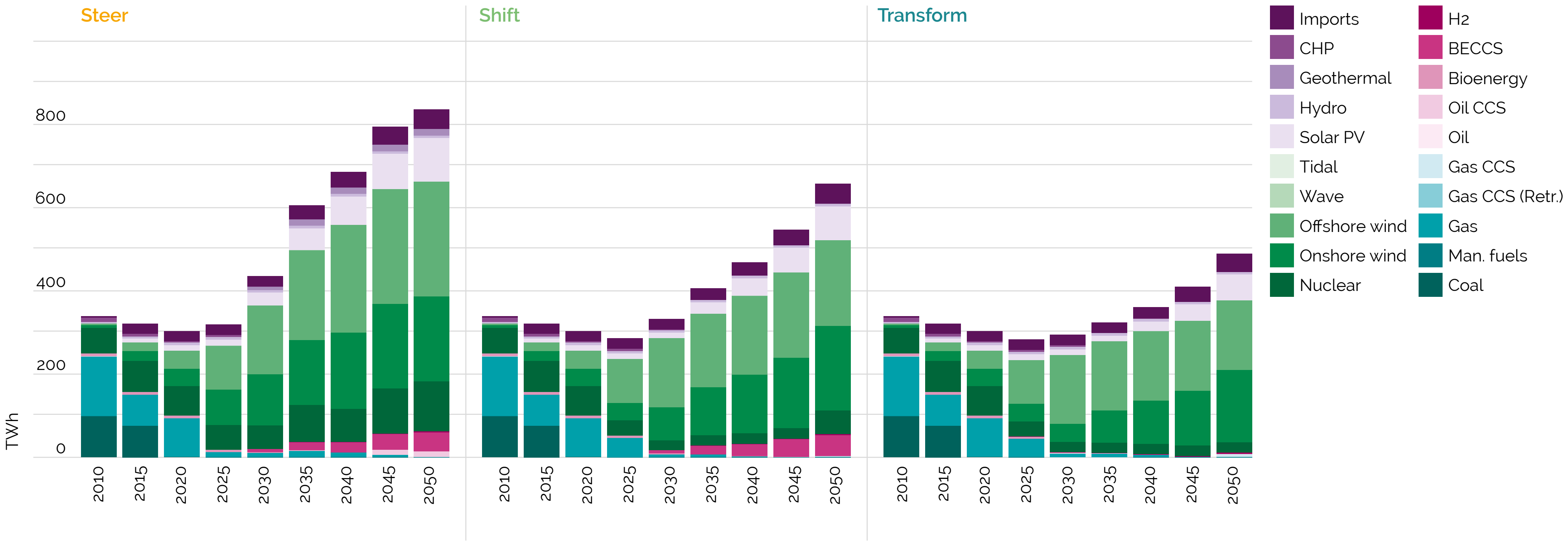


Figure 10: Contributions from efficiency and avoid/shift measures to reductions in energy demand in 2050 between a) Ignore demand and Shift demand and b) Ignore demand and Transform demand.

The **Transform demand** scenario shows a greater percentage of reductions in energy demand coming from broader societal changes. There is significant change in the non-domestic building sector, where efficiency now represents 55% of the reduction compared to 86% in the **Shift demand** scenario. The change in domestic buildings is very small between the two scenarios. Transport changes from efficiency representing 57% of the reductions down to 46%. The changes are relatively small in nutrition, and materials and products that already had a strong reliance of broader societal changes.

Figure 11: Power generation by scenario, 2010–2050.



4.5 A smaller energy system moderates the technical challenges of building out low carbon infrastructure

A net-zero target means that the energy system has to be transformed to fully decarbonise the UK economy. This includes retrofitting homes to make them more energy efficient, replacing all vehicles with low carbon technology, investing in new industrial processes, and replacing fossil-based energy supply infrastructure. The challenge is enormous. It relies strongly on high levels of societal acceptance of new technologies, and presumes that the very real technical hurdles of building out a new infrastructure in a relatively short period of time are overcome. A smaller energy system, resulting from reductions in energy demand, can help to moderate this challenge.

A key part of the future system is the power generation sector, which needs to be both decarbonised and then scaled to meet the growing demand for electricity as a key low carbon energy vector. In the **Steer demand** scenario, we estimate that generation in 2050 will exceed 800 TWh, representing a 150% increase on current generation levels (Figure 11).

While the importance of electricity as a critical decarbonisation lever does not go away in the low energy demand cases, the reductions do lead to a much smaller system than in **Steer demand**. While **Shift demand** and **Transform demand** do see increases of 94% and 44% on current generation levels in 2050, these remain respectively 21% and 42% lower than levels required under the **Steer demand** case. When considering implications for specific technologies, this means that significant capacity expansion in difficult-to-build nuclear power and highly uncertain bioenergy with carbon capture and storage (BECCS) for power technologies are either reduced, or not required as demand reduction ambitions increase. Differences in system capacity are shown in Figure A4 (Appendix).

More broadly, the energy infrastructure required across the system also shrinks. In the Appendix, Figure A5 shows the reduction in mobility demand across different road transport modes. These can be directly translated into vehicle fleet numbers, as we make a simplifying assumption that all vehicles deliver the same level of mobility service in a given year. A 13% increase in cars by 2050 in **Steer demand** compares to a 70% reduction in the **Transform demand** case, and a halving of the car fleet in **Shift demand**. Reductions, albeit not at the same level as for cars, are seen across other vehicles types; of course, this is, to some extent, offset by increases in public transport provision, with bus numbers increasing.[10]

10 For detailed breakdowns of modal shift assumptions in transport, refer to the transport sector report released in conjunction with this report.

4.6 Lowering energy demand reduces reliance on high-risk engineered removals

There are a wide range of options that will be needed for the UK to get to net-zero emissions. While all have different associated risks, these are particularly significant for those decarbonisation strategies that rely heavily on the scale up of CCS and CDR (Anderson and Peters, 2016). The inherent risks of these technologies failing to scale in future years mean that they lack robustness, while the confidence they project in reaching stringent emission reduction goals in the longer term reduces the sense of urgency for the required mitigation action to take place today (Pye et al., 2021). Strong demand-side action can reduce the requirements for energy use across the economy, lowering associated emissions and thereby reducing the reliance on such engineering solutions. Removals through BECCS and direct air capture (DAC), shown by the green and purple bars in Figure 12a, total 49 $MtCO_2$ in 2050 for the **Steer demand** scenario, which increases to 76 $MtCO_2$ if we infer that the emissions gap to net-zero also requires removals. This level can be more than halved to 37 $MtCO_2$ in **Shift demand**, or removed completely under **Transform demand**, where no engineered removals are required.

Fossil CCS, shown by the purple bars in Figure 12, is deployed across all scenarios; in the lower demand scenarios this is primarily for industry and hydrogen production via steam methane reforming. However, this could conceivably be reduced to much lower levels by a stronger focus on electrolysis for hydrogen production.[11]

11 The UKTM model underestimates the potential role of hydrogen production from electrolysis as it is unable to effectively represent the low cost electricity from renewables that is surplus to demand (or subject to curtailment) and which could be used for hydrogen production.

The low energy demand cases focus more on nature-based removals, with ambitious rates of tree planting, enabling removals of close to 60 $MtCO_2$ by 2050 in **Transform demand**. In this scenario, the increase in tree planting reflects a strategy to meet other broader environmental goals around biodiversity and land management. This is partly enabled by the reduction in livestock farming linked to changes in diet. The fast roll out of such planting programmes has arguably been challenging in recent years, so it is worth noting that the **Transform demand** scenario, because of the lower pressure across the system, still has the flexibility to avoid engineered removals and meet the net-zero GHG target with just 27 $MtCO_2e$ from forest-based sequestration – that is, at less than half the total displayed below.

The cumulative level of sequestration across all of the options is shown in Figure A2 (Appendix). Cumulative engineered removals total 780 $MtCO_2$ (including 130 $MtCO_2$ from the emissions gap[12]) in **Steer demand**, compared to 550 $MtCO_2$ in **Shift demand** and zero in **Transform demand**.

In summary, a key feature of the LED scenarios are the earlier efforts they display to reduce energy consumption, instead of waiting to scale engineered removals in future years. Energy demand reduction measures can be implemented immediately. When considering the UK's impact on the changing climate, meeting targets in 2050 can be achieved with different cumulative emissions along the way. The lower the cumulative CO_2 emissions, the lower the risk of increasing our contribution to rising temperatures.

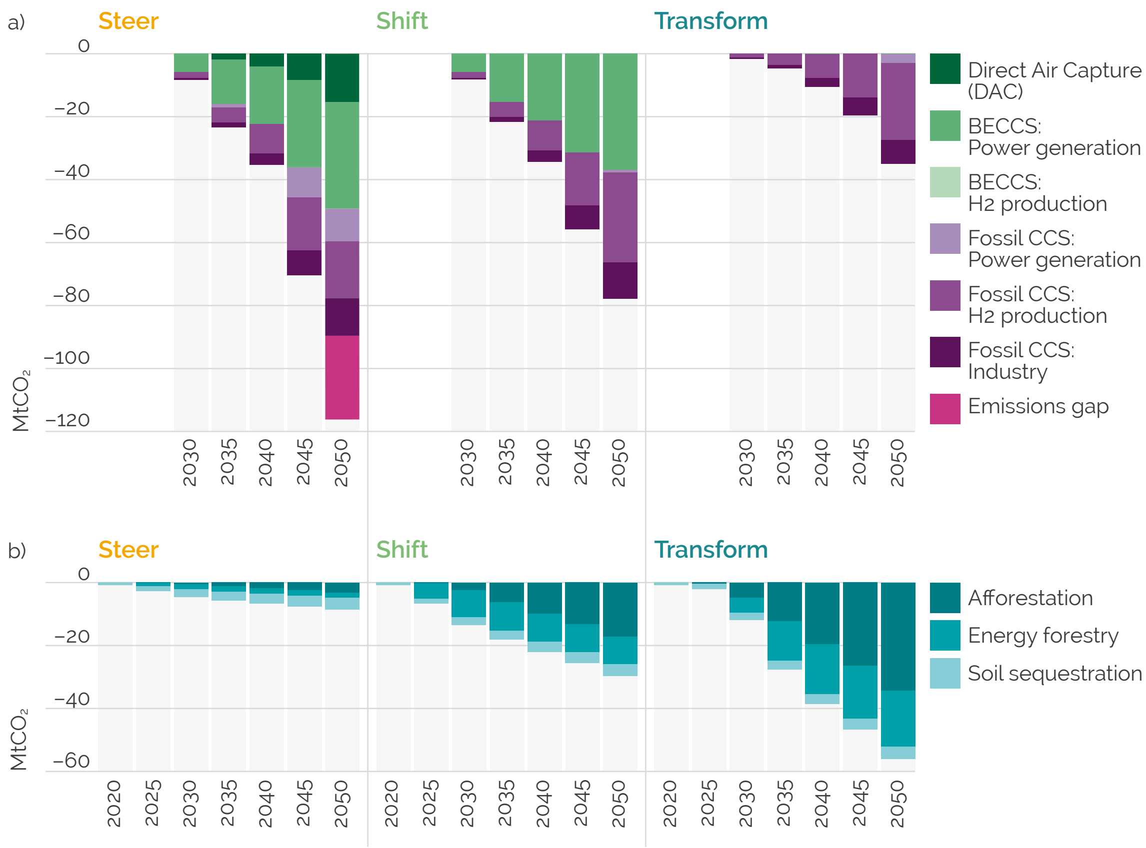


Figure 12: CO_2 emissions sequestration from a) CCS and engineered removals (DAC and BECCS) (2030–2050), and b) nature-based removals (2020-2050) by scenario. Panel a) has a category called emissions gap which accounts for the additional removal required if that scenario was to achieve a net-zero GHG emissions in 2050, corresponding to the emissions gap level in Figure 7.

12 Implied gap over a 5 year period.

This again underlines the importance of a strong focus on reducing energy consumption alongside decarbonising energy supply today, in order to de-risk the net-zero strategy. It is evident that some CCS and removals will be required, even in the most ambitious low energy demand case, but at much lower levels and with a focus on nature-based removals with their associated co-benefits.

4.7 A smaller system means lower investment and running costs

The transition to a net-zero economy means very high levels of investment to build out new energy supply infrastructure and invest in end-use, demand side technologies e.g. cars, boilers. As already highlighted, LED cases can significantly reduce both investment levels and the cost of operating the energy system. Normalising results to 2020, Figure 13 shows how much less these costs increase over time for the LED cases compared to **Steer demand**. Costs in 2050 are comparable to those seen today under **Transform demand** and only increase by 30% under **Shift demand**; this compares to an increase of almost 70% under **Steer demand**. Figure 13b shows how Shift and **Transform demand** cases have an annual expenditure more than 20% and 40% lower, respectively, than Steer in 2050, offering increasing levels of savings in system operation as the pathways unfold. These percentages translate to an annual reduction in cost of around £95 and £170 billion/year in 2050 from the £410 billion required for the **Steer demand** case.

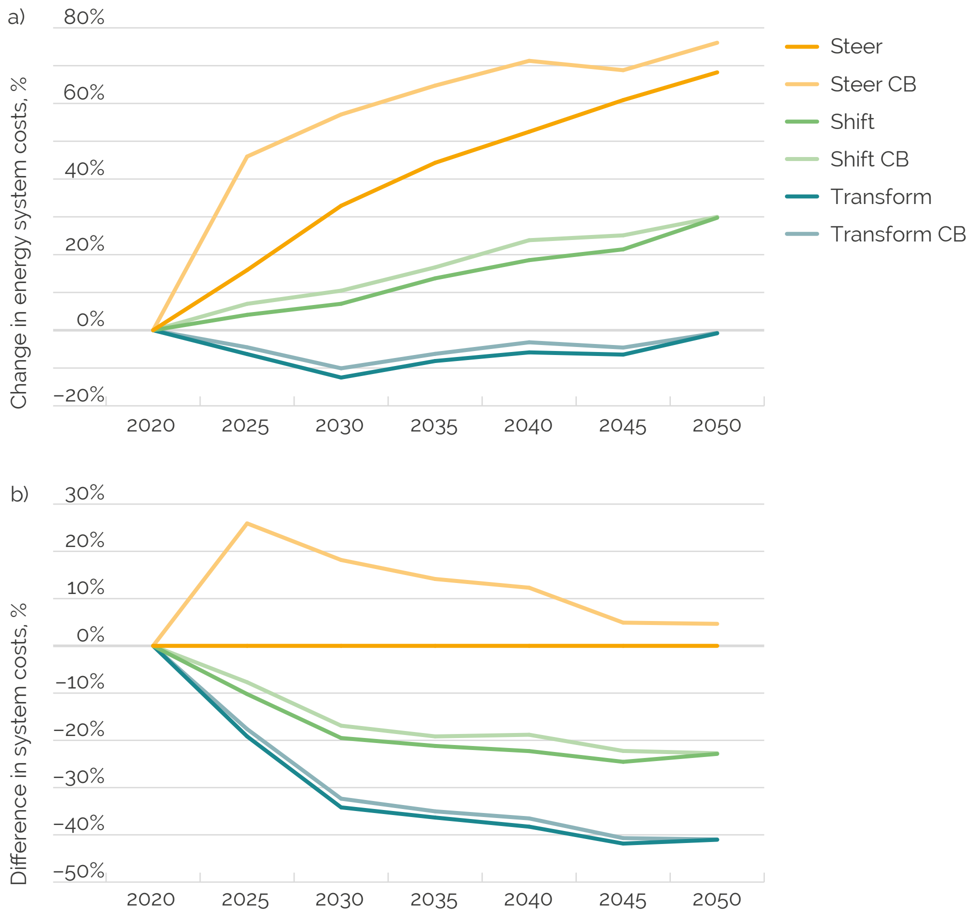


Figure 13: Change in energy system costs by scenario, 2020-2050. a) change in cost relative to 2020, and b) change in cost relative to Steer. Scenarios suffixed CB refer to scenarios run with a more stringent cumulative carbon budget of 3.87 $GtCo_2$. These costs (in £2010) are undiscounted, and include all costs associated with the energy system as represented in UKTM (capital, fixed and variable O&M, fuel) plus other non-energy costs associated with agriculture sector mitigation options and forestry. They do not include costs associated with the policies required to drive some of the energy service demand reductions.

The 'CB' cases represent higher mitigation ambition variants (as described in the section below). Interestingly, the relative additional costs of increasing ambition appear much lower for the LED cases compared to that for **Steer demand**. They also occur on a different timescale with the **Steer demand** case seeing higher relative investment requirements very early on. Comparatively, the LED cases measured increases in budget needs spread more evenly between now and 2050. This, in part, reflects the increased optionality the LED cases have due to lower energy demand and smaller energy systems.

Investments not spent on energy system infrastructure and technologies can be re-directed elsewhere, including on the policy packages required to realise the energy demand reductions mapped out in these scenarios. Further information on sectoral investment in the power generation and transport sectors is provided in Figures A6 and A7 in the Appendix.

4.8 Lowering energy demand makes increased climate ambition possible

The UK has consistently tightened its climate targets over the last 15 years. While the adoption of a net-zero target in 2020 continued this trend, there have been calls for even stronger ambition, to reflect what might be considered a more equitable allocation of global efforts to reduce emissions. In a recent paper, Anderson et al. (2020) account for markedly increased rates of mitigation required in futures where the "common but differentiated responsibilities and respective capabilities" approach is applied in a quantified framework looking at energy related emissions that remain possible while remaining, globally, well below 2°C of global warming.

Taking the UK as an exemplar country for their approach, their proposed cumulative budget of 3.7 $GtCO_2$ between 2020 and 2050 has been implemented as a Carbon Budget (CB) variant to each of the cases used in this analysis.

In Figure 14, this budget is shown implemented with the **Transform demand** scenario, as Transform CB. The lower energy demand case allows for stronger near-term reductions with incremental changes occurring in the CB variant as early as 2025 (grey marker). By 2030 this scenario sees a 47% emissions reduction relative to 2020, compared to 37% under **Steer demand**. This level of climate ambition can be achieved without engineered removals and at additional costs that only marginally exceed those observed under **Transform demand**, as shown in Figure 14. Crucially, this earlier action also keeps the window open for further strengthening of climate ambition. The less ambitious LED scenario, **Shift demand**, is also able to achieve this tighter carbon budget.

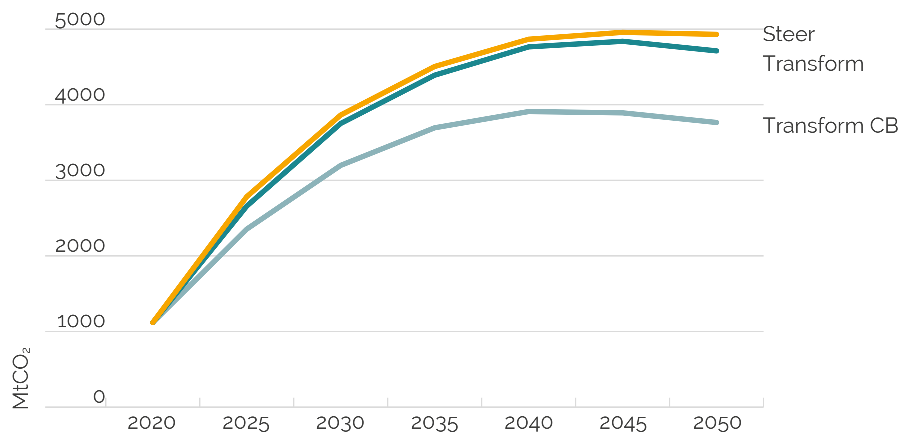


Figure 14: Cumulative CO_2 emissions under different scenarios, 2020-2050 ($MtCO_2$).

5. Conclusions, broader implications, recommendations and further analysis

5.1 Conclusions

Without energy demand reduction we will not achieve the UK's emissions reduction target of 78% below 1990 levels, or our 2050 net-zero target. The UK Government has yet to define how energy demand will contribute to achieving our climate ambitions. Given the evidence presented in this report, it is imperative that the UK Government outline a detailed strategy and supporting policies to enable energy demand reduction to fulfil its necessary role in achieving rapid emissions reductions in the UK.

The limited government focus on energy demand has mostly been on improving technology efficiency with little attention to the other mechanisms that involve reducing the need for energy service demands. Reducing energy demand to the extent, and at the speed, that is needed requires both an acceleration in energy efficiency improvement and shifts to the consumption patterns of products and services, travel and diets to avoid the consumption of energy services. None of our LED scenarios compromise our quality of life. Instead, they seek to enhance it with numerous co-benefits associated with healthier diets, active living, clean air, safe communities, warm homes, rebalancing work and driving down inequality. All this is possible while halving the UK's energy demand.

There are clear advantages associated with energy demand reduction in achieving our path to net-zero compared to other options. Lowering energy demand has five important effects:

1. It accelerates transitions to a low carbon energy supply in the short-term by directly reducing our need for fossil-fuel energy production;
2. It reduces the technical challenges associated with building out larger low carbon energy supply systems that other futures require;
3. As a result, it reduces the overall investment requirements to achieve net-zero GHG emissions and therefore household and business energy bills; and iv) it provides flexibility to ratchet up climate ambition further;
4. It reduces reliance on risky CDR technologies;
5. Pursuing energy demand reductions diversifies the risks of failing to achieve the UK's climate ambitions.

5.2 Broader implications

Our scenarios demonstrate that there is a significant gap between our current trajectory and the pathway necessary to achieve our net-zero goal. Here we outline five broader implications of our analysis:

1. Changes are required in the way we live, move and consume. The majority of changes needed to deliver the UK's 2035 and 2050 targets will require both changes to technology and the way we live. To reach 2035 targets, early action to deploy both clean technologies and support lower-carbon lifestyles is urgently needed.

2. The challenge is truly systemic in nature and therefore requires oversight of the role of different actors to ensure system change. This leadership must be undertaken by Governments so that it can be overseen by democratically elected representatives. It is only possible if the UK Government has a clear vision outlining the role of different agents in achieving the goal of improving quality of life within net-zero aligned carbon budgets. Much of this change will stem from devolved, regional and local activities, and require a coordinated approach between levels of government, communities, businesses and other stakeholders. Delivery is not solely undertaken by Government but roles are clearly defined and all agents are pointing in the same direction.

3. The response to reducing our energy demand does not mean a collection of energy policies alone but aligned policies in all areas. The system is interconnected in that demands in certain sectors relate to practices and behaviours in others. This intrinsic link implies that some policies necessarily bridge any traditional divide. Examples of this would be infrastructure development, innovation funds, recovery packages, procurement, planning and public health. It is policy coherency that delivers the scale of change required, not the piecemeal introduction of new energy policies alone.

4. This analysis raises questions on the measurement of progress and the tools applied to assess policy options inside Government. All UK Government policies are assessed for their "economic efficiency", rather than their broader value to both society and net-zero goals. While adjustments are made in economic analysis to try and address these exclusions, these are done using approaches that monetise social and environmental gains. An alternative approach is to create a strong vision of the UK that aligns improvements in the quality of life of citizens, whilst meeting net-zero targets. This involves monitoring and modelling a range of quality of life indicators and relevant Sustainable Development Goals (SDGs), and aligning these with net-zero goals. All policies, whether climate-related or not, need to be assessed against these broader objectives.

5. Social legitimacy is critical to delivering change. The changes required to deliver ambitious climate goals will have impacts on peoples' lives. The speed and scale of change will make the strategies and policies needed challenging to implement. As highlighted already, this can improve quality of life while reducing energy demand. However, even where there will be significant benefits to society, it requires public understanding and an honest public discussion, to give governments at all levels the social legitimacy to act. This will require deliberative methods such as those used in the UK Climate Assembly and similar exercises undertaken in several localities.

5.3 Recommendations

To achieve this vision, we look to Government to provide the strategies and policies, and therefore recommend the creation of an "Energy Demand Reduction Delivery Plan" to be created as soon as feasibly possible, recognising the need for cross-departmental collaboration. This must include a quantitative assessment of the role of energy demand reduction in achieving short term carbon budgets and the long term goal of net-zero by 2050, feeding into Government planning on net-zero strategy. The plan must consider the role of energy efficiency improvements and technologies but also extend the analysis to societal changes that shift consumption and avoid unnecessary energy services.

The plan must also consider whether an energy demand target is required to support other important targets. For example, there is a target for the electricity generated by renewables in the UK but not a target on the level of energy demand.

The plan is required to consider whether non-energy policies are aligned with reducing energy demand, or are in fact making the challenge more difficult by increasing energy demand. This is particularly important in the area of infrastructure development, where it is essential to avoid the lock-in of high energy lifestyles. The plan must outline the role of different actors in achieving the reduction in energy demand, including the role of public and private actors for each sector. It is essential that UK citizens are fully engaged and this transition is not seen as a top-down approach to climate policy.

For specific sectors, any assessment considering how to reduce energy demand should consider:

- For agriculture and food, the promotion of healthy diets is essential to ensure that a significantly greater proportion of meals are plant-based and overall calorific intake is reduced in line with health guidelines;
- For industry, with limited energy efficiency improvements in energy intensive industrial processes available, reducing material consumption is essential through the introduction of targeted resource efficiency strategy;
- For buildings, a triple approach of the rapid roll-out of heat pumps, retrofit of existing building stock and addressing the inefficiency of occupancy rates is required;
- For mobility, the scale of reduction required cannot be achieved with electric vehicles alone but requires a reduction in distance travelled delivered through investment in active travel and not the further expansion of road networks.

5.4 Further analysis

Further analysis is required to consider the broader implications of the LED scenarios to society, the energy system and economy. These could include:

- A more detailed appreciation of peak demand – while the UKTM model takes into account the need for peak demand to define the size of the energy system, this analysis could be much improved by applying more appropriate models that calculate hourly demand.
- Broader economic implications – we propose that a macro-economic analysis is undertaken to understand and manage the structural changes associated with our scenarios.
- A more detailed appreciation of distributional effects – while every attempt has been made to ensure that our selected interventions avoid negative distributional effects, further analysis is required to understand where specific changes occur across different socio-economic groups.
- Alignment of energy demand reduction with quality of life indicators – a further analysis could provide additional evidence to support the improvements in quality of life that we anticipate from our **Transform demand** scenario.
- There is a need to identify key gaps in evidence for the potential of energy demand reductions to inform future work.
- The analysis of energy demand reduction strategies on the UK's consumption based GHG emissions.
- Gaining an understanding of public acceptance and support of various LED scenarios, and the co-benefits produced by them.

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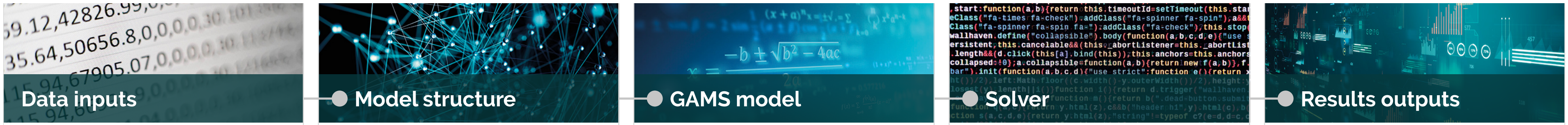
7. Appendix: Additional information on the UKTM model and input assumptions

UKTM overview

UK TIMES Model (UKTM) represents the existing energy system in 2010, including the existing infrastructure assets (power generation plants, vehicle stock etc.) across sectors, and flows of energy.

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 energy service demands needed across the economy, such as mobility, heating, and industrial production.

Figure A1: Core components of the UKTM modelling framework



Data inputs

Technology costs, performance, deployment rates

Energy resources potential & costs

Energy service demand projections

Model structure

Network of how system components link together

Referred to as Reference Energy System (RES)

GAMS model

Rules written in mathematical equations as to how the system & its components work:

- Minimise costs
- Supply-demand balance
- Activity of technology as a function of capacity
- Technology efficiency
- Other user-defined constraints e.g. carbon emissions cap

Solver

Commercial solver e.g. CPLEX allows for the linear programme to be optimised

Solver can be run as continuous linear program (core), in mixed-integer version with unit commitment, or in a non-linear version for other problems such as TIMES-MACRO or Stochastic programming

Results outputs

Numerous metrics are produced for each time period, including:

- Energy production / consumption
- Electricity system capacity
- Investment levels
- System costs
- GHG emissions

For scenario exercises, projected energy service demands are exogenous inputs into the model. The model then solves by exploring least cost supply-side solutions to meeting those future service demands. The whole system representation allows for the trade-offs between sectors in respect of resource allocation. Demands for energy vectors, such as electricity and hydrogen, are determined endogenously by the model, and are 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 energy-related greenhouse gases, and includes other key non-energy sources, such as agriculture and land use. This means the model can be used for exploring energy systems that meet climate and energy policy goals.

Structurally, UKTM is a single spatial node model covering the whole of the UK. As such the import and export of energy commodities take place with the rest of the world by combining assumptions of unit cost, and maximum supply levels based on expectations for the markets that these commodities are exchanged on. The model, calibrated to 2010, explores system evolution out to 2060. Time within the model is represented by 16 time-slices (one typical day for each season, split into daytime, evening peak, late evening and night). This structure was determined based on the shape of the electricity demand load in 2010. To find the partial equilibrium, the supply-demand balance has to be found across all different energy commodities, both annually but also at a sub-annual level e.g. for a given time-slice.

The component parts of UKTM are shown in Figure A1.

TIMES Model equations

The model input assumptions are compiled and used in the linear programme (using GAMS code), in which the rules of the system operation and evolution are defined based on a set of mathematical equations. Below we outline some of the key equations used in the model; the full source code can be found on Github, with full documentation available on the ETSAP website.[13]

In simple terms, an optimisation model such as UKTM will –

- minimise the objective function (total system costs)
- whilst satisfying the energy service demand requirements
- and respecting user-defined system constraints.

The key equations that set the rules of the model LP (linear programming) problem are summarised below.

- **Objective function** (EQ_OBJ). The function is to minimise total discounted system costs.

$$\text{Min} \sum_{y} disc_{y} \left[\begin{array}{l} \sum_{p}\sum_{ts} \cdot varom_{y,p,ts} \cdot ACT_{y,p,ts} + \sum_{p} crf_{y,p} \cdot invcost_{y,p} \cdot NCAP_{y,p} + \sum_{p} fixom_{y,p} \cdot CAP_{y,p} \\ + \sum_{c}\sum_{ts} impprice_{y,c,ts} \cdot IMP_{y,c,ts} - \sum_{c}\sum_{ts} expprice_{y,c,ts} \cdot EXP_{y,c,ts} + \sum_{c}\sum_{p}\sum_{ts} flocost_{y,p,c,ts} \cdot FLO_{y,p,c,ts} \end{array} \right]$$

Where disc is the global discount rate, varom is the variable O&M costs associated with technology activity (ACT), invcost is the capital expenditure associated with new investment (NCAP), discounted using the crf (capital recovery factor), impprice is the price of imports, multiplied by import level (IMP), expprice is the price of exports, multiplied by export level (EXP), and flocost is the cost of other domestic energy commodities (FLO).

13 The TIMES model code can be found on GitHub. Documentation can be found on the IEA-ETSAP website.

Where index y is year, p is process (technology), c is energy commodity, and ts is time segment.

- **Commodity balance** (EQ(l)_COMBAL). This equation ensures that the production of a commodity is equal to its consumption, to balance commodity markets.

$$\sum_{p \in Production} \sum_{ts} FLO_{t.p.c.ts} + \sum IMP_{t.c.ts} = \sum_{p \in Consumption} \sum_{ts} FLO_{t.p.c.ts} + \sum_{ts} EXP_{t.c.ts}$$

- **Transformation equation** (EQ_PTRANS). This establishes the relationship between an input commodity to a technology and an output commodity e.g. technology efficiency

$$\eta_{t.p.cin.cout.ts} \cdot FLO_{t.p.cin.ts} = FLO_{t.p.cout.ts}$$

Where η is the efficiency factor, and FLOcin and FLOcout represent the input and output commodities of a technology.

- **Product allocation constraint** (EQ(l)_INSHR/OUTSHR). Allows for the control of different commodity shares, where there are more than one input or output commodities into a technology.

$$\frac{FLO_{t.p.com.ts}}{\sum_{c \in cg} FLO_{t.p.c.ts}} \leq (=,\geq) floshar_{t.p.com.cg.ts.bd}$$

Where floshar defines the share of the single commodity (numerator) over the sum of commodities (denominator), or commodity group (index cg).

- **Activity definition** (EQ_ACTFLO). Activity of a technology is a function of the commodity flow, either of inputs but more typically outputs.

$$ACT_{t.p.ts} = FLO_{t.p.c.ts}$$

- **Utilisation constraint** (EQ_CAPACT). Ensures that the activity of a technology is a function of its capacity.

$$ACT_{t.p.ts} \leq \alpha_{t.p.ts} \cdot CAP_{t.p}$$

While the above equations constitute the key set used in the linear programme, a full listing can be found in Loulou et al. (2016) in Table 24. These include specific equations that bound capacity, activity and commodity production, set the rules for the operation of storage technologies, or ensure capacity exceeds demand for a selected commodity in a given time period (often used to ensure a peak margin for electricity systems).

User-defined equations can also be built to provide more control over the model operation. Most are built using the standard LHS form, where the left hand side of the equation includes the variables to be controlled, while the right hand side (RHS) sets the rule, e.g. must be greater than 10% of total generation (share) or less than 50 GW capacity (absolute). Other user constraints are more dynamic in nature e.g. growth constraints that set % changes on the preceding period levels. A number of these constraints are outlined in the next section.

Key model assumptions

A range of assumptions have been incorporated into UKTM from the sector-based analysis; these are described below. We first present the energy service demands, followed by other assumptions added into UKTM, in addition to what is already included in the standard model.

Energy service demands

Energy service demands are provided directly from the sector analyses, as described in section 3.4, and shown in Tables A1 and A2.

For non-energy sectors emissions, land use change and agriculture, we add projections directly in emission terms (CO_2e). The projected non-energy agriculture emissions are taken directly from the nutrition analysis (Garvey et al., 2021), based on the impact of demand side shifts in diet. Remaining on-farm emissions can be mitigated-based on a marginal abatement cost curves for UK agricultural GHGs provided by Defra. Baseline land use emission projections are taken from BEIS with various reforestation options (e.g. different tree types) available to the model.

Table A1: Energy service demands for building sectors (indexed to 2010)

			Steer				Shift				Transform			
Sector	Energy service demand	2010	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Shelter	Space heating: Existing cavity walled houses	1.00	0.99	0.98	0.96	0.94	0.99	0.98	0.95	0.92	0.99	0.98	0.95	0.91
Shelter	Space heating: Existing solid walled houses	1.00	0.99	0.98	0.96	0.94	0.99	0.98	0.96	0.93	0.99	0.98	0.96	0.92
Shelter	Space heating: Existing cavity walled flats	1.00	0.99	0.98	0.94	0.91	0.99	0.98	0.93	0.88	0.99	0.98	0.94	0.87
Shelter	Space heating: Existing solid walled flats	1.00	0.99	0.98	0.94	0.91	0.99	0.98	0.94	0.88	0.99	0.98	0.94	0.87
Shelter	Space heating: New houses	1.00	23.20	49.02	70.50	93.24	23.20	49.02	68.80	92.63	23.20	49.02	49.30	49.72
Shelter	Water heating: Existing cavity walled houses	1.00	0.99	0.98	1.00	1.01	0.99	0.98	1.00	1.01	0.99	0.98	1.00	1.00
Shelter	Water heating: Existing solid walled houses	1.00	0.99	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.98	0.98	0.98
Shelter	Water heating: Existing cavity walled flats	1.00	0.99	0.98	0.99	0.99	0.99	0.98	0.99	0.98	0.99	0.98	0.99	0.98
Shelter	Water heating: Existing solid walled flats	1.00	0.99	0.98	0.98	0.97	0.99	0.98	0.98	0.97	0.99	0.98	0.97	0.96
Shelter	Water heating: New houses	1.00	10.13	21.40	21.72	22.04	10.13	21.40	23.78	26.64	10.13	21.40	21.52	21.70
Shelter	Lighting	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	0.93	0.83
Shelter	Refrigerators	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	1.09	1.09
Shelter	Freezers	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	1.09	1.09
Shelter	Wet appliances	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	0.93	0.93
Shelter	Consumer electronics	1.00	1.04	1.07	1.09	1.11	1.04	1.07	1.09	1.11	1.04	1.07	0.84	0.75
Shelter	Computers	1.00	1.04	1.07	1.09	1.11	1.04	1.07	1.09	1.11	1.04	1.07	0.84	0.75
Shelter	Cooking: Other appliances	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	1.04	1.04
Shelter	Cooking: Hobs	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	1.04	1.04
Shelter	Cooking: Ovens	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	1.04	1.04
Shelter	Cooling	1.00	1.70	2.46	3.28	4.15	1.70	2.46	3.28	4.15	1.70	2.46	3.12	3.74
Shelter	Other	1.00	1.04	1.09	1.12	1.14	1.04	1.09	1.12	1.14	1.04	1.09	1.09	1.09

			Steer				Shift				Transform			
Sector	Energy service demand	2010	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Non-domestic	Space heating: Low consumption buildings	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Water heating: Low consumption buildings	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Space heating: High consumption buildings	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Water heating: High consumption buildings	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Cooling: High consumption buildings	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Lighting: Offices	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Lighting: Other	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Computing	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Cooking	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Refrigeration	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99
Non-domestic	Other	1.00	0.98	1.03	1.09	1.15	0.98	1.02	1.06	1.10	0.98	0.98	0.98	0.99

Table A2: Energy service demands for transport, industrial and agriculture sectors (indexed to 2010)

			Steer				Shift				Transform			
Sector	Energy service demand	2010	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Mobility	Passenger cars	1.00	1.06	1.10	1.13	1.15	1.06	1.09	0.93	0.76	1.06	1.08	0.79	0.50
Mobility	Two wheelers	1.00	1.05	1.05	1.07	1.09	1.05	1.05	2.55	4.08	1.05	1.03	4.25	7.25
Mobility	Buses	1.00	0.94	0.82	0.84	0.85	0.94	0.81	1.43	2.07	0.94	0.80	1.66	2.52
Mobility	LGVs	1.00	1.17	1.35	1.50	1.64	1.17	1.35	1.37	1.36	1.17	1.35	1.32	1.24
Mobility	HGVS: Rigid	1.00	1.06	1.11	1.17	1.23	1.06	1.11	1.07	1.02	1.06	1.11	1.03	0.93
Mobility	HGVS: Articulated	1.00	1.08	1.13	1.19	1.26	1.08	1.13	1.09	1.04	1.08	1.13	1.05	0.95

			Steer				Shift				Transform			
Sector	**Energy service demand**	**2010**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Mobility	Rail: Passenger	1.00	1.09	1.08	1.10	1.12	1.09	1.08	1.34	1.60	1.09	1.06	1.44	1.78
Mobility	Rail: Freight	1.00	1.09	1.15	1.22	1.30	1.09	1.15	1.22	1.30	1.09	1.15	1.23	1.30
Mobility	Aviation: Domestic	1.00	0.94	0.65	0.89	0.92	0.94	0.65	0.75	0.74	0.94	0.65	0.65	0.62
Mobility	Aviation: International	1.00	1.09	0.57	1.07	1.13	1.09	0.57	0.85	0.84	1.09	0.57	0.65	0.62
Mobility	Shipping: Domestic	1.00	1.00	0.93	0.88	0.76	1.00	0.93	0.88	0.76	1.00	0.93	0.88	0.76
Mobility	Shipping: International	1.00	1.09	1.09	1.09	1.14	1.09	1.09	1.09	1.14	1.09	1.09	1.09	1.14
Materials & Products	Iron and steel	1.00	1.12	0.76	0.74	0.73	1.12	0.76	0.71	0.67	1.12	0.76	0.64	0.55
Materials & Products	Cement	1.00	0.88	0.94	0.99	1.05	0.88	0.94	0.98	1.02	0.88	0.94	0.59	0.61
Materials & Products	Non-metallic minerals	1.00	0.88	0.94	0.98	1.03	0.88	0.94	0.97	1.00	0.88	0.94	0.53	0.54
Materials & Products	Paper	1.00	0.93	0.83	0.76	0.70	0.93	0.83	0.74	0.67	0.93	0.83	0.73	0.63
Materials & Products	Chemicals: HVC	1.00	0.88	0.83	0.80	0.80	0.88	0.83	0.80	0.78	0.88	0.83	0.79	0.76
Materials & Products	Chemicals: Ammonia	1.00	0.88	0.83	0.80	0.80	0.88	0.83	0.80	0.79	0.88	0.83	0.79	0.77
Materials & Products	Chemicals: Other	1.00	0.88	0.83	0.80	0.80	0.88	0.83	0.80	0.79	0.88	0.83	0.80	0.79
Materials & Products	Non-ferrous metals	1.00	0.77	0.78	0.71	0.66	0.77	0.78	0.70	0.64	0.77	0.78	0.69	0.62
Materials & Products	Food and drink	1.00	1.06	1.08	1.10	1.11	1.06	1.08	1.09	1.10	1.06	1.08	1.09	1.09
Materials & Products	Other industry	1.00	0.99	1.00	1.01	1.01	0.99	1.00	0.99	0.98	0.99	1.00	0.98	0.94
Materials & Products	Chemicals: Non-energy	1.00	0.88	0.83	0.80	0.80	0.88	0.83	0.80	0.79	0.88	0.83	0.80	0.79
Agriculture	Transport	1.00	1.08	1.09	1.09	1.09	1.08	1.09	1.09	1.07	1.08	1.09	1.09	1.06
Agriculture	Electricity	1.00	1.08	1.09	1.09	1.09	1.08	1.09	1.09	1.07	1.08	1.09	1.09	1.06
Agriculture	Heat	1.00	1.08	1.09	1.09	1.09	1.08	1.09	1.09	1.07	1.08	1.09	1.09	1.06

Mobility

For mobility, the differences between scenarios are all driven by changes in energy service demands. In respect of meeting those demands, all technology-based assumptions are the same across scenarios. For road transport, all vehicle efficiency information has been aligned with the Transport Energy and Air pollution Model (TEAM) model assumptions.

<table>
<tr><th>Assumption</th><th>Description</th><th colspan="4">Value</th></tr>
<tr><td colspan="6">Road transport</td></tr>
<tr><td>Restrict sales of ICE cars</td><td>Year when ban into force on car sales that are not zero carbon based on tail pipe emissions</td><td colspan="4">2035</td></tr>
<tr><td rowspan="3">Battery electric vehicles (BEV) costs</td><td rowspan="3">Update of BEV costs (£2010/vehicle)</td><td></td><td>2030</td><td>2040</td><td>2050</td></tr>
<tr><td>Car</td><td>15,900</td><td>14,300</td><td>13,000</td></tr>
<tr><td>Bus</td><td>121,000</td><td>110,000</td><td>100,000</td></tr>
<tr><td>Biofuel use</td><td>Maximum share of biofuels in ICEs</td><td colspan="4">20%</td></tr>
<tr><td rowspan="6">Constraints: upper limits on vehicle shares</td><td>Diesel cars</td><td colspan="4">78%</td></tr>
<tr><td>Electric buses</td><td colspan="4">80%</td></tr>
<tr><td>Electric rail (freight and passenger)</td><td colspan="4">82%</td></tr>
<tr><td>HGV hybrids (pre-2030, unconstrained after)</td><td colspan="4">2%</td></tr>
<tr><td>Car PHEVs (pre-2025, unconstrained after)</td><td colspan="4">58%</td></tr>
<tr><td>ULEV buses sales (battery electric and H2) unconstrained after</td><td colspan="4">80%</td></tr>
<tr><td rowspan="2">Annual growth constraints</td><td>Electric vehicles</td><td colspan="4">30%</td></tr>
<tr><td>All other low carbon technologies</td><td colspan="4">25%</td></tr>
<tr><td colspan="6">Shipping and aviation</td></tr>
<tr><td>Biokerosene use</td><td>Biokerosene maximum share by 2050</td><td colspan="4">35%</td></tr>
<tr><td>Ammonia use</td><td>Maximum level of ammonia use in shipping by 2050</td><td colspan="4">70%</td></tr>
</table>

Shelter

Assumption	Description	Steer	Shift	Transform
Building retrofit (Maximum technical potential)	Building retrofit related energy savings are accounted for in the sectoral analysis using the National Housing model (NHM). The corresponding MTP is therefore removed from UKTM.	0 TWh		
Use of gas for cooking	The minimum level of gas-based cooking in the residential sector is lowered to appropriate levels.	From 35% in 2010 to 0% by 2030		
Use of gas boilers	The installation of gas boilers in new build dwellings is phased out by a given target year. This includes all fossil boilers (e.g. kerosene) and also applies to district heating for new build.	2030	2020	2020
Hybrid boiler fuel use	Hybrid boiler systems – i.e. systems that include a combined boiler and HP system – are assumed to use either hydrogen or clean syngas from a given year onwards. This applies to new and existing dwellings.	2030		
HP efficiency alignment	Heat pump coefficients of performance (CoP) used in UKTM are aligned with values assumed in the NHM. CoP values detailed for ASHP and GSHP in existing and new dwellings as well as for DH. All adjustments are made to align by 2030.	DH HP 3.5 Ex ASHP 2.51 Nw ASHP 2.89 Ex GSHP 3.04 Nw GSHP 3.5		
HP availability	Year from which HP technologies are made available in new and existing dwellings to align dynamics of technology change with NHM assumptions. This combines both ground and air source HP systems.	Ex 2030 Nw 2035	Ex 2025 Nw ASHP 2020 Nw GSHP 2025	Ex 2025 Nw
HP rollout	S-curve based restriction to HP MTP (Year, % share). MTP calculated assuming 5kW system per household and 1.5 million installations p.a.	2025, 10 2030, 40 2035, 70 2045, 80	2025, 20 2030, 50 2035, 85 2045, 100	2025, 15 2030, 60 2035, 100 2045, 100

HC: cavity insulated house; HS: solid wall insulated house; FC: cavity wall insulated flat; FS: solid wall insulated flat; NH: new home; Ex: Existing dwellings; Nw: New dwellings; DH – district heating; HP: heat pump; ASHP: air source heat pump; GSHP: ground source heat pump; WSHP: water source heat pump

Assumption	Description	Steer	Shift	Transform
Gas boiler efficiency	Values included in UKTM are adjusted to values that align in principle with the NHM. Adjustment made by 2030 in all cases and maintain the relative difference across the wider range of technology options included in UKTM. Values declared per Sector, boiler input, and value.	DH, NG and H2, 95% DH, BM, 90% HS, NG, 89% HS, oil, 89% HS, H2, 89% HS, BM, 79%		
Solar hot water	Share of hot water provided through solar thermal systems. This applies to the combined use of household and district-based solutions.	25%	30%	–
Low energy lighting (LED – light emitting diode)	Non-LED lighting is phased out as an option by a target year in line with NHM assumptions.	2025		
Limits to micro combined heat and power (CHP)	Not used in the NHM, micro-CHP is left as an option in UKTM but constrained to start later and grow at a limited pace. Start year and annual growth rate cover total micro-CHP capacity in all dwellings	2030, 10% p.a.		
Biomass use	Not used in the NHM, biomass is kept as an option in UKTM but constrained by limiting resource input to the sector to an assumed MTP.	2015 – 10PJ/a 2050 – 20 PJ/a Linear increase		
Limit to DH	Maximum use of district heat in supplying residential demand for heat.	34%		
Use of wet heating systems	Minimum share of wet heating systems in residential buildings	HC 94%; HS 94%; FC 67%; FS; 82%; NH 87%*		
HP penetration	Maximum share of residential buildings compatible with using a HP due to space constraints.	HC 82%; HS 79%; FC 13%; FS; 10%; NH 68%*		
Natural gas connections	Maximum limit on gas connections in the residential sector accounting for rural locations.	HC 93%; HS 89%; FC 63%; FS; 83%; NH 90%*		

*HC: cavity insulated house; HS: solid wall insulated house; FC: cavity wall insulated flat; FS: solid wall insulated flat; NH: new home; Ex: Existing dwellings; Nw: New dwellings; DH – district heating; HP: heat pump; ASHP: air source heat pump; GSHP: ground source heat pump; WSHP: water source heat pump

Non-domestic

Assumption	Description	Steer	Shift	Transform
Annual technology growth rate	Upper limit on annual increase in quantity of heat supplied using selected technologies ((ASHP, GSHP, WSHP, biomass boilers)	10%/a		
Energy saving through building retrofit	Gradual increase in total energy savings available through building retrofit measures as roll-out capacity is assumed to increase with larger workforce and supply chains. Values reported below for individual measures include potential in [2020;2050] in TWh for high (H) and low (L) energy consuming buildings.			
	Efficient hot water delivery	L [0.01; 0.15] H [0.01; 0.22]	L [0.03; 0.22] H [0.04; 0.35]	
	Building instrumentation and carbon & energy management	L [0.5; 7.5] H [0.88; 14.0]	L [1.26; 11.44] H [2.01; 18.3]	
	Improved cool storage, cooling & ventilation	H [0.01; 0.13]	H [0.05; 0.42]	
	Improved efficiency of small appliances			L&H [0.04; 0.34]
Heat pump CoP	Annual per-cent increase in heat pump CoP. Increase is applied to existing values in UKTM. It is capped based on the number of years it takes to reach full roll-out (saturation)	1%/a cap 3.51	cap 3.47	cap 3.57
Hydrogen cooking availability,	Option for hydrogen cooking adjusted for consistency – avoiding its adoption independently of hydrogen heating in buildings.	Option removed		

Materials and products

Assumption	Description	
CCS deployment	Limit on CCS in industry sectors such as cement	2030
Steel production share	Upper limit on the share of steel that can be produced by electric arc furnaces	55%
Biomass use	Upper limits on fuel shares in selected industry subsectors	15%
Gas consumption	Minimum shares of gas use for combustion removed from specific sectors	

Electricity

Assumption	Description	Steer	Shift	Transform
Nuclear capacity limit	Cumulative lower and upper limit on fleet capacity by 2050	Upper limit: 18 GW (Price et al., 2018) Lower limit: 3.2 GW (existing fleet is retired and no new build beyond Hinkley C)		
New nuclear capacity growth rat	Limit on the build rate of new nuclear power	3 GW (one Hinkley C sized plant) per 5 yrs		
Existing nuclear retirement	All existing plant retired by 2040			
Coal phase-out	Coal generation phase-out by 2025, as per UK policy	All		
Variable renewables capacity growth rates	Annual capacity growth rate assumptions for solar PV and wind. For PV and onshore the absolute rates are slightly more ambitious than the historical peak deployment. For offshore, this assumes peak build rates are sufficient to achieve the Offshore Wind Sector Deal's 40 GW target by 2030.(Vaughan, 2018b; Vaughan, 2018a).	Solar: 15% per yr and 4.5 GW/yr Wind: 20% per yr and 3 GW/yr each for onshore and offshore wind.		
Offshore Wind Sector Deal	The Offshore Wind Sector Deal target of 40 GW by 2030 is achieved.	All		
Storage (grid electricity) capacity growth rates	Annual capacity growth rate assumptions for all storage technologies combined.	10% per yr and 5 GW/yr in 2025, rising to 10, 15 and 20 GW/yr by 2030, 2035 and 2050 respectively.		
Annual net interconnector flow	Annual net imports limited to a share of total generation	5%		
Variable renewable capex	Capex assumptions for solar PV, on and offshore wind (£2010/kW).	**2030** PV: 330 Onshore: 770 Offshore: 1207 (BEIS, 2019a)	**2040** 247 720 1038	**2050** 208 697 1038
Total new build capacity limit	The annual rate at which the power system can deploy new capacity in GW/yr	**2030** 20	**2040** 20	**2050** 30

Bioenergy, carbon dioxide removal and CCS

Assumption	Description	Steer	Shift	Transform
Bioenergy availability	Levels of biomass output available from domestic and international sources. These levels define the amount of energy available in TWh per annum from different biomass feedstocks. Levels are derived from the CCC 2018 report on biomass availability applying their "Global governance and innovation" scenario. 2050 limits are listed below (CCC, 2018a).			
	Imported solid biomass	102 TWh/a		
	Imported liquid biofuels	53 TWh/a		
	Domestic solid biomass	50 TWh/a		
	Domestic agricultural and forestry residues	67 TWh/a		
	Domestic wastes & residues	28.3 TWh/a		
CCS availability	Year from which commercial scale CCS deployment is permitted	2030		
BECCS deployment limits	Direct limits on BECCS sequestration to constrain the model to only what it needs, so that BECCS becomes an option of last resort	No limit imposed	37 $MtCO_2$	0 $MtCO_2$
BECCS emission credit	Due to feedstock sustainability concerns, percentage of CO_2 generated available for negative emission credit.	70%		
DAC availability	Deployment potential of DAC	No limit	0 $MtCO_2$	0 $MtCO_2$
Forestry planting rates	Upper limit on planting rates in ha/yr for biodiversity and energy crops. Rates are applied separately to both classes and are available from 2023.	9,200	50,000	100,000

Additional results from UKTM modelling

Figure A2 shows the energy demand reductions in the Steer and LED cases (Shift and Transform) by sector. For buildings, this is largely driven by electrification but also much lower new build rates in the Transform cases.

In transport, large reductions result from electrification – but also large reductions in the level of passenger mobility in the LED cases. Industry sees decarbonisation of the energy mix through a range of energy vectors, including hydrogen (green bars) plus resource efficiency gains in the LED cases.

Figure A2: Final energy consumption by sector and scenario, 2010–2050.

Figure A3 shows the cumulative sequestration from different options in the model, with Steer dominated by engineered removals and CCS, while LED scenarios have a much higher level of nature-based solutions, through types of forestry and soil management.

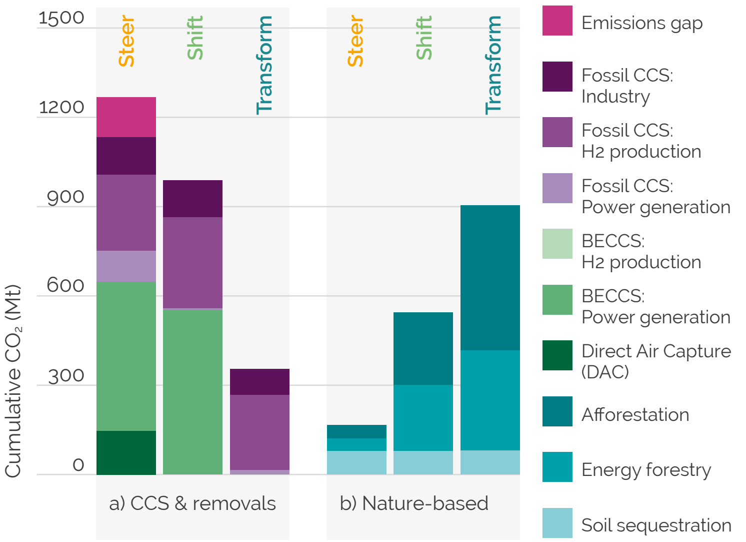


Figure A3: Cumulative sequestration by CCS or CDR option by scenario, 2020–2050. a) CCS and engineered removals, and b) Nature-based solutions.

As implied by the power sector generation trajectories in Figure A4, the system capacity levels are much larger in **Steer demand** compared to the LED cases. This is expected as higher shares of renewable generation (orange and yellow blocks) come online with lower capacity factors. This also requires higher levels of storage (lime green block), with 73 GW in 2050 in the Steer demand case, compared to 46 GW in Transform.

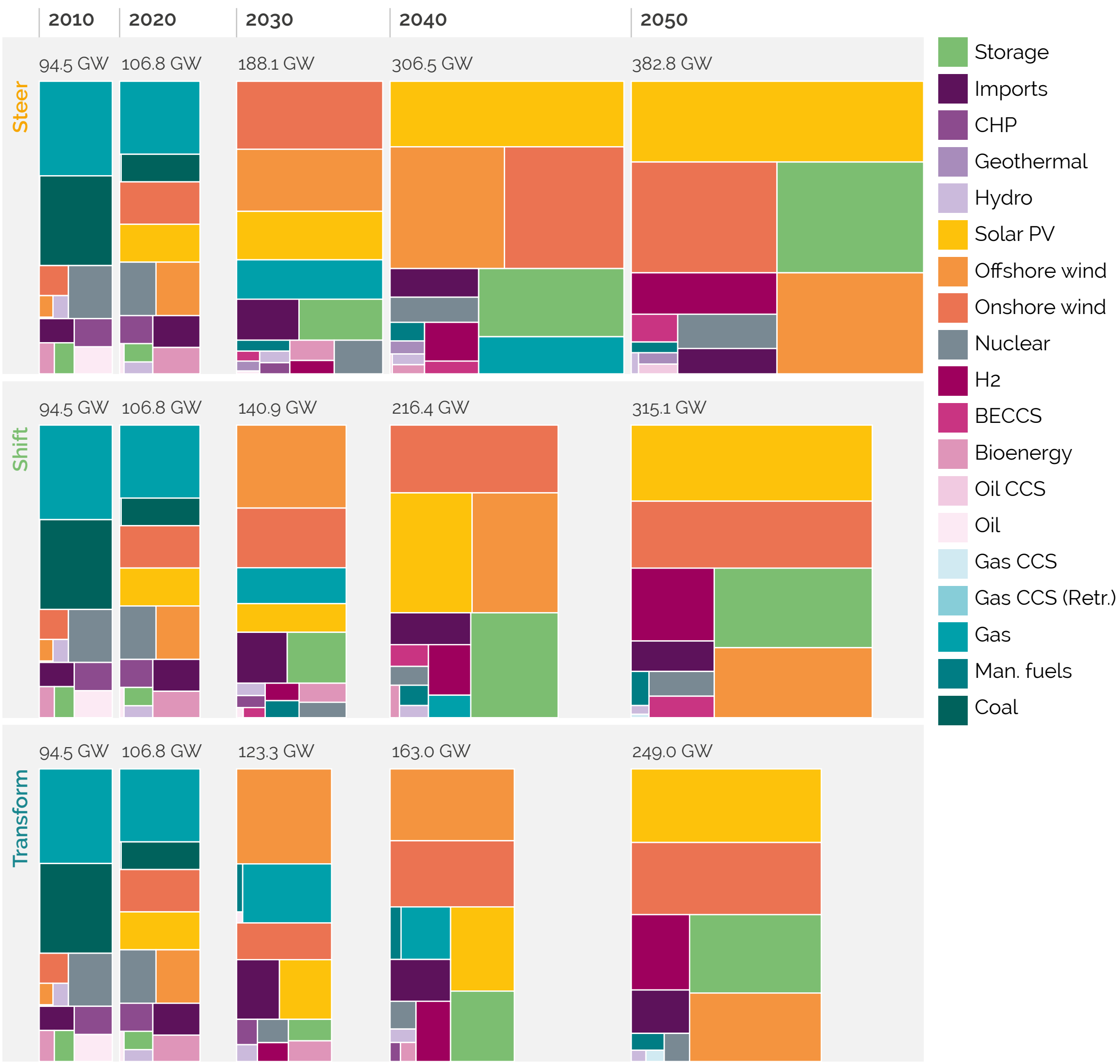


Figure A4: Power generation capacity by generation type and scenario, 2010–2050.

The road transport sector mobility demands are shown below, and the evolution of technology type that meets those demands over time. For cars and LGVs, this means as strong push towards electrification; this also occurs in the Ignore case as EVs become increasingly competitive due to the global shift in manufacturing, irrespective of domestic climate policy.

The level of EVs deployed to meet passenger car demand is massively reduced in the LED cases, compared to the Steer case, which would have huge implications for reducing charging infrastructure, road capacity, and other impacts associated with vehicles (congestion, accidents etc). HGV mobility demand sees a transition towards hydrogen, although a much stronger push towards electrification could be seen under stronger battery cost reductions.

Figure A5: Transport demand for selected road transport modes by fuel and scenario, 2010–2050.

Heat provision in the residential sector is shown in Figure A6, with the impact of retrofit measures taken into account. The strong reduction in energy services in Transform reflects stronger ambition in retrofit plus very low levels of new build. In the main, the pathways show strong heat pump deployment, with smaller shares for heat networks and hydrogen-based systems in specific localities.

Investment in the power sector across the scenarios highlights the increased levels for low carbon generation. However, this is significantly lower for the LED cases, which require much lower levels of capacity on the system.

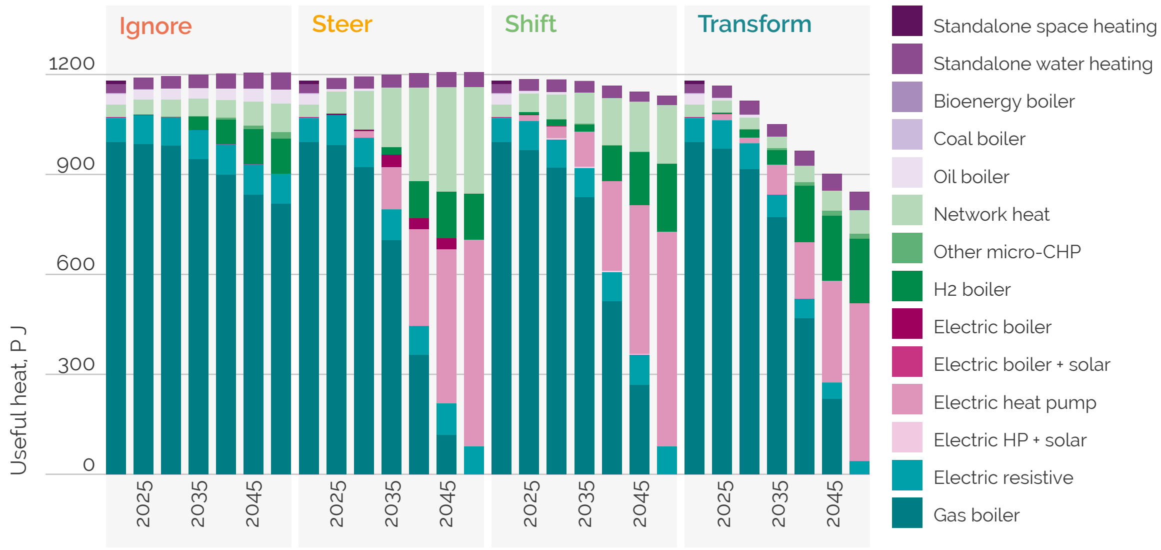


Figure A6: Residential heat demand by heat provision technology and scenario, 2010–2050.

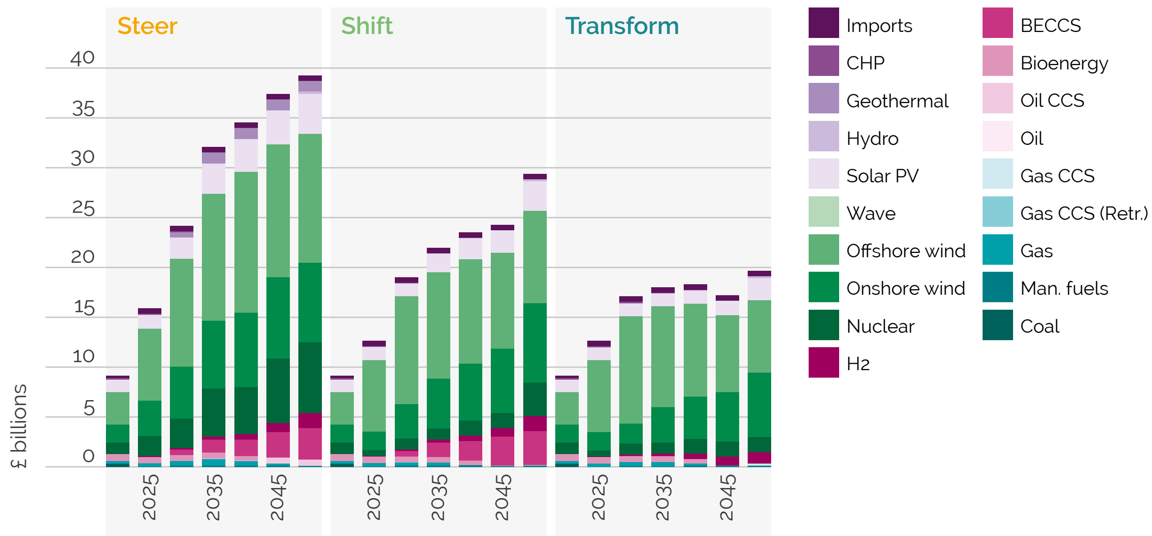


Figure A7: Annual power sector investment by generation type and scenario, 2010–2050. Investment already made prior to 2010 are considered sunk, and therefore do not appear in this figure.

The lower levels of capacity requirement are seen across all sectors, not just power generation. The levels of investment across the transport sector decrease dramatically under both LED scenarios, in the main driven by reduced levels of car ownership.

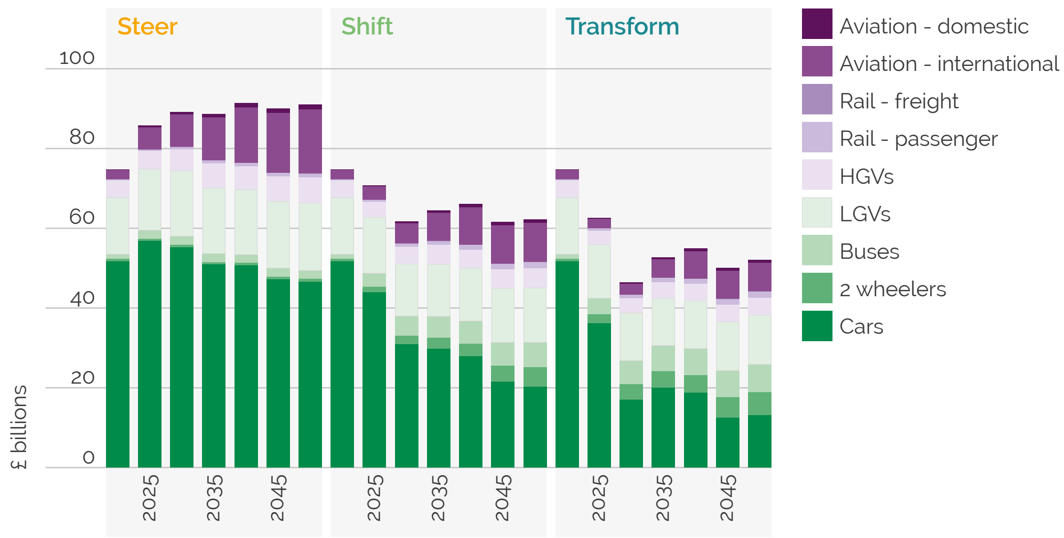


Figure A8: Transport sector investment by transport mode and scenario, 2010–2050.

C R E D S

This report

This study, undertaken by the Centre for Research into Energy Demand Solutions (CREDS), provides the most comprehensive assessment to date of the role of reducing energy demand to meet the UK's net-zero climate target. The study brings together 18 energy demand modelling experts from within CREDS to provide extensive detail on the possibilities to reduce energy demand in every sector. These sectoral reductions in energy demand are brought together into a whole-system modelling approach, to understand the potential contribution of energy demand reduction to support climate action in the UK.

About CREDS

The Centre for Research into Energy Demand Solutions (CREDS) was established as part of the UK Research and Innovation's Energy Programme in April 2018, with funding of £19.5M over 5 years. Its mission is to make the UK a leader in understanding the changes in energy demand needed for the transition to a secure and affordable, net-zero society. CREDS has a team of over 140 people based at 24 UK universities.

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