UK Energy Research Centre

UKERC Technology and Policy Assessment

Modelling Demand-side Energy Policies for Climate Change Mitigation in the UK: A Rapid Evidence Assessment

Working Paper

February 2019 Version 2.0

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The Technology and Policy Assessment (TPA) was set up to inform decision-making processes and address key controversies in the energy field. It aims to provide authoritative and accessible reports that set very high standards for rigour and transparency. Subjects are chosen after extensive consultation with energy sector stakeholders and upon the recommendation of the TPA Advisory Group, which is comprised of independent experts from government, academia and the private sector.

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In Phase III of UKERC (2014-2019), the TPA team have developed a methodology for Rapid Evidence Assessments (REAs), which is the basis for the method outlined in this report.

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Summary

As early impacts of climate change are being felt around the world, effective actions to curb greenhouse gas (GHG) emissions are becoming ever more urgent. Achieving the necessary reductions in emissions in the UK will require the use of a wide range of options, including demand-side policies that can reduce energy consumption. Such policies can pursue various goals, ranging from the use of more efficient appliances and better insulated homes to an increase in teleworking or the use of less energy-intensive materials. Energy models are widely used to inform energy policy in the UK. However, the potential of demand-side policies has so far only received partial attention in these models. To investigate how these policies can be better represented, we have undertaken a Rapid Evidence Assessment (a constrained form of systematic review) to examine the energy models that inform UK energy policy. The overarching question this review seeks to address is

> ***How suitable are the energy models used to inform UK government energy policy for exploring the full range of contributions that demand-side energy policies can make to climate change mitigation?***

To answer the question, we firstly identified thirteen core energy models based on a review of over thirty policy documents published by the UK government between 2007 and 2017 in the areas of energy and climate policy. As we focus exclusively on policy documents published by the UK government the thirteen selected models reflect those that feed most directly into policy making at the UK level. Our analysis does not capture models used for policy making at regional, local or EU level. It also doesn't capture models used at universities which perform work for the government but are not directly cited in policy documents.

These thirteen models present a range of different types of modelling approaches, cover different parts of the energy system and are used for different purposes. The first group are models that cover the whole energy system, using econometric-based approaches (e.g. BEIS Energy Demand Model), and which are generally employed to produce baseline forecasts of energy demand. The second group are system-optimisation models (e.g. UK TIMES), which cover the whole energy system and employ cost-optimisation approaches to explore viable long-term scenarios for climate change mitigation. The third group are economic models, such as the HMRC environmental computable general equilibrium (CGE) model, which are used to assess the economic impacts of climate change mitigation scenarios. The fourth group consists of a range of models covering specific sectors, such as the National Transport Model or the National Household Model. These sector-specific models are used to identify and compare specific policy options in their respective sectors for the short and medium terms, for example feeding into the development of marginal abatement cost curves. Finally there are a group of models that were developed to investigate the feasibility or impact of specific policy instruments (e.g. the Green Deal Household Model).

Using published documentation as well as interviews and questionnaires we analysed the thirteen models in detail, to find out how they represent demand-side energy policies. Our analysis reveals that the core strength of current energy modelling is the detailed representation of technologies, with many models featuring information on hundreds of potential technological options for increasing energy efficiency. Although uncertainties exist around these technological options, these models allow us to gain a coherent and realistic understanding of how different combinations of technologies could satisfy our future energy

service demands under different low-carbon scenarios. They also allow us to estimate and compare the technological costs of such scenarios and some models, such as UK TIMES, are set up to provide cost-optimal solutions under different constraints. The technological elements of the range of demand-side solutions is therefore well covered in the models, in the sense that they are well positioned to explore the potential reductions in energy demand that technological options can produce compared to a business-as-usual scenario.

In contrast to the technological detail, however, the modelling landscape reveals some limitations with regard to the representation of non-technological drivers of energy demand.

Firstly, the potential of non-technological demand-side policies to contribute to energy demand reductions and climate change mitigation is not well represented. Economic, social and behavioural drivers of energy demand, such as thermostat settings or the output shares of different economic sectors, are usually included as exogenous assumptions in the models. Hence, changes in such drivers are not considered as potential levers of climate change mitigation. In addition the economic, social and behavioural assumptions that feed into the model are often not described explicitly and are frequently not presented in a transparent manner. As a result, the models effectively hide the potential contributions from non-technological demand-side policies and so risk excluding them from the discussion of climate change mitigation options. There are some encouraging exceptions, with some models featuring a limited range of behavioural options, for example reductions in hot water demand per person. However, these options are few and far between and strongly outnumbered by the technological options.

Secondly, the models not only show limitations in representing the potential contributions from non-technological demand-side policies, but also in modelling how behavioural, social and economic change happens. While many of the models provide a wealth of detail on different technological options they are not so well-equipped to investigate how technological change comes about and how it could be steered into the right direction using different policy instruments. In many models, the uptake of different technological options is specified exogenously by the user, or is determined endogenously by cost-optimisation, which does not reflect the many non-cost factors influencing technology diffusion. However, some models show progress in this area, for example the technology diffusion models for cars and heating systems integrated into the E3ME model. In addition there is limited representation of the processes of economic, social and behavioural changes not related to technology diffusion. Of these three factors it is the modelling of economic interactions that is perhaps most developed, as energy prices are a common factor influencing energy demand in the models. However, energy economy relationships are generally modelled only one way, as only two models in our review include feedbacks from the energy system back into the wider economy.

Not all demand-side policies lend themselves to a representation in formal models. Utilising the full potential that demand-side policies can bring to the reduction in energy demand therefore needs to be informed by insights gained both from models as well as other forms of enquiry. Nevertheless, there is still considerable scope for energy models to provide better representations of demand-side energy policies, especially with regard to non-technological aspects. The academic literature contains some promising attempts of incorporating more realistic representations of social and behavioural processes in energy models. However, these are not currently used widely to inform policy development and require further development. Based on our review, we have identified a number of important pathways to help improve the representation of demand-side energy policies in energy models:

1. **Develop consistent and transparent processes for estimating exogenous inputs into energy models, such as energy service demands and socio-economic drivers**. All the models rely on various exogenous inputs to calculate energy demand, such as socio-economic drivers (e.g. population, income, GDP), energy services (e.g. passenger-kms) or technological assumptions (e.g. costs). These inputs are important determinants of energy demand, but the data sources, assumptions and off-model calculations are often not published in detail. The development of a transparent framework for developing and publishing these model inputs would be helpful for highlighting the importance of exogenous inputs in determining energy demand as well as the potential that changes in these exogenous inputs could have for reducing energy demand.
2. **Quantify the potential of non-technological demand-side policies and include them in models**. There is a need for more research quantifying the mitigation potential and costs of non-technological demand-side solutions, for example teleworking, and for them to be included as mitigation options in the models. This way models could be used to envisage different low-carbon pathways by examining the combined impact of demand-side options that are both technological and non-technological. In a similar way to some of the current energy models, these models would not need to represent the processes of change, but would focus on the potential energy demand reductions that these changes could achieve. Such an approach is not without challenges as estimates of potential energy savings from different behavioural options depend on the context of other measures that are applied and are not easily transferred between models. Nevertheless, there is scope for some fruitful research that extends existing energy models with explicit non-technological options.
3. **Integrate economic, social and behavioural processes into energy models where feasible and useful**. There is ongoing research on how economic, social and behavioural factors influence energy demand and how they could be changed by policy to reduce energy demand and carbon emissions. Insights from this research should be reflected in energy models where this is feasible and helpful. There exist some attempts to represent social and behavioural processes in energy models. For example the incorporation of technology learning and consumer preferences in system-optimisation models or the development of new models based on a socio-technical transitions perspective. However, such attempts are currently not widely applied in policy development. For those social and behavioural aspects that are difficult to represent in quantitative models, other ways of synthesising the insights from technology models and social science research should be developed to make the latter more visible and complement the models.
4. **Research the potential implications of interactions between different drivers of energy demand.** Interactions between different drivers of energy demand are likely to play an important role, but these are not well understood. An example of such an interaction would be the impact that a modal shift from cars to cycling would have on the growth and energy demand of the automotive industry. Research on such interactions is limited, so this work could start with a systematic review to identify interactions between energy demand drivers that are likely to be important for the transition to a low-carbon society. When more knowledge is available such feedbacks could be explored by integrating them into models, building new models focused on these interactions, or by empirical research alongside modelling.

1 Introduction

As early impacts of climate change are being felt around the world, effective actions to curb greenhouse gas (GHG) emissions are becoming ever more urgent (IPCC 2018). Under the climate change act, the UK aims to reduce its GHG emissions by at least 80% by 2050 compared to 1990. However, more ambitious targets would be required to make UK emissions compatible with the global goals of the Paris agreement. Energy-related CO_2 emissions account for more than 80% of GHG emissions in the UK (BEIS 2018a). Therefore a rapid energy transition is required to reduce energy-related CO_2 emissions. This energy transition will require both a switch to low-carbon sources of energy supply, as well as a reduction in energy demand compared to a business-as-usual trajectory. Both of these aspects therefore play an important role in the Clean Growth Strategy published by the UK Government (HM Government 2017b).

To help deliver the necessary size and speed of the energy transition, a policy-led response is required, as markets left on their own will be insufficient (Stern 2007). Energy policy has to cover the supply-side of energy use (e.g. ensuring clean, affordable and reliable energy is available to end-users) but also energy demand issues (e.g. reducing energy demand). In the past, policy action on climate change has largely focused on the supply of energy and the transition to renewable and other low-carbon sources and less on the demand for energy (Wilson et al. 2012). However, in recent years there has been increasing attention given to the contributions that demand-side policies could make to climate change mitigation (Creutzig et al. 2018; Grubler et al. 2018). In this report we will focus on exploring those demand-side policies that can contribute to climate change mitigation through reductions in energy demand. However, it is worth highlighting that there are several demand-side policies that are important for climate change mitigation because they reduce GHG emissions not related to energy use, such as the promotion of plant-based diets to reduce agricultural methane emissions (Smith et al. 2014). Demand-side policies that can reduce energy demand include such measures as improved building insulation, more efficient use of materials or modal shifts in transport. In addition, demand-side policies that make energy demand more flexible and responsive can make an important contribution to the energy transition by balancing variable renewable energy sources. Overall the potential of such demand-side policies to reduce energy demand are significant. A recent study that investigated 90 demand-side changes in the UK estimated that these changes could reduce the global carbon emissions associated with the supply chains of UK consumption by 25% (Moran et al. 2018).

Given the scale and the speed of carbon reductions that are needed to mitigate dangerous climate change, demand-side policies have to play an important role in the energy transition (Anderson et al. 2014; Creutzig et al. 2018; Cullen et al. 2011). This suggests that the UK should aim to fully realise the large potential that such demand-side policies can bring in reducing energy demand and the associated carbon emissions. Demand-side policies also have the additional benefit that they impact the whole supply chain and therefore offer a way to impact the carbon emissions associated with UK consumption that are produced outside the UK (Scott et al. 2016). In addition many demand-side policies can deliver social benefits beyond the reduction of energy demand and carbon emissions, for example modal shifts towards cycling and public transport produce health benefits from reduced air pollution and increased physical activity (Rojas-Rueda et al. 2012; Woodcock et al. 2009).

Realising the full potential of demand-side policies will require an extension in the scope of what is currently considered to constitute ‘energy policy’ by the UK government as well as an extension of the evidence base that informs such UK policy. Quantitative energy models form a key part of this evidence base, and as such are the focus of this Rapid Evidence Assessment (REA). Energy models represent different aspects of the energy system and are used for different purposes. Some models represent the whole of the UK energy system (e.g. UK-TIMES). These whole-system models are often used to identify long-term pathways for meeting the UK climate change targets. Other models represent only a specific sector of the energy system, such as transport or housing (e.g. the National Transport Model). These sectoral models are often used to develop detailed policies for their respective sectors. In addition some models are developed to investigate the effectiveness of specific policies (e.g. the Green Deal Household Model).

It is currently not well understood how these energy models could represent the increasingly diverse range of demand-side energy policies. We therefore conducted this REA to address the following research question:

> *How suitable are the energy models used to inform UK government energy policy for exploring the full range of contributions that demand-side energy policies can make to climate change mitigation?*

We focus our research on policy documents published between 2007 and 2017 by the UK government and hence do not consider policy documents at the level of the EU or UK regions. Our research is structured to address the following three sub-questions:

RQ1	What are the core energy models used to inform energy policy developed by the UK government?
RQ2	How do these models represent energy demand and its drivers?
RQ3	How suitable are the models for exploring different kinds of demand-side UK energy policies?

The insights we have gained from the analysis provide us with a better understanding of how demand-side energy policies can be represented in current models and what further improvements might be required to capture and make visible the full potential of demand-side energy policies. This understanding is important for the development of effective demand-side policies in the UK and, ultimately, for making the right societal decisions for how to achieve climate change targets.

Section 2 of the report outlines the conceptual framework that we use to tackle the questions and the overall approach adopted for the REA. Sections 3, 4 and 5 then discuss the methods and results related to each of the three research questions outlined above. Section 6 contains concluding remarks and recommendations for future research.

2 Conceptual framework and general approach

2.1 Conceptual Framework of Energy Demand

For the purpose of this report we consider **energy demand** to refer to the use of energy carriers and energy services by end users. Energy demand can be measured at the final energy stage or downstream stages in the energy conversion chain, i.e. useful energy and energy services (Figure 1). End users include households, businesses and public bodies.

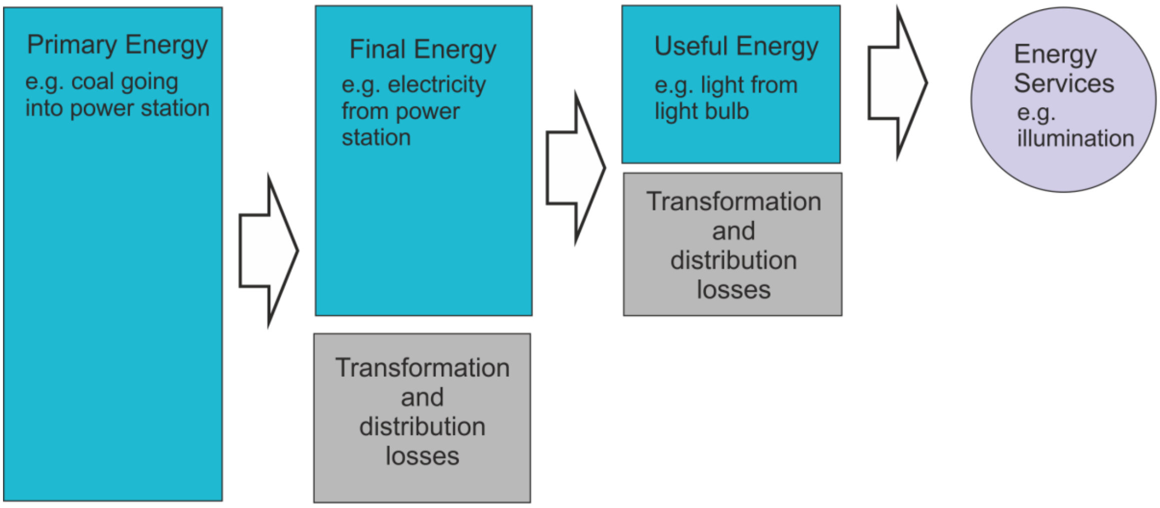

Figure 1: Conceptual diagram of the energy conversion chain.

The focus of our research is **demand-side energy policies.** We use the word 'policy' in a broad sense in that it can refer to both specific policy instruments (e.g. a carbon tax) as well as the desired changes that these policies try to achieve (e.g. modal shifts in transport). We consider policies as 'demand-side' based on the type of goals that they pursue. Specifically we define demand-side policies as policies that attempt to:

1. Increase flexibility of energy demand or shift energy demand in time
2. Increase the technical efficiency with which final energy carriers are converted into useful energy and useful energy is converted into energy services
3. Reduce or transform energy service demands

We consider this classification helpful for our analysis because it covers a wide range of goals that are associated with energy policy on the demand side. At the same time, however, the categories are not tied to any specific area of energy policy in the sense that all of these policy goals could be pursued as part of wider efforts to achieve climate change mitigation, energy affordability and energy security. Table 1 provides some illustrative examples of policies for each policy goal and for the different sectors of energy use.

The first category of policy goals essentially refers to changes in the temporal distribution of energy demand and in the capacity of energy demand to respond more flexibly to changes in energy supply. Examples of this are reductions in peak demand through variable pricing or mechanisms that allow end-users to respond to the intermittent availability of renewable energy sources.

Table 1: Illustrative examples of demand-side energy policy goals in different sectors (partially drawing on Creutzig et al. (2018))

	Demand-side energy policy goals		
	Flexibility of demand	**Increase technological efficiency**	**Reduce or transform energy service demands**
Transport	Vehicle-to-grid technology	Increased fuel efficiency Smaller vehicles Eco-driving	Modal shifts from car to cycling Teleworking Urban densification[1]
Industry	Capacity markets	More efficient machines Recycling New manufacturing processes	Use of low-energy materials Longer-lasting products Sharing economy Less processed food
Buildings	Building automation systems Variable pricing	Condensing boilers Retrofit insulation More efficient appliances	Lower indoor temperatures Smaller fridges

The second category of policy goals captures any changes in technology that increase the efficiency of delivering specific energy service demands. Examples of this are improvements in the fuel economy of cars, insulation in buildings to reduce the need for heating or more energy efficient machines installed in factories.

Finally, the third category is harder to define. On the one hand it includes reductions in energy service demands, such as reductions in travel or reduced indoor temperatures in homes. However, we also consider this category to capture any transformations in energy service demands. We envisage these transformations as systemic changes that allow wider societal needs to be met using different energy services. Examples of such transformations are reductions in commuting travel because of teleworking, construction methods that rely on fewer energy-intensive materials or changes in consumption and production patterns that reduce the need for freight transport. Such transformations often involve some element of new technologies. However, while the technologies related to the second goal increase the efficiency with which a specific energy service is delivered, the technologies used in the transformation of energy services allow energy users to substitute one energy service for another. The changes that bring about the reduction or transformation of energy services are often outside of what is conventionally considered to be the 'energy system' and might not necessarily be considered as the realm of energy policy. However, given the potential of such options to contribute to energy demand reductions and climate mitigation policy, it is important for this study to analyse how far the models used in UK energy policy making are able to explore such transformations.

To achieve the goals outlined above, demand-side energy policies can take different forms, including regulation, market-based incentives, information-based interventions, voluntary agreements and government procurement and provision (Karamanos 2001; Park 2015). Some examples of how different types of instruments might be used to achieve the different aims of demand-side energy policies are provided in

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[1] Appropriate planning for more compact cities can reduce heating requirements and travel distances (Creutzig et al. 2016).

Table 2.

Table 2: Examples of different types of instruments aimed at achieving different goals of energy demand-side policy

	Demand-side energy policy goals		
	Flexibility of demand	**Increase technological efficiency**	**Reduce or transform energy service demands**
Regulation		Building and vehicle standards	Car-free Sundays
Market-based interventions	Capacity market Differentiated tariffs Support development of smart appliances	Fuel taxes Green Deal subsidies EV car subsidies	Fuel taxes
Gov. procurement and provision		Government vehicle fleet Government-provided building upgrade	
Information-based interventions	Smart meters	EPCs Appliance labelling	Smart meters
Voluntary agreements		Climate Change Agreements	Employer car sharing schemes

Devising effective demand-side energy policies is difficult because there is a **complex system of drivers** governing energy demand, ranging from individual behaviours to large-scale developments, such as economic growth. For the purpose of this report four interrelated categories of energy demand drivers were identified drawing on a number of contributions from the literature (Butler et al. 2017; Fleiter et al. 2011; Geels et al. 2018; Hoolohan et al. 2016; Krysiak & Weigt 2015; Sorrell 2015).

1. **Technology and Infrastructure**: This refers to the availability and characteristics of infrastructures, conversion devices and passive systems used by end-users to convert final energy carriers into desired energy service.
2. **Behaviour**: This refers to the behaviour of individuals and organisations with regard to the buying, use and disposal of technology and infrastructures.
3. **Society**: This refers to wider social norms and institutions that shape energy demand.
4. **Economy**: This refers to the overarching economic developments that shape energy demand, including growth in living standards, structural change and changes in prices.

The overall framework for our analysis is presented in Figure 2. We recognise that this is a simplified representation of the social, economic and technological systems and their interlinkages governing energy demand. However, we consider this framework helpful for analysing how energy models can represent the drivers of energy demand and demand-side energy policies.

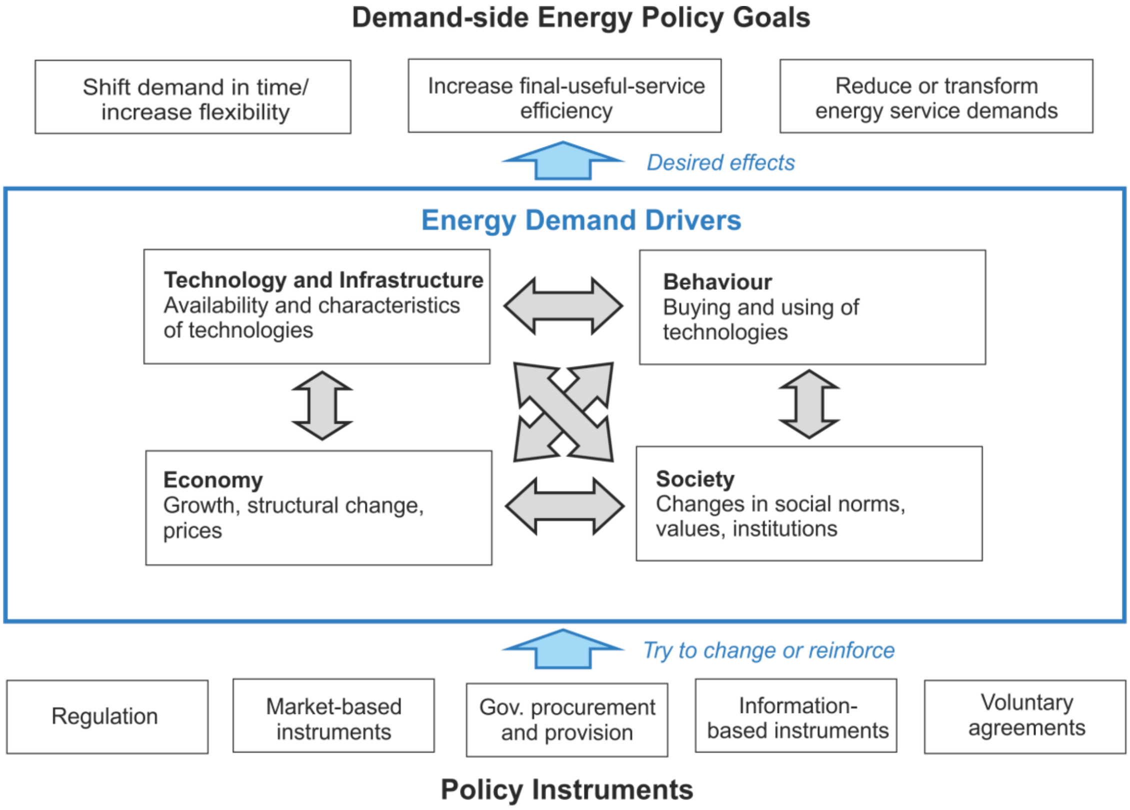

Figure 2: Graphical representation of the conceptual framework employed for the analysis.

2.2 Rapid Evidence Assessment process

The Government Social Research Service (GSR 2013) lists six types of review methods in its REA toolkit, ranging from unsystematic literature reviews to highly rigorous and systematic multi-arm systematic reviews. Figure 3 provides a schematic of the different review methods mapped against rigour and the time needed to conduct them.

An REA is defined as "a short but systematic assessment on a constrained topic" (GSR 2013). REAs have been designed to maintain the rigour of a full systematic review, but to deliver results rapidly within constraints imposed by cost and time (Hailey et al. 2000; Khangura et al. 2012). The proposed approach follows the procedures established by the UKERC Technology and Policy Assessment research theme, which are directly comparable to 5 established protocols for conducting REAs (Collins et al. 2015).

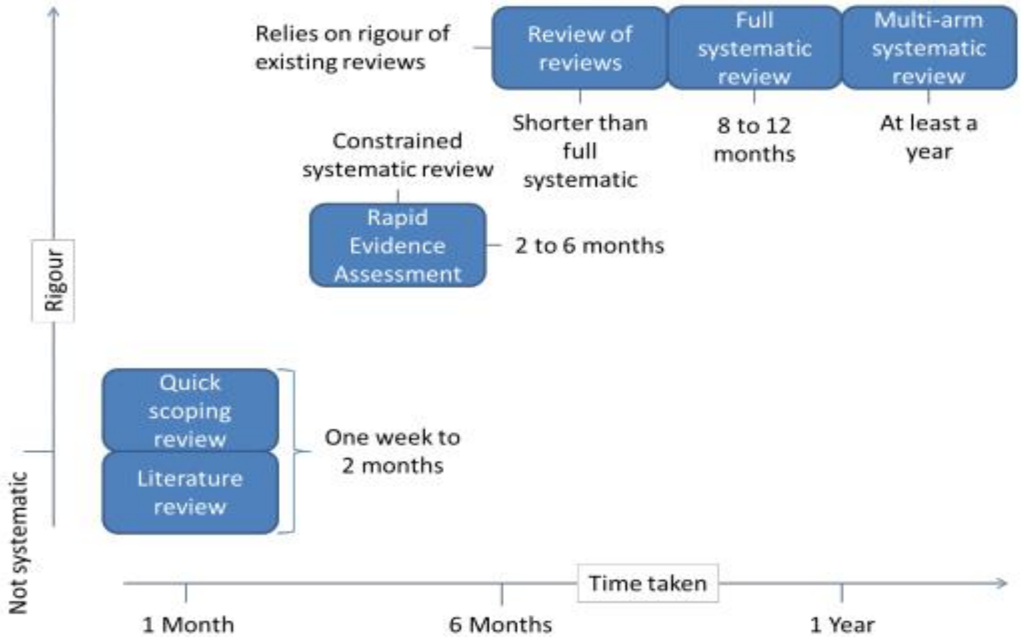

Figure 3: Schematic of different methods of evidence review (adapted from GSR 2013).

As such we conducted the REA in this project according to the following steps:

- Publication of a Scoping Note on the UKERC website.
- Establishing a small group of experts, representing a variety of opinions and perspectives, to advise the project team; this will be carried out through a streamlined consultation process (i.e. using electronic consultations rather than meetings).
- A systematic search of a clearly defined evidence base using keywords.
- Categorisation, prioritisation and analysis of the evidence, including an appraisal of methodological quality.
- Drafting of a Working Paper.
- Expert feedback and peer review of the working paper.
- Publication and dissemination through appropriate mechanisms.

3 The models used in UK energy policy making

3.1 Method for model identification

To answer research question 1 we identified the core energy models used to inform UK government energy policy based on the citation of models in policy documents. Specifically we analysed 2007-2017 policy documents and policy impact assessments of energy policy at the UK level covering either all sectors or only specific sectoral (e.g. transport) areas. Policy documents at the regional or city level were not considered. Similarly, EU policies, such as the Energy Efficiency Directive, are not covered. In the first step of selecting relevant policy-documents, we drew up an initial short list based on the expertise of the authors and suggestions from the steering group. We then compared the short list to the Arup energy policy timeline (Arup 2017) to ensure that no major energy policies were missed. In addition to the policy documents and impact assessments we included the reports by the Committee on Climate Change (CCC) proposing the carbon budgets as well as the reports outlining the National Infrastructure Assessment by the National Infrastructure Commission (NIC). These reports are not policy documents. However, we consider them relevant because the proposals outlined in the reports play an important role in informing energy policy in the UK. While the sample of documents selected does not provide a comprehensive list of energy policies in the UK, we consider it sufficient to identify the most important models used in UK energy policy making.

The list of documents that we analyse is shown in Table 3 and represents the clearly defined evidence base for the REA (see section 2.2). To identify the models used to inform the policy documents we conducted a systematic search using keywords. Each document was searched using the terms ‘model’, ‘analysis’ and ‘evidence’ (using three separate searches).

Based on the search we recorded which quantitative models are cited in the document and for what purpose they are used. As a detailed analysis of all identified models was beyond the scope of this project, we selected a subset of the models to form the evidence base for research questions 2 and 3. We used the following criteria to ensure that the selected subset of models include the most relevant models as well as a reasonable representation of the full range of model types used:

- Models with the highest numbers of citations should be included
- Models which have been important in informing the most recent policy documents should be included
- The model selection should represent all important model categories
- Information on the selected models needs to be available, either through published documentation or through other sources, such as interviews with modellers (see section 2.4)

Table 3: Documents analysed for research question 1

National Policy documents	Reference
2007 Meeting the Energy Challenge: A White Paper on Energy	(HM Government 2007)
2008 Meeting the Energy Challenge: A White Paper on Nuclear Power	(HM Government 2008)
2009 The UK Low Carbon Transition Plan	(HM Government 2009a)
2009 The UK Renewable Energy Strategy	(HM Government 2009b)
2011 Planning our electric future: A White Paper for secure, affordable and low- carbon electricity	(DECC 2011b)*
2011 The Carbon Plan: Delivering our low carbon future	(HM Government 2011)
2012 UK Bioenergy Strategy	(DfT et al. 2012)
2012 Gas Generation Strategy	(DECC 2012b)
2012 The Energy Efficiency Strategy: The Energy Efficiency Opportunity in the UK	(DECC 2012c)
2012 The Future of Heating: A strategic framework for low carbon heat in the UK	(DECC 2012d)
2013 The Future of Heating: Meeting the challenge	(DECC 2013e)
2017 The Clean Growth Strategy Leading the way to a low carbon future	(HM Government 2017b)
2017 Industrial Strategy: Building a Britain fit for the future	(HM Government 2017a)
Policy Impact Assessments	
2008 Impact Assessment of the Government's White Paper on Nuclear Power	(BERR 2008)
2009 Impact Assessment of Low Carbon Transport: A Greener Future	(DfT 2009a)
2009 Impact Assessment of the Climate Change Act	(DECC 2009)
2011 Proposals on the future of Climate Change Agreements	(DECC 2011c)
2011 Smart meter rollout for the small and medium non-domestic sector GB	(DECC 2011d)
2012 Final Stage Impact Assessment for the Green Deal and Energy Company Obligation	(DECC 2012a)
2013 Electricity Demand Reduction – Amendment to Capacity Market Clauses	(DECC 2013a)
2013 Simplification options for the CRC Energy Efficiency scheme to help business : CRC (Amendment) Order 2013	(DECC 2013d)
2013 Electricity Market Reform – ensuring electricity security of supply and promoting investment in low-carbon generation [update: May 2013]	(DECC 2013b)
2013 RHI Tariff Review, Scheme Extensions and Budget Management	(DECC 2013c)
2014 Energy Saving Opportunity Scheme	(DECC 2014a)
2014 Renewable Transport Fuel Obligation: Post Implementation Review	(DfT 2014)
2014 The Future of the Energy Company Obligation: Final Impact Assessment	(DECC 2014b)
2015 Periodic Review of FITs 2015	(DECC 2015)
2016 Smart Meter Roll-out Cost-Benefit Analysis	(BEIS 2016b)
2016 Domestic Heating Replacement Regulations	(BEIS 2016a)
2016 The Renewable Heat Incentive: A reformed and refocused scheme	(BEIS 2016c)
2016 New legislative powers for ULEV infrastructure	(DfT 2016)
2016 Impact Assessment for the level of the fifth carbon budget	(DECC 2016)
CCC and NIC reports	
2008 Building a low-carbon economy – the UK's contribution to tackling climate change	(CCC 2008)
2010 The Fourth Carbon Budget: Reducing emissions through the 2020s	(CCC 2010)
2015 The Fifth Carbon Budget: The next step towards a low-carbon economy	(CCC 2015)
2017 Congestion, Capacity, Carbon: Priorities for national infrastructure, Consultation on a National Infrastructure Assessment	(NIC 2017)

*In July 2016 the Department for Energy and Climate Change (DECC) became part of the newly formed Department for Business, Energy & Industrial Strategy (BEIS)

3.2 Models used in UK energy policy making

3.2.1 Energy models identified in policy documents

Altogether 27 models were cited in the documents analysed, with 14 of those only being mentioned in a single document (Table 4). These models are based on a wide variety of approaches. To provide an overview we allocated the models first into three overarching categories, related to the scope of the models, namely 1. all-sector models, 2. sector-specific models and 3. policy-specific models. In the case of models that also feature energy supply components the following analysis is focused on the demand-side components of the model.

Firstly, all models which cover all sectors of energy demand are grouped under the term **all-sector models** (Table 4). Altogether eleven all-sector models were identified with the Energy Demand Model of the Department for Business, Energy and Industrial Strategy (BEIS EDM) being by far the one most cited. The identified all-sector models include all important energy carriers and some representation of all the sectors in which energy carriers are used. Beyond these characteristics, however, the models identified represent a range of different types. We have therefore subdivided this category into a set of three (still very broad) sub-categories, namely econometric models, system-optimisation models and economic general equilibrium models.

The sub-category of econometric models represents models which are based on econometric equations to project energy demand into the future. For simplicity we have also allocated the National Infrastructure Systems Model (NISMOD) into this category, even though it is not based on econometric equations (see Annex I for a brief descriptions). Models in the econometric category do not feature an element of cost- or utility-optimisation.

The second sub-category is system-optimisation models. These models include details on a large range of technologies for both energy production and consumption. These models are classed as optimisation models because they can estimate the least-cost pathways for future energy systems based on projections of energy service demands and other scenario constraints (e.g. carbon targets).

The third sub-category is economic general equilibrium models. These models represent the whole economy as a set of markets and can estimate changes in the economic equilibrium that result from changes in energy prices or energy efficiency. They generally feature only a crude representation of the energy system. The Global Carbon Finance Model (GLOCAF) sits somewhat outside these sub-categories as it is a model representing carbon abatement options on a global level. It is used by BEIS to estimate financial flows and carbon prices resulting from different global agreements on climate change mitigation. Section 3.3 provides a more detailed discussion on the purpose of the different model types.

The next category of models we identified in this study are **sector-specific models** (Table 4). These models focus on a specific sector of the energy system, including either production sectors (e.g. electricity production) or energy using sectors (e.g. transport or housing). Since they only focus on a subset of the system, sector-specific models are often able to provide more detail on their respective sectors than all-sector models. The analysis of the documents identified ten sector-specific model with the BEIS Dynamic Dispatch Model (DDM) and the Department for Transport's (DfT's) National Transport Model being the most cited. Of the ten models, four represent the buildings sector (including domestic and non-domestic buildings), three the electricity sector, two the industry sector and one the transport sector.

Table 4: List of models cited in the policy documents analysed, including information on number of citations and the publication years of the documents which first/last cite the model. It is also indicated which models were selected for further analysis.

Model	Selected		Citations	Year cited first	Year cited last
All-sector models		**Sub-category**			
BEIS Energy Demand Model (BEIS EDM)	X	Econometric	13	2007	2017
MARKAL		System optimisation	7	2007	2011
UK TIMES	X	System optimisation	4	2015	2017
Energy System Modelling Environment (ESME)	X	System optimisation	4	2011	2013
HMRC environmental CGE Model	X	Economic general equilibrium	3	2008	2016
Global Carbon Finance Model (GLOCAF)		Other	3	2008	2016
E3ME model*	X	Econometric	2	2008	2015
National Infrastructure Systems Model (NISMOD)	X	Econometric	1	2017	2017
Redpoint Energy System Optimisation Model (RESOM)		System Optimisation	1	2013	2013
Blake CGE Model		Economic general equilibrium	1	2009	2009
Oxford economics (unnamed model)		Economic general equilibrium	1	2007	2007
Sector-specific models		**Sector**			
BEIS Dynamic Dispatch Model		Electricity	8	2012	2017
National Transport Model	X	Transport	7	2008	2017
National Nondomestic Buildings Energy and Emissions Model (N-DEEM)		Buildings	5	2011	2014
Energy Use Simulation Model (ENUSIM)	X	Industry	4	2008	2014
NERA/AEA Low carbon heat Model		Buildings	3	2010	2012
Redpoint electricity sector model (unnamed)		Electricity	3	2007	2011
BEIS Non-domestic Building Model	X	Buildings	1	2017	2017
BEIS Industry Pathways Model	X	Industry	1	2017	2017
National Household Model	X	Buildings	1	2015	2015
Zephyr (Pöyry's wholesale electricity model)		Electricity	1	2010	2011
Policy-specific models		**Policy**			
Green Deal Household Model	X	Green Deal	3	2011	2014
Electric Car Consumer choice model (ECCo)		ULEV infrastructure	1	2016	2016
Domestic EPC PRS Packages Model (DEPP Model)		Energy Performance Certificates (EPCs)	1	2014	2014
AEA's small emitters model (SEM)		Energy Saving Opportunity Scheme (ESOS)	1	2014	2014
EDR Take-up Model	X	Electricity Demand Reduction (EDR)	1	2012	2012
World Alliance for Decentralized Energy Model (WADE Model)		Distributed Generation	1	2007	2007

* The analysis in this study is based on the current global version of the E3ME model run by Cambridge Econometrics. Some of the policy documents analysed might have used an older version of the model which use data from the Office for National Statistics for the UK part of the model, rather than the EUROSTAT data employed in the current version. However the model construction(s) remain consistent.

The last category of models represents **policy-specific models** (Table 4). These are models that represent smaller but specific aspects of the energy system in the UK and have been developed to support specific policy issues. Most of the sector-specific models identified in this study are only cited in one document.

3.2.2 Selection of energy models for further analysis

A detailed analysis of all of the 27 models identified is beyond the scope of this study. Hence we selected a core set of 13 models, based on the criteria in section 3.1, which we analyse in detail in the remainder of this document. The selected models, indicated in Table 4, feature models from all three overarching categories as well as a representation of all sub-categories and sectors, except for the electricity sector. We excluded models representing only the electricity sector, because these models are mostly focused on modelling energy supply. While they include assumptions about electricity demand, they are not used to model processes that shape energy demand, such as the drivers outlined in section 2.1. Overall we are therefore satisfied that the models form a good basis to assess the way that demand-side energy policies are modelled for UK energy policy making. The focus of this research lies on those energy models that directly inform, and are cited in, policy documents. It is therefore not surprising that the majority of the 13 models we selected are developed and/or hosted by government departments. There exist more energy modelling research that is conducted at universities on the behalf of government, but feeds only indirectly into policy-making. In our research we pay only limited attention to this modelling work, but this field would constitute another interesting area for further research.

Of the all-sector models that have been used recently, we excluded the MARKAL model, because it has been superseded by UK TIMES, which is built on a newer version of the same framework. We also excluded the GLOCAF model because it is more focused on the global, rather than the UK level. In the sector-specific models, we excluded the NERA/AEA Low Carbon Heat Model because it has not been recently used. Of the policy-specific models we decided to focus on only two, the Green Deal Household Model and EDR Take-up Model, because documentation was available for these models.

The analysis of models in general is made complicated by the fact that models change over time and that there can exist different versions of the same model in parallel. In addition, many of the policy documents we analysed do not specify the model version that was used. In our analysis it was mostly the availability of documentation material that determined the version of each model that we analysed. If multiple documentations were available, we focused on the newest version of the model. The model descriptions in Annex I contain more detail on the specific model version that we analysed, if this information was available. In many respects our analysis is concerned with the high-level features of the different models, which are generally quite stable across different version. Therefore we believe that this source of uncertainty is only a small limitation of this study. Nevertheless, we recommend that authors of policy (and other) documents clearly state what versions of models have been used and where relevant documentation can be obtained.

3.3 How the models are used

The different model types outlined above are used for different purposes in the development of UK energy policy. This section will outline the different purposes that the models are used for in the policy documents that we analysed.

In general the models are employed in a forward-looking manner rather for the analysis of past developments. They are employed to explore and compare scenarios of the future development of the whole energy system, both in business-as-usual settings and in different policy contexts, as well as to investigate the impact of specific technologies and policies. Figure 4 depicts a somewhat simplified overview of the role of different models.

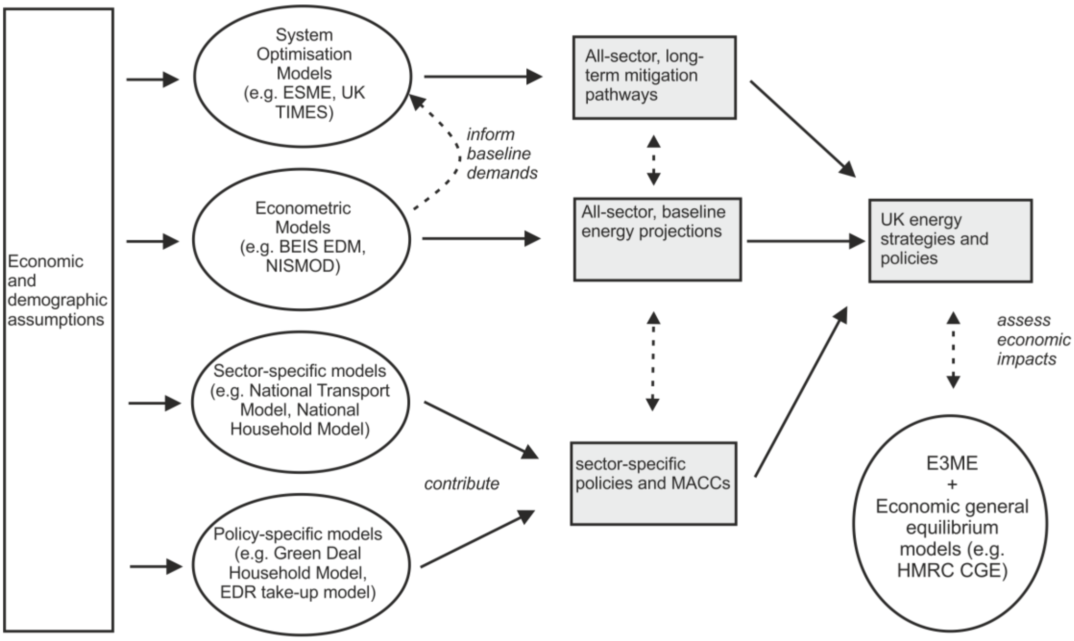

Figure 4: Conceptual representation of how different models and model categories are used in UK energy policy documents related to climate change mitigation.

3.3.1 Use of all-sector models

The different types of all-sector models are used for very different purposes in the documents we analysed. Firstly, the all-sector models classified as econometric have largely been used to provide baseline energy demand projections for all sectors. Such baseline projections can include a range of scenarios featuring different assumptions on the overarching drivers of energy demand, such as GDP, population or fuel prices.

The most important example is the Energy and Emissions Projections (EEP) which are published annually by BEIS (BEIS 2018b) and provide projections of UK energy demand and GHG emissions, currently covering the period to 2035. They include a reference scenario, based on central estimates of overarching drivers (incl. population and GDP), as well as scenarios reflecting different fuel price assumptions and a scenario that removes the influence of all policies implemented since 2009. These projections rely heavily on the BEIS EDM but are also informed by other model inputs, including from the National Transport Model, and a range of other specific models used to estimate the emission savings from different policies. The EEP are used in two important ways in the policy documents we analysed. Firstly, they assess how close current policies are to meeting the UK carbon targets. They therefore provide evidence on the magnitude of further emission savings that will be needed to achieve the carbon targets. Secondly, some results from the EEP feed into analyses conducted with other models. For example the EEP often provide the underlying energy demands for scenarios analysed in UK TIMES, the BEIS Industrial Pathway Model and the BEIS Non-domestic Building model.

The E3ME model has been used in a similar fashion to provide projections of baseline energy demand and GHG emissions. These projections have been used in the CCC reports on the UK's 5th carbon budget (CCC 2015) and on the first three UK carbon budgets (CCC 2008) to cross-check and verify the results from the Energy and Emissions Projections. The NISMOD model suite, developed by the Infrastructure Transitions Research Consortium, is one of the models used by the National Infrastructure Commission (NIC 2017) to provide baseline projections of energy demand under different scenarios. While the E3ME model and the NISMOD model suite are only used to provide baseline projections in the documents we have analysed, both of these models can also be used to explore alternative, low-carbon pathways (e.g. Dagoumas & Barker 2010; Hall et al. 2016).

Secondly, the all-sector models classified as system optimisation models, are generally used to explore different long-term pathways for the whole of the UK energy system, often up to 2050. These pathways or scenarios are often explicitly constrained to meet the UK carbon targets and provide the cost-optimal combination of technologies that can be used to meet the targets under different circumstances. The models use cost-optimisation approaches to identify the least-cost combination of technologies that could meet a set of underlying energy service demands given the scenario constraints. The underlying energy service demands are often (but not always) informed by the EEP and the BEIS EDM. The key purpose of these long-term pathways is to provide guidance on the general direction of UK energy policy (e.g. what technologies could play what role at what point in the transition) and to make sure that sector-specific policies for the short and medium term are consistent with a viable long-term pathway to meet the carbon targets. For example UK TIMES is used in the Clean Growth Strategy (2017) to explore three different pathways that can meet the UK climate target, including an electricity pathway, a hydrogen pathway and an emissions removal pathway.

Finally, a third way in which all-sector models are used is the assessment of the economic impacts of different climate change mitigation pathways generally and the implementation of carbon budgets specifically. For this purpose models are needed that include an endogenous representation of the economy and can model the feedback from energy policies to the economy. The energy-economy models used for this purpose therefore have stronger focus on the economy, rather than the energy system, and include economic general equilibrium models as well as Cambridge Econometrics' E3ME, which is based on a macroeconometric representation of the economy. For example, the HMRC environmental CGE model is used in the impact assessment of the 5th carbon budget to assess the economic growth impacts of meeting different potential levels of the budget. There also exist versions of the system optimisation models MARKAL and UK TIMES that have been linked to simple macroeconomic models to assess the economic impacts. These are occasionally used for policy development, but were not included specifically in the subset of documents that we analysed.

3.3.2 Use of sector- and policy-specific models

While the all-sector models are mostly used to develop long-term pathways and scenarios for the whole energy system, the sector-specific models are used to identify and compare specific policy options in their respective sectors for the short and medium terms. Policy-specific models are used for similar purposes as their results feed into the comparison of different policies with regard to their cost and feasibility. They are often employed to understand how specific policy interventions can be designed in order to be most effective. For example the Green Deal Household Model was developed to assess the uptake rates of different measures for energy efficiency in the domestic sector covered by the scheme.

An important way in which the sector-specific and policy-specific models provide evidence for the development of specific policies are through inputs into marginal abatement cost curves (MACCs). MACCs are constructed and cited as the key evidence for the development of explicit, short- to medium-term policy options in several important documents that we analysed. Documents that draw on MACCs include the Clean Growth Strategy (HM Government 2017b), the Energy Efficiency Strategy (DECC 2012c), the Carbon Plan (HM Government 2011) as well as the impact assessments for the 5th carbon budget (DECC 2016) and the CCC reports on the 4th carbon budget (CCC 2010) and the first three carbon budgets (CCC 2015). The MACCs present the potential emission savings that can be achieved for different mitigation options against the costs of delivering these options. These MACCs combine a large amount of information on different mitigation options from different sources, including both sector-specific and policy-specific models as well as other evidence, such as expert assessments and stakeholder consultations.

Current policy documents, such as the Clean Growth Strategy or the Impact Assessment of the 5th Carbon Budget, outline the evidence base that goes into the MACCs with the sector-specific models often described as key sources of evidence. Unfortunately, there is often only limited information available on how the models contribute to the development of the MACCs and how the MACCs feed into decision-making on specific policy goals and strategies.

4 Energy demand and its drivers

4.1 Method of analysis

The conceptual framework outlined in section 2 provides the basis for our analysis of the 13 core models selected. We analysed how the models represent energy demand and demand-side energy policies by assessing each aspect outlined in the conceptual framework (Figure 2), namely energy demand drivers, policy goals and policy instruments. We assessed these aspects by devising a list of questions, which were answered for each model. The list includes a number of questions on the general descriptions of the model, sections 1-2 in Table 5, as well as questions that are directly derived from the conceptual framework, sections 3-4 in Table 5. The answers to the questions were entered into a spreadsheet. For each model we obtained the relevant information to answer the questions using a two-step procedure.

In the first step we obtained any documentation of the models that is available in written form. Based on the documentation we produced answers to as many of our questions as we could. In the second step we attempted to obtain further information from a person who has applied knowledge of the model. Relevant participants were identified either from our existing contacts or, if we did not know of a relevant contact, by contacting the host institution. Information provided from participants was obtained either via a phone interview or via a written questionnaire depending on the participant's wishes. Interview schedules and the written questionnaires were produced by adapting the list of questions provided in Table 5. However, to reduce the time requirements for interviews and questionnaires we limited both interviews and questionnaires to the questions in sections 1-3 in Table 5.

We obtained the answers to the questions in section 4 based on the information available from the documentation and interview responses to the questions in sections 1-3. Any discussions of the potential for including demand-side energy policies in the different models are therefore the result of our own analysis and do not necessarily represent the opinion of the modellers themselves.

For some models, where detailed documentation was available, the procedure for the interview or questionnaire was adapted to reduce the time requirements on the participants. In these cases we used the interview or questionnaire to obtain only information and clarifications on those questions we could not answer satisfactorily from the documentation. Overall we conducted six interviews and obtained questionnaire responses for another four models (Table 6). For the remaining three models we were not able to obtain any information from the modellers, so the analysis for these models is based entirely on available written documentation.

The information obtained through interviews and questionnaires was then used to update the spreadsheet and produce a final dataset which forms the basis of our analysis. We then used a form of qualitative coding to compare the answers between questions and models and draw out relevant patterns and insights.

Table 5: List of questions we used to analyse the models.

Number	Questions
1 General information	
1.1	What is the purpose of the model?
2 Conceptualisation of energy demand	
2.1	Which sectors of energy demand are represented in the model (e.g. Buildings, Transport, Industry?)
2.2	Which stages of the energy conversion chain are represented in the model?
2.3	In what form are the different stages represented in the models (e.g. physical units, cost in £)?
2.4	How is the model disaggregated along spatial dimensions?
2.5	How is the model disaggregated along temporal dimensions?
2.6	Does the model utilise exogenous estimates of energy demand as inputs into the model (final, useful or energy services)? How are they included?
2.7	What tasks does the model perform? a) endogenous estimation of some form of energy demand (final, useful, service) from non-energy inputs (e.g. GVA projections) b) transformation of exogenous demand for energy into a different form (e.g. transformation of exogenous energy service demands into demand for final energy carriers) c) Representation of some process that is relevant for energy demand, without explicit calculation of energy demand itself (e.g. technology uptake rates)
2.8	What are the important exogenous factors that influence any endogenous calculation of energy demand? What are the sources of these exogenous factors?
3 Representation of energy demand drivers	
3.1	How are technologies represented in the model?
3.2	How are end-user behaviours represented in the model?
3.3	How are social norms and institutions represented in the model?
3.4	How does the model represent economic drivers of energy demand? Is there feedback from the energy system to the economic system?
4 Representation of demand-side energy policies	
4.1	How can the policy goal of demand-shifting/ flexibility be represented in the model?
4.2	How can the policy goal of increasing technical efficiency be represented in the model?
4.3	How can the policy goal of reducing or transforming energy services be represented in the model?
4.4	How can regulation-based policy instruments be represented in the model?
4.5	How can market-based policy instruments be represented in the model?
4.6	How can government procurement or provisioning be represented in the model?
4.7	How can information-based policy instruments be represented in the model?
4.8	How can voluntary agreements be represented in the model?

Table 6: List of models analysed with information on the data sources and methods used to obtain information.

Model	Host institution	Step 1: Written data sources	Step 2: Interview/Questionnaire
All-sector models			
BEIS EDM	BEIS	(BEIS 2018b)	Questionnaire
E3ME	Cambridge Econometrics	(Cambridge Econometrics 2014; Knobloch et al. 2018; Mercure et al. 2018)	Interview
NISMOD	UK Infrastructure Transitions Research Consortium	(Hall et al. 2016; NIC 2017)	Interview
UK TIMES	UCL Energy Institute	(Daly & Fais 2014)	Interview
ESME	Energy Systems Catapult	(Heaton & Bunn 2014; Energy Systems Catapult 2017)	Interview
HMRC environmental CGE model	HMRC	(HMRC 2013; Böhringer & Rutherford 2013)	Not available
Sector-specific models			
National Transport Model	DfT	(DfT 2018; DfT 2009b; RICARDO-AEA 2014)	Interview
ENUSIM	Ricardo Energy & Environment	(AEA Energy & Environment et al. 2008; Fletcher & Marshall 1995)	Interview
BEIS Industry Pathways Model	BEIS	-	Questionnaire
BEIS Non-domestic Building Model	BEIS	-	Questionnaire
National Household Model	BEIS	-	Questionnaire
Policy-specific models			
Green Deal Household Model	BEIS	(DECC 2012a; DECC 2011a)	Not available
EDR Take-up Model	BEIS	(DECC 2013a)	Not available

4.2 Energy demand conceptualisation

All of the models contain a representation of final energy demand and this is often considered the most important form of energy demand and a main output of the model. However, other stages are also represented (**Error! Reference source not found.**). Several of the all-sector models also represent the primary stage of energy use. These are models such as UK TIMES or ESME which represent the whole energy system of the UK including energy supply and energy demand.

In addition, some of the models feature an explicit ‘useful energy’ stage of energy conversion. Referring to Figure 1, this is the last stage of the primary-to-final-to-useful energy conversion chain, where final energy (e.g. electricity in kWh) is converted through an end-use appliance to provide a required energy service (e.g. illumination). It is therefore the energy usefully used “*at the output end of energy-using devices*” (Percebois 1979).

Useful energy can be defined and thus measured in two different forms. First is ‘useful energy’, based on thermodynamic first law and measures the energy usefully used as thermal/physical content terms. Second, useful energy can be defined on a thermodynamic second law basis as 'useful exergy' (also known as 'useful work'), and is defined as *"the minimum amount of [physical] work required to produce a given end-use"* (Guevara et al. 2016, p.2).

Both metrics require the estimation of thermodynamic final-to-useful conversion factors for different classes of devices and applications. An useful energy example at a UK level are the Useful Energy Balances produced by Eurostat in the 1970s-1980s for countries including the UK (Eurostat 1983). Useful exergy examples for the UK include Brockway et al. (2014).

Of the models we analysed, only the BEIS EDM produces projections of useful-stage energy. The BEIS EDM model uses 'useful energy' (i.e. a first law basis), estimating energy in the unit of useful therms, which are then converted into final energy variables, for example measured in kilotonnes of oil equivalent (ktoe). The relationship between useful and final energy is kept constant for each fuel over time.

Table 7: Overview of general model features for the 13 models analysed in detail. The term "ns" indicates that we did not have sufficient information on the specific issue.

Model	Code	Sector coverage	Spatial coverage and disaggregation	Temporal disaggregation	Stages in conversion chain included
BEIS EDM	EDM	All sectors	UK, one region	Annual	Primary, final, useful
E3ME	E3ME	All sectors	UK, one region	Annual	Some primary, final
NISMOD	NIS	All sectors	UK, several regions (GB only for transport)	Annual	Final
UK TIMES	UKTM	All sectors	UK, one region	Annual + seasonal and diurnal time slices	Primary, final
ESME	ESME	All sectors	UK, several regions	Annual + seasonal and diurnal time slices	Primary, final
HMRC environmental CGE model	HMRC	All sectors	ns	ns	Final
National Transport Model	NTM	Transport	GB, several regions	Annual + diurnal time slices	Final
ENUSIM	ENUSIM	Industry	UK, one region	Annual	Final
BEIS Industry Pathways Model	IPM	Industry	UK, one region	Annual	Final
BEIS Non-domestic Building Model	NDBM	Non-domestic buildings	UK, one region	Annual	Final, useful
National Household Model	NHM	Residential sector	GB, several regions	Annual	Final
Green Deal Household Model	GDH	Residential heating	GB, one region	ns	Final
EDR Take-up Model	EDR	Commercial electricity	ns	ns	Final

Adding a little confusion, we found the term "useful energy" was used outside of these strict thermodynamic-based definitions in the model documentation of some models. In UK TIMES and ESME, the term is sometimes used to describe underlying final energy demands (or indices thereof) that can be met by different technologies, leading to different levels of final energy consumption. For example the final energy demand (e.g. in kWh) for space heating can be met by different technologies and can be reduced by building insulation.

Most of the models are based on a linear framework for determining energy demand, which can be described in three stages (Figure 5). Firstly, it is envisaged that there are some overarching, socio-economic drivers, such as population and economic growth. Secondly, these drivers then determine energy service demands, for example vehicle kilometre. Energy service demands are discussed in more detail in section 4.3. Thirdly, these energy service demands are translated into final energy demand through the technologies that are used to obtain energy service demands. However, while the linear conception is similar in the models, only very few models contain all three stages (**Error! Reference source not found.**). As discussed in section **Error! Reference source not found.**, the distinction between socio-economic drivers and energy services is not necessarily clear-cut in practice. Nevertheless we consider it helpful to outline three different groups of models representing different combinations of the representation of the three stages.

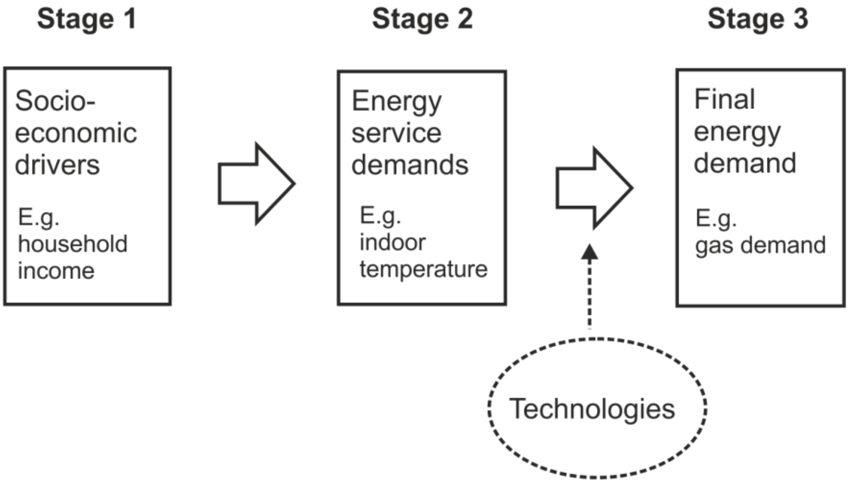

Figure 5: Simplified representation of the conceptual stages through which final energy demand is calculated in the models.

The first group of models do not feature an explicit representation of energy service demands. Instead final energy consumption is calculated directly from the socio-economic drivers. This group includes the all-sector, econometric models (E3ME, NISMOD and non-transport sectors in BEIS EDM) as well as the HMRC environmental CGE model. The Green Deal Household Model can also be considered in this category, but it is more concerned with the uptake of specific technologies than the projection of comprehensive energy demand scenarios in the domestic sector.

The second group of models includes energy services but do not include any socio-economic drivers in the model itself. Instead these models rely on the projections of energy service demands, which are calculated off-model. This group of models include the system-optimisation models, UK TIMES and ESME, as well as some of the sector-specific models, the BEIS Non-domestic Building Model. The Industry Pathway model and the EDR Take-up Model can also be considered in this group. Instead of energy service demands, they feature exogenous baseline values of final energy demand which are then modified according to the uptake of new technologies.

The third group of models includes all three stages, including socio-economic drivers, energy service demands and final energy demands. This group includes the National Transport Model, ENUSIM and the National Household Model.

Table 8: Representation of different stages of final energy calculation in the models. “x” indicates that the stage is represented in the model, “-“ indicates that the stage is not explicitly represented in the model.

Model	Socio-economic drivers	Energy service demands	Final energy demand	Brief description of final energy demand calculation
All-sector models				
BEIS EDM	x	-	x	calculated directly from socio-economic drivers based on econometric equations (except for transport)
E3ME	x	-	x	calculated directly from socio-economic drivers based on econometric equations, bottom-up technology diffusion models for personal transport and heating
NISMOD	x	-	x	calculated by adding the effects of different drivers and transition options to the baseline energy projections
HMRC environmental CGE model	x	-	x	calculated based on production functions and output in economic sectors
UK TIMES	-	x	x	model chooses least-cost combination of technology options that can satisfy energy service demand
ESME	-	x	x	model chooses least-cost combination of technology options that can satisfy energy service demand
Sector-specific models				
National Transport Model	x	x	x	calculated from vehicle-km using fuel-efficiency values for different vehicle categories
ENUSIM	x	x	x	calculated from economic output and employed technologies
BEIS Industry Pathways Model	-	-	x	exogenous baseline projections for final energy demand in industry sectors are modified according to uptake of new technologies
BEIS Non-domestic Building Model	-	x	x	calculated from energy service demands and employed technologies
National Household Model	x	x	x	calculated by combining assumptions on household profiles and indoor temperatures with housing stock and technologies
Policy-specific models				
Green Deal Household Model	x	-	x	calculate changes in heating energy demand based on levels of technology take-up
EDR Take-up Model	-	-	x	calculate changes in electricity demand based on levels of technology take-up

4.3 Energy service demands

We have identified policies that aim to reduce or transform energy service demands as an important group of demand-side energy policies (section 2.1). It is therefore helpful to examine how energy services are represented in the models. Energy services are conventionally defined as the immediate benefits that we derive from the use of energy, such as the movement of people from A to B, or a warm and comfortable home (Cullen et al. 2011; Sousa et al. 2017). However, while energy services are conceptually helpful for describing the drivers of energy demand, they are difficult to define in practice and the boundaries between socio-economic drivers and energy services are not clear cut. This section presents a summary of discussion about how different energy services are represented in the models. A detailed listing of the different variables for socio-economic drivers and energy services for all the models can be found in Tables A1-A4 in Annex II.

4.3.1 Transport

Transport is the sector in which the delineation of energy services from socio-economic drivers and final energy use is most clear-cut. Energy services in this category are usually described as vehicle-kilometre, passenger-kilometre or tonne-kilometre. Models that include a representation of the transport sector generally include at least some of such energy service variables, the only exception being the HMRC environmental CGE model. However, the detail with which energy service variables are resolved varies significantly. The UK TIMES and ESME models include the biggest range of energy service variables, including several road passenger transport modes, several categories of freight vehicles, rail freight and passenger transport as well as aviation and marine transport. In other models, energy service variables are more aggregated or might not be included at all for certain modes. For example the BEIS EDM features vehicle-km for car, LGV, HGV and aggregated public transport, but no energy service variables for rail, aviation and marine transport, for which final energy demand is estimated exogenously. Most of the models could therefore represent the impact of modal shifts in transport. However, in most models the energy demand for different transport modes are either given exogenously (e.g. UK TIMES, ESME) or are estimated independently of each other (BEIS EDM, E3ME). Only the National Transport Model features an endogenous process of modal choice based on generalised costs of different transport modes.

4.3.2 Buildings

In this sector, the definition of energy services is much less clear. The domestic sector and the public and commercial services sectors are mostly concerned with energy use in buildings. However, conceptually this includes a wide range of energy services, ranging from warm and comfortable rooms to cooking facilities, food storage and the various services delivered by electronic devices. Specific variables for such services are difficult to define which makes it challenging to delineate which model variables are socio-economic drivers and which are energy service demands. However, for the assessment of demand-side energy policies the level of detail in the models is more important than a clear distinction between energy service demands and socio-economic drivers. There are essentially two groups of models featuring different levels of detail.

The first group are models featuring a quite detailed representations of energy use in buildings, including ESME, UK TIMES, the National Household Model, and the BEIS Non-domestic Building Model. For heating in the domestic sector these models combine data on the size and make-up of the current and future housing stock with assumptions on internal and external temperatures to estimate the amount of heat required in the buildings. Energy demands for other purposes in buildings are usually represented as an energy use per building in a base year, which can then be reduced by introducing more efficient technologies (e.g. petajoule (PJ) of energy for cooking, PJ for refrigeration). In UK TIMES energy services in some categories are also approximated using the number of devices (e.g. number of freezers).

The second group are models with a less detailed treatment of energy use in buildings, including the BEIS EDM, the E3ME model and the HMRC environmental CGE model. These models do not feature a representation of energy services in the sense of different end-uses of energy in buildings. Instead they directly estimate the consumption of different fuels from variables such as household numbers, external temperatures or household income. While it is generally more aggregated, the E3ME model includes a bottom-up model of the residential heating sector that features the effective heat demand for spacing heating and hot water and then models the diffusion of technologies used for satisfying this demand.

4.3.3 Industry

Defining energy services in the industry sectors is difficult as it is in the domestic sector, because the purposes for which energy is used are very diverse. Similar to the buildings sector, models can be divided into two groups, based on the level of detail in the representation of the processes in which energy is used in industry.

In the models with less detailed treatment, final energy consumption is estimated for different industry sectors and fuels using high-level equations. Drivers of final energy consumption featuring in these equations include economic sector output and energy prices. In effect these models do not include a representation of energy services. Models with this representation include the BEIS EDM, the E3ME model and the HMRC environmental CGE model.

Models with a more detailed treatment effectively add one more stage into the calculation by breaking up the energy used in each industry sector into different processes. This is important for the representation of specific technologies (see section 4.4). The models in this group include UK TIMES, ESME, NISMOD, ENUSIM and the BEIS Industry Pathways Model. For most models and sectors final energy use is broken down into a number of generic types of energy end-uses, such as high temperature heat, low temperature heat, motors, drying and separation, and others. These demands are expressed in energy units. In some sectors UK TIMES and ESME also feature representations of specific processes, for example in production of steel or ammonia. In these sectors energy services are not approximated in energy units but in tons of different products produced.

4.4 Technology

We have identified technologies and their associated infrastructures as a key determinant of energy demand in our conceptual framework. There are two aspects worth discussing with regard to the representation of technology in models. The first is the level of technological detail, the second is the mechanism through which the deployment of technologies is determined.

4.4.1 Level of technological detail

With regard to the level of technological detail, there are essentially two approaches that can be distinguished (Behaviour and social norms

While individual behaviours and wider social norms and institutions feature as two different categories of drivers in our conceptual framework (Figure 2), we will discuss them together as they are similarly (under-)represented in the models.

Behaviour and social norms are important in two aspects. The first aspect is the choices that energy users make with regard to buying new energy-using equipment. The second aspect is the behaviours and norms governing the way that energy is used, e.g. the norms and behaviours around comfortable indoor temperatures or choice of available transport modes. Both of these aspects are not only important for understanding how behavioural and social changes can contribute to reductions in energy demand. They are also important for understanding how they might act in the other direction, for example by increasing energy use or by negating technological efficiency improvements through rebound effects.

With regard to the choice of technologies, almost half of the models we analysed do not feature any endogenous representation of technology choices (see discussion in section 4.4.2). Only a few models explicitly model the endogenous choice of technologies by energy users, with the bottom-up diffusions models incorporated in E3ME standing out as an interesting example. In the remaining models technology choices are either implicit in econometric relationships (BEIS EDM) or are strictly determined by cost optimisation within given constraints (ESME, UK TIMES, HMRC CGE model). It should be noted that there has been more academic research on integrating more realistic representations of technology diffusion into energy models. However, this was not reflected in the policy documents. This is discussed in more detail in section 5.2.2.

Representation of the second aspect, i.e. the behaviours and norms of energy use, is even more limited than the representation of technological choices (Table 9). The models that rely on econometric relationships are essentially the only ones where the behaviours of energy use are endogenous (e.g. BEIS EDM, E3ME, NTM). However, behaviours and norms are implicit in the econometric equations, for example in an equation describing the relationship between household income and electricity use. In addition these econometric relationships are fixed.

In the system optimisation models (ESME and UK TIMES) norms and behaviours with regard to energy use are reflected in the energy service demands that serve as input into the model. They are therefore exogenous and the assumptions on behaviours and norms, such as indoor temperatures, are hidden in the off-model projections of energy services. However, both models feature versions in which energy service demands are somewhat responsive to price changes and therefore partially endogenous (e.g. Pye et al. 2014). Unfortunately the policy documents we analysed did not provide details in how widely these price elastic version of the models were used.

The remaining models do not feature any endogenous representations of energy using behaviours and norms. However, some of the models include some options for behavioural change that can be implemented exogenously by the model user, similar to other technological options that are implemented exogenously. For example NISMOD features the options to reduce hot water demand in homes and the National Household Model allows for different assumptions on indoor temperatures.

). Firstly, the econometric and CGE models present the technologies for different sectors in an aggregated fashion without detail on specific technologies. This can include either a specific variable that expresses the energy intensity of a sector, or it is implicit in the econometric equation describing the relationship between socio-economic drivers and final energy consumption. For example this is the case in the BEIS EDM, where energy demand in the baseline scenario is calculated from different socio-economic drivers using econometric equations. However, to produce the reference case in the EEP, the effect of technology improvements achieved by policies since 2009 are calculated in more detail outside the model and the baseline projections are then corrected for these changes in energy demands. The HMRC environmental CGE model represents technologies through the aggregate production function, which means that the technology is partially endogenous because the combination of production factors, and hence the energy needed per unit of production, changes according to the relative prices of the production factors. In the E3ME model, the aggregate energy intensity parameters for different sectors also change over time according to relationships between output, energy intensity and investment. While the majority of the sectors are treated using this approach in the E3ME model, it also includes more detailed bottom-up models in the domestic heating and car transport sectors.

The second group of models differs from the first in that the models include specific technological options that can be used in different combinations to satisfy the energy service demands outlined in the section **Error! Reference source not found.**. The different technological options are described by a range of variables, depending on the model. However, some common key variables are the final energy needed by a technology to satisfy a specific energy service demand, the overall potential energy savings compared to the baseline scenario, the technology cost (both capital and operational) and the potential deployment rates. The number of potential technological options varies across models but is generally large. For example the all-sector models UK TIMES, ESME and NISMOD feature hundreds of options. An exception is the National Transport Model which features only average technological fleet characteristics for a few vehicle classes (cars, LGVs, HGVs).

4.4.2 Choice of technologies

For the models where technologies are not implicit in econometric equations, it is important to consider how the different combinations of technologies are chosen, both in business-as-usual and low-carbon scenarios. Here the models employ a range of different approaches (Behaviour and social norms

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).

Firstly, UK TIMES and ESME are cost-optimisation models. The models choose the technologies for the whole energy system based on the minimisation of overall system costs and subject to a number of constraints. For example such constraints can be inherent in the system, such as resource or deployment constraints, or they can be political, for example constraints reflecting the UK targets for carbon emissions.

Table 9: Overview of the ways in which the different categories of energy demand drivers are represented in the models

Driver	Representation	Models
Technology & Infrastructure		
Level of detail	Aggregate energy intensity of different sectors	EDM, E3ME, HMRC

	Explicit description of different technologies and their characteristics	E3ME, NIS, UKTM, ESME, NTM, ENUSIM, IPM, NDBM, NHM, GDH, EDR
Technology choices	Implicit in econometric equations or production functions	EDM, E3ME, HMRC
	Least-cost optimisation of whole system	ESME, UKTM
	Explicit modelling of technology uptake decisions	E3ME, GDH, EDR
	Cost-effective technologies deployed according to S-curves	ENUSIM
	Specified exogenously by user	NIS, NTM, IPM, NDBM, NHM
Behaviour & Society (beyond technology choices)		
	Implicit in econometric equations or consumption function	EDM, E3ME, HMRC, NTM
	Exogenous, but potentially price elastic, energy service demands	UKTM, ESME
	Exogenous behavioural options for energy demand reductions (e.g. reduced hot water use)	NISMOD, NDBM, NHM
	No representation of behaviour and society beyond technology choices	ENUSIM, IPM, GDH, EDR
Economy		
	Endogenous calculation of economic variables with two-way interactions between energy system and economy	E3ME, HMRC
	Exogenous projections of economic variables included in the model, but no feedback from energy system to economy	EDM, NIS, NTM, ENUSIM
	Economic drivers are implicit in off-model calculations of energy service demands	UKTM, ESME, IPM, NDBM
	No representation of the economy	NHM, GDH, EDR

Secondly, there are models that model the uptake of a few specific technologies but not the energy system as a whole. The Green Deal Household Model and the EDR Take-up Model were developed to model explicitly the uptake behaviour for technologies in the residential heating and commercial electricity saving sectors respectively. These models calculate the probability that specific technological options are taken up under different circumstances, especially different subsidy and financing regimes. In addition the E3ME stands out by employing technology diffusion models for the areas of the domestic heating and personal road transport. These bottom-up models are not based on cost-optimisation, instead they endogenously model the technology choices of consumers using discrete choice theory. The approach considers that consumers are heterogeneous, that they only have limited information on the available options and that they are more likely to buy technologies that are already visible and wide-spread (Knobloch et al. 2018; Mercure et al. 2018).

Finally, there exists a group of models for which the choice of technologies is determined completely by the model user. This includes both the choice of technologies that are employed, as well as their uptake path (usually S-curves). This group is the largest group and includes the NISMOD model, the BEIS Industrial Pathway Model and the National Household Model. These models effectively serve as tools with which modellers can explore different technological combinations, without any endogenous processes in the model influencing the uptake of the different technologies. The ENUSIM model sits somewhere in the middle between the last two groups. The model initiates the up-take of technologies when they become cost-effective, but the path of technology up-take follows a pre-specified logistic uptake curves.

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4.6 Economy

4.7 The last driver of energy demand in our conceptual framework is related to economic developments in the UK. This refers especially to the macroeconomic changes in the UK, both with regard to the level of aggregate GDP as well as the composition of the economy. These two factors, economic growth and structure, are important determinants of energy demand in almost all of the models (Behaviour and social norms

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). The only exceptions include the National Household Model, which is solely focused on residential energy use, or the two policy-specific models which do not produce general projections of energy demand and are therefore less concerned with macroeconomic projections.

Only the E3ME model and the HMRC environmental CGE model produce endogenous projections of GDP at an aggregate and sector level and can therefore incorporate some two-way interactions between the economy and the energy system. They rely on two different forms of macroeconomic modelling. The E3ME model is based on a macroeconometric approach, in which future GDP, investment and consumption and other economic variables are projected forward based on econometric equations derived from historical observations. The HMRC environmental CGE model is based on a general equilibrium framework and can be used to assess changes in the equilibrium state of the economy that result from changes in energy prices or efficiency. In all other models, macroeconomic drivers are included as exogenous variables, so the models cannot model potential feedbacks from changes in the energy system into the economy. In some of the models, these exogenous projections are directly included, e.g. NISMOD, while in others they are used in the off-model calculations performed to produce exogenous energy service demands (e.g. UK TIMES).

The way that macroeconomic drivers are incorporated in the models depends strongly on the different sectors. In the transport sector, aggregate income or GDP is often used as an important driver for personal transport demand. This relationship is implemented directly in NISMOD or the BEIS EDM, whereas in the National Transport Model income is an important predictor of car ownership. For freight transport, several models specifically use an index of manufacturing output rather than total GDP (e.g. BEIS EDM, National Transport Model).

In the domestic sector, the importance of macroeconomic drivers varies. In the models featuring a more aggregated representation of the domestic sector, GDP and household income play an important role in the determination of energy demand (e.g. BEIS EDM, E3ME). However, in the models that start from a more detailed representation of the housing stock and specific technologies, income is less important for determining the demands for energy (e.g. National Household Model).

In industry and other economic sectors, it is sector-specific economic output that is a key driver of energy service demands. These are often already disaggregated by sectors when included in the model. In the BEIS EDM, only aggregate GDP is exogenous and the growth rates for different economic sectors are derived from data on aggregate GDP using econometric equations. In some models the relationship between economic output and demand for energy services is assumed to be directly proportional (e.g. ENUSIM) while in others the relationship can be mediated by other factors, such as energy prices (e.g. E3ME, BEIS EDM). In some models the commercial and public service sectors are treated somewhat differently, in the sense that not economic output but other variables are used as drivers of energy service demands. Examples of this are public sector employment in the BEIS EDM or service sector floor space in ESME.

The exogenous nature of economic drivers has two important implications for the exploration of low-energy or carbon scenarios. Firstly, all the results obtained for the scenarios are strongly dependant on the exogenous economic projections used. It is therefore important to assess which economic projections are used and the uncertainties associated with them. The key source for future projections of GDP used by government is the Office for Budget Responsibility (OBR). GDP projections from the OBR are used in the Energy and Emissions Projections (BEIS 2018b), the Road Traffic Forecast, the Clean Growth Strategy (HM Government 2017b) and the interim National Infrastructure Assessment (NIC 2017). Using the same economic forecasts has the advantage that the simulations are more comparable across the different models and publications. However, it also means that the OBR forecasts have a very strong impact on most energy projections in UK policy making. To assess the uncertainty, all of the publications cited above also implement scenarios that vary the level of GDP growth from the OBR's central forecast. While policy documents in which the models are applied usually provide some information on the exogenous drivers included in the models, the level of detail varies. For example, the Clean Growth Strategy does not provide any details on the drivers used in its UK TIMES scenarios.

Secondly, the models cannot implement any feedbacks to the economy that arise from any energy saving measures. For example, there is some evidence that macroeconomic rebound effects could limit the impact of energy efficiency improvements on energy consumption because energy efficiency improvements might stimulate aggregate economic growth (Barker et al. 2009; Brockway et al. 2017) or because efficiency improvements in one part of the economy might reduce overall energy prices and hence increase energy use in other parts of the economy (Hanley et al. 2009). Another example of feedbacks from energy policies to the economy could be the impact of a transition to electric cars on the UK automotive industry.

As discussed in sections 4.4 and 4.5 energy prices only influence behaviour and hence energy demand in some of the models. Market prices for globally traded energy carriers (e.g. coal, oil and gas) are usually exogenous in most models. A key source for these prices are the BEIS fossil fuel price scenarios which are produced by BEIS each year. Although information on the sources of price data is rarely provided, it is likely that most of the energy modelling in policy development relies on these fuel price scenarios, with similar ramifications as discussed for GDP projections. An exception is the E3ME model which calculates fuel prices endogenously based on a representation of global markets and cost-supply curves. Several of the models are able to endogenously calculate the prices of other derived energy carriers, e.g. electricity, for consumers, using the information on technology costs included in the model. For example, UK TIMES calculates shadow prices – the marginal cost of increasing the production of an energy carrier by a unit and the BEIS EDM includes a sub-model that projects retail fuel prices econometrically.

5 Demand-side policy goals and instruments

Based on the results of our analysis presented in the preceding sections, we discuss how well the models can assess the range of contributions that demand-side energy policy can bring to climate change mitigation. The discussion is structured around the three categories of demand-side energy policy goals identified in section 2.1, namely increasing responsiveness and flexibility of demand, increasing the technical efficiency of converting final energy into energy services and reducing or transforming energy service demands.

5.1 Increasing responsiveness and flexibility of energy demand

The first goal refers to a shift of energy use in time or increased flexibility in the timing of energy use so that the demand peak can be reduced or the pattern of energy demand across a day matched more closely to energy supply. This flexibility goal is most relevant for electricity and heat consumption and therefore not applicable to all the models we analysed. It is arguably also becoming more important, due to the increasing share of electricity supplied from variable (across different timescales) renewables, such as solar photovoltaics (PV) and wind.

The models that include electricity and heat demands generally include some way of representing their diurnal and seasonal fluctuations. For example, the NISMOD energy model contains an explicit peak demand module and the ESME and UK TIMES models divide energy use into different time slices for different seasons and different times of the day (Table 10). These models therefore need to ensure that not only is the demand for electricity and heat met on an annual basis, but also on shorter time periods – often of only a few hours duration at a particular time of day. They also often explicitly model peak electricity and heat demand so ensuring that sufficient supply capacity is built to meet the maximum demand in a year. They could also in principle capture changes in the demand profile due to the changing use of a particular energy carrier over time (e.g. the greater use of electricity to meet space heating demands).

However, while ESME and UK TIMES represent diurnal variations to some degree, they still face two important limitations. Firstly, the temporal resolution is still quite coarse and the time slices relatively long. This means that the need to meet short-term fluctuations in demand is not recognised in the models. For example they cannot explore whether particular scenarios are able to match supply and demand every half-hour, potentially underestimating the need for electricity and heat storage to help balance supply and demand (e.g. in response to short-term fluctuations in PV and wind output). Incorporating more granular time slices into system optimisation models is possible to some extent, but makes the models considerably more computationally expensive. Alternatively, the effect of high-resolution temporal variations in electricity demand and supply can be explored by linking the system optimisation models to electricity sector models designed to explore more granular time slices, for example as done by Deane et al. (2012).

Secondly, the time profile of energy service demands and resulting electricity demands is generally specified exogenously, rather than responding endogenously to price signals within the model. The models can therefore explore the impacts that shifts of energy demand in time would have on the upstream supply and network infrastructure by varying the demand profiles under different scenarios. However, it is not obvious from the various policy documents that such scenario variations are often used and the low temporal resolution of the time slices also allows on limited insights.

What the models are less able to capture is the dynamic response of demand to changes in the availability or price of energy supply over the course of a day or year. The result is that they are more likely to build additional firm supply capacity to ensure that demand is met, rather than exploring how demand-side management options might be able to achieve a similar effect without the need for new supply capacity. However, recently there have been attempts to capture some of these dynamic effect by incorporating demand-side response functions into energy system models (e.g. Li & Pye 2018) or sector-specific models (e.g. Strbac et al. 2018). Nevertheless, the use of such approaches to support policy is currently not that common.

Table 10: Treatment of within-year variation of energy demand in models that feature an explicit representation of peak demand or within-year variation.

Model	Time resolution	Sectors where time resolution is applied	Variation of energy demand
UK TIMES	16 time slices from a combination of 4 seasonal time slices (Winter, Spring, Summer, Autumn) 4 diurnal time slices (Night, Day, Evening peak, Late evening) Includes a commodity peaking constraint that ensures that the installed capacity can meet the peak demand in each time slice. Variations at lower time scales are approximated by reserve capacity margins for energy supply technologies	Electricity and heat use diurnal time slices Natural gas and hydrogen use seasonal time slices	Exogenous time profile for relevant energy service variables
ESME	10 time slices from a combination of 2 seasonal time slices (Summer, Winter) 5 diurnal time slices (Morning, Mid-day, Early evening, Late evening, Overnight) Representation of explicit peak demand (electricity and heat) that the system needs to be able to meet. Peak demands are calculated using historical ratios between typical demand and peak demand. Variations at lower time scales are approximated by reserve capacity margins and flexibility parameters for energy supply technologies	Not sufficient information	Exogenous time profile for relevant energy service variables
NISMOD	Specific peak demand model that estimates an annual figure for peak demand. Annual peak demand figures are then disaggregated to spatial, seasonal and diurnal levels according to historical profiles and then feed into energy supply model. Energy supply model features capacity margins for different technologies.	Peak demand is only calculated for electricity and gas	Business-as-usual annual peak loads are based on historical relationships between total and peak demand. This can be modified through the estimated impact of different transition options (e.g. electric vehicles) which are imposed exogenously.

5.2 Increasing technological efficiency

5.2.1 Representing the potential of energy efficiency technologies

The second goal is the improvement in the technical efficiency of converting final to useful energy and to energy services. As discussed in section 4.4.1, the level of technological detail is a major strength for many of the models we analysed and most of them are well suited to explore the potential of technological energy efficiency measures that can reduce the final energy needed to produce energy services. Although the level of detail varies, most of the models contain considerable amounts of information on a large number of potential technological options, including their potential for energy savings as well as their cost. ESME considers around 250 technologies, including, for example, several technologies that can satisfy the need for space heating, including biomass boilers, different kinds of heat pumps district heating and more. Overall, the modelling landscape therefore contains helpful tools to explore a variety of potential technological pathways and compare them with regard to different criteria, such as energy and carbon savings or costs.

Some of the more recently developed models do not contain endogenous processes to determine which technologies are employed. Instead they rely on frameworks in which the combinations of technologies and their deployment paths are completely specified by the model user. This applies to NISMOD, the BEIS Industry Pathways Model, the National Household Model and the BEIS Non-domestic Building Model. Such a flexible framework possibly means that the application of the model for identifying and choosing energy transition pathways is more difficult, as the possible number of combinations and pathways is likely to be large. However, such models have the advantage that they make it easier to consider non-cost criteria in the development of low-carbon scenarios. Although system-optimisation models can be somewhat constraint to represent other concerns, cost is, by definition, the main criterion for choosing technology pathways in system-optimisation models. In reality, however, the choice of a viable low-carbon pathway is a political choice that needs to consider a whole range of concerns that go beyond monetary costs, including, for example issues of public acceptance. A flexible modelling framework that is not bound by cost optimisation might be better able to facilitate the discussion of such non-cost concerns and their impacts on possible low-carbon scenarios. However, an important pre-requisite is that criteria used by modellers to choose specific pathways needs to be made transparent and explicit.

5.2.2 Modelling technological change

While the models are well suited to explore different potential technological pathways, they are less able to assess how technological change happens. There is effectively a trade-off between the flexibility for model users to specify technologies and the ability of models to represent endogenous processes of technological change. If the technological pathways are completely specified exogenously, as discussed in the previous section, they do not give any insights into the processes that could make the different pathways happen. This means that most of the models are not well suited to assess how policy instruments can affect technological change.

The only exception to this are regulatory instruments, especially technology standards. If it is assumed that compliance with the standards can be achieved, such changes can probably be represented quite easily. For example, technologies can be excluded (e.g. a ban of internal combustion engines after year X) or mandatory (e.g. double glazed windows in all houses by year X).

However, beyond simple regulations, only very few of the models endogenously model the uptake and diffusion of specific technologies. In the system-optimisation models, such as UK TIMES and ESME the technology pathways are chosen by optimising the whole system according to the sole criteria of cost. This approach does not consider many factors that shape technological uptake and diffusion, such as imperfect information, preferences and social norms, and these models are therefore not good predictors of real technological change (Mercure et al. 2018; Trutnevyte 2016). In response to such limitations there exist several examples of academic research that try to incorporate an improved representation of technological learning and diffusion into system optimisation models. Examples include the incorporation of household preference constraints on the choice of technologies (Li et al. 2018), the endogenisation of technology learning through the introduction of learning curves (Huang et al. 2017) or linking system-optimisation models to technology diffusion models (Barreto & Kemp 2008).

Of the models we analysed only the bottom-up models on heating and transport in E3ME explicitly model technology diffusion in a similar fashion as diffusion models developed in the literature (Knobloch et al. 2018; Mercure et al. 2018). In addition the Green Deal Household Model and the EDR model estimate the likelihood that specific end-use technologies are adopted by energy users. These models are therefore able to represent a wider set of policies. For example, the Green Deal Household Model was developed to specifically estimate the impact of the Green Deal policy on the uptake of different insulation measures in homes. The Cambridge Econometrics technology-diffusion model for passenger transport can represent the impact of policy measures on the composition of the vehicle fleet and emissions, including measures such as the introduction of electric vehicles in new markets and aggressive taxation in line with rated emissions (Mercure et al. 2018).

The development and diffusion of new technologies undoubtedly forms a crucial part of the low-carbon transition and hence it will be vital to gain further understandings of such dynamics can be integrated into energy models. A large body of literature exists on the topic of technology development and diffusion (Barreto & Kemp 2008) and socio-technical transitions (Geels et al. 2016). Although not all insights from these literatures lend themselves to a translation into quantitative models, there is potential to develop a more realistic representation of technology diffusion and wider socio-technical transitions in energy models (Holtz et al. 2015; Li et al. 2015). For example Li & Strachan (2017) present a dynamic simulation model of technology diffusion and energy use which contains multiple types of actors and is based on the multi-level perspective. However, such efforts to integrate technology diffusion and socio-technical transitions into energy models are so far restricted to interesting examples in the academic literature but are not widely used to inform the policy documents we analysed in this study. Therefore we consider it an important research endeavour to bring together the research on technology diffusion with the energy models that are used to energy policy in the UK.

5.3 Reducing or transforming energy services

Compared to the technological detail in many of the models, demand-side energy policies that are not related to technological improvement of energy efficiency, are represented only very sparsely. These are demand-side energy policies that achieve reductions in energy demand by changing the economic, behavioural and social drivers of energy demand to reduce or transform the utilisation of energy services. This can range from modal shifts in transport through to urban densification and the use of less energy-intensive construction materials. For convenience we will refer to such policies in the following as non-technological demand-side policies. In the models we analysed in this study such policies are not well represented. There are a number of major short-comings that can be identified. Firstly, the potential contribution of non-technological demand-side policies is often invisible and they are not considered as potential levers for climate change mitigation. Secondly, in most models the representation of economic, social and behavioural processes is limited which inhibits the analysis of how specific policy instruments can influence such processes to reduce energy demand. Thirdly, there is very little consideration in the models about the interactions between different drivers of energy demand and their implications for the low-carbon transition.

5.3.1 The potential of non-technological demand-side policies

As discussed in section 4, the economic, social and behavioural drivers of energy demand are often supplied to the model exogenously and/or hidden in econometric equations. As a result neither the economic, social and behavioural assumptions underlying the projections nor the potential energy demand reductions from non-technological demand-side policies are clearly visible.

However, this does not necessarily have to be the case. While it is difficult to quantitatively model many economic, social and behavioural changes, demonstrating the potential energy demand reductions that would arise from such changes is easier to do, even in existing models. As discussed in section 4.3, many of the models we analysed serve as tools to put together technological options that allow the envisioning of alternative technological futures. This can similarly be applied to non-technological demand-side policies. To make the potential of non-technological demand-side energy policies more visible, these policies would have to be translated into changes in the exogenous variables, i.e. energy services or socio-economic drivers. For example, a modal shift in transport would change the relative demand for passenger kilometres of different modes, or reductions in internal temperatures reduce the demand for heating. This is not necessarily easy and might require new research, as some demand-side policies might affect a range of energy service demands (e.g. a dietary change might mean less demand for transport as well as structural changes in economic output).

However, this challenge does not seem insurmountable and it would make the potential reductions from the non-technological energy reductions more visible. To a certain extent the impact of changes in non-technological demand drivers are already explored in the application of the models, namely to assess the uncertainties of model projections with regard to the assumptions on socio-economic drivers. However, the difference is that such non-technological changes are considered as sources of uncertainty in projections, but not as levers for reducing energy demand and carbon emissions. For example in the Road Traffic Forecasts (DfT 2018) assumptions on GDP growth as well as its relationship to car ownership are varied to assess uncertainty in projections. However, reductions in car ownership and travel demand, let alone GDP, are not considered potential options for reducing energy demand.

A fruitful research endeavour would therefore be to try to integrate non-technological demand-side changes as potential options for reducing energy demand into the models, by adding explicit levers that allow for changes in the economic, social and behavioural assumptions. The difficulty of integrating such non-technological demand-side policies into the models depends on the type of model. It is most straightforward in those models that already rely on the user to exogenously specify the uptake of different technological options, such as NISMOD or the National Household Model. In such models, specific options to reduce or change energy service demands could be added to the technological options the models already have. In fact, these models already feature some non-technological options. For example NISMOD features an option to reduce hot water use in homes and the National Household Model allows for the change in heating schedules. However, these non-technological options are still far outnumbered by technological energy efficiency options. Interestingly, they are also largely restricted to energy use in buildings.

In models that feature more endogenous processes for projecting energy demand, integrating non-technological demand-side options is likely to be more difficult. Cost-optimisation models, such as UK TIMES and ESME can only include options in the optimisation process which can be assigned a cost. For example modal shifts in transport can be included by making the energy demands for different transport modes responsive to their prices (e.g. Pye & Daly 2015; Salvucci et al. 2018). However, finding a meaningful cost estimate might be impossible for many non-technological demand-side options. Nevertheless cost-optimisation models could still be used to explore non-technical demand-side options by changing the exogenous energy service demands going into the model. For example, they could determine how a reduction in indoor temperatures would impact the technological cost necessary for meeting the UK's carbon targets.

Econometric models might face similar challenges to the exploration of non-technical demand-side options. The BEIS EDM is generally not used to model low-carbon scenarios, so this challenge is largely applicable to the E3ME model and the National Transport Model. These models feature a high level of endogeneity of the processes that determine energy demand. This has the advantage that the models can assess the potential effect of some policy instruments, such as a carbon tax, because they explicitly model the processes through which such a policy instrument would impact behaviour and technological change. However, this also makes it more difficult to explore the potential for non-technological demand-side options, if the economic and social processes relevant to these options are not explicitly represented in the model and are instead implicit in econometric equations. For example in BEIS EDM the relationship between income and electricity consumption is governed by econometric equations. A change in social norms leading to a shift towards less energy-intensive products which deviates from the historic relationship would therefore require an estimate of how the econometric equation would change.

5.3.2 Modelling policy instruments for non-technological change

While we certainly consider it possible to demonstrate the potential contributions of non-technological demand-side policies, it is much more difficult to model how specific policy instruments can contribute to achieving the desired changes. To do so would require a realistic representation of the economic, social and behavioural processes that influence energy demand. The representation of such processes is very limited in most models, but some representations exist.

In terms of processes influencing non-technological demand-side changes, price mechanisms are the ones that are most often represented in the models explicitly. As discussed in section 4.5 there are five models in which the demand for energy services or final energy is directly influenced by the price of energy. For example, fuel costs are an important factor in determining model choice in the National Transport Model. In both the BEIS EDM and the E3ME model energy prices play a prominent role in the econometric equations determining energy demand across sectors. As a result, such models can estimate the impact that price-based policies, such as a carbon tax, can have on the consumption of energy. However, these models only represent price-based changes in the behaviour that is directly related to energy consumption. Only the two economic models, the E3ME model and the HMRC environmental CGE model, also estimate the wider effects of price-based policies on energy demand. In these models changes in energy prices lead to shifts in the relative prices of different products which changes consumption patterns, the structure of the economy and therefore energy consumption.

However, prices are only one aspect of the many interacting economic, social and behavioural factors that shape behaviours and energy consumptions (Geels et al. 2016; Holtz et al. 2015). Non-price policies, such as information campaigns and voluntary agreements are expected to play an important part in achieving many of the changes that non-technological demand-side policies envisage (Dietz et al. 2009). However, such policies and the processes through which they act are generally not represented in the models. There exists research and knowledge on how economic, social and behavioural aspects shape energy demand which can provide insights into how to achieve such changes (e.g. Geels et al. 2018; Shove 2010; Stern et al. 2016). A full review of this literature is outside the scope of this study, but it is likely that many of these processes might not lend themselves to a helpful representation in a quantitative model. In addition many of the proposed non-technological demand-side options envision changes that are not currently considered to be part of the energy system. For example shifts to low-carbon materials in production and construction, dietary changes towards more local and plant-based foods or an increase in teleworking are not typically seen as the realm of energy policy and are generally outside the scope of the energy models analysed in this study.

The analysis of the full range of demand-side energy policies therefore requires a broadening of the scope of what is currently considered energy modelling. However, we consider that the creation of large and complex models that try to represent many economic, behavioural, social and technological aspects of energy demand may not be helpful, as such models will be very difficult to interpret. Instead we envision that there will be different ways in how a broadening of scope can be achieved, depending on the specific policy and social process that is considered. While some aspects can be integrated into existing models, others might require the development of new models, and some might not be modelled at all. The challenge is to usefully integrate our understanding of social, economic and behavioural processes to be able to take full advantage of the potential that demand-side energy policies can bring to climate change mitigation.

5.3.3 Considering interactions between drivers

Finally we want to highlight an important area that is currently not well understood and not well represented in the models, that is, the interactions between different demand drivers. Firstly, the models are generally built around a one-directional conceptualisation of energy demand, from socio-economic drivers, to energy services to final energy demand. Therefore they do not feature feedbacks, for example from energy services back to socio-economic drivers. The only exceptions are the economic models, such as the E3ME model and the HMRC environmental CGE model. In these models changes in the energy system can feed back into the economic system, for example in the fuel consumption by households is directly linked to the economic output of the fuel-producing sectors.

Secondly, there are interactions between drivers of energy demand. For example a significant modal shift from private cars to public transport would have implications for the output and hence energy use in the car-producing industry. In most models, however, the energy service demands in different sectors are treated separately without any interactions. While this is a reasonable assumption when small changes are considered, such interactions will be important for the large and rapid changes in energy use and carbon emissions that will be required to achieve the UK climate change target of 80% reduction in GHG emissions by 2050, and any more stringent UK targets derived from the Paris agreement.

Currently such interactions are not represented in the models. For example the different exogenous energy service demands driving UK TIMES and ESME are often developed using a range of different sources which are not necessarily consistent. Gaining a better understanding of these interactions is absolutely crucial for developing consistent and realistic pathways for reducing energy demand and carbon emissions and for producing effective energy and climate policy. Understanding these interactions is also important because they present the direct links between energy and climate policy and other policy areas. For example it is important to understand how the economic changes that are pursued as part of the UK Industrial Strategy (UK Government 2017) might impact the energy systems and any efforts to reduce carbon emissions (Ross et al. 2018). While understanding such interactions is important for all kinds of demand-side energy policy, it is most pressing in the area of non-technical demand-side policies, because these policies might require interventions in areas that are currently not considered to be part of the energy system, such as food consumption, work patterns or material use.

6 Conclusion

There is growing evidence that demand-side energy policies can make significant contributions to climate change mitigation. In our study, we identify thirteen core energy models cited in energy policy documents published by the UK government between 2007 and 2017. The first group are models that cover the whole energy system, using econometric-based approaches (e.g. BEIS Energy Demand Model), and which are generally employed to produce baseline forecasts of energy demand. The second group are system-optimisation models (e.g. UK TIMES), which cover the whole energy system and employ cost-optimisation approaches to explore viable long-term scenarios for climate change mitigation. The third group are economic models, such as the HMRC environmental CGE model, which are used to assess the economic impacts of climate change mitigation scenarios. The fourth group consists of a range of models covering specific sectors, such as the National Transport Model or the National Household Model. These sector-specific models are used to identify and compare specific policy options in their respective sectors for the short and medium terms, for example feeding into the development of marginal abatement cost curves. Finally there are a group of models that were developed to investigate the feasibility or impact of specific policy instruments (e.g. the Green Deal Household Model).

We analyse these models and discuss how well they represent the full diversity of demand-side energy policies. Our analysis reveals some key strengths as well as short-comings in the model landscape. A key strength lies in the high level of technological detail that many models provide. These models are helpful for envisioning and comparing realistic and internally consistent technological pathways for increasing the technological efficiency with which we provide energy services.

However, the model landscape also shows some important short-comings. Firstly, non-technological energy policies, such as behavioural and economic changes, are considered very sparsely. Social, economic and behavioural processes are often exogenous and hidden in underlying or input assumptions. In addition, changes in these processes are not explicitly presented as levers for reducing energy use and carbon emissions. This means that the current modelling landscape forecloses many demand-side policy options that could make an important contribution to climate change mitigation and should therefore be part of the discussions concerning the pathways to meet the UK's carbon targets.

Secondly, while the models do well in exploring the range of potential technological pathways, they often do not feature a realistic process of how technological change happens. Processes of economic, social and behavioural change related to non-technological demand-side policies are even less well represented, especially if they go beyond price mechanisms. While some of the models represent some of these processes, these efforts are few and far between. However, a good understanding of such processes is important for developing effective policy instruments to achieve demand-sided energy policy goals.

Not all demand-side policies lend themselves to a representation in formal models. Utilising the full potential that demand-side policies can bring to the reduction in energy demand therefore needs to be informed by insights gained both from models as well as other forms of enquiry. Nevertheless, there is still considerable scope for energy models to provide better representations of demand-side energy policies, especially with regard to non-technological aspects. The academic literature contains some promising attempts of incorporating more realistic representations of social and behavioural processes in energy models. However, these are not currently used widely to inform policy development and require further improvements. Based on our review, we have identified a number of important pathways to help improve the representation of demand-side energy policies in energy models:

1. **Develop consistent and transparent processes for estimating exogenous inputs into energy models, such as energy service demands and socio-economic drivers**. All the models rely on various exogenous inputs to calculate energy demand. While some models start from socio-economic drivers (e.g. population, income, GDP), others include exogenous projections of energy services (e.g. passenger-kms). In addition all the models feature important technological assumptions, such as marginal abatement costs and uptake rates. These inputs are important determinants of energy demand calculations in the energy models. However, there is very little consistency in the methods used and the data sources and assumptions are often not published in detail. The development of a transparent framework for developing and publishing these model inputs would be very helpful for highlighting the importance of exogenous inputs in determining energy demand as well as the potential that changes in these exogenous inputs could have for reducing energy demand.
2. **Quantify the potential of demand-side policies and include them in models** There is a need for more research quantifying the mitigation potential and costs of non-technological demand-side solutions, for example teleworking, and for them to be included as mitigation options in the models. This way models could be used to envisage different low-carbon pathways by examining the combined impact of demand-side options that are both technological and non-technological. In a similar way to some of the current energy models, these models would not need to represent the processes of change, but would focus on the potential energy demand reductions that these changes could achieve. Such an approach is not without challenges as estimates of potential energy savings from different behavioural options depend on the context of other measures that are applied and are not easily transferred between models. Nevertheless, there is scope for some fruitful research that extends existing energy models with explicit non-technological options.
3. **Integrate economic, social and behavioural processes into energy models where feasible and useful**. There is ongoing research on how economic, social and behavioural processes influence energy demand and how they could be changed by policy to reduce energy demand and carbon emissions. Insights from this research should be reflected in energy models where this is feasible and useful. There exist some attempts to represent social and behavioural processes in energy models. For example through the incorporation of technology learning and consumer preferences in system-optimisation models or through the development of new models. However, such attempts are currently not widely applied in policy development. For those social and behavioural aspects that are difficult to represent in quantitative models, other ways of synthesising the insights from technology models and social science research should be developed to make the latter more visible outside the models.
4. **Research the potential implications of interactions between different drivers of energy demand.** Interactions between different drivers of energy demand will play an important role but are very little researched. An example of such an interaction would be the impact that a modal shift from cars to cycling would have on the growth and

energy demand of the automotive industry. Research on such interactions is limited, so this work could start with a systematic review to identify interactions between energy demand drivers that are likely to be important for the transition to a low-carbon society. When more knowledge is available such feedbacks could be explored by integrating them into models, building new models focused on these interactions, or by empirical research alongside modelling.

The analysis shows that the current landscape of energy models features a range of very different models that are used to answer different questions. We envisage that this will similarly be the case for future research that addresses these new questions. It will involve adaptions of existing models as well as the development of new models focusing specifically on non-technical parts of the energy system. In addition many of the economic, social and behavioural processes that are relevant for climate change mitigation cannot be usefully represented in quantitative models, but can be investigated using other research. The academic literature already offers growing insights on the social and behavioural drivers of energy use, as well as some promising attempts at incorporating such drivers into energy models. The challenge for realising the full potential of demand-side options for climate change mitigation is to effectively combine the different forms of knowledge that are required to understand how the different forms of demand-side policies could work, especially with regard to non-technological aspects.

Acknowledgements

We want to thank Kate Sambrook and Izzy Cotton, who worked as internship students at the University of Leeds in 2017, for their contributions to the policy analysis conducted in this report.

The works completed in this project and the preparation of this report was supported by a group of expert advisors, who were asked to comment on the scope of the project and review draft outputs. We want to thank all the members of the expert group for bringing their experience and perspectives to this project. The group of expert advisors included:

Ruth Curran, Department for Business, Energy and Industrial Strategy

Jason Chilvers, University of East Anglia

Nick Eyre, University of Oxford

Federica Odifreddi/Bianca Letti, National Infrastructure Commission

Sarah Livermore, Committee on Climate Change

Hector Pollitt, Cambridge Econometrics

Steve Pye, University College London

Steve Sorrell, University of Sussex

Jim Watson, UKERC and University College London

References

AEA Energy & Environment, ECOFYS & Consortium, T.C., 2008. Review and update of UK abatement costs curves for the industrial, domestic and non-domestic sectors RM4851. *Final report to the Committee on Climate Change*. Available at: https://www.theccc.org.uk/publication/building-a-low-carbon-economy-the-uks-contribution-to-tackling-climate-change-2/macc-energy-end-use-final-report-v3-2/.

Anderson, K., Le Quéré, C. & McLachlan, C., 2014. Radical emission reductions: The role of demand reductions in accelerating full decarbonization. *Carbon Management*, 5(4), pp.321–323.

Arup, 2017. *UK Legislation Timeline: Emisssions, Energy, Efficiency* 10th ed., Available at: https://www.arup.com/publications/promotional-materials/section/uk-energy-legislation-timeline.

Barker, T., Dagoumas, A. & Rubin, J., 2009. The macroeconomic rebound effect and the world economy. *Energy Efficiency*, 2, pp.411–427.

Barreto, L. & Kemp, R., 2008. Inclusion of technology diffusion in energy-systems models: some gaps and needs. *Journal of Cleaner Production*, 16(1 SUPPL. 1), pp.95–101.

BEIS, 2016a. Domestic Heating Replacement Regulations. *IA No: BEIS028(C)-16-HB*, pp.1–42.

BEIS, 2018a. Final UK greenhouse gas emissions national statistics: 1990-2016. Available at: https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-2016.

BEIS, 2016b. Smart Meter Roll-Out Cost-Benefit Analysis. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/567168/OFFSEN_2016_smart_meters_cost-benefit-update_Part_II_FINAL_VERSION.PDF.

BEIS, 2016c. The Renewable Heat Incentive: A reformed and refocused scheme. *IA No: BEIS032(F)-16-RH*.

BEIS, 2018b. Updated energy and emissions projections 2017. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/671187/Updated_energy_and_emissions_projections_2017.pdf.

BERR, 2008. Impact Assessment of the Government's White Paper on Nuclear Power. , pp.1–19.

Böhringer, C. & Rutherford, T.F., 2013. CGE Peer Review of Environmental Extension. Available at: https://data.gov.uk/data/contracts-finder-archive/download/1482217/d7d41ccb-ce3d-4948-b763-414e5c88b199.

Brockway, P.E. et al., 2014. Divergence of trends in US and UK Aggregate Exergy Efficiencies 1960-2010. *Environmental Science & Technology*, 48, pp.9874–9881.

Brockway, P.E. et al., 2017. Energy rebound as threat to a low-carbon future: Results and implications from an exergy-based UK-US-China empirical study. *Energies*, 10(51).

Butler, C., Parkhill, K.A. & Luzecka, P., 2017. Rethinking energy demand governance: Exploring impact beyond "energy" policy. *Energy Research and Social Science*, 36, pp.70–78. Available at: http://dx.doi.org/10.1016/j.erss.2017.11.011.

Cambridge Econometrics, 2014. *E3ME Technical Manual , Version 6.0*, Cambridge: Cambridge Econometrics. Available at: http://www.camecon.com/EnergyEnvironment/EnergyEnvironmentEurope/ModellingCapability/E3ME/E3MEManual.aspx.

CCC, 2008. *Building a low-carbon economy - the UK's contribution to tackling climate change*, Available at: www.tsoshop.co.uk.

CCC, 2015. The Fifth Carbon Budget: The next step towards a low-carbon economy.

CCC, 2010. The Fourth Carbon Budget: Reducing emissions through the 2020s.

Collins, A. et al., 2015. *The Production of Quick Scoping Reviews and Rapid Evidence Assessments: A How to Guide*, DEFRA, Joint Water Evidence Group. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/560521/Production_of_quick_scoping_reviews_and_rapid_evidence_assessments.pdf.

Creutzig, F. et al., 2016. Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. *Annual Review of Environment and Resources*, 41(1), pp.173–198. Available at: http://www.annualreviews.org/doi/10.1146/annurev-environ-110615-085428.

Creutzig, F. et al., 2018. Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, 8(4), pp.268–271.

Cullen, J.M., Allwood, J.M. & Borgstein, E.H., 2011. Reducing Energy Demand: What Are the Practical Limits? *Environmental Science & Technology*, 45(4), pp.1711–1718. Available at: http://dx.doi.org/10.1021/es102641n%5Cnfiles/733/es102641n.html.

Dagoumas, A.S. & Barker, T.S., 2010. Pathways to a low-carbon economy for the UK with the macro-econometric E3MG model. *Energy Policy*, 38(6), pp.3067–3077. Available at: http://dx.doi.org/10.1016/j.enpol.2010.01.047.

Daly, H.E. & Fais, B., 2014. UK Times Model Overview. *UCL Energy Institute*. Available at: https://www.ucl.ac.uk/drupal/site_energy-models/sites/energy-models/files/uk-times-overview.pdf.

Deane, J.P. et al., 2012. Soft-linking of a power systems model to an energy systems model. *Energy*, 42(1), pp.303–312. Available at: http://dx.doi.org/10.1016/j.energy.2012.03.052.

DECC, 2013a. Electricity Demand Reduction - Amendment to Capacity Market Clauses. *IA No: DECC0133*.

DECC, 2013b. Electricity Market Reform – ensuring electricity security of supply and promoting investment in low-carbon generation [update: May 2013] IA. *IA No: DECC0130*, pp.1–88.

DECC, 2014a. Energy Saving Opportunity Scheme. *IA No: DECC0142*, pp.1–42.

DECC, 2012a. Final Stage Impact Assessment for the Green Deal and Energy Company Obligation. *IA No: DECC0072*.

DECC, 2012b. *Gas Generation Strategy*, Available at: http://www.decc.gov.uk/en/content/cms/meeting_energy/oil_gas/gasgenstrat/gasgenstrat.aspx.

DECC, 2011a. Green Deal Household Model Assumptions Document. *Report to DECC by elementenergy*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachme nt_data/file/43021/3592-green-deal-household-model-assumptions.pdf.

DECC, 2016. Impact Assessment for the level of the fifth carbon budget. *IA No: DECC0231*, pp.1–97.

DECC, 2009. Impact Assessment of the Climate Change Act. , pp.1–103. Available at: http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf.

DECC, 2015. Periodic Review of FITs 2015. *IA No: DECC0196*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/486084/IA_-_FITs_consultation_response_with_Annexes_-_FINAL_SIGNED.pdf.

DECC, 2011b. *Planning our electric future: a White Paper for secure, affordable and low-carbon electricity*, Available at: http://www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/emr_wp_2011.aspx%5Cnhttp://linkinghub.elsevier.com/retrieve/pii/S0264410X12014399.

DECC, 2011c. Proposals on the future of Climate Change Agreements. *IA No: DECC0040*, pp.1–42.

DECC, 2013c. RHI Tariff Review, Scheme Extensions and Budget Management. *IA No: DECC0153*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263581/Impact_Assessment_RHI_Tariff_Review_Extensions_and_Budget_Management_Dec_2013.pdf.

DECC, 2013d. Simplification options for the CRC Energy Efficiency scheme to help business : CRC (Amendment) Order 2013. *IA No: DECC0066*, pp.1–61.

DECC, 2011d. Smart meter rollout for the small and medium non-domestic sector (GB). *IA No: DECC0010*, pp.1–82.

DECC, 2012c. The Energy Efficiency Strategy: The Energy Efficiency Opportunity in the UK. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65602/6927-energy-efficiency-strategy--the-energy-efficiency.pdf.

DECC, 2012d. The Future of Heating: A strategic framework for low carbon heat in the UK. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48574/4805-future-heating-strategic-framework.pdf.

DECC, 2013e. The Future of Heating: Meeting the Challenge.

DECC, 2014b. The Future of the Energy Company Obligation: Final Impact Assessment.

DfT, 2009a. Impact Assessment of the Carbon Reduction Strategy for Transport: Low Carbon Transport A Greener Future.

DfT, 2009b. National Transport Model: High Level Overview. Available at: http://webarchive.nationalarchives.gov.uk/20110202223628/http://www.dft.gov.uk/pgr/economics/ntm/.

DfT, 2016. New legislative powers for ULEV infrastructure. *IA No: DfT00376*, pp.1–42.

DfT, 2014. Renewable Transport Fuel Obligation: Post Implementation Review.

DfT, 2018. Road Traffic Forecasts 2018: Moving Britain Ahead. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/740399/road-traffic-forecasts-2018.pdf.

DfT, DECC & DEFRA, 2012. Uk Bioenergy Strategy. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf.

Dietz, T. et al., 2009. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences*, 106(44), pp.18452–18456. Available at: http://www.pnas.org/cgi/doi/10.1073/pnas.0908738106.

Energy Systems Catapult, 2017. ESME Data References Book. Available at: https://d2umxnkyjne36n.cloudfront.net/documents/ESME-v4.4-Data-References-Book-March-2018.pdf?mtime=20180302125442.

Eurostat, 1983. Useful energy balance sheets 1980. *Statistical Office of the European Communities*.

Fleiter, T., Worrell, E. & Eichhammer, W., 2011. Barriers to energy efficiency in industrial bottom-up energy demand models - A review. *Renewable and Sustainable Energy Reviews*, 15(6), pp.3099–3111. Available at: http://dx.doi.org/10.1016/j.rser.2011.03.025.

Fletcher, K. & Marshall, M., 1995. Forecasting Regional Industrial Energy Demand: The ENUSIM End-use Model. *Regional Studies*, 29(8), pp.801–811.

Geels, F.W. et al., 2018. Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates. *Energy Research and Social Science*, 40(November 2017), pp.23–35. Available at: https://doi.org/10.1016/j.erss.2017.11.003.

Geels, F.W., Berkhout, F. & Van Vuuren, D.P., 2016. Bridging analytical approaches for low-carbon transitions. *Nature Climate Change*, 6(6), pp.576–583. Available at: http://dx.doi.org/10.1038/nclimate2980.

Grubler, A. et al., 2018. A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies. *Nature Energy*, 3(6), pp.515–527. Available at: http://dx.doi.org/10.1038/s41560-018-0172-6.

GSR, 2013. Rapid Evidence Assessment Toolkit: How to do an REA. Available at: http://webarchive.nationalarchives.gov.uk/20140402163101/http://www.civilservice.gov.uk/networks/gsr/resources-and-guidance/rapid-evidence-assessment/how-to-do-a-rea.

Guevara, Z., Sousa, T. & Domingos, T., 2016. Insights on Energy Transitions in Mexico from the Analysis of Useful Exergy 1971–2009. *Energies*, 9(7), p.488. Available at: http://www.mdpi.com/1996-1073/9/7/488.

Hailey et al., D., 2000. The use and impact of rapid health technology assessments. *International Journal of Technology Assessment in Health Care*, 16(2), pp.651–656. Available at: http://resolver.shef.ac.uk/?http://journals.cambridge.org/article_S0266462300101205.

Hall, J.W. et al., 2016. Appendix B ITRC Energy Systems Modelling & Analysis Methodology. In

J. W. Hall et al., eds. *The Future of National Infrastructure: A Systems-of-systems Approach*. Cambridge, UK: Cambridge University Press, pp. 1–20. Available at: https://www.itrc.org.uk/wp-content/PDFs/AppendixB-Energy-methodology.pdf.

Hanley, N. et al., 2009. Do increases in energy efficiency improve environmental quality and sustainability? *Ecological Economics*, 68(3), pp.692–709. Available at: http://dx.doi.org/10.1016/j.ecolecon.2008.06.004.

Heaton, C. & Bunn, D.W., 2014. Modelling Low-Carbon Energy System Designs with the ETI ESME Model. *Energy Technologies Institute*. Available at: https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2014/04/ESME_Modelling_Paper.pdf.

HM Government, 2017a. *Industrial Strategy: Building a Britain fit for the future*, Available at: http://digital-library.theiet.org/content/journals/10.1049/ir_19930092.

HM Government, 2007. Meeting the Energy Challenge: A White Paper on Energy.

HM Government, 2008. Meeting the Energy Challenge: A White Paper on Nuclear Power. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/228944/7296.pdf.

HM Government, 2011. The Carbon Plan: Delivering our low carbon future. Available at: http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf.

HM Government, 2017b. The Clean Growth Strategy: Leading the way to a low carbon future. , p.165. Available at: https://www.gov.uk/government/publications/clean-growth-strategy.

HM Government, 2009a. The UK Low Carbon Transition Plan: National strategy for climate and energy.

HM Government, 2009b. *The UK Renewable Energy Strategy*, Available at: http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/res/res.aspx.

HMRC, 2013. HMRC’s CGE model documentation. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/263652/CGE_model_doc_131204_new.pdf.

Holtz, G. et al., 2015. Prospects of modelling societal transitions: Position paper of an emerging community. *Environmental Innovation and Societal Transitions*, 17, pp.41–58.

Hoolohan, C., McLachlan, C. & Mander, S., 2016. Trends and drivers of end-use energy demand and the implications for managing energy in food supply chains: Synthesising insights from the social sciences. *Sustainable Production and Consumption*, 8(June), pp.1–17. Available at: http://dx.doi.org/10.1016/j.spc.2016.06.002.

Huang, W., Chen, W. & Anandarajah, G., 2017. The role of technology diffusion in a decarbonizing world to limit global warming to well below 2 °C: An assessment with application of Global TIMES model. *Applied Energy*, 208(October), pp.291–301. Available at: https://doi.org/10.1016/j.apenergy.2017.10.040.

IPCC, 2018. Summary for Policymakers. In V. Masson-Delmotte et al., eds. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. Geneva, Switzerland: World Meteorological Organization, p. 32.

Karamanos, P., 2001. Voluntary environmental agreements: Evolution and definition of a new environmental policy approach. *Journal of Environmental Planning and Management*, 44(1), pp.67–84.

Khangura, S. et al., 2012. Evidence summaries: the evolution of a rapid review approach. *Systematic reviews*, 1(10), pp.1–9.

Knobloch, F. et al., 2018. Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 °C. *Energy Efficiency*, pp.1–30.

Krysiak, F.C. & Weigt, H., 2015. The Demand Side in Economic Models of Energy Markets: The Challenge of Representing Consumer Behavior. *Frontiers in Energy Research*, 3(May), pp.1–10. Available at: http://www.frontiersin.org/Energy_Systems_and_Policy/10.3389/fenrg.2015.00024/abstract.

Li, F.G.N. & Strachan, N., 2017. Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions*, 24, pp.106–129. Available at: http://dx.doi.org/10.1016/j.eist.2016.08.002.

Li, F.G.N., Trutnevyte, E. & Strachan, N., 2015. A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change*, 100, pp.290–305. Available at: http://dx.doi.org/10.1016/j.techfore.2015.07.017.

Li, P.H., Keppo, I. & Strachan, N., 2018. Incorporating homeowners' preferences of heating technologies in the UK TIMES model. *Energy*, 148, pp.716–727. Available at: https://doi.org/10.1016/j.energy.2018.01.150.

Li, P.H. & Pye, S., 2018. Assessing the benefits of demand-side flexibility in residential and transport sectors from an integrated energy systems perspective. *Applied Energy*, 228(July), pp.965–979. Available at: https://doi.org/10.1016/j.apenergy.2018.06.153.

Mercure, J.F. et al., 2018. Integrated assessment modelling as a positive science: private passenger road transport policies to meet a climate target well below 2∘C. *Climatic Change*.

Moran, D. et al., 2018. Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. *Climate Policy*, pp.1–11. Available at: https://doi.org/10.1080/14693062.2018.1551186.

NIC, 2017. Congestion , Capacity , Carbon: priorities for national infrastructure - Modelling Annex. Available at: https://www.nic.org.uk/wp-content/uploads/Congestion-Capacity-Carbon-Modelling-Annex.pdf.

Park, S., 2015. State Renewable Energy Governance: Policy Instruments, Markets, or Citizens. *Review of Policy Research*, 32(3), pp.273–296.

Percebois, J., 1979. Is the concept of energy intensity meaningful? *Energy Economics*, 1(3), pp.148–55.

Pye, S. & Daly, H., 2015. Modelling sustainable urban travel in a whole systems energy model. , 159, pp.97–107. Available at: http://dx.doi.org/10.1016/j.apenergy.2015.08.127.

Pye, S., Usher, W. & Strachan, N., 2014. The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. *Energy Policy*, 73, pp.575–586. Available at: http://dx.doi.org/10.1016/j.enpol.2014.05.025.

RICARDO-AEA, 2014. Production of Updated Emission Curves for Use in the National Transport Model. *Report to the Department for Transport*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/662795/updated-emission-curves-ntm.pdf.

Rojas-Rueda, D. et al., 2012. Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: A health impact assessment study. *Environment International*, 49, pp.100–109. Available at: http://dx.doi.org/10.1016/j.envint.2012.08.009.

Ross, A.G. et al., 2018. The Economic Impacts of UK Trade-enhancing Industrial Policies and their Spillover Effects on the Energy System. *UKERC Working Paper*, (July), pp.1–47. Available at: https://pure.strath.ac.uk/portal/en/publications/the-economic-impacts-of-uk-tradeenhancing-industrial-policies-and-their-spillover-effects-on-the-energy-system(f44016d9-c398-444a-b9cf-c49d161c2bd2).html.

Salvucci, R. et al., 2018. Modelling transport modal shift in TIMES models through elasticities of substitution. , 232(July), pp.740–751.

Scott, K. et al., 2016. National climate policy implications of mitigating embodied energy system emissions. *Climatic Change*, 136(2), pp.325–338. Available at: http://dx.doi.org/10.1007/s10584-016-1618-0.

Shove, E., 2010. Beyond the ABC: Climate change policy and theories of social change. *Environment and Planning A*, 42(6), pp.1273–1285.

Smith, P. et al., 2014. Agriculture, Forestry and Other Land Use (AFOLU). In O. Edenhofer et al., eds. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 811–922. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf.

Sorrell, S., 2015. Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews*, 47, pp.74–82.

Sousa, T. et al., 2017. The Need for Robust, Consistent Methods in Societal Exergy Accounting. *Ecological Economics*, 141, pp.11–21. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0921800916309363.

Stern, N., 2007. *The Economics of Climate Change: The Stern Review*, Cambridge, UK: Cambridge University Press.

Stern, P.C., Sovacool, B.K. & Dietz, T., 2016. Towards a science of climate and energy choices. *Nature Climate Change*, 6(6), pp.547–555. Available at: http://dx.doi.org/10.1038/nclimate3027.

Strbac, G. et al., 2018. Analysis of Alternative UK Heat Decarbonisation Pathways: For the

Committee on Climate Change. *Imperical College London*. Available at: https://www.theccc.org.uk/wp-content/uploads/2018/06/Imperial-College-2018-Analysis-of-Alternative-UK-Heat-Decarbonisation-Pathways.pdf.

Trutnevyte, E., 2016. Does cost optimization approximate the real-world energy transition? *Energy*, 106, pp.182–193. Available at: http://dx.doi.org/10.1016/j.energy.2016.03.038.

UK Government, 2017. Building our Industrial Strategy. *Green Paper*.

Wilson, C. et al., 2012. Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change*, 2(11), pp.780–788. Available at: http://dx.doi.org/10.1038/nclimate1576.

Woodcock, J. et al., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet*, 374(9705), pp.1930–1943. Available at: http://dx.doi.org/10.1016/S0140-6736(09)61714-1.

Annex I: Model Descriptions

In this section we provide descriptions of the thirteen models that we analysed. The descriptions are highly simplified and are intended to provide a basic understanding for readers who are not familiar with the models. For more detail on the models, please refer to the relevant documents referenced in Table 6.

The BEIS EDM

The BEIS EDM is one of the key tools used in the production of the annual Energy and Emissions Projections (BEIS 2018b). The model uses econometric equations to project energy use and carbon emissions for the whole economy into the future. For this purpose the economy is split into a number of sectors including Transport, Domestic, Agriculture, Public & Commercial services as well as 11 industry sectors. For each sector the model utilises relevant exogenous projections of socio-economic drivers such as population or GDP growth. These socio-economic drivers are translated into energy consumption using econometric equations estimated from historic data. Energy consumption is then further disaggregated into the consumption of different fuels. In addition the model features a module that projects future energy prices, also based on econometric equations.

The E3ME model

The E3ME model is an energy-environment-economy model used to assess the effectiveness of climate mitigation policies and their impact on the economy. The model represents the whole global economy disaggregated into several countries and regions, each of which is split into a number of economic sectors. The economy is modelled using a macroeconometric framework, which utilises econometric equations to endogenously project the development and interactions of key economic variables, including GDP, investment, consumption, employment, prices and technological changes. The econometric equations describing the relationships between the economic variables are estimated from historic data, so that the model does not rely on the assumption that competitive markets and optimising agents lead to an economic equilibrium. Similar to economic variables, energy use in each sector is also estimated using econometric equations, based on the projected economic output as well as other variables. In addition to such a top-down estimation of energy use, the model features two integrated bottom-up models relevant for energy demand, one for domestic heating and one for personal car transport. These bottom-up models estimate energy demand in their respective sectors by explicitly modelling the diffusion of new technologies.

NISMOD

National Infrastructure Systems Model (NISMOD) has been developed by the UK Infrastructure Transitions Research Consortium (ITRC). For our analysis we have focused on the NISMOD-LP version which has been developed for the analysis of the long-term performance of interdependent infrastructure systems in the UK and which has been used by National Infrastructure Commission in their Interim National Infrastructure Assessment (NIC 2017). The model utilises a modular approach to represent different infrastructure systems, such as transport, waste, energy and water. For the purpose of our study we have focused on the energy and transport modules. On a detailed sectoral level energy demand is projected starting from a baseline value in the base year. Energy demand in the future is determined based on (a) exogenous scenario drivers, such as population and economic growth and (b) the uptake of different transition options (e.g. new technologies). The uptake of transition options is modelled using S-curves which are specified by the model user. This allows the exploration of different scenarios, including non-price policies and structural changes.

The HMRC environmental CGE model

The HMRC environmental CGE model is used to assess the economic impacts of climate change mitigation policies. As computable general equilibrium (CGE) model it represents the whole economy of the UK as a set of economic sectors which buy materials from each other and sell final products to consumers. Production is described using KLEM production functions and consumption using a utility function. It is assumed that producers substitute input factors to maximise profits and consumers maximise utility while prices adjust to balance supply and demand and produce an economic equilibrium. The model can then be used to test how different interventions change the economic equilibrium. Energy is represented in the model as a production input in each sector and there are several sectors producing energy products.

UK TIMES

The UK TIMES model is a whole-systems energy model developed by the UCL Energy Institute. The model represents the whole energy system of the UK, including energy production and consumption, using a number of sectors, processes and technologies. Energy demand estimations in the model are driven by projection of energy service demands in the future (e.g. vehicle-km, homes to be heated, industrial output) which need to be satisfied in each time period. Given the information on available technologies and their costs, the model then determines the least-cost technology combination that can satisfy all the energy service demands. The cost optimisation can be constrained, for example to force the model to achieve specific emission targets or to exclude specific technologies, such as nuclear power.

ESME

The Energy Systems Modelling Environment (ESME) was developed by the Energy Technologies Institute (ETI) and is now hosted by the Energy Systems Catapult. It represents a whole-systems energy model for the UK, disaggregated into several regions. It describes the whole energy conversion chain from primary energy to final energy consumption and energy services for a number of sectors, processes and technologies. Energy demand estimations in the model are driven by projection of energy service demands in the future (e.g. vehicle-km, homes to be heated, industrial output) which need to be satisfied in each time period. Given the information on available technologies and their costs, the model then determines the least-cost technology combination that can satisfy all the energy service demands. The cost-optimisation can be constrained, for example to force the model to achieve specific emission targets or to exclude specific technologies, such as nuclear power.

The National Transport Model

The National Transport Model represents a suite of models that is hosted by the Department for Transport (DfT) and is used to produce the regularly published Road Traffic Forecasts (DfT 2018). The first sub-model in the suite is the National Trip End Model (NTEM). The NTEM uses spatially disaggregated demographic projections (incl. households, employment, population, income) to determine car ownership and then the number and destination of trips that will be done by the population. In addition the model suite features two sub-models determining the traffic volumes of light goods vehicles (LGV) and heavy goods vehicles (HGV) based on economic data. The outputs of the three sub-models are then combined in the National Transport Model. The National Transport Model takes the trip rates calculated in the NTEM and allocates them to different modes of transport based on the generalised costs of different modes. Non-car modes of travel (trains, buses) are included to represent the impact of mode-switching on car traffic, but the travel of non-car modes of transports is not an output of the model. The model calculates the energy use and various air emissions from road vehicles using emission and fuel curves for cars, LGV and HGV. These curves link fuel use and emissions to the distance travelled by the different vehicle classes as well as the speed of travel. The curves are prepared outside the model and represent projections of the average properties of the relevant vehicle fleet.

The National Household Model

The National Household Model is an open-source model that has been developed by the Centre for Sustainable Energy. It has also been used by BEIS in the Clean Growth Strategy to assess the policy options for reducing energy demand and carbon emissions in the domestic sector (assuming that the Domestic Buildings Scenario Model cited in the report is based on the National Household Model). The model contains a detailed representation of the housing stock in Great Britain, disaggregated to different regions and dwelling types. This is matched by information on the type of occupants and technologies installed in the properties. Model users can define scenarios to explore how changes in technology use or practices impact energy demand, for example by specifying the roll-out of specific technologies or changing the assumptions on indoor temperatures. Based on the scenarios the model then calculates energy use, carbon emissions, fuel bills and SAP ratings for different regions or different segments of the housing stock.

The BEIS Non-domestic Building model

The BEIS Non-domestic Building Model is hosted by BEIS and has been used in the Clean Growth Strategy (HM Government 2017b) to assess the heating, cooling and ventilation demand in non-domestic buildings in the future. The model utilises the projections of energy demand in the Public and Commercial services sectors in the Energy and Emissions Projections. These projections are then allocated to demand for different end-use categories (e.g. PJ of heat, PJ of cooling) based on current fuel uses. These demands for energy are met by different technologies which are specified by the model user. Model users can also specify scenarios by defining roll-out profiles for new technologies, which changes the final energy demand needed to satisfy the different categories of energy demands.

The BEIS Industry Pathways Model

The BEIS Industry Pathways Model is hosted by BEIS and has been used in the Clean Growth Strategy (HM Government 2017b) to explore future pathways of energy use in the industry sectors. The model utilises the projections of energy demand in the industry sectors from the Energy and Emissions Projections. These projections are then allocated to demand for different end-use categories. These end-use categories reflect specific processes in some sectors (iron and steel, paper, cement and a part of chemicals) and generic processes, such as high and low temperature heat, in the remaining sectors (other chemicals, non-metallic minerals, non-ferrous metals, food and drink and 'other' industry). These end-use demands are met by different technologies which are specified by the model user. Model users can also specify scenarios by defining roll-out profiles for new technologies, which changes the final energy demand needed to satisfy the different categories of energy demands. Technology assumptions are based on UK TIMES data.

ENUSIM

The Energy Use Simulation Model (ENUSIM) has been used to project energy consumption in the UK industry sectors. It is currently hosted by Ricardo Energy & Environment, but has not been used in the analysed policy documents for several years. The model utilises projections of economic output in each industry sector to estimate demand for final energy relative to a base year. The demand for final energy is disaggregated into different sub-sectors and satisfied using technological devices. Each device satisfies a unique demand for energy and translates it into final energy demand. Each device can also be improved using multiple technologies. The uptake of technological options is partially endogenous as technologies are only taken up if they are cost-effective. If technologies are cost-effective, however, they are taken up according to an S-curve that is specified exogenously.

The Green Deal Household Model

The Green Deal Household Model was developed by the Department for Energy and Climate Change (now BEIS) to simulate the uptake of insulation measures under the Green Deal Policy. Since the end of the Green Deal policy it is no longer used. The model features a detailed representation of the housing stock model of the UK disaggregated into several thousand categories. Each year a certain amount of households consider to take up a Green Deal to install loft insulation, cavity wall insulation or solid wall insulation. The probability that a house type will take up a measure is calculated based on a utility function featuring inputs such as bill savings, upfront capital and assessment costs and length of the Green Deal plan. The utility coefficients are based on a consumer-preference survey. The probability that an individual house type will take up a measure is then multiplied by the housing stock to estimate the total uptake of the measure.

The EDR Take-up Model

The EDR Take-up Model was developed by the Department for Energy and Climate Change (now BEIS) to provide a high level estimate of how much electricity demand reduction could be achieved in the business sector for different levels of a financial incentive. The model features a representation of different electricity demand reduction technologies and their costs. The responsiveness of firms to a financial incentive for electricity demand reductions is approximated using an assumed distribution of minimum payback periods required to take action. Together these information can be used to estimate how the level of EDR take-up might vary for different levels of financial incentives.

Annex II: Detailed tables of model features

Table A1: Socio-economic drivers, energy service and final energy variables in the transport sector for each model. Only the seven (of thirteen) models with a representation of the transport sector are shown. Level of detail varies depending on the information available. n/a = not included or not applicable

		Transport	
Model	**Socio-economic drivers**	**Energy service variables**	**Final energy variables**
BEIS EDM	GDP Population Manufacturing output Fuel prices	HGV vehicle km LGV vehicle km Public transport km Cars vehicle km	HGV energy use LGV energy use Public transport energy use Total commercial energy use by fuel Car energy use by fuel Rail energy use (exogenous) Aviation energy use (exogenous) Fishing and domestic navigation energy use (exogenous)
E3ME model	Population Global oil price Demographic change Endogenous economic drivers: Economic activity Energy prices R&D by energy sector Global R&D Investment by energy sector	*Bottom-up model of personal car transport:* Vehicle km Passenger km *Top-down model for other sectors:* n/a	*Bottom-up model of personal car transport:* Fuel use for 9 vehicle types 3 vehicle classes (economy, mid-range, luxury) for 3 engine types (diesel, petrol, electric) *Top-down models for other sectors:* Sectoral energy use in total and by fuel 4 top-down transport sectors (Rail transport, Road transport, Air transport, Other transport services)
NISMOD	Population Trip rates Economic growth Cost of travel	Intrazonal veh-km Interzonal passenger car units Rail passenger journeys	Energy use by mode and fuel 8 fuels 4 major modes from 6 sub-models
HMRC environmental CGE model	Endogenous economic variables (incl. sectoral GVA, sectoral consumption) Prices of energy inputs	Not sufficient information	Intermediate input of energy carriers in sectoral production functions Direct consumption of energy carriers by households

Transport

Model	Socio-economic drivers	Energy service variables	Final energy variables
UK TIMES	Exogenous, depends on scenario	Car travel (veh-km) Bus travel (veh-km) 2 wheeler travel (veh-km) LGV freight travel (veh-km) HGV freight travel (veh-km) Passenger rail travel (pass-km) Domestic aviation (pass-km) Domestic shipping (ton-km) Rail freight travel (ton-km) International Aviation (PJ)	Fuel use for each end-use technology
ESME	Exogenous, depends on scenario	2 types of car travel (veh-km) Bus travel (pass-km) 4 types road freight HGV (ton-km) 2 types road freight LGV (ton-km) Road freight MGV (ton-km) Passenger diesel rail (pass-km) Passenger electric rail (pass-km) Freight diesel rail (ton-km) Domestic passenger aviation (pass-km) International passenger aviation (pass-km) Maritime domestic freight (ton-km) Maritime international freight (ton-km) 6 categories of off-road agric. and construction vehicles (all in operating hours)	Fuel use for each end-use technology
National Transport Model	Population Household numbers Household structures Housing supply Employment GDP Income Fuel prices License holding Car costs Manufacturing index	Weekly personal trips by purpose Car vehicle-km LGV vehicle-km HGV vehicle-km Includes travel demands for rail, bus, cycling and walking but only to determine their impact on car travel	Energy consumption by cars Energy consumption by HGV Energy consumption by LGV

Table A2: Socio-economic drivers, energy service and final energy variables in the domestic sector for each model. Only the eight (of thirteen) models with a representation of the domestic sector are shown. Level of detail varies depending on the information available. n/a = not included or not applicable.

		Domestic	
Model	**Socio-economic drivers**	**Energy service variables**	**Final energy variables**
BEIS EDM	Household numbers Heating degree days Fuel prices Household income	n/a	Energy use by fuel 4 fuels (gas, solid fuel, oil, electricity)
E3ME model	Population Global oil price Demographic change *Endogenous economic drivers:* Economic activity by sector Energy prices R&D by sectors Global R&D Investment by sector	*Bottom-up model of space heating:* Effective energy demand for space heating and hot water in residential buildings *Top-down model for other uses:* n/a	*Bottom-up model of space heating:* Fuel demand for each heating technology 6 fuels (coal, middle distillates, natural gas, electricity, district heat, biomass) *Top-down model for other uses:* Sectoral energy use in 1 domestic sector by fuel
NISMOD	Population Household size Average dwelling size External temperatures	n/a	9 end-uses 6 energy carriers
HMRC environmental CGE model	*Endogenous economic variables:* Prices of energy products Household income	Not sufficient information	Consumption of energy products by households

Domestic			
Model	**Socio-economic drivers**	**Energy service variables**	**Final energy variables**
UK TIMES	exogenous, depends on scenario	Space heating for existing homes (PJ) Space heating for new homes (PJ) Hot water demand for existing houses (PJ) Hot water demand for new houses (PJ) Lighting demand (number of units) Refrigerators demand (number of units) Freezers demand (number of units) Wet appliances demand (PJ) Consumer electronics demand (PJ) Computers (PJ) Cooking demands, other (PJ) Cooking demands, hobs (number of units) Cooking demands, ovens (number of units) Cooling demand (number of units) Others demand (PJ)	Fuel use for each end-use technology
ESME	Exogenous, depends on scenario	High density dwellings (number) Low density dwellings (number) Mid density dwellings (number) Domestic air conditioning (TWh) Domestic appliances (TWh) Domestic cooking (TWh) Internal temperatures Dwelling numbers are combined with assumptions on internal temperatures to produce required HDD per dwelling	Fuel use for each end-use technology
National Household Model	Dwelling numbers and occupancy Floor area External temperatures Household characteristics	Internal temperature Hot water demand per person Heating schedules	Energy consumption by 4 end-uses (cooking, lighting, heating, appliances) and 3 fuels (electricity, gas, oil) Disaggregation available for different areas, housing types and technologies
Green Deal Household Model	Household projections Energy prices Interest rates Consumer preferences	n/a	Final energy use for heating

Table A3: Socio-economic drivers, energy service and final energy variables in the industry sector for each model. Only the nine (of thirteen) models with a representation of the industry sector are shown. Level of detail varies depending on the information available. n/a = not included or not applicable, ns = no sufficient information available to authors

		Industry	
Model	Socio-economic drivers	Energy service variables	Final energy variables
BEIS EDM	Energy prices Sectoral output (derived from UK GDP, treasury 3-months bond rates, sectorial terms of trade)	n/a	Sectoral energy use by fuel 11 sectors (Chemicals; construction; engineering and vehicles; food, drink and tobacco; iron and steel; other industries; non-ferrous metals; non-metallic minerals; paper, pulp and printing; textile products)
E3ME model	Demographic change *Endogenous economic drivers:* Sectoral economic activity Energy prices R&D by energy-using sector Global R&D Investment by energy-using sector	n/a	Sectoral energy use by fuel 12 fuels 11 sectors (Iron and steel; non-ferrous metals; chemicals; non-metallic minerals; ore-extraction; food, drink and tobacco; textiles, clothing & footwear; paper and pulb; engineering etc; other industry; construction)
NISMOD	sectoral GVA	n/a	Sectoral energy use by fuel and end-use 28 sectors 5 fuels 9 generic end-uses (High temp. heat, low temp. heat, drying and separation, motors, compressed air, lighting, refrigeration, space heating, other) 5 sectors use specific end-use processes (Iron & Steel, Cement & Minerals, Pulp & Paper, Chemicals, Food & Beverages)
HMRC environmental CGE model	*Endogenous economic drivers:* Demand for sectoral products Prices of energy inputs	Not sufficient information	Intermediate input of energy products in sectoral production functions

		Industry	
Model	Socio-economic drivers	Energy service variables	Final energy variables
UK TIMES	Exogenous, depends on scenario	5 process-based sectors as Mtonnes of specific product (Iron & Steel, Cement, Paper, Chemicals HVC, Chemicals Ammonia) 6 generic sectors as PJ useful energy (Other Chemicals, Non-ferrous Metals, Food & Drink, Other Industries, Chemicals Non-energy Use, Agriculture) Generic sectors disaggregated to different end-uses (High temp. heat, low temp. heat, drying, refrigeration, etc.)	Energy use by sector and end-use technology
ESME	Exogenous, depends on scenario	Energy demand by sector and end-use (as energy demand relative to 2010) 9 sectors: Iron, Steel & Non-ferrous metals; Chemicals; Metal Products; Food, Drinks & Tobacco; Paper, Printing and Publishing; Other Industry; Cement Industry; Refined Petroleum Products; Agriculture 6 end-uses (High temp. heat, low temp. heat, space heating, drying and separation, motors, other)	Energy use by sector and end-use technology
ENUSIM	Economic output in each industry sector Energy prices	n/a	Final energy demand in 19 industry sectors, disaggregated to subsectors and 'devices'
BEIS Industry Pathways Model	n/a	n/a	Final energy demand in 11 sectors (Chemicals; construction; engineering and vehicles; food,drink and tobacco; iron and steel; other industries; non-ferrous metals; non-metallic minerals; paper, pulp and printing; textile products)
EDR Take-up Model	Energy prices Interest rates	n/a	Final demand for electricity by commercial companies

Table A4: Socio-economic drivers, energy service and final energy variables in the non-industrial sectors for each model. Only the seven (of thirteen) models with a representation of the non-industrial sectors are shown. Level of detail varies depending on the information available. . n/a = not included or not applicable, ns = no sufficient information available to authors

	Non-industry sectors (i.e commercial and public services, agriculture, fishing)		
Model	Socio-economic drivers	Energy service variables	Final energy variables
BEIS EDM	Commercial services GVA Public sector employment Fuel prices Heating degree days	n/a	Commercial services energy use, total and by fuel Public services energy use, total and by fuel Agriculture energy use, total and by fuel
E3ME model	Population Global oil price Demographic change *Endogenous economic drivers:* Economic activity Energy prices R&D by energy sector Global R&D Investment by energy sector	n/a	Sectoral energy use in total and by fuel 3 non-industry sectors (Agriculture, forestry, etc.; fishing; other final use)
NISMOD	Sub-sectoral GVA Cooling degree days Heating degree days	n/a	7 end-uses 11 sub-sectors 6 fuels
HMRC environmental CGE model	Endogenous economic variables (incl. sectoral GVA, sectoral consumption) Prices of energy inputs	Not sufficient information	Intermediate input of energy carriers in sectoral production functions
UK TIMES	Exogenous, depends on scenario	Space heating low consumption buildings (PJ) Space heating high consumption buildings (PJ) Hot water low consumption buildings (PJ) Hot water high consumption buildings (PJ) Cooling in high consumption buildings (PJ) Lighting offices (number of units) Lighting other (number of units) Computing (PJ) Cooking (PJ) Refrigeration (PJ) Other demand (PJ)	Fuel use for each end-use technology
ESME	Exogenous, depends on scenario	Commercial Floorspace (sq metres) Public Floorspace (sq metres)	Fuel use for each end-use technology
BEIS Non-domestic Building Model	n/a	Useful energy requirements (PJ) for different purposes in non-domestic buildings, incl. heating, cooling, etc	calculated from energy service demands and employed technologies