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Capturing the distributional impacts of long-term low-carbon transitions

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ABSTRACT

Major policy proposals often require a distributional impact assessment, focusing on differential financial and other impacts across population segments. Such assessments are rare, however, at the multi-decadal scale addressed in long-term (e.g. to 2050) low carbon transition modelling. There is therefore a risk of socially inequitable outcomes, which in turn presents a socio-political risk for decision-makers driving transitions. This paper uses a literature review and expert interviews to identify mechanisms by which low carbon transitions could differentially impact population sub-groups. As well as impacts of policy costs on bills, this includes factors such as ability to connect to heat networks or install onsite generation or storage. An approach to exploring distributional impacts across a range of long term scenarios from a United Kingdom energy model (ESME), is proposed. This sets out how bill changes and other costs associated with low carbon transition could impact different income quintiles in the UK.

1. Introduction

1.1. Background and introduction to research

Almost all countries now have some commitment to limiting greenhouse gas (GHG) emissions under the Paris Agreement. Under the agreement, each signatory must produce its own plan (or Nationally Determined Contribution) to reduce GHG emissions in the coming decades. Many of these plans will require wholesale changes to energy systems. In the United Kingdom (UK), the Climate Change Act (2008) requires at least an 80% reduction of GHG emissions on 1990 levels by 2050. Importantly, the UK Government also has an obligation to consider 'social circumstances, and in particular the likely impact of the decision on fuel poverty' when setting interim targets, or carbon budgets, necessary to meet the long term 2050 goal[1] .

It is an important part of new policy or major infrastructure proposals to conduct a distributional impact assessment. In the UK, assessment is primarily defined in The Green Book (2018), in which it mandates (where necessary) a thorough identification and quantification of the "impact of interventions on different groups in society" (p77). These may be focused on the income/expenditure effects on different segments of the population, or consider a broader range of potential benefits or harms. The impacts are usually assessed by the use of models or other analytical tools. These exercises are essentially a way of managing risk – the consequential risk of socially inequitable outcomes which could result from the policy or project. They allow recognition of the kind of negative impacts

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[1] Article 10(2) of the Climate Change Act 2008, http://www.legislation.gov.uk/ukpga/2008/27/section/10

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that may occur (and who is likely to be impacted), can inform changes to projects to reduce the probability of negative outcomes occurring, and identify those impacts that cannot be managed away and may therefore need to be compensated for.

Such assessments help manage a further risk – that those driving the project or proposal lose the support of their stakeholder base. For example, politicians or governments may be concerned that by supporting a certain policy, the negative social impacts on some groups (and negative perceptions regarding those impacts) may be such that they risk losing power in future elections. This concern may be so great that it prevents the government pursuing pro-transition policy measures in some areas at all – thereby presenting an implementation risk. An example of this could be the rolling back of UK government support for onshore wind power and 'green levies' (which support measures such as energy efficiency) (Carter and Clements, 2015). The purpose of a distributional impact assessment is also, therefore, to help manage uncertainty. As Stone (2009) explains, governments may fail to act in the face of challenges which will almost certainly have bad outcomes (such as climate change) because of the uncertainty both around the extent and distribution of those outcomes, but also because of uncertainty around the impacts of response measures. While better climate modelling exercises can help address the first uncertainty, improved assessment of how policies will impact populations can help minimize (or at least render more clearly) the latter.

The kind of distributional impact assessment discussed so far tend to be specific to a given policy, on a relatively short timescale over which potential impacts can be assessed with relatively low levels of uncertainty (for example, see (Heindl and Löschel, 2014)] for a review of studies of the distributional impacts of climate and energy taxation). Low-carbon transitions, on the other hand, are multi-decadal strategic programmes combining multiple projects and policies applicable across a range of sectors. This multiplies potential sources of uncertainty. As such, as this paper shows, consideration of distributional impacts of such transitions has so far been quite rare. However, we argue in this paper that modelling and assessment exercises, as well as informing the development of possible scenarios, also serve to structure the subjects that are debated when discussing transitions. In current practice, by not including distributional impacts in assessments, they remain absent from discussions, with the risk that negative consequences that could have been anticipated will be missed.

Approaches to modelling transitions fall into different categories, all of which have respective strengths and weaknesses (Pye and Bataille, 2016) set out some of the main approaches considered, from more simple accounting frameworks, to techno-economic bottom-up approaches representing the physical system and its costs over time, to macro-economic approaches that consider the impacts of transitions across the economy, and hybrid versions that take elements from both.

In this paper we focus on techno-economic energy system models, which provide an explicit representation of an energy system, its component parts e.g. technologies, processes and energy flows, and the interactions between these parts. Our focus is motivated by the extensive use of these model frameworks for analysing the economic costs of energy system investment and operation, often from an economic efficiency perspective (DeCarolis et al., 2017; Pfenninger et al., 2014). They are also able to capture environmental aspects related to the energy system, with respect to emissions of GHGs and air quality pollutants. However, those segments of the population who stand to be winners and losers under different pathways are not typically revealed in such models. Households are 'averaged', and industrial opportunity and decline are not explicitly recognised. This is often a function of the type of techno-economic model framing used, i.e. modelling at scale and so losing the detail, issues of model tractability, lack of data to input and so on. This resulting lack of recognition of distributional impacts means that effective policy to support households or communities that might experience the downsides of the transition may be absent. An important research gap remains concerning the distributional impacts of longer term transitions to a low carbon energy system.

With this motivation, we set out to consider the possible distributional impacts that could be associated with different long term low-carbon transition pathways. The work takes in three main elements. Firstly, we conducted a review of existing projects and approaches relevant to the description and estimation of distributional impacts of long-term low carbon transitions. We followed this up with a mixed methods approach, combining exploratory development of a model for quantitative assessment of distributional impacts of long-term low carbon transitions with qualitative stakeholder interviews. The stakeholder interviews were required to supplement the literature review and inform our view on the range of different kinds of distributional impact that might be associated with long-term transitions, and which particular population sub-groups might be at risk of negative impacts. The interviews also play another valuable role: that of ensuring that when the model results are presented, they can be discussed alongside a qualitative assessment of additional risks.

The modelling exercise develops a framework for extending the ESME model, typical of energy system models being used to support long term strategy in many countries (Pye and Bataille, 2016) including the UK (Taylor et al., 2014). We develop an approach to estimate the magnitude of direct impacts associated with energy expenditure in the building and transport sectors, although as Section 2 makes clear, there is a much wider range of possible impacts. Our work is focused in the building and transport sectors because these are the principal domains where private citizens experience direct energy expenditure (rather than indirect, such as through provision of goods and services) (Chitnis and Hunt, 2012). The modelling approach does not set out to capture non-expenditure-related impacts but, as suggested above, stakeholder interviews have helped identify other areas of impact for either qualitative assessment or future modelling exercises.

The remainder of this section summarizes the review of existing work in this area. Section 2 presents the method and results for the stakeholder interviews, while Section 3 provides a description of the ESME model and then explores how it could be extended to incorporate consideration of distributional impacts. The final section presents the main conclusions of the work along with possibilities for future development.

1.2. Previous relevant modelling exercises

While many studies have considered the distributional impacts of specific energy or climate policy measures such as taxes or subsides (principally on costs and affordability, see (McInnes, 2017) for an overview), relatively few have explicitly focused on longer-term transitions and the distributional impacts associated with economy wide targets. In the UK, the Committee on Climate Change's UK Climate Change Risk Assessment (CCC, 2017a, 2017b) and report on Energy Prices and Bills (2017c) both draw on work by the Centre for Sustainable Energy (CSE) which used modelling to assess the possible impacts of climate policy costs on bills on households in fuel poverty, as well as the effect of different ways of targeting energy efficiency measures funded through policy (Thumin et al., 2014). This work in turn built on a previous study for the Joseph Rowntree Foundation (Preston et al., 2013). In this work, policies which specifically target efficiency improvement measures at people in fuel poverty (according to the Low Income High Cost definition[2]) without funding the cost through bills reduce the proportion of households in fuel poverty to less than 5% by 2030 (from 11% in 2013). Conversely, where costs are fully recovered through bills and the fuel poor do not receive measures, the proportion increases to over 14%.

CSE developed the DIMPSA ('Distributional Impacts Model for Policy Scenario Analysis') model to allow the distributional impacts of different domestic energy policy scenarios to be explored. Run in an SQL database, the model is informed by data from a number of national surveys (Preston et al., 2010). By harmonizing socio-demographic variables between surveys, people can be classified as energy tariff switchers or non-switchers on the basis of those characteristics, making them more or less vulnerable to price changes passed on in suppliers' standard variable rate tariffs. The same approach is used to combine survey data to predict people's wall, loft and heating type (and therefore potential for improvement), based on socio-demographic characteristics. Model runs can vary when energy efficiency upgrades are targeted by socio-demographic characteristic, and the extent to which costs are passed on in bills, and explore the effect of resultant price changes on different groupings. The data underpinning DIMPSA is available freely online[3], though the model itself is not open source.

CSE has also modelled climate policy impacts on fuel poverty using the National Household Model (NHM) (Thumin et al., 2014). This is a bottom-up physical model of Great Britain's housing stock based on data from the English Housing Survey and Scottish and Welsh House Condition Surveys. It contains an element allowing calculation of the energy required to heat living areas in homes to 21 °C based on physical characteristics. The work also takes into account household income after rents, mortgages and other housing payments, and equivalized for household composition (number of children and adults). Standard Assessment Procedure (SAP) assumptions are used to define heating regimes. By varying where energy efficiency improvements are deployed, and the effect of any cost recovery on income, they are able to model the impact of fuel poverty under different scenarios. The NHM is open source[4] .

Looking outside the UK context, perhaps the most comparable work when considering longer term distributional impacts is that by (Rausch and Mowers, 2014), who integrate a general equilibrium model of the US economy (MIT USREP [U.S. Regional Energy Policy model]) with a bottom-up model of electricity demand, generation, capacity expansion and transmission (NREL's ReEDS [Renewable Energy Deployment System] model). The economy-wide model captures geographical regions, and models nine household types within each region differentiated by income. The integrated model is therefore able to model distributional impacts of a range of energy policies by decade to 2050. While the models used apply to the US, the approach employed is similar to that envisaged for the current project in that it disaggregates results from an energy system model to explore distributional impacts.

Another recently published US study has taken the approach of constructing vulnerability score driven by populations' exposure to, sensitivity to and ability to adapt to the US energy transition (Carley et al., 2018). The score is based on income factors such as proportion of income spent on electricity, along with factors such as potential for job loss, change in land values and membership of 'susceptible demographics' (e.g. elderly, minors). They use the score to spatially model distribution of impacts across the US of a single policy (renewable portfolio standards) at a point in time. However, they suggest that this scope could be significantly expanded pending further development and validation of the vulnerability score.

Other modelling studies are increasingly building in some consideration of equity impacts of long term transitions. (Chapman and Pambudi, 2018) complement MARKAL/TIMES modelling with public and expert surveys which capture both public preferences regarding energy transitions as well as expert assessments of equity factors important to energy policy. These included employment, environmental impacts, health, subsidy allocation, energy price impacts and participation. However, the modelling itself does not seek to capture equity considerations. Other work by (Chapman et al., 2016) in Australia considers the different impact of a range of scenarios for policy support of renewable to 2020, and includes analysis of the equity impacts by income band. Weighting each band according to the six equity factors identified above, they produce findings such as that under a feed-in tariff scenario, low income groups are worst affected due to the increase in electricity costs.

A simpler tool has been developed by the International Monetary Fund aimed at exploring how changes in fuel prices impact household welfare, driven by the proportion of household expenditure accounted for by fuel (Fabrizio et al., 2016). The user can import household survey data for the country in question, and fuel price changes by fuel type. The model outputs direct and indirect

[2] Under the LIHC indicator, "a household is considered to be fuel poor if: (a) they have required fuel costs that are above average (the national median level) and (b) were they to spend that amount, they would be left with a residual income below the official poverty line" (BEIS and BRE, 2018).

[3] CSE DIMPSA UK energy consumption by household income. http://ukerc.rl.ac.uk/DC/cgi-bin/edc_search.pl?GoButton=Detail&WantComp=14&WantResult=LD&&BROWSE=1

[4] National Household Model website. Available at http://deccnhm.org.uk/

effects of these changes by income quintiles/deciles, how any subsidies accrue to each group, and price changes in other sectors of the economy. The model is freely available and runs in Excel.

The above review highlights approaches to modelling distributional impacts characterised primarily by either macroeconomic or micro-simulation, driven by analysis of specific policies or policy packages. This paper contributes to the literature in two new ways. Firstly, it focuses on developing a method for assessing distributional impacts in the long-term (to 2050) for different transition pathways, as opposed to near term and/or specific policy measures. The type of model to which this method is applied is a techno-economic energy systems model, because as described above, this is often the modelling framework used for such pathway analyses but for which consideration of distributional impacts has largely been absent. Secondly, we also build in consideration and expert assessment of the key distributional impacts that matter, their relevance for modelling in the long term, and recognition of the uncertainty of doing so. The interviews are therefore an important basis for informing the value and design of the modelling approach. The next section sets out the interview approach and results regarding the perceived value in principle of modelling distributional impacts, and on the range of impacts that could be associated with long-term low-carbon transitions.

2. Stakeholder engagement

2.1. Stakeholder interview method

We conducted stakeholder interviews in May and June 2017. We selected a purposive sample of organizations whose remit is relevant to the issue of distributional impacts of low-carbon transitions, and who we expected to have considered the issue in some detail. In total twelve individuals participated across six individual and group interviews drawn from government, regulators, an independent policy advice body, a consumer organization, a university department and a non-academic research organization. Appropriate named contacts at these organizations were identified and invited to participate in an interview. Interviews were held in person where possible, or via telephone/Skype. Interviews were semi-structured and covered the following topic areas, lasting approximately 45-60 minutes:

- View on how well distributional impacts are currently captured in consideration of longer term (i.e. to 2050) low-carbon transitions.
- Concerns around types of impacts on vulnerable groups (and the composition of those groups) to different aspects of low-carbon transitions – this includes both changes in generation but also demand side technologies such as electric cars, heat pumps, thermal efficiency improvements.
- Other aspects of low carbon transitions which could have detrimental effects on vulnerable groups.
- View on potential usefulness/concerns around building consideration of distributional impacts into long term scenario modelling exercises.
- View on specific proposals for how this could be done (see Section 3).

The interviews were not recorded, but detailed notes were taken by the interviewer (one of the authors, varying depending on interview) and used to write an interview summary. These ssummaries were then subject to thematic analysis (Braun and Clarke, 2006). Analysis was mainly inductive (in that themes that were identified in the data were noted rather than coding for any pre-existing concepts), but a more directed approach was also employed where the interview topics were used to organise themes (Hsieh and Shannon, 2005). These directed topics form the basis of the subheadings in the relevant results section.

2.2. Interview results and discussion

In this section, we reflect the main themes of the interviews without attributing specific comments to specific organisations.

2.2.1. On modelling long-term distributional impacts

There was broad agreement from stakeholders that due consideration of distributional impact issues, including fuel poverty, is important in policy appraisal. They saw this is an issue that needs to be taken into account not only for short term policy but also in the longer term, at least as far out as the carbon budget setting process (currently 2032). However, there were mixed views as to the current political priority placed on these considerations. Some viewed this type of research as an opportunity to consider how a low carbon transition could actually be used to actively address current issues of consumer vulnerability and energy poverty.

There was concern about the level of uncertainty that would be introduced in working at the multidecadal timescale of interest in this study – both around projecting energy use in particular, and broader socio-demographic trends in general. Some organizations felt that current understanding of how energy use (and related impacts) varies across the population now is poor, so looking forward and trying to account for changes and how they might interact would be a significant challenge. The risk of this would be that the uncertainty is so high as for the results to be meaningless, or that they just reflect existing assumptions without shedding new light. An example given of this was lack of knowledge around the types of tariffs that different householders were on, and how this might change in the future. This could strongly impact on the distribution of energy costs, and is not well understood now. There is also the issue of traction with decision makers; if they don't recognize the numbers, which are usually carefully managed in any impact assessment, it may be hard to get buy-in to the analysis.

Despite this, there was agreement that considering distributional impacts of long-term low carbon transitions was a useful exercise. This was principally because it would give greater prominence to the subject, but could also highlight where certain risks or rewards might be associated with different kinds of scenario. It may also be a means by which to help bring attention to the kinds of (widely) unanticipated impacts that might arise – especially where this might avoid unknowingly storing up problems for the future.

2.2.2. Groups that could be impacted (and types of impact)

Several organizations highlighted the evolving nature of distributional impacts, connected either with the low carbon transition itself or other societal or market changes. On the transition side, the types of distributional impacts are likely to be quite different by 2030 and 2050. To 2030, the impacts are likely to be lesser given the majority of effort happening in the power sector. In 2050, a more radical picture emerges across scenarios, where fundamental change has to happen in the transport and residential sectors. On the societal side, factors which have traditionally been seen as important for vulnerability (such as age) may be modified or replaced by other factors. The risk factors mentioned which may leave people open to detrimental impacts included:

- Propensity to switch energy tariff, as this is a key driver of household energy costs. However, it is hard to say how prominent this issue will be in the long term as the market evolves.
- Limited access to capital for upfront costs of low-carbon technologies could limit people's ability to become prosumers, and therefore gain access to cheaper electricity.
- Ability to understand and respond to more complex tariffs.
- Rental status, with particular concern around private tenants.
- Living in an area with congestion on the electricity distribution network, as this could either prevent or impose high costs on ownership or electric vehicles and heat pumps, or the connection of distributed generation. There are questions around who bears the costs of network reinforcement (i.e. there may be increased regional differences in network charging). This is especially likely in rural areas, which may also suffer from lack of access to EV charge-points or higher costs of charging.
- If there is defection from the gas grid to electricity, there is a risk that those remaining on gas could have to bear higher costs for operating that network (and there may be a tipping point beyond which the gas grid is uneconomical).
- Living in housing such as a flat where installation of rooftop solar is not considered an option, or without a garden to permit a ground-source heat pump.
- A much higher proportion of low income households using electricity for heating. As electricity costs go up (a possibility in an increasingly electrified system), they will be disproportionally impacted. They already pay disproportionately to support measures paid for via tariffs.

Some interviewees also suggested that changes in the way that energy is bought could have important distributional considerations. For example, if there is a transition to a service-based model (where flat fees are paid for a given level of service such as heat) away from payment per unit, factors such as home energy efficiency and access to automating technologies and home energy storage (which could be important criteria for access to such service offerings, and for which capital investment are required) are likely to be key. Interviewees also highlighted possible health implications arising from transitions, although the range of effects (positive and negative) and impacted populations here is very broad and giving the full consideration is beyond the scope of this study.

We have drawn on the interviews to construct Fig. 1, a diagram summarizing the types of (direct) detrimental distributional impact that could arise in long-term low carbon transition, the mechanism by which they could arise, and the (potentially observable) population sub-group which are at greatest risk. Such a diagram is of use not only for visualising the possible routes of impact, but also because it can inform future research. Each of the links presents a hypothesis which can be tested against existing or new evidence, which the diagram revised accordingly to reflect the state of the evidence.

It was highlighted (and is now fairly widely recognised in policy) that vulnerability risk factors cannot be considered in isolation, but in combination with others – such as whether someone is not only elderly, but also lives alone and in a poorly insulated house. Income is sometimes an important consideration, but other times not (such as regarding access to the gas grid). For all of the above groups, it is important to consider not just the direct impacts but also the impact of how any measures are funded – such as whether though energy bills or general taxation. Some considerations here have received little attention until recently – such as what the ramifications might be of reductions in petrol duty receipts associated with a transition to EVs.

It is also important to note that the interview discussions, and therefore Fig. 1, focus on negative impacts. This is justified on the basis that there is a need for special caution around negative impacts that might befall otherwise vulnerable population sub-groups. However, it is very likely that positive impacts will also be apparent for both vulnerable and non-vulnerable groups. These could include, for example, reduced energy costs for those with more efficient homes and other low-carbon technologies, reduced congestion, improved air quality, etc. Future cost-benefit analyses could usefully integrate all of these aspects.

The interviews highlighted a variety of mechanisms and contexts by or in which distributional impacts might be expected to arise. As Section 3 makes clear, we have only been able to consider a relatively small subset of these in our proposed modelling work – specifically those related to energy or fuel costs and the cost of efficiency measures. This is in line with our focus on the direct costs arising from low-carbon transition. It also is necessary to strike a pragmatic balance between representation of the variety of impacts that might arise, and the variables and processes which are captured in existing system models which are already well-used in research and to inform policy. The key value of the interviews is in highlighting the range of additional factors that can be presented qualitatively alongside modelled findings, and which could be captured in future or alternative model development exercises. The next section describes an approach by which certain distributional impacts highlighted in the interviews can be captured in the ESME

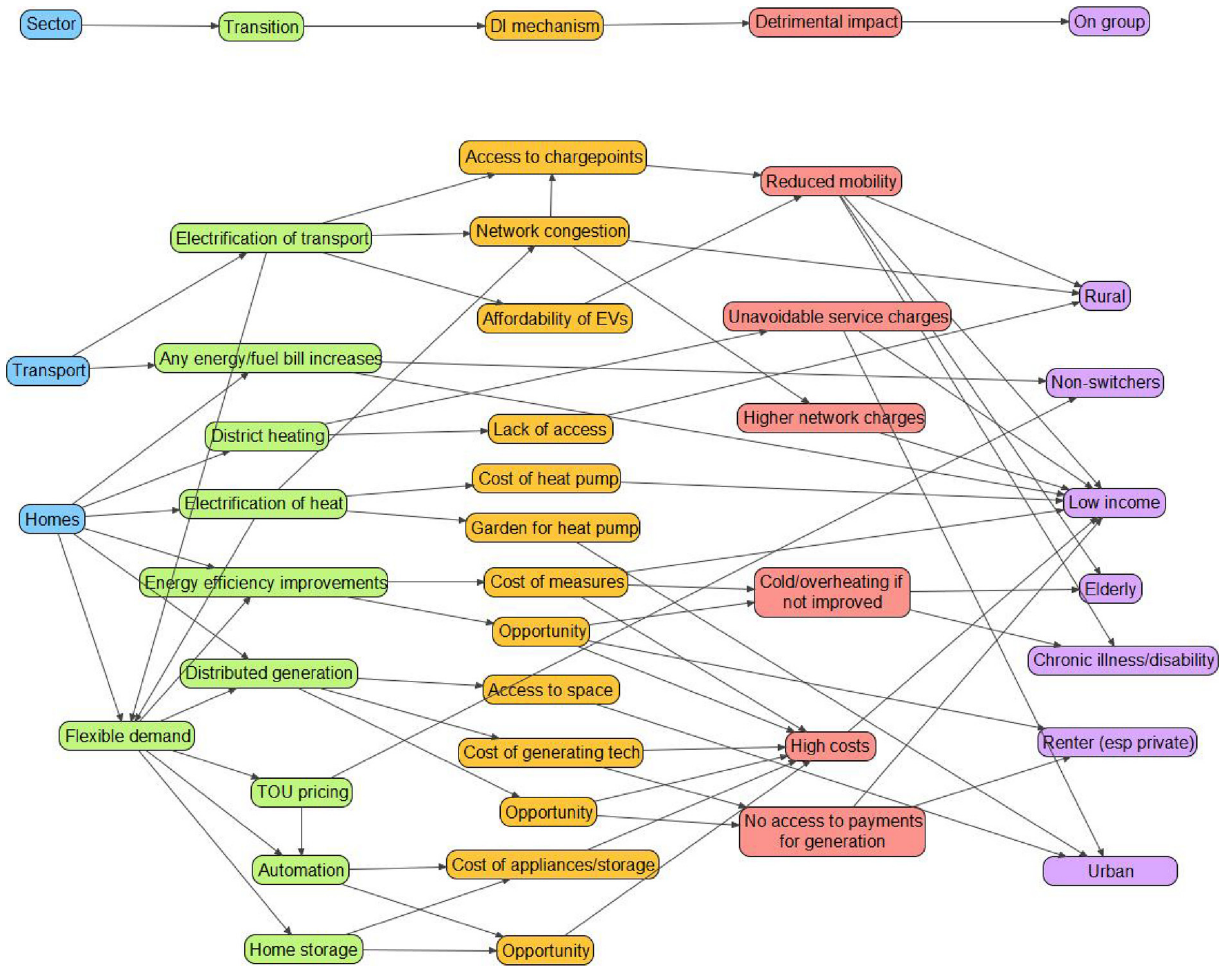

Fig. 1. Diagrammatic representation of mechanisms of distributional impacts, type of detriment and where these detriments might be expected to fall. Abbreviations used: DI = distributional impact; TOU = time of use; EV – electric vehicle.

model, and also includes additional interviewee views on the value of this proposed approach and possible enhancements.

3. Modelling distributional impacts using ESME

3.1. Background to the ESME model

As noted earlier, energy system models are often employed to explore future transition pathways out to the long term e.g. 2050. The ESME model, developed by the Energy Technologies Institute (ETI) is such a model, providing a whole systems perspective of the UK, and used to explore the different technology investments across conversion and end use sectors required for energy system decarbonisation (Heaton, 2014). It is spatially resolved, providing insights on the energy system change in different regions of the UK (Li et al., 2016), and features a module for simulating large numbers of runs to explore parametric uncertainty of model inputs, through Monte Carlo sampling (Pye et al., 2015, 2014). In addition to its use in research, ESME has been used to inform energy policy and strategy in the UK, both for the Department for Energy and Climate Change (DECC, 2011),[5] and the UK Committee on Climate Change (CCC) (CCC, 2013, 2011).

Due to their complexity, with a coverage of the whole energy system from resource extraction to end use, and representation of economics, engineering and environmental domains, this type of model typically characterises average households in terms of expenditure on energy, investment choices and energy using behavior. The real world heterogeneity across socio-economic factors e.g. income, age, employment level, is therefore missing, resulting in an inability of these models to provide any insight on the distribution of impacts (negative and positive) of a low carbon pathway on different household groups.

Taking ESME as an example, the model characterises the residential sector according to physical attributes of the stock that matter

[5] The department now covering the DECC function is the Department for Business, Energy and Industrial Strategy (BEIS).

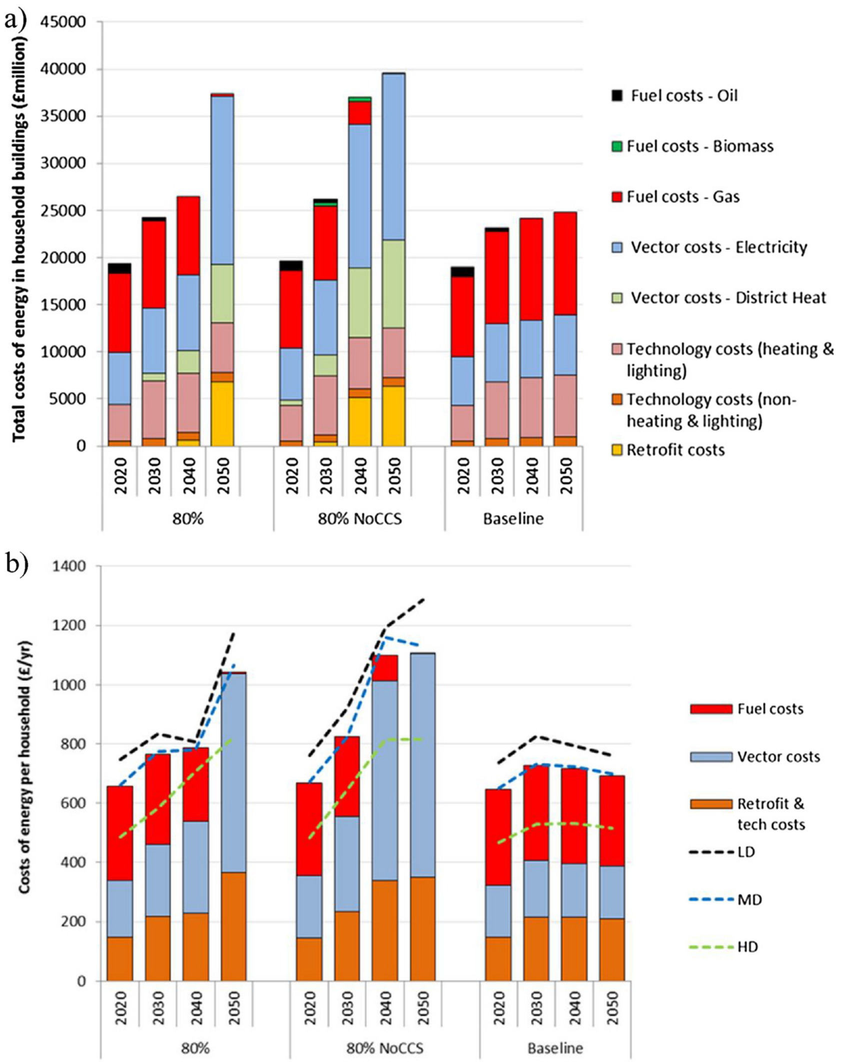

Fig. 2. Residential costs of energy provision under selected ESME scenarios (excluding the cost of new build). a) Total annual total cost of delivering energy services in household buildings and b) annual average cost per household, and by dwelling type, of delivering energy services in residential buildings. LD, MD, and HD (low/medium/high density) trend lines show average costs for low, medium and high density buildings respectively. Source: authors' own analysis.

for energy use. Buildings are therefore represented according to their density (e.g. 'low' being a detached home, and 'high' an apartment) and fabric condition (SAP rating). Similarly, the demand for private passenger mobility represented in the transport sector has no socio-economic characterisation, nor is it linked explicitly to the different household categories in ESME. It is rather an estimate of the total mobility demand for the projected population overall. This structure therefore sets the level of detail of model outputs. To illustrate this, the example of energy costs on the residential sectors is provided in Fig. 2 for three distinct scenarios[6] :

- *80%*: A scenario that meets UK climate policy, including carbon budgets 1–5 and the 2050 target.
- *80% NoCCS*: as for *80%*, but with no CCS technology deployment assumed.
- *Reference*: A scenario that assumes no climate policy.

Fig. 2(a) shows the total costs for providing energy to the residential sector. While costs can be disaggregated by type, they do not suggest how these costs may differ between households e.g. for lower income households compared to others. In Fig. 2(b), costs are provided on a 'per household' basis; the most detail that can be obtained is a breakdown by density for a given region of the UK, reflecting the model structure.

[6] The version of ESME used was v4.1.

Given that these types of model will likely to continue to be used for developing strategy, the question of whether methods can be adapted to better understand the distribution of financial impacts across households is worth considering, and further discussed in Section 2.2.

3.2. Extending the insights of energy modelling to distributional impacts

In determining approaches for exploring longer term distributional impacts using energy system models, the key objective is to highlight the issue so it is given visibility and deliberation on strategies and policy packages can start to explore mitigation of such impacts. However, due to the type of model and long term timescale, such an approach will be subject to large uncertainty, and therefore caveats need to be provided in respect of the insights that may be determined, given the limitations of the approach adopted.

For a techno-economic modelling framework, two approaches can be considered; first one where a model such as ESME could itself be disaggregated to represent different household groups – and their characteristics. This approach has three key disadvantages; i) it increases the structural detail of the model significantly, for what is already a highly complex model. This matters as it reduces the consistency and comparability with other assessments, and impacts the balance of the model. This latter point is important, as with these types of models, it is important to represent sectors with similar levels of detail; ii) it requires existing models to be re-built, which is both time and resource intensive, and iii) once re-built, the model become more computationally-intensive, and requires increased levels of resource to maintain.

The second approach is to assess distributional impacts of different pathways by taking key metrics from the model, and feeding them into a stand-alone analytical tool that can estimate impacts based on relevant datasets. None of the stated disadvantages arise, with existing models not having to increase in complexity nor having to be restructured.

Our approach to building the stand-alone tool in which to feed ESME metrics was formulated based on the following steps, and illustrated below.

1 Associate a socio-economic profile to the ESME dwellings
2 Determine the cost of energy services to households in different dwelling groups
3 Adjust the energy costs associated with different households

Step 1 associates socio-economic profiles (e.g. income, tenure, risk of poverty, composition etc.) to the dwelling types in the ESME model. This is done by using the housing condition surveys from across the UK which hold both information on the dwelling stock, and the socio-economic characteristics of householders. This is illustrated for income quintiles by box B in Fig. 3 below. A key issue is that we do not know whether the socio-economic profile of a given building type will hold in the long term. Due to this uncertainty, we would propose that this assumption is subject to scenario analysis, and can therefore be user-defined to test different socio-economic profiles.

Step 2 (represented by box A) is to determine the costs of energy based on different service delivery options in the model, which are then allocated to dwellings based on their demand for energy services such as heating and lighting. The ESME model both provides the costs and allocates these options across the dwelling types (as illustrated by the red dashed line between A and B).

In step 3, we can then estimate the costs for different dwelling types, and across the socio-economic profile of that dwelling group. Take the following illustrative example, the model determine 10,000 retrofits in 2030 for low density dwellings with poor fabric condition. It can be assumed that these are equally allocated across the quintiles. However, this approach would allow for the testing

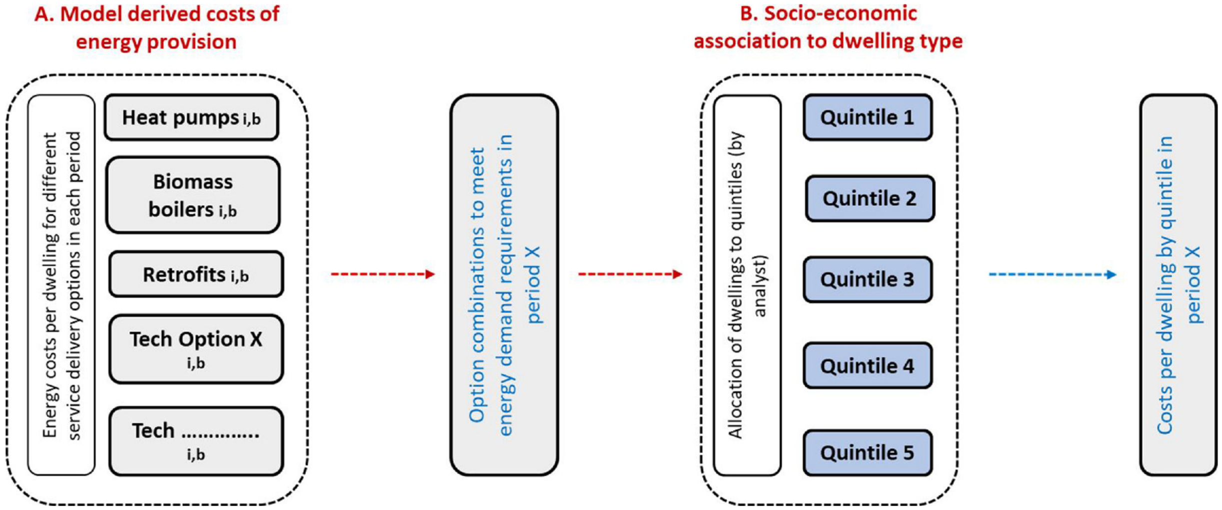

Fig. 3. Approach to allocating dwelling energy costs across households, defined by income quintiles.

of policy intervention. For example, more retrofits could be allocated to the lowest income decile, with cost implications determined for such a policy intervention, and savings to households in terms of energy expenditure.

In summary, this proposed framework provides an ability to take model metrics and consider distributional impacts. It allows for:

- An assessment of the costs facing households in different dwelling groups, broken down by a range of socio-economic variables
- An approach to exploring how these costs may change in a given period if investments are reallocated to different households e.g. based on income quintile or alternative socio-economic classification. This allows for high level policy insights, and an assessment of where costs lie, and who might meet them
- An ability to compare the costs associated with different transition pathways

It is important to underline that this tool is not for policy design, for example to assess how a given policy mechanism might impact on different households. Rather it is a tool to use alongside ESME to identify distributional issues arising from different pathways, and an understanding of what drive energy costs. It is therefore a tool for the identification of impacts and a basis to inform where decision makers might need to intervene to mitigate additional costs for specific household groups.

It also worth noting how the modelling framework deals with uncertainty. First, there is the uncertainty parameterisation in the ESME model, whereby input assumptions have uncertainty ranges. These ranges are sampled using the Monte Carlo approach, with the model then run multiple times to explore future pathways under the many combinations of uncertain assumptions (Pye et al., 2018, 2015). The different pathway metrics emerging from the analysis would provide some understanding of the uncertainty inherent in the energy systems model, and what this means for options for household and transport energy. Second, there is also uncertainty inherent in the stand-alone tool (to which the ESME metrics are passed), notably the change in socio-economic profiles of different households. Given the uncertainty of such projections, we would propose user-defined scenarios are used to explore these possible futures.

3.3. Stakeholder views on the proposed approach to modelling

Stakeholder interviewees (see Section 2) were given a brief oral introduction to the proposed modelling approach set out in the previous section. The interviews did not highlight any particular concerns (beyond the more general caveats relating to uncertainty mentioned in Section 2.2.1), and it was acknowledged that it was unlikely that all the distributional considerations in the previous subsection could be captured. However, they should be useful in interpreting and contextualizing the output. It was suggested that it would be useful if some quantification of uncertainty could be presented, even if this is only relative (i.e. between different kinds of impact or across scenarios). It should also be as clear as possible where the uncertainty arises (such as around assumptions of socio-demographic trends, transition pathways, types/extents of impact, etc.

It is important that a tool should not only be able to identify costs but also provide insights into how policy can address such impacts. These are two distinct issues. On the policy side, it would also be interesting to be able to test different ways of implementing policy; for example, i) all costs of new hydrogen infrastructure are socialised and paid by everyone, ii) only users of hydrogen pay, or iii) a carbon price is added to gas to disincentivise its use. Ideally it would permit sensitivity analysis to give insight into which factors (whether specific transitions, funding mechanisms, or broader societal or market shifts) may be most significant in terms of their potential distributional impact.

There was some support for an approach based around representative consumer groups, similar to existing classifications (such as Acorn or Mosaic[7]) but tailored to be compatible with ESME outputs and considerations specific to distributional impacts of low carbon transitions as listed above and the review section of this report. This could help provide a top-level narrative that would be of some use from a policy perspective (especially if the size of each grouping could be estimated). However, where possible, it was seen as being more directly useful to policy to have data broken down to as great a degree of granularity as possible, as this can inform exercises such as cost-benefit analyses. It was acknowledged that this may be difficult for the longer-term scenarios, but that a hybrid approach, moving to greater levels of generality (such as thought use of representative groups) further in the future, could be an appropriate balance. The vulnerability scoring approach developed by (Carley et al., 2018) is one potential route towards this.

Also from the policy side there was interest in capturing regional effects if possible, as this would be a useful addition to existing modelling (such as by National Grid, the transmission system operator). Of particular interest was the question of regional disparities, and the extent to which these might be addressed or exacerbated by transition ((Balta-Ozkan et al., 2015)] consider possible approaches to this). Some questions were raised about the extent to which it would be possible to map technologies like PV onto specific household types in specific regions, since those households would see direct costs and benefits – this is more important for distributed generation than technologies such as offshore wind. There was also interest in the possibility of considering the wider non-energy impacts of energy related measures, such as on health.

4. Conclusions

This article described a mixed methods study proposing an extension to the ESME energy systems model to allow modelling of distributional impacts of long-term low-carbon transitions. This was combined with expert stakeholder (including a range of

[7] See https://acorn.caci.co.uk/ and https://www.experian.co.uk/marketing-services/products/mosaic-uk.html

government, policy and research organizations) interview results reflecting on the use of modelling in this context and considering distributional impact mechanisms more broadly. The modelling approach differs from others that have been proposed in that it both applies over long timescales (to 2050) and attempts to capture impacts of system wide mitigation based on an overarching target rather than focus on individual policies. It should therefore be able to provide an assessment and comparison of costs facing households with different incomes and in different dwelling types under a range of transition pathway scenarios. It also allows exploration of how re-allocating these costs (e.g. through policy measures) might affect these impacts. Therefore, while it is not a policy design tool (in that it does not provide assessment of impacts of specific policies), it could provide information of how policy might be used to mitigate negative impacts and maximize equity of outcomes (therefore also reducing political risk).

The benefits of the approach are that it can be used in conjunction with aggregate energy system models through the use of proxy data to disaggregate model metrics. This allows for consideration of distributional impacts in existing models used for strategy development without wholesale restructuring, which otherwise would be a key barrier. There are of course limitations to the approach that should be recognized; only direct impacts relating to the energy system are considered, not the wider economic impacts on consumption, employment and growth that other macroeconomic models can provide. Another limitation is that the impacts are not endogenous to the modelling, meaning that there could be issues of consistency between the model itself and the stand-alone tool that would need to be carefully considered. Further, the proposed approach is not able to capture many of the possible routes to distributional impact identified through the stakeholder engagement exercise. It is therefore important that any results emerging through employing the modelling approach should be presented as only part of the picture.

Stakeholder interviews revealed broad support for the ambition to model distributional impacts of long-term low carbon transitions. While there was considerable concern about the level of uncertainty that must be inherent in undertaking such an exercise, this was perceived across the board as being outweighed by the benefit of increasing the likelihood that distributional impacts are considered in policymaking processes. The modelling approach which we propose was supported, although there was also demand for user-friendly outputs (such as through the use of consumer segmentation) and for presentation of results alongside other contextualizing information which is not captured by the modelling. This may include impacts of factors such as propensity to switch to and understand more complex energy tariffs, the role of rental status, network issues (such as electricity network congestion due to electric vehicles and heating, or gas network defection), lack of access to rooftops (for photovoltaics), garden (for ground source heat pumps), etc. We used the interview results and the background research to construct a diagram of possible long-term mechanisms of distributional impacts and groups most likely to be impacted, which provides testable hypotheses for future evidence reviews and empirical research. Further work is required to both develop the proposed ESME extension and then explore how the results can be most usefully conveyed and framed to users (especially given the considerable uncertainty).

In concluding, we note that work on distributional impacts of low carbon transitions is increasingly using an energy justice frame, considering not only the different impacts of different population subgroups but also the extent to which those groups' voices are heard (or not) and represented in decision-making processes (Jenkins et al., 2016). While we believe that incorporating distributional impacts in transition pathways modelling may contribute to giving greater prominence to the issue, it should be complemented by a more inclusive debate about how to meet carbon reduction targets in an equitable way, within nations as well as (as is more common) internationally.

Author contributions

All authors were engaged in the planning and execution of the project. MF conducted the literature review, undertook a number of stakeholder interviews and analysis, and led on writing the paper. SP was the overall project lead, and conceived the original research idea. [S/he] conducted the ESME model development work, undertook stakeholder interviews, and contributed to writing the paper. IH identified available data sources and contributed to writing the paper.

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References

Balta-Ozkan, N., Watson, T., Mocca, E., 2015. Spatially uneven development and low carbon transitions: insights from urban and regional planning. Energy Policy 85, 500–510. https://doi.org/10.1016/j.enpol.2015.05.013.

BEIS, BRE, 2018. Fuel Poverty: Methodology Handbook Fuel Poverty: Methodology Handbook. GOV.UK.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3, 77–101. https://doi.org/10.1191/1478088706qp063oa.

Carley, S., Evans, T.P., Graff, M., Konisky, D.M., 2018. A framework for evaluating geographic disparities in energy transition vulnerability. Nat. Energy 1.

Carter, N., Clements, B., 2015. From 'greenest government ever' to 'get rid of all the green crap': David Cameron, the conservatives and the environment. Br. Polit. 10, 204–225. https://doi.org/10.1057/bp.2015.16.

CCC Committee on Climate Change, 2011. The Renewable Energy Review.

CCC, 2013. Fourth Carbon Budget Review – Part 2: The Cost-effective Path to the 2050 Target.

Chapman, A.J., Pambudi, N.A., 2018. Strategic and user-driven transition scenarios: toward a low carbon society, encompassing the issues of sustainability and societal equity in Japan. J. Clean. Prod. 172, 1014–1024. https://doi.org/10.1016/j.jclepro.2017.10.225.

Chapman, A.J., McLellan, B., Tezuka, T., 2016. Proposing an evaluation framework for energy policy making incorporating equity: applications in Australia. Energy

Res. Soc. Sci. 21, 54–69. https://doi.org/10.1016/j.erss.2016.06.021.

Chitnis, M., Hunt, L.C., 2012. What drives the change in UK household energy expenditure and associated CO2 emissions? Implication and forecast to 2020. Appl. Energy 94, 202–214. https://doi.org/10.1016/j.apenergy.2012.01.005.

DeCarolis, J., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., Pye, S., Strachan, N., Trutnevyte, E., Usher, W., Winning, M., Yeh, S., Zeyringer, M., 2017. Formalizing best practice for energy system optimization modelling. Appl. Energy 194. https://doi.org/10.1016/j.apenergy.2017.03.001.

DECC, 2011. The Carbon Plan. London, UK. .

CCC, 2017a. UK Climate Change Risk Assessment 2017 Evidence Report, Committee on Climate Change.

CCC, 2017b. UK Climate Change Risk Assessment 2017 (Presented to Parliament Pursuant to Section 56 of the Climate Change Act 2008).

CCC, 2017c. Energy Prices and Bills: Impacts of Meeting Carbon Budgets. London, UK. .

Fabrizio, S., Goumilevshi, A., Kpodar, K.R., 2016. A New Tool for Distributional Incidence Analysis : An Application to Fuel Subsidy Reform [WWW Document]. IMF.

Heaton, C., 2014. Modelling Low-Carbon Energy System Designs with the ETI ESME Model.

Heindl, P., Löschel, A., 2014. Addressing Social Implications of Green Growth–energy Sector Reform and Its Impact on Households (Issue Note Prepared for Session 1 of the Green Growth and Sustainable Development Forum, 13–14 November 2014). OECD, Paris, France.

HM Treasury, The Green Book, 2018. Central Government Guidance on Appraisal and Evaluation. HM Treasury, London, UK.

Hsieh, H.-F., Shannon, S.E., 2005. Three approaches to qualitative content analysis. Qual. Health Res. 15, 1277–1288. https://doi.org/10.1177/1049732305276687.

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: a conceptual review. Energy Res. Soc. Sci. 11, 174–182. https://doi.org/10.1016/j.erss.2015.10.004.

Li, F.G.N., Pye, S., Strachan, N., 2016. Regional winners and losers in future UK energy system transitions. Energy Strateg. Rev. 13–14, 11–31. https://doi.org/10.1016/j.esr.2016.08.002.

McInnes, G., 2017. Understanding the Distributional and Household Effects of the Low-Carbon Transition in G20 Countries. OECD.

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2014.02.003.

Preston, I., White, V., Guertler, P., 2010. Distributional Impacts of UK Climate Change Policies (Final Report to Eaga Charitable Trust).

Preston, I., White, V., Thumim, J., Bridgeman, T., 2013. Distribution of Carbon Emissions in the UK: Implications for Domestic Energy Policy. Joseph Rowntree Foundation.

Pye, S., Bataille, C., 2016. Improving deep decarbonization modelling capacity for developed and developing country contexts. Clim. Policy 16. https://doi.org/10.1080/14693062.2016.1173004.

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, 575–586. https://doi.org/10.1016/j.enpol.2014.05.025.

Pye, S., Sabio, N., Strachan, N., 2015. An integrated systematic analysis of uncertainties in UK energy transition pathways. Energy Policy 87, 673–684. https://doi.org/10.1016/j.enpol.2014.12.031.

Pye, S., Li, F.G.N., Petersen, A., Broad, O., McDowall, W., Price, J., Usher, W., 2018. Assessing qualitative and quantitative dimensions of uncertainty in energy modelling for policy support in the United Kingdom. Energy Res. Soc. Sci. 46, 332–344. https://doi.org/10.1016/j.erss.2018.07.028.

Rausch, S., Mowers, M., 2014. Distributional and efficiency impacts of clean and renewable energy standards for electricity. Resour. Energy Econ. https://doi.org/10.1016/j.reseneeco.2013.09.001.

Stone, R.W., 2009. Risk in international politics. Glob. Environ. Polit. 9, 40–60.

Taylor, P.G., Upham, P., McDowall, W., Christopherson, D., 2014. Energy model, boundary object and societal lens: 35 years of the MARKAL model in the UK. Energy Res. Soc. Sci. 4, 32–41.

Thumin, J., White, V., Bridgeman, T., Searby, G., Hinton, T., Tiffin, R., Roberts, S., 2014. Research on Fuel Poverty: the Implications of Meeting the Fourth Carbon Budget. Centre for Sustainable Energy.