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Integrating housing stock and energy system models as a strategy to improve heat decarbonisation assessments

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HIGHLIGHTS

- We completely revise the representation of heat in the UK MARKAL energy systems model.
- Novel features include heat delivery infrastructure with dynamic growth constraints.
- We also integrate a simplified housing stock model into UK MARKAL.
- Disaggregation does not change the total residential fuel consumption.
- The additional detail enables us to examine policies targeting different house types.

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ABSTRACT

The UK government heat strategy is partially based on decarbonisation pathways from the UK MARKAL energy system model. We review how heat provision is represented in UK MARKAL, identifying a number of shortcomings and areas for improvement. We present a completely revised model with improved estimations of future heat demands and a consistent representation of all heat generation technologies. This model represents all heat delivery infrastructure for the first time and uses dynamic growth constraints to improve the modelling of transitions according to innovation theory. Our revised model incorporates a simplified housing stock model, which is used produce highly-refined decarbonisation pathways for residential heat provision. We compare this disaggregated model against an aggregated equivalent, which is similar to the existing approach in UK MARKAL. Disaggregating does not greatly change the total residential fuel consumption in two scenarios, so the benefits of disaggregation will likely be limited if the focus of a study is elsewhere. Yet for studies of residential heat, disaggregation enables us to vary consumer behaviour and government policies on different house types, as well as highlighting different technology trends across the stock, in comparison with previous aggregated versions of the model.

1. Introduction

The Climate Change Act 2008 requires the UK government to reduce UK greenhouse gas emissions in 2050 by 80% relative to 1990 levels [1]. In 2010, UK households emitted 85 $MtCO_2$ by direct combustion of mainly natural gas for heat [2]. Decarbonising heat has received increasing attention recently with the publication of a number of journal papers e.g. [3,4], reports examining heat decarbonisation scenarios e.g. [5–8] as well as more general technology appraisals e.g. [9,10]. The UK government published a heat strategy framework in March 2012 [11] and a heat strategy in March 2013 [12] that identify heat pumps, biomass boilers, solar heating, micro-CHP,[1] district heat networks and possibly hydrogen as low carbon alternatives to gas, and recommend large-scale deployment of these technologies in the 2020s and 2030s.

These government publications were supported by a number of energy systems studies including Ref. [13], which identifies decarbonisation pathways for the whole UK economy using the UK MARKAL energy system model. Energy system models are useful because they identify decarbonisation pathways for each sector of the economy that supply all energy service demands and meet all decarbonisation targets, across the entire energy system, at least cost. UK MARKAL has underpinned UK climate policy for the last 10 years [14,15].

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[1] CHP stands for "Combined heat and power"; micro-CHP devices are house-sized versions.

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1.1. Representing the residential sector in energy system models

While energy system models have comprehensive representations of the entire energy system, they necessarily tend to have aggregated representations of the individual sectors, and UK MARKAL is no exception [16]. The residential sector of UK MARKAL contains only two houses to represent the entire housing stock, one for existing houses (pre-2000) and one for new houses (post-2000). Other energy system models similarly have few house categories, as shown in Table 1, although the criteria for disaggregation varies between models with the age, type, occupancy and the location of houses all used. Yet none of these models are designed to specifically look at the residential sector, which is important because increasing the level of disaggregation greatly increases the size and complexity of such bottom-up models as separate sets of heat generation technologies have to be defined for each representative house. For example, the UK MARKAL disaggregation explored in this paper approximately doubles the size of the model and triples the time required to find the solution.

If the residential sector is not the specific focus for an energy system model, which is the case for all of the models in Table 1, then any disaggregation should be justified by an improvement in the representation of the energy system. It is always a challenge for the energy system modeller to find a balance between minimising the complexity of each sector while including enough detail to gain meaningful results. Identifying the appropriate level of disaggregation for each sector is a key decision for energy system modellers but is rarely explored in the literature ([17] is an exception for the transport sector). The decision is particularly important for the residential sector because heat in temperate countries accounts for a substantial proportion of total energy use. To our knowledge, no studies have reported a comparison of otherwise identical models that have different levels of aggregation in representations of residential houses, and one contribution of this study is to perform such a comparison.

1.2. Housing stock models

In contrast to energy system models, housing stock models contain disaggregated representations of the residential sector so can potentially be used to produce highly-refined decarbonisation pathways and policies *for that sector* [24]. Stock models tend to have many house categories; for example, the UKDCM [25] and BREHOMES [26] models of the UK stock have around 20,000 and 1000 categories, respectively, a Japanese model has 228 categories [27] while the BEAM European Union model has only 126 categories [28]. The chosen levels of disaggregation clearly to do not reflect the stock diversities, spatial areas or the size of the populations in the countries covered by these models.

One drawback with some stock models is the lack of representation of varying occupant behaviour in houses that are notionally in the same category [29]; for example, the temperature to which houses are heated can vary widely [30], and sophisticated tools are being developed to support the development of improved stock models (e.g. [31–33]). Such details should be important considerations when creating appropriate policies to avoid unintended consequences [34], but do not affect broader decarbonisation pathways within sectors unless there are large-scale changes in behaviour over time. This means that representing this level of detail is unlikely to improve the skill of energy system models in assessing the most appropriate system-wide pathways (in contrast to *how* the pathways should be achieved, which is a policy question that should take into account the differing circumstances of different population segments). In our experience, the aggregated nature of energy system models is sometimes identified as a weakness by policymakers, perhaps because they must deal with complex details such as these when drafting policy. It is important not to confuse the identification of the most appropriate pathways, for which an energy system model is a suitable tool, with the method of achieving them, for which a stock model might be more appropriate tool for the residential sector.

A further disadvantage of stock models is the requirement for exogenous information that is normally fixed but can vary greatly between decarbonisation scenarios, for example the permissible sectoral CO_2 emissions or the carbon intensity of electricity [24]. Energy system models represent many of these factors endogenously. For stock models that incorporate economic factors, commodity prices are represented exogenously, yet they also vary between scenarios and are calculated endogenously by energy system models. Some hybrid stock models have been developed to partly address such issues by incorporating parts of the wider energy system (typically electricity generation and perhaps transport). Examples of hybrid stock models for the UK are RESOM [8] and DynEMo [35].

1.3. Model transparency and replicability of results

Energy system models have large, complicated structures and are sometimes criticised for lacking transparency about the underlying data and assumptions, to the extent that one paper has argued that many should not be classed as scientific models as the results are not replicable [36]. To address this concern, some models have manuals made available (Ref. [22] is a particularly transparent example) while other models combine this with dedicated websites (e.g. [37]). Manuals normally explain the overall structure of the model and present some data and assumptions, but rarely make available all data and assumptions and do not generally justify model choices in terms of all the options. For example, the reasoning behind the choice of a particular level of disaggregation for a sector is not normally explained in terms of all the available statistics and options.

Even when manuals are provided, models are usually updated over time and the updates are often not fully documented. There is a tendency for such updates to gradually increase the complexity of models over time, for example by increasing the number of constraints on model behaviour [38], and there is a danger of such

Table 1
Number and description of house categories for space heating in some energy system models. The number refers to the representative houses in each spatial region or sub-region.

Model	House categories	Description
ETSAP-TIAM [18]	1	Average
Pan-European TIMES [19]	3	Flats, urban and rural houses
US EPA 9-region MARKAL [20]	1	Average
Canada TIMES [21]	4	Detached houses, attached houses, apartments; mobile homes
Belgian TIMES [22]	6	Age (existing, new) × type (rural house, urban house, flat)
Norway TIMES [23]	5	Age (existing, new) × occupancy (single, multiple-family), cottage
UK MARKAL [24]	2	Existing, new