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

Paul E. Dodds *

UCL Energy Institute, 14 Upper Woburn Place, London WC1H 0NN, UK

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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* Tel.: +44 203 108 9071.
E-mail address: p.dodds@ucl.ac.uk

[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

updates being inconsistent with previous assumptions, particularly if the modeller is not the original author. In this paper, we identify an example of the accumulation of such constraints for residential heating and consider how they can be removed or justified using a consistent strategy with clear assumptions.

For researchers that are not familiar with a model, it is difficult to understand from the documentation whether particular results are influenced more by the choice of data and assumptions or by the level of disaggregation. As well as examining the appropriate level of disaggregation, this paper identifies different options for heat representation in energy system models and examines the impacts of changing the data and assumptions using the UK MARKAL model as a case study. We aim to be fully transparent with the assumptions and data that we use in the revised model.

1.4. Contribution and structure of this paper

The relative benefits of energy system and housing stock models have previously been compared in Ref. [24]. In this paper, we build on this work by disaggregating the residential sector by house type and location within an energy system model, UK MARKAL, to internalise a simple housing stock model that offers the advantages of both model types. Our disaggregated version has 36 effective house categories, a substantial increase compared to both the standard version of UK MARKAL and the other energy system models listed in Table 1. We compare this disaggregated version with a similar aggregated version to assess the benefits of disaggregation and we use this analysis to identify how to gain the benefits of disaggregation in the aggregated version of the model.

We also critically appraise the representation of the built environment in the UK MARKAL model, identify shortcomings and options for the model, and create a completely revised version of the model that revises heat demands to match recent trends and greatly improves the representation of heat generation and delivery technologies. The focus on heat delivery infrastructure in particular is unusual for energy system models, which tend to concentrate on fuel conversion technologies and often represent infrastructure poorly [39].

The paper is structured as follows. We give a brief overview of the MARKAL model generator in Section 2 and we review and identify shortcomings in the representation of heat in the UK MARKAL model in Section 3. We present a completely revised representation of heat in Section 4 and Appendix A. We examine the impact of this revision in Section 5, including an appraisal of the benefits of disaggregating the residential sector. Finally, we identify further model limitations and discuss how these could be overcome in Section 6, making recommendations for future energy systems studies.

2. The MARKAL model generator

MARKAL is a widely-applied partial equilibrium, bottom-up, dynamic, linear programming optimisation model [40]. MARKAL models are used to identify the energy system that meets energy service demands with the lowest discounted capital, operating and resource cost, subject to constraints such as greenhouse gas emission targets and government policies. MARKAL allows us to draw insights about the relative importance of different technologies, costs and policies in the energy system, including the use of different fuels to satisfy energy demands across the economy, but the results should be interpreted in light of the limitations of the model paradigm. MARKAL identifies cost-optimal pathways for scenarios of the future that have a range of assumptions; it cannot predict the future.

A schematic diagram of a typical MARKAL model is shown in Fig. 1. Resources are converted into useful commodities in processing plants and then consumed by demand technologies in order to meet all energy service demands each year. Thousands of processing plants (termed technologies) and commodities can be represented in a single model. There are numerous unique routes from resources to energy service demands and there are no limits on the number of energy industry technologies in each route, but each route can have only one demand technology. Numerous exogenous parameter inputs are specified for each technology including capital and operating costs, the commodity conversion efficiency, the availability/capacity factor and the technology lifetime.

MARKAL represents only the annual flows of most commodities, using the assumption that there is sufficient energy storage at negligible cost to cope with demand peaks and supply interruptions. The exceptions are electricity and heat, which are treated differently as heat demand is very seasonal in nature and electricity storage is very expensive. MARKAL uses time-slices to represent these commodities. Electricity flows (ELC) are tracked using the seasonal and intra-day time-slices in MARKAL, while heat flows (LTH) are only tracked seasonally. Residential heat technologies can be defined as either demand technologies, which accounts for time-slicing for technologies consuming electricity, or as heat generation plants that supply seasonally-varying LTH to demand technologies.

3. Overview of heat in the base version of UK MARKAL

The UK MARKAL model [16] portrays the entire UK energy system as a single region. It includes imports and domestic production of fuel resources, fuel processing and supply, explicit representation of infrastructures, conversion of fuels to secondary energy carriers (including electricity and heat), end-use technologies, and energy service demands of the entire UK economy. It is calibrated to UK energy consumption in the year 2000. Six time-slices represents day (16 h) and night (8 h) for three seasons, with the intermediate season having twice the length of summer and winter.

In this paper, our base version of UK MARKAL is v3.26 [41], which was used in Ref. [13] to support the UK government heat strategy framework [11]. The residential sector is described in Chapter 6 of the UK MARKAL manual [16] and in Ref. [24].

All costs are defined in British Pounds in the year 2000. MARKAL calculates the cost-optimal pathway over the whole time horizon. Following HM Treasury [42], future costs are discounted in this calculation using a social discount rate of 3.5%, so delaying investment reduces the net present value of the costs. In addition, many technologies have a hurdle rate applied to investment costs to reflect the cost of financing investments or other barriers to use of the technology. Residential technologies in UK MARKAL have a 5% hurdle rate, although a higher rate is used for energy conservation measures as described below.

3.1. Energy service demands

The residential sector in the base version of UK MARKAL is represented using two groups of houses, with one containing existing houses and the other containing new houses (those built after the year 2000). A single average house represents all house types, from detached houses to flats, in each group. Four energy service demands are specified, representing space heating and water heating for both existing and new houses. Heat demands from new houses are assumed to be 40% lower than demands from existing houses due to the incorporation of energy conservation measures during construction. Future energy demand is estimated from housing stock projections, assuming constant space and water heating demands from each house in the future.

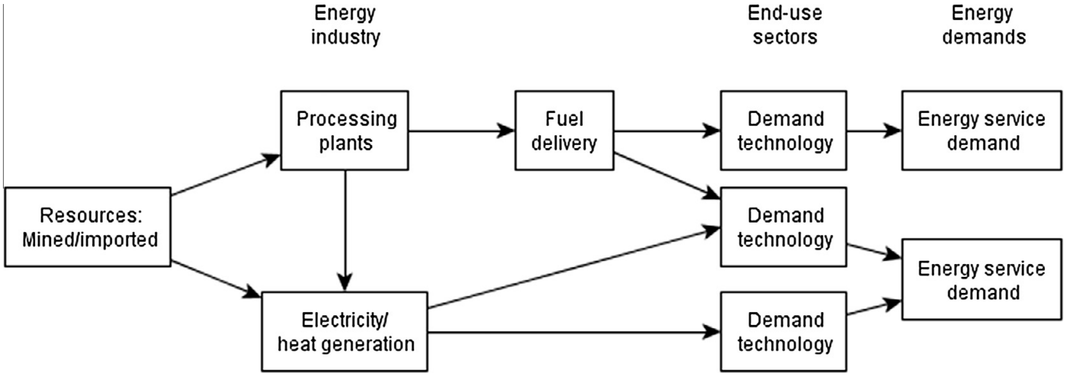

Fig. 1. Schematic diagram of a typical MARKAL model.

3.2. Heat generation technologies

Numerous heating technologies, using a range of fuels, can be used to satisfy each heat demand, including boilers, air-source heat pumps, standalone heaters, solar water heaters, fuel cell micro-CHP and district heating. The structure of these technologies in UK MARKAL is shown in Fig. 2. All of these technologies except for fuel cells are represented as demand technologies that supply heat demand(s).

3.2.1. Heat networks and micro-CHP

Numerous CHP and boiler technologies are defined in the model to produce district heat. Heat pipe networks are a substantial part of the capital cost of district heat systems and are represented in UK MARKAL as an incremental transmission investment cost on each heat generation plant (using the DTRANINV parameter). These pipes have lifetimes of many decades but using this parameter forces the model to decommission the pipes when the plant is decommissioned, after around 20 years in UK MARKAL. This means that district heating can be viewed as a transient technology in the model, despite it almost certainly being the least-cost long-term option once the pipes have been constructed.

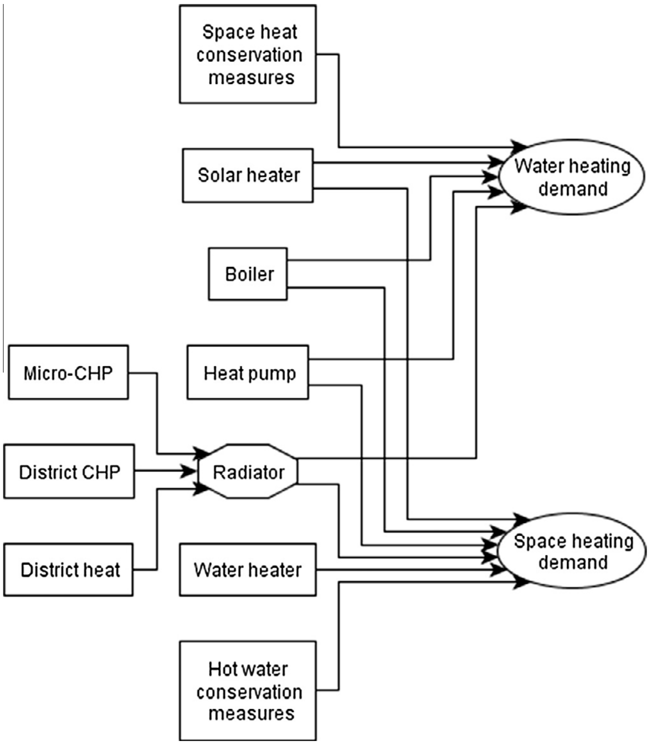

Fig. 2. Residential and service heat sector structure in the base version of UK MARKAL (v3.26). Heat production technologies are shown in rectangles, delivery infrastructure in octagons and energy service demands in ellipses.

3.2.2. Previous heat technology revisions in UK MARKAL

The current methodology for representing heat technologies has been used since the first version of the current model (v2.1 in 2006), and 93% of the residential technologies in the first version are still present in the latest version [38], but the parameter data for all heat technologies have been updated since 2006. These changes have generally focused on energy efficiency and capital cost but a lack of clear guidelines for representing technologies has led to inconsistencies as the model has been updated by different teams. For example, all of the technologies are represented with a capacity factor of 100% (i.e. they are assumed to operate constantly) while the actual capacity factor is only 5–10% for modern boilers. This approach is accurate if the capital costs are increased by a factor of 5–20 to reflect the actual capacity factor, an approach that is used in the ETSAP-TIAM model [18]. However, an update to UK MARKAL v3.26 reduced the capital costs of air-source heat pumps by a factor of 4 as the new cost was based on the power output rather than the annual energy output, causing the cost of heat pumps to be underestimated in the most recent version. Data consistency is a key issue for more established models that have received numerous updates and is one driver that contributed to the model revision presented in Section 4.

3.3. Energy conservation measures

Seventeen heat-related energy conservation measures are represented for existing houses only, including wall and loft insulation, double-glazed windows and behaviour-related measures such as improved heating controls. All of the technologies contribute directly to reducing space or water heating demands. The sum of the demand reductions from all technologies is 476 PJ/year but a separate system-wide constraint limits the total deployment of conservation measures to 221 PJ/year. Conservation measures have a hurdle rate on capital costs of 8.75% to represent factors that deter householders from deploying them, even when it is in their interests to do so.

3.4. Non-economic constraints

Heat technology uptake in the base version of UK MARKAL v3.26 is restricted by eight broad constraints that are listed in Table 2. These constrain investment in or the use of different groups of technologies to represent non-cost factors and are mostly applied to low-carbon technologies. The scenarios produced for DECC [11] changed three of these constraints and introduced a further eight new constraints, also listed in Table 2, to set market shares in line with the UK government's Carbon Plan [43]. This approach presupposes that all current government plans will be completed successfully. More importantly, there is often uncertainty over the appropriate levels for constraints, as exemplified by the DECC increase in the maximum proportion of heat pumps from 30% to 52% of the total heat supply.

Highly-constrained models give few insights into different decarbonisation pathways. For example, while Fig. 3(a) shows an apparently rich pathway for UK heat decarbonisation from the DECC study, this is partly an artefact of the constraints on the sector. Fig. 3(b) shows a similar scenario which has the minimum supply constraints and the heat pump maximum share constraint removed; in this case, solar heating is the most competitive technology in 2050 but is heavily constrained, and heat pumps are the next most competitive. We are not suggesting that such constraints are unwarranted but this comparison does illustrate the importance of carefully choosing such constraints and being explicit about their impacts. One aim of the model revision presented in this paper is to remove or justify such constraints.

4. Revised built environment heat model in UK MARKAL

In this section, we describe our revised version of UK MARKAL that completely redefines the residential sector with a new structure and with new, internally-consistent data. We incorporate a simplified housing stock model by disaggregating the residential sector by house type to better represent the diversity of decarbonisation options across house types. Our disaggregated representation of the residential sector has six house types: bungalow; detached; semi-detached; terraced; converted flat; and purpose-built flat. Each of these house types is implemented for both new and existing houses, so there are twelve house types in the model in total. We chose to disaggregate by house type because larger houses tend to have lower capital:fuel cost ratios for heat provision so are more likely to favour capital-intensive technologies than smaller houses and flats. We apply constraints to each house type to reflect the restrictions on houses that are located in rural areas and have no connection to the natural gas networks. Further constraints restrict district heating to urban areas. The disaggregated model therefore effectively represents 36 house types, with an urban/suburban/rural split for each of the main twelve house types.

We concentrate on the changes to the model in this section. We collected our revised data from numerous sources and these are described in Appendix A in the Supplementary Data.

4.1. Revised energy service demands

Total annual residential heat demand in the base version of UK MARKAL assumes that existing houses have fixed energy demands to 2050 of 32.7 GJ/year for space heating and 13.4 GJ/year for water heating, and that new house demands are 40% lower than existing house demands. Statistics of energy demand for heating are not available but there are statistics for space and water heating fuel consumption [45], which are summarised in Table 3. We combined these fuel consumption statistics with information about the market share of each heat technology, from the English housing survey 2009 [46], to estimate the breakdown of fuel consumption by house type and by technology in 2008 (when gas consumption was close to the 5-year average). We estimated the total heat demands for each house type using the average energy efficiency of each technology. While space heating demand is almost unchanged from the base version, at 33.0 GJ/year, the water heating demand is 34% lower at 8.8 GJ/year (Table 3). In the revised model, we assume that only space heating will reduce in new houses and that water heating will be the same as for existing houses. The housing stock trends that we use are shown in Fig. 4.

We derived new heat seasonal demand fractions based on natural gas consumption statistics as 85% of households currently use gas for heating. We calculated total gas demand in each season by combining daily gas consumption statistics with estimates of the gas used by low-consumption consumers (<73 MW h/year), using data from National Grid [47]. We estimated space heat demand by subtracting hot water and cooking gas demands from this total. Fig. 5 shows the seasonal breakdown of space heating demands in the base and revised versions of UK MARKAL, as well as the total gas consumption.

4.2. Revised heat sector

A diagram of the structure of the revised heat sector is shown in Fig. 6. This structure is repeated for existing and new houses, for each disaggregated house type. Only district heating technologies

Table 2
List of constraints applied to heat generation technologies (excluding district heat technologies) in the residential sector of UK MARKAL in v3.26 of the model (denoted "v3.26"), including those added or altered for the scenarios supporting the DECC fourth carbon budget report [44] (denoted "DECC").

v3.26	DECC	Description
X		Minimum district heat supply increases from 2.3 PJ/year in 2010 to 3.4 PJ/year in 2050 (applies to residential and commercial/government sectors)
X		Electric boilers/heaters supply at least 8% of heat consumption in all years
X		Electric boilers/heaters supply limited to 15% of heat consumption until 2030
X		Electric night storage heaters limited to 30% of total electric boiler/heater supply
X		Investment in non-condensing gas boilers prohibited
X	X	Solar thermal heat supply limit ranges from 0.7 PJ/year in 2010 to 16.6 PJ/year from 2020 onwards; DECC increased the upper limit to 76 PJ/year from 2035
X	X	Maximum heat pump supply limits range from 1.1 PJ/year in 2010 to 39 PJ/year in 2050; DECC increased the 2050 limit to 1397 PJ/year
X	X	Maximum heat pump supply limited to supplying 30% of heat demand (including energy conservation in the total) in all years; DECC introduced a range of limits from 24% in 2015 to 53% in 2050
	X	Maximum heat pump capacity investment increases from 75 PJ/year in 2015 to 278 PJ/year in 2050
	X	Maximum heat pump capacity investment of 175 PJ/year in all years
	X	Heat pumps produce at least 28 PJ/year heat in all years
	X	Solar thermal heaters produce at least 7.4 PJ/year heat in all years
	X	Solar thermal heater capacity investment limits range from 12.5 PJ/year in 2015 to 37.5 PJ/year in 2050
	X	Biomass boilers produce at least 2.1 PJ/year heat in all years
	X	Upper investment limit in pellet boiler capacity increases from 21 PJ/year in 2015 to 64 PJ/year in 2050
	X	Upper investment limit in wood boiler capacity increases from 5 PJ/year in 2010 to 64 PJ/year in 2050

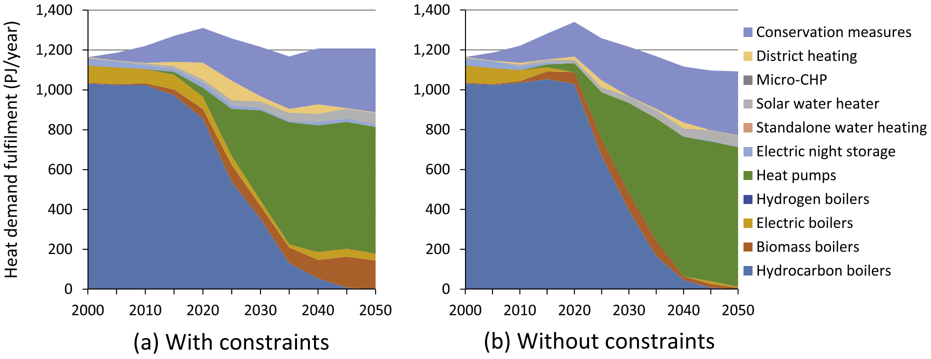

Fig. 3. Heat demand fulfilment in existing houses for the UK with a 90% reduction in CO_2 emissions in 2050 relative to 1990 (scenario DECC-1A-IAB-2A in Ref. [13]). Graph (a) is similar to Fig. 8 of Ref. [13], but excludes demand response, while Graph (b) is a similar scenario with some residential heat constraints removed as described in the text. Total demand fulfilment in (b) is lower than (a) due to a higher elastic demand reductions. Hydrocarbon boilers include natural gas, coal and oil-fired boilers, but only natural gas boilers are used after 2030.

Table 3
UK housing stock and energy consumption statistics in 2008. Total fuel consumption data are from Table 3.7 of DECC [45] and are disaggregated by house type using data from Table 3.23 of the same source.

	Number (000s)	Floor area(m^2)	Total fuel consumption (PJ/year)		Heat demand per house (GJ/year)	
			Space heating	Water heating	Space heating	Water heating
Bungalow	2468	76	120	30	36.2	9.4
Detached	4569	148	302	77	49.2	12.7
Semi-detached	6887	93	347	88	37.7	9.7
Terraced	7757	84	303	77	27.5	7.5
Flat (Converted)	1082	67	44	11	26.7	7.7
Flat (Purpose built)	4097	56	108	28	17.2	5.0
Total/weighted average	26,861	91	1224	311	33.0	8.8

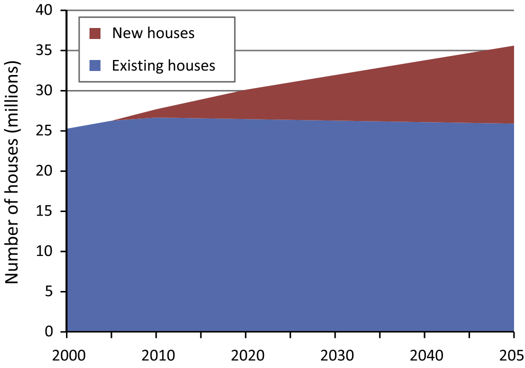

Fig. 4. Existing and new house trends in UK MARKAL in the period to 2050.

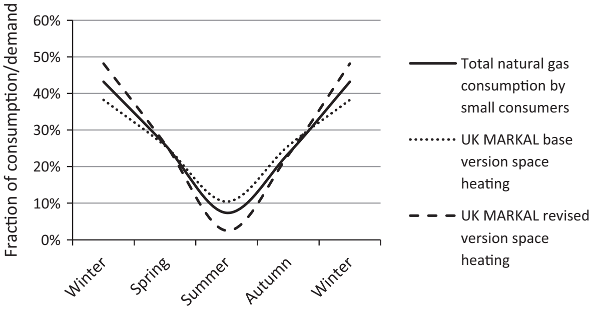

Fig. 5. The solid line shows the fraction of UK natural gas consumed in each season, averaged over the period 2005–2011, by small residential and commercial users (<73 MW h/year) for all purposes (space heating, water heating and cooking). These data are from National Grid [47]. The dotted lines show the seasonal fraction of residential space heating only in the base and revised versions of UK MARKAL.

are represented as a single sector, which supplies heat to separate water pipes for each house type.

4.2.1. Heat delivery infrastructure

The revised model has a much more comprehensive representation of heat delivery infrastructure than the base model, with district heating pipes, wet radiator systems and underfloor heating systems all represented explicitly. This means, for example, that flats which are currently heated using standalone electric radiators must pay to have wet radiator systems fitted, in addition to heat network piping, in order to use district heating; such costs are not represented in the base model. This approach also allows us to constrain the model to use minimum amounts of wet heating to reflect consumer preferences, as an alternative to the base model approach of constraining specific heat technologies. Underfloor heating systems enable heat pumps to operate more efficiently than existing radiator systems, which operate at higher temperatures, and we include this consideration in the revised model. We assume that the cost of installing wet heating systems in new homes is half the cost of retro-fitting existing homes. For district heating, we represent the pipes as separate technologies from the heat generation plant with 50-year lifetimes so district heat is no longer treated as a transient technology in the model. For the aggregated version of the model, we model these pipes using a cost curve that accounts for the differences between house types.

4.2.2. Heat generation technologies

New technologies in the revised model include hydrogen boilers, electric night storage heaters, ground-source heat pumps and a much improved representation of micro-CHP, including natural gas and wood-fired Stirling engines. All of the heat generation technologies produce heat (LTH) with the exception of night storage heaters, which do not use wet heating systems and must be

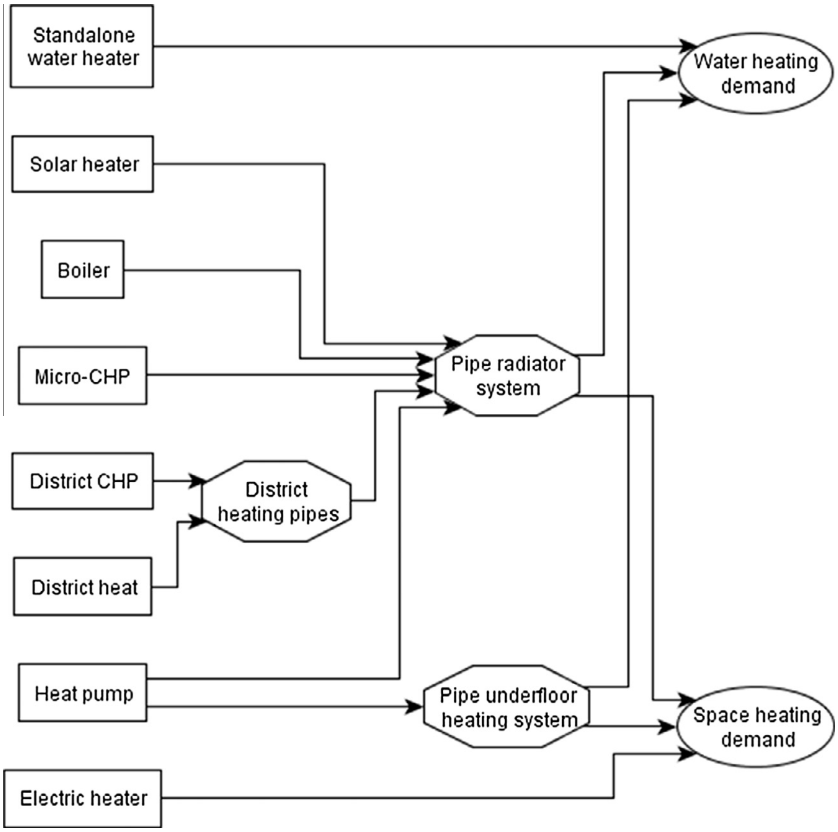

Fig. 6. Residential and service heat sector structure in the revised version of UK MARKAL. Heat production technologies are shown in rectangles, delivery infrastructure in octagons and energy service demands in ellipses.

represented as a demand technology to use the MARKAL night storage capability.

We calculate the MARKAL investment costs for the maximum power output of each technology and we specify seasonal capacity factors to reflect the average annual output. This approach avoids the data discrepancies in the base version of the model (discussed in Section 3.2.2). The revised heat sector has new cost and efficiency data for all technologies and the sources of these are summarised in Appendix A. Each technology is separately defined for each house type, with differences between house types represented using the assumptions in Table A8 of Appendix A, because both the energy demand per household and the size (and hence capital cost) of the technologies vary by house type. We used cost rather than price data for each technology where possible and we did not include the impact of value added tax (VAT).[2]

4.2.3. Energy conservation measures

To incorporate conservation measures into the disaggregated version of the model, we split the demand reduction from each measure between the house types in proportion to their heating demands, assuming that measures would be deployed equally across all house types.

4.3. Non-economic constraints on technology deployment

We use a number of additional constraints to account for non-economic limitations on some technologies as shown in Table 4. We force the model to maintain the current deployment of wet central heating in all buildings to account for consumer preference for central heating systems, particularly in larger houses. The deployment of heat pumps is limited for each house type to account for the large space requirements in the house and in the garden, and also for consumer preferences against noisy external equipment and for planning regulations that prevent deployment in some houses. The maximum natural gas supply is set at 5% above the current supply for all buildings to account for rural areas that are too remote to be served by the gas network (these houses are also prevented from using district heating). Finally, these constraints do not account for the small number of houses in rural areas that can use neither heat pumps nor natural gas, so we use a separate constraint for these buildings.

We produce aggregated residential constraint data for an average house by averaging the disaggregated data, weighted according to the total energy demand of each house type.

4.4. Technology growth constraints

The deployment of new technologies in MARKAL-type models is limited only by economic concerns (usually the retirement of previous capacity), but in reality there are non-economic limitations that restrict the rate of growth of new technologies such as the presence of existing infrastructure with long lifetimes (e.g. the gas distribution networks), technology interrelatedness and a regulatory structure built around current practices [48,49]. A characteristic s-shape deployment curve has been observed for many technologies e.g. [50]. Constraints can be added to MARKAL models to represent growth curves in each technology, although they have not previously been used in UK MARKAL.

In the base version of UK MARKAL, user constraints are used to implement growth curves that are fixed in time, which are only effective if the optimum technology deployment occurs at the time

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[2] VAT in the UK is levied at 20% for fossil-fuelled boilers but at lower rates for renewable heat technologies and energy conservation measures.

Table 4
Technology deployment constraints in the revised version of UK MARKAL. Heat pump and natural gas constraints are applied only to heat generation technologies and any energy conservation measures are excluded.

	Minimum central heating (%)	Maximum heat pumps (%)	Maximum natural gas (%)	Neither heat pumps nor gas (%)
Bungalow	91	80	86	2.8
Detached	98	80	90	2.1
Semi-detached	95	70	95	1.4
Terraced	91	50	96	2.1
Flat (Converted)	76	25	79	16.0
Flat (Purpose built)	71	20	71	23.5
Average house	89	57	89	6.0

Table 5
Maximum annual growth rates applied to new residential heat technologies in the revised version of UK MARKAL.

Technology	House type	Maximum annual growth rate	Source
Boilers	All	None	
Central heating	All	None	
Heat pumps	All	50%	Radov et al. [51]
Micro-CHP	All	40%	Staffell [52]
Solar water heater	All	50%	Assumed
District heating pipes	Existing	10%	Euroheat & Power [53]
	New	30%	Assumed-fit during construction
Underfloor heating	Existing	10%	Assumed-retrofit difficult
	New	50%	Assumed-fit during construction

Table 6
Technology market share for residential heat provision in 2050, for the scenario with no CO_2 emissions constraint. Results are presented for the revised model, firstly by house type in the disaggregated version and secondly for the average of the disaggregated version and for the aggregated version. Rounding causes some rows to not sum to 100%.

	Boiler (%)	Heat pump (%)	District heating (%)	Other (%)
Bungalow	80	10	0	9
Detached	90	8	0	2
Semi-detached	91	3	1	5
Terraced	90	2	0	8
Converted flat	55	5	16	24
Purpose-built flat	50	13	8	29
Disaggregated version	85	6	1	8
Aggregated version	87	4	0	9

assumed by the modeller. In the revised version, we instead implement dynamic growth constraints on the initial deployment of new technologies using the MARKAL GROWTH function. We specify the annual growth rate of several technologies as a function of the existing capacity as shown in Table 5. We assume a minimum capacity at which each growth rate starts to be applied equivalent to around 10,000 average houses using each technology.

Our growth constraints account for the first part of the s-curve. We do not use additional constraints for the other parts of the curve as there is much uncertainty about the gradient of the curve and we believe that the main limiting factor at that stage will be economic, through the retirement of existing stock. It would be possible to apply overall investment constraints, similar to those used in the base model (Table 2), to limit the gradient and the total deployment of specific technologies, but in our experience, growth rates have a much greater influence on the model.

5. Impact of the model changes

In this section, we examine the impact of our model changes for two scenarios that characterise the evolution of the UK energy system both with and without a CO_2 emissions constraint. UK climate policy is implemented in UK MARKAL by constraining CO_2 emissions to reduce linearly between 2000 and 2050. Some studies interpret the 80% emissions reduction target in 2050 as a 90% reduction in CO_2 in the model e.g. [13,54], to recognise uncertainties in the contribution of non-CO_2 GHGs and the emissions from land-use change and from international bunker fuels. In this study, following the approach of Refs. [39,55,56], we use an 80% target for consistency with UK policy and we exclude the UK share of international aviation and shipping emissions from all scenarios. All scenarios use elastic demands that reduce consumption as prices rise due to policy changes.

The revised version of the model includes all of the residential sector changes described in Section 4 and also includes the revised representation of the gas network described in Ref. [39]. We prevent the model from building a new low-pressure hydrogen pipe network to supply houses and we also prevent the conversion of the natural gas network to deliver 100% hydrogen as both of these are speculative options; the latter case is explored in Ref. [56].

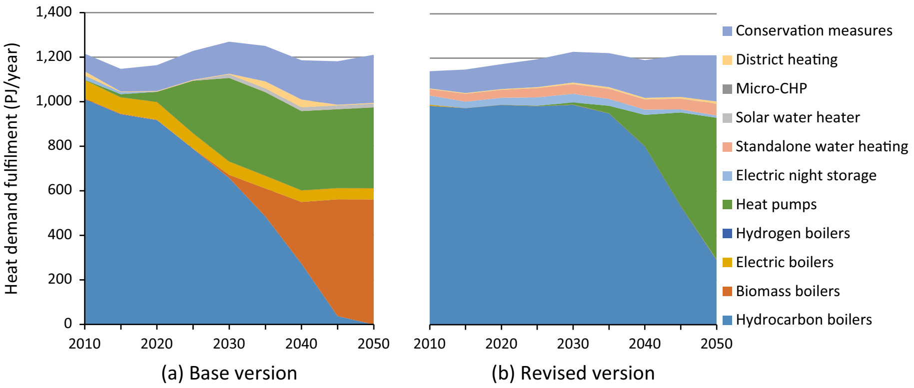
5.1. Impact of the model changes with unconstrained CO_2 emissions

For the scenario without a CO_2 emissions constraint, the share of gas boilers in the base version reduces from 85% in 2010 to only 18% in 2050, with district heating, air-source heat pumps and boilers (gas, biomass and electric) each supplying a third of heat demand. In contrast, the optimal technology configuration in the revised version has a similar market share for gas boilers to the present, with only a small number of heat pumps deployed in areas lacking a connection to the gas network (Table 6). This change is primarily driven by the higher capital costs of non-gas technologies in the revised version.

5.2. Impact of the model changes with constrained CO_2 emissions

The optimal technology mixes in the base and revised versions for the scenario with a CO_2 emissions constraint are compared in Fig. 7. In the base version, gas boilers are phased out completely by 2050 and are replaced by air-source heat pumps (to the 30% limit) and by biomass pellet boilers. The revised version also deploys air-source heat pumps to the maximum extent allowed by the non-economic constraints in Section 3.4 but continues to deploy natural gas boilers in the remaining houses. This means that residential CO_2 emissions increase from 2 $MtCO_2$ in the base version to 18 $MtCO_2$ in the revised version. Hence the increased heat decarbonisation costs in the revised version cause the optimum balance of CO_2 emissions to shift between sectors, which is an important insight that could not be derived from a single-sector model such as a housing stock model. This change is reflected by the marginal price of emitting CO_2 in 2050 increasing from £288/tCO_2 in the base version to £361/tCO_2 in the revised version.

The breakdown of technologies in each house type is shown in Table 7 for the revised case. Air-source heat pumps are deployed to the limit for almost every house type, in preference to



(a) Base version (b) Revised version

Fig. 7. Residential heat demand fulfilment in the base and revised versions of UK MARKAL with an 80% reduction in CO_2 emissions in 2050. The base version is different from that shown in Fig. 3(a) as it does not include the additional DECC constraints from Table 2 and because an 80% rather than 90% CO_2 reduction in 2050 is used. Hydrocarbon boilers include natural gas, coal and oil-fired boilers, but only natural gas boilers are used after 2030.

Table 7
Technology market share for residential heat provision in 2050, for the scenario with an 80% CO_2 emissions reduction in 2050 relative to 1990. Results are presented for the revised model, firstly by house type in the disaggregated version and secondly for the average of the disaggregated version and for the aggregated version. Rounding causes some rows to not sum to 100%.

	Boiler (%)	Heat pump (%)	District heating (%)	Other (%)
Bungalow	14	80	0	6
Detached	20	78	0	2
Semi-detached	25	70	1	4
Terraced	43	50	0	7
Converted flat	45	25	14	16
Purpose-built flat	50	20	6	24
Disaggregated version	29	63	1	6
Aggregated version	32	63	0	5

ground-source heat pumps. District heating is deployed in smaller properties, mainly for new houses as the capital costs of laying district heating pipes are lower. Gas boilers continue to be used in houses where heat pumps and district heating cannot be used but where a central heating system is required. Underfloor heating, which allows heat pumps to operate at higher efficiencies but has a high retro-fit cost, is not installed in any existing houses but is installed in 13% of new houses by 2050. Other technologies, such as standalone water heaters and night storage radiators, are used in a substantial proportion of flats but not in larger houses.

5.3. Impact of non-economic and growth constraints

The impact of the non-economic and dynamic growth constraints, described in Sections 4.3 and 4.4, are illustrated in Fig. 8 for air-source heat pumps. Heat pump deployment is much higher when the non-economic constraints are not applied, demonstrating the importance of choosing such constraints carefully. Imposing a growth constraint has little impact on the final energy system but does affect the rate of the transition to air-source heat pumps, with a typical s-curve produced that delays the transition by several years. The rate of deployment after 2040 could be further slowed if necessary by imposing a separate constraint on investment rates in new capacity.

5.4. Comparison of annual running costs of competing technologies

Since MARKAL identifies the cost-optimal evolution of an energy system, it is difficult to understand the relative competitiveness of different technologies using the model results. This is important because we make numerous assumptions about the future costs and performances of technologies, which are inherently uncertain. One method of comparing technologies is to calculate the costs of each technology off-model using marginal fuel prices from a model scenario. Care must be taken when interpreting such results because the prices depend on the supply and demand for each fuel across the economy and include the cost of emitting CO_2, so are only valid for the technology mix and assumptions from the chosen scenario.[3]

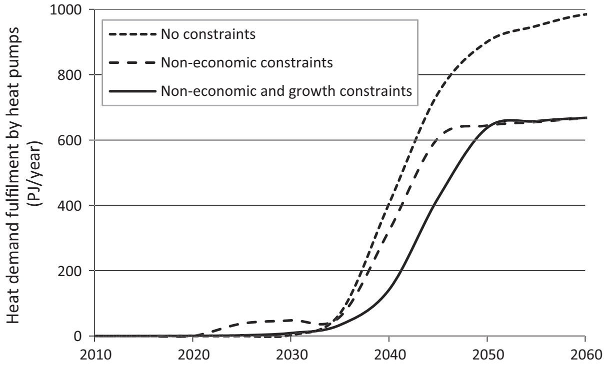


Fig. 8. Effect of non-economic and growth rate constraints on air-source heat pump deployment in the scenario with an 80% reduction in CO_2 emissions in 2050 relative to 1990.

Table 8 compares the costs of the principal heat technologies in 2050 for an average UK house using fuel prices from the constrained emissions scenario. Gas and electric boiler, storage radiator and gas-powered CHP costs are dominated by fuel costs, despite the income from electricity generation being subtracted from the CHP fuel cost. In contrast, biomass-fuelled boiler and heat pump costs are dominated by the capital and O&M costs. The air-source heat pump, which is assumed to be cheaper and more efficient in the future than currently-available models, is the cheapest option for a wet heating system; if these technological improvements were not realised in the future then gas boilers would continue to be cheaper, despite the inclusion of the cost of CO_2 emissions in the marginal price of gas. The cost of biomass-fuelled boilers is very high due to the high capital costs, which explains why they are not deployed in the revised version. In UK MARKAL v3.26, biomass is more competitive because the biomass boiler capital costs are too low.

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[3] The calculation of market commodity prices across the economy is an important advantage of energy system models over simpler accountancy-based methods.

Table 8
Comparison of annual running costs for a range of heat technologies installed in an average UK house in 2050. All costs have units £(2011)/house. The capital cost, which includes installation costs, is annualised across the technology lifetime using a hurdle rate of 5%. The fuel costs are calculated from UK MARKAL residential marginal fuel prices in the scenario with a CO_2 emissions constraint for the year 2050 and, where applicable, include the marginal price of emitting CO_2 calculated by the model (£361/tCO_2 in £[2011]). Value-added tax (VAT) is not included in any of the costs.

	Capital cost	Annual capital and O&M cost	Net fuel cost	Total annual cost	Cost for fuel (%)
Boiler-natural gas	£1903	£374	£1323	£1697	78
Boiler-electric	£1978	£388	£1842	£2230	83
Boiler-pellet	£8726	£1713	£920	£2634	35
Night storage radiator[a]	£1243	£244	£605	£849	89
Air-source heat pump in 2010	£7526	£980	£785	£1766	44
Air-source heat pump in 2025	£5952	£775	£687	£1462	47
Ground-source heat pump	£9326	£1215	£621	£1835	34
Stirling micro-CHP 2030 gas	£3102	£454	£1553	£2007	77
Stirling micro-CHP 2030 wood	£7077	£1036	£1096	£2132	51
PEMFC CHP with gas reformer	£2148	£407	£1602	£2009	80

[a] Night storage radiators supply only space heating while all of the other technologies supply both space heating and hot water.

6. Discussion

The disaggregated housing sector enables us to gain insights about the use of different technologies in different house types. We could use the revised version of UK MARKAL to examine broad impacts of government policies on different parts of the market, although the level of disaggregation is coarse compared to a typical housing stock model. We could also use different elasticities of demand for each house type to represent differing responses to price rises, since richer people, who tend to occupy larger houses, might be less willing to reduce energy consumption in response to price rises than poorer people. However, even this level of disaggregation might be insufficient for policy analysis and it might be more appropriate to use the energy systems results as boundary conditions in a housing stock model.

If the residential sector is not the principal focus of a research study then the disaggregated version only provides additional insights if it produces different results to a similar aggregated version. We compare the results of disaggregated and aggregated versions of the revised model in Tables 6 and 7. The aggregated version has only slightly different technology market shares and these differences would have negligible impact on the other economic sectors in the model. One reason that the results are so similar is that one of the most important differences between housing types, the cost and availability of building district heat infrastructure, is represented in the aggregated model using a cost curve that accounts for the different house types. This is a much more efficient method for incorporating many of the differences between house types than fully disaggregating the sector. With the inclusion of this (and other similar cost curves as required), the aggregated version of the revised model is sufficiently accurate for studies that are not focused on the residential sector.

It is possible that disaggregating the residential sector in a different way, for example by household income, would produce more subtle trends across the sector, although this might be better accomplished using a housing stock model with the results fed back into an energy system model. Yet houses tend to be categorised in most stock models according to the physical structures and locations rather than the occupants [24]. An income-based disaggregation in an energy system model would facilitate the use of macroeconomic modelling to examine income changes and energy service affordability over time.

6.1. Robustness of the revised model

Energy system model outputs are sometimes interpreted as the most appropriate future configuration of the energy system. Yet the results depend on a large number of hypotheses and assumptions about the future, including demand levels, commodity price trends and learning curves of heat generation technologies. Moreover, energy system models are prone to ‘tipping point’ behaviour, where small changes in costs cause great variations in the optimal pathway. These uncertainties have generally been examined in a very limited way in previous studies, for example by examining a small number of scenarios with varying commodity and technology prices e.g. [44]. More comprehensive methods to analyse uncertainties are now being developed including stochastic [57], Monte Carlo [58] and MGA (Modelling to Generate Alternatives) [59] approaches, but these have generally been applied to electricity generation or to the whole energy system in these studies rather than to residential heat.

6.1.1. Energy service demands

There is uncertainty over future heat demands. A rise in average house air temperature between 1970 and 2000 from 14 °C to 18 °C (derived from [45]) contributed to increased space heat demand in that period but the widespread deployment of energy conservation measures has reduced demands since 2000. It is unclear how demands will continue to change in the future, but we have experimented with different levels of demand and our results are robust to demand variations.

UK MARKAL represents behavioural change by reducing demands in response to price rises using demand elasticities. It would be possible to represent non-economic behavioural changes that reduce heat demand using additional energy conservation measures.

6.1.2. Heat technology costs

The cost of installing new heating systems can vary markedly; for example, the installed cost of 15 kW wood-fuelled boilers in the UK varied between £3175 and £16,479 in one study [60]. The drivers of these variations are unclear. We use typical representative capital costs in this study but these account for neither variations within each type of technology, caused by technical differences between models, nor installation differences due to variations in the housing stock. Our approach is clearly not going to account for niches where such technologies can be successful. The aggregated nature of energy system models means that they do not represent niches very well and a housing stock model that also disaggregates the stock according to the degree of urbanisation and the age of the buildings might be a more useful tool for this type of analysis. The insights from such models can be used to improve the representation of the heat in energy system models.

6.1.3. Converting the gas networks to deliver hydrogen

Micro-CHP technologies are not used in any decarbonisation scenarios because these technologies produce higher emissions than standard boilers, as a result of their higher gas consumption, and it is cheaper to generate zero-carbon electricity using alternative technologies. We do not allow hydrogen to be piped directly to houses for use in micro-CHP fuel cells, as the technical feasibility of this option is not well understood, but Ref. [56] examines a scenario where the gas network is converted to deliver hydrogen and concludes that micro-CHP could be the most cost-effective technology to decarbonise heat in the UK if the conversion costs are low enough.

6.1.4. Heat pump representation

Heat pumps work most efficiently in well-insulated homes, yet the UK has some of the oldest and least thermally-efficient buildings in Europe [11]. In the revised model, the heat pump energy efficiencies are chosen to represent the entire stock irrespective of the age and energy efficiency of different buildings. Expanding the house type disaggregation according to age and energy use would enable us to refine the heat pump energy efficiencies for different buildings, if sufficiently-reliable heat pump data were to become available, but this would be at a cost of a larger and more complicated model.

6.2. Policy implications of the revised model

The UK government has identified a range of alternative low-carbon technologies to gas boilers including heat pumps, biomass boilers, solar heating, micro-CHP and possibly hydrogen boilers. Our results suggest that biomass boilers are not likely to be cost-optimal methods of meeting CO_2 emission targets in the future, while continuing to use natural gas in some homes might be a cheaper and still acceptable alternative. The government has forecast large-scale deployment of low-carbon technologies in the 2020s and 2030s in order to meet the 2050 emissions target [11,12]; in our study, the cost-optimal time for deployment of these technologies is later, in the period 2035–2050, but the government's ambition should be praised.

There are currently three main policies to encourage a shift to low-carbon heat technologies in the residential sector. First, the Renewable Heat Premium Payment subsidises the installation of solar, biomass and heat pump technologies in order to assess their performance in different environments and to develop supply chains and markets for each technology (DECC, 2012e). Second, the government has proposed extending the Renewable Heat Incentive to the same technologies with annual payments linked to the quantity of produced heat (DECC, 2011d). Third, feed-in tariffs (FITs) subsidise electricity generation from micro-CHP (DECC, 2012c). While experimentation with alternative technologies is very valuable for understanding their efficacy and for identifying the best long-term options, we question whether large-scale deployment of biomass and solar technologies should be supported by government subsidies at the present time.

7. Conclusions

We have completely revised the residential heat sector in the UK MARKAL model. Our revised model integrates a housing stock model into UK MARKAL, building on the comparison of these two types of model in Ref. [24]. It is unusual in two regards: (i) it includes many more building categories than the other energy system models received in Table 1; and, (ii) it represents heat delivery infrastructures, including radiator and underfloor heating systems. New non-economic and dynamic growth constraints represent real-world limits and consumer preferences on the adoption of new technologies. Our revisions greatly change the cost-optimal mix of heat technologies in scenarios both with and without a CO_2 constraint, demonstrating the importance of the choice of data and assumptions that underpin the model.

We have examined whether disaggregating the residential sector changes the overall model results in a systematic way for the first time. In our scenarios, disaggregation does not affect the overall residential fuel consumption when compared to a similar aggregated version with district heat cost curves, so the model skill for representing the total residential fuel consumption is not improved. This finding supports the aggregated approach used in the energy system models in Table 1.

Yet integrating a building stock model does offer some advantages. The disaggregated model shows that different technologies are optimised to different house types. It enable us to examine residential heating trends across the stock and the impact of broad government policies on different house types, which enables us to devise sector-specific policies while still benefiting from an internally-consistent representation of the whole energy system.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2014.06.079.

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