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Handling uncertainty in housing stock models

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ABSTRACT

Housing stock models can be useful tools in helping to assess the environmental and socio-economic impacts of retrofits to residential buildings; however, existing housing stock models are not able to quantify the uncertainties that arise in the modelling process from various sources, thus limiting the role that they can play in helping decision makers. This paper examines the different sources of uncertainty involved in housing stock models and proposes a framework for handling these uncertainties. This framework involves integrating probabilistic sensitivity analysis with a Bayesian calibration process in order to quantify uncertain parameters more accurately. The proposed framework is tested on a case study building, and suggestions are made on how to expand the framework for retrofit analysis at an urban-scale.

1. Introduction

1.1. Impacts of domestic energy demand

Residential energy use accounts for 29% of global energy consumption and 21% of global CO_2 emissions [1], making the residential sector an important focal point in relation to the dual issues of climate change and resource depletion. The majority of energy use in households in developed countries is for space heating, which accounts for 53% of residential energy consumption, followed by electricity for appliances (which includes air-conditioning) at 21%. Domestic hot water (DHW), lighting, and cooking account for the remaining energy consumption, at 16%, 5%, and 5% of the total residential energy consumption respectively [1]. In the UK, the energy used for space heating is higher than the average for developed countries, accounting for 58% of all domestic energy usage, whilst electricity demand for appliances is lower due to less use of air-conditioning in homes [2]. Reducing the heating demand of the UK housing stock is therefore a priority in terms of meeting the UK Government's emissions reduction targets.[1]

Whilst modern techniques, such as PassivHaus,[2] are capable of producing "zero-carbon" homes, it is estimated that 75% of the dwellings that will exist in 2050 in the UK have already been built [3], which implies that improvements to the energy efficiency of the UK housing stock will have to be obtained primarily by retrofitting existing buildings. Indeed, studies by Enkvist et al. [4] and by the Intergovernmental Panel on Climate Change (IPCC) [5] show that retrofitting buildings is one of the most cost-effective ways of reducing CO_2 emissions.

Improving heating in households would also have important socio-economic impacts, especially in relation to the health of the occupants. For example, according to the Office for National Statistics, in 2008/09 there were an estimated 36,700 extra deaths during the winter period in England and Wales compared to an average non-winter period.[3] Much of this excess mortality has been attributed to "fuel poverty". According to the UK Government Department for Energy and Climate Change (DECC), "a household [is considered] to be in fuel poverty if it needs to spend more than 10 percent of its income on fuel for adequate heating (usually 21 °C for the main living area, and 18 °C for other occupied rooms)".[4]

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[1] The UK Government has legally binding targets to reduce CO_2 emissions by 34% (from 1990 levels) by 2020 and by 80% by 2050. These are set out in the 2008 Climate Change Act.

[2] The term "PassivHaus" refers to a specific construction standard for buildings that do not require any active heating or cooling systems, but also have excellent comfort conditions in both winter and summer.

[3] http://www.statistics.gov.uk/cci/nugget.asp?id=574.

[4] http://www.decc.gov.uk/en/content/cms/funding/fuel_poverty/fuel_poverty.aspx.

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The most recent figures show that, in total, there were an estimated 4 million households considered to be in fuel poverty in 2007 in the UK, of which approximately 81% are considered "vulnerable" households[5] [6]. The main causes of fuel poverty are: low levels of income; high energy prices; poor energy efficiency of dwellings. Improving the energy efficiency of existing dwellings, therefore, could help to alleviate the problem of fuel poverty, by lowering per unit heating costs and thus allowing occupants to reinvest energy savings into improved indoor conditions. In particular, if low-income households were targeted for energy efficiency improvements, then the health benefits of retrofitting would be even greater.

1.2. Implementing policy

Whilst targets and policy for CO_2 emissions and fuel poverty are decided at a national (or international) level, the actual implementation of policy in relation to the UK housing stock is carried out at a much smaller scale, often by local authorities or owners of large housing stocks, such as housing associations.

In order for owners of large housing stocks to implement retrofit programmes, some form of reliable cost-benefit analysis of possible intervention options is necessary. For example, it is suggested in a study by Jenkins [7] that fuel-poor social housing, which consists of approximately 550,000 households in the UK, could be used as "low-carbon exemplars". This study [7] estimates that a programme involving a 50% reduction in the CO_2 emissions of these 550,000 households would save 1.7MtCO2 annually, and would take 16% of fuel-poor households out of fuel poverty. The estimated costs of such a programme are given in the range of £3.9–17.5 billion, in comparison to the approximately £20 billion that UK Government has spent on benefits to alleviate fuel poverty since 2000.

Typical owners of large housing stocks, such as local authorities or housing associations, will often manage several thousand properties spread over a fairly concentrated urban area. Any cost-benefit analysis, therefore, must be able to operate at the urban-scale.

Housing stock energy models can play a role in helping to provide this cost-benefit analysis of different retrofit options. For such an analysis to be useful in any meaningful sense, housing stock models must be accurate, efficient, and interpretable. A framework is needed that allows decision makers to choose appropriate retrofit options based on information about the risk associated with any interventions to the housing stock.

2. Background

2.1. Housing stock models

A number of housing stock models already exist, with a variety of different methods employed. These can broadly be divided into three categories: top-down, statistical bottom-up, and engineering-based. Detailed reviews of existing housing stock models by Swan and Ugursal [8] and Kavgic et al. [9] tell us that top-down models are less suitable for assessing technology related policies since they do not model the actual physical behaviour of dwellings and their systems. Similarly, bottom-up statistical models, which establish statistical relationships linking a set of input and outputs, are also less capable of assessing the impact of retrofits. Meanwhile, statistical models rely on historical consumption data in order to establish these relationships between inputs and outputs, and therefore are inflexible when it comes to modelling the introduction of a new technology.

Bottom-up engineering-based housing stock models overcome many of the limitations of top-down or statistical models by modelling residential energy demand using actual building physics. However, there are still a number of limitations with engineering-based models in terms of their ability to provide a cost-benefit analysis of retrofit options. Firstly, five main BREDEM-based models, as described in Kavgic et al. [9], are all designed as national policy advice tools with a fairly high level of aggregation. This means that the implementation of specific technologies at the urban-scale cannot be assessed with any of these tools, limiting their use for local authorities or housing associations who wish to compare the impact of different retrofit options.

Regional or urban-scale housing stock models overcome some of this limitation, but the existing models that operate at these scales also have limitations: the housing stock sub-module of the Energy and Environment Prediction (EEP) tool by Jones et al. [10] requires a time-intensive data collection process, taking approximately 18 person-months to collect data for 55,000 properties; the city-scale model by Shimoda et al., [11–13] is expensive in terms of computational time, requiring days rather than hours in order to simulate an urban-scale housing stock; and the Scottish housing stock model by Clarke et al. [14] is held back by the same limitations as statistical models, since it uses regression techniques to link physical characteristic inputs to energy demand outputs.

Another limitation of existing engineering-based housing stock models is their inability to display the uncertainty associated with the inputs to the model, and to propagate this uncertainty so that decision makers can see the effect of uncertainties on the output. This is also recognised in the review by Kavgic et al. [9], who state that, "The most important shortcoming of all these models is their lack of transparency and quantification of inherent uncertainties".

Any housing stock model that is to be used practically by decision makers needs to be able to provide a full cost-benefit analysis, which should include information on the potential risks of possible interventions. Rather than giving a single, deterministic value of the cost-benefit of a retrofit measure, therefore, housing stock models should display a distribution that quantifies the level of confidence of any output due to various sources of uncertainty.

From the discussion above, the limitations of existing housing stock models can be categorised into five areas:

1. *Accuracy* - the ability to model the real processes that define energy usage in households is limited, and therefore engineering-based models are not completely accurate. Statistical models are often more accurate than engineering-based models, but are less flexible in their predictive capabilities.
2. *Data collection* - the quantity of data required for statistical models can be difficult to gather, whilst urban-scale engineering-based models can also require a time-intensive data collection process.
3. *Computational time* - engineering-based models that attempt to simulate energy transfer processes more accurately using dynamic simulation are considerably more computationally expensive than statistical models. Quasi-steady state models can be used to reduce computational times, but often at the expense of accuracy.
4. *Decision-making* - existing engineering-based models are unable to propagate uncertainties through the model, and are therefore limited in their ability to display the impact of uncertainties to decision makers.
5. *Flexibility* - statistical models are less flexible in their ability to assess retrofits, since they rely on historical data to formulate

[5] A "vulnerable" household is one that contains either an elderly person or a child, or somebody who is disabled or suffering from a long-term illness.