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A review and critique of UK housing stock energy models, modelling approaches and data sources

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ABSTRACT

The UK housing stock is responsible for some 27% of national energy demand and associated carbon dioxide emissions. 80% of this energy demand is due to heating (60%) and domestic hot water (20%), the former reflecting the poor average thermal integrity of the envelope of the homes comprising this stock. To support the formulation of policies and strategies to decarbonise the UK housing stock, a large number of increasingly sophisticated Housing Stock Energy Models (HSEMs) have been developed throughout the past 25 years. After describing the sources of data and the spatio-temporal granularity with which these data are available to represent this stock, as well as the physical and social phenomena that are modelled and the range of strategies employed to do so, this paper evaluates the 29 HSEMs that have been developed and deployed in the UK. In this we consider the models' predictive accuracy, predictive sensitivity to design parameters, versatility, computational efficiency, the reproducibility of predictions and software usability as well as the models' transparency (how open they are) and modularity. We also discuss their comprehensiveness. From this evaluation, we conclude that current HSEMs are lacking in transparency and modularity, they are limited in their scope and employ simplistic models that limit their utility; in particular, relating to the modelling of heat flow and in the modelling of household behaviours relating to investment decisions and energy using practices. There is a need for an open-source and modular dynamic housing stock energy modelling platform that addresses current limitations, can be readily updated as new (e.g. housing survey) calibration data is released and be readily extended by the modelling community at large: improving upon the utilisation of scarce developmental resources. This would represent a considerable step forward in the formulation of housing stock decarbonisation policy that is informed by sound evidence.

Contents

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1. Introduction

Building stocks are responsible for a significant proportion of the energy demands and Greenhouse Gas (GHG) emissions of most countries [1]. In the UK, the domestic sector is responsible for 27% of national energy demand [2]. A first step towards reducing the energy demand of dwellings is to measure that demand precisely. Measurements of energy demand should deepen our understanding of the relationships between elements of the dynamic system that comprise a dwelling. These measurements can then be analysed to target policies promoting new energy technologies (e.g. smart meters), behaviour change (e.g. reducing standby power), or financial incentives to encourage investments (e.g. energy-related taxes) [3–6]. Crucially such measurements can also be used to calibrate models with which to evaluate the effectiveness of alternative policies destined to decarbonise the housing stock [7,8].

It is useful to identify the principal component parts of the energy system, in terms of energy supplied (S) and energy demanded (D), which in turn may be split into energy used (U) and energy lost via transformation (L). Gas is the most common supply of domestic energy (68%), which in the UK became prominent in the 1990s when electricity generation switched from using coal to natural gas. Electricity is also a prominent supply (24%) and is generated by nuclear, wind, and hydro-power plants; other fuels include petroleum, coal, coke and breeze, and with minor share solid fuels such as bio-energy and waste [9]. By contrast, the energy demand of dwellings is shaped by the needs of individual households, which in turn are a function of their socio-demographic characteristics and associated activities. In dwellings, this energy demand is attributable to four key services: 60% to space-heating, 20% to domestic hot water, 17% to lighting and appliances, and 3% to cooking. Satisfying an energy demand generally implies the emission of pollutants to the environment when combustion is involved, but is dependent on the fuel properties and the processes required to deliver that energy to the 27 million dwellings that comprise the UK housing stock. The UK's Climate Change Act aims to reduce national GHG emissions to 80% below 1990 levels by 2050 [10]. Before formulating policies to help meet this ambitious target, a full understanding of a dwelling's energy system is required, which can be scaled up to consider stocks of dwellings.

The development of a Housing Stock Energy Model (HSEM) starts with a basic abstraction that captures the energy flow pathways in a single dwelling. This mainly comprises the heat transfer through the envelope (to or from the external environment or conjoined buildings), via conduction and associated surface convective and radiative transfers and by infiltration and exfiltration, as well as the thermal gains from occupants and appliances. A key example of this abstraction is the Building Research Establishment Domestic Energy Model (BREDEM), which forms the basis of many other UK dwelling energy models. This abstraction for a single dwelling can be replicated for a given housing stock, to capture the variation in dwelling geometry, age, and context. When dwellings share properties they can be allocated to *groups*, *clusters*, or *typologies* that make a dataset more manageable and can be used to study a stock of dwelling through extrapolation [11–14]. However, this implies that some of the unique properties of each dwelling are replaced by a representative value when they are allocated to a specific group. This loss of information increases uncertainty in the stock model [15] and so tracing it is important.

The first attempts to model energy flows in dwellings were made in the mid-1970s [16,13], but were constrained by computing power, availability of dwelling information, and the ability to process it [12]. More recently, the adoption of more sophisticated algorithms, facilitated by improved computing power, and the increased availability and resolution of representative data have improved the accuracy and usability of HSEMs [17,18]. However, as HSEMs have become more sophisticated they require more inputs, which increases the likelihood of data input errors [19]. Therefore, a sound understanding of domestic energy flow pathways and the factors influencing them (both housing and household factors) is essential in formulating policies designed to reduce the energy demand and associated carbon emissions of any housing stock. It is then imperative to identify a parsimonious housing stock energy modelling strategy.

Stock modelling strategies are shaped by two key aspects. The first is the information (or stock data) required to achieve satisfactory levels of predictive accuracy and consistency. Such data might describe the physicality of dwellings (fabric, shape, location), their components and systems (fuel, water, technology), and their occupancy and use (household composition, patterns of presence and behaviour). The second aspect relates to the faithfulness with which the underlying energy model represents reality: the rigour of its modelling of energy flow pathways. The level of disaggregation required to represent a stock, the energy flow pathways within it, and the reliability of any of the adopted assumptions [20,21] are important factors. It is relatively straightforward to assign individual dwellings to a group, but the energy-modelling of the housing stock is complicated by the fact that most dwellings display heterogeneity, both physically (the housing) and socio-economically (the household behaviour),[1] and so can also be considered unique. Household behaviour is a known area of modelling uncertainty, and may be influenced by collective (peer pressure influencing the penetration of technology), circumstantial (environmental responses or local incentives to acquire devices), biological (occupants' needs according to age and health conditions), or cultural (habits and patterns) factors [23–26]. Some of these drivers are strongly interrelated. HSEMs should ideally consider the influence of these socio-economic factors on the underlying energy flow pathways being modelled, and be regularly updated as housing and household stock composition changes. This requires an evaluation of the descriptive data sources and the employed modelling strategies so that they can be accessed and used by different developers and stakeholders [27].

The aim of this paper is to review existing HSEMs used to estimate the energy demand of UK housing stocks for a range of scenarios, utilising existing and possible future sources of input data. Section 2 describes the composition of the current UK housing stock and discusses sources of information that are used by

[1] A household is defined as one or more persons sharing living accommodation and who are not necessarily related by blood or marriage [22].