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Replication Studies

An open-source simulation platform to support the formulation of housing stock decarbonisation strategies

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ABSTRACT

Housing Stock Energy Models (HSEMs) play a determinant role in the study of strategies to decarbonise the UK housing stock. Over the past three decades, a range of national HSEMs have been developed and deployed to estimate the energy demand of the 27 million dwellings that comprise the UK housing stock. However, despite ongoing improvements in the fidelity of both modelling strategies and calibration data, their longevity, usability and reliability have been compromised by a lack of modularity and openness in the underlying algorithms and calibration data sets. To address these shortfalls, a new open and modular platform for the dynamic simulation of national (in the first instance, the UK) housing stocks has been developed—the *Energy Hub (EnHub)*. This paper describes EnHub's architecture, its underlying rationale, the datasets it employs, its current scope, examples of its application, and plans for its further development. In this we pay particular attention to the systematic identification of housing archetypes and their corresponding attributes to represent the stock. The scenarios we analyse in our initial applications of EnHub, based on these archetypes, focus on improvements to housing fabric, the efficiency of lights and appliances and of the related behavioural practices of their users. In this we consider a perfect uptake scenario and a conditional (partial) uptake scenario. Results from the disaggregation of energy use throughout the stock for the baseline case and for our scenarios indicate that improvements to solid wall and loft thermal performance are particularly effective, as are reductions in infiltration. Improvements in lights and appliances and reductions in the intensity of their use are largely counteracted by increases in heating demand. Housing archetypes that offer the greatest potential savings are apartments and detached dwellings, owing to their relatively high surface area to volume ratio; in particular for pre-1919 and inter-war epochs.

1. Introduction

The UK's Climate Change Act aims to reduce the 1990 Greenhouse Gases (GHG) emissions level by 80% by 2050 [1]. To this end, the Committee on Climate Change (CCC) has established a series of incremental targets (or budgets) for the whole energy sector, including the production of 30% of electricity from renewable sources by 2020, and the reduction of GHG emissions by 50% by 2025. The UK emitted a total of $564MtCO_{2e}$ in 2011, which is 36% below the peak value registered in 1979 and 28% below that of 1990 [2]. This reduction was mainly caused by a shift from coal to natural gas, by a displacement of industrial activity (primarily to Asia), and by major improvements in the performance of the transport sector [3]. This means that even though the reduction in this period is close to the CCC target, this has largely been achieved in the absence of systematic structural improvements to reduce energy demands. Some of the more significant opportunities for de-

Abbreviations: ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; BREDEM, Building Research Establishment Domestic Energy Model; CCC, Committee on Climate Change; CHM, Cambridge Housing Model; CLI, Command Language Interface; DHW, domestic hot water; DOMVENT, Domestic Ventilation Model; EHS, English Housing Survey; EnHub, housing stock Energy Hub; EPW, EnergyPlus Weather; FPCA, Focused Principal Component Analysis; GHG, Greenhouse Gases; GLM, Generalised Linear Model; GUI, Graphical User Interface; HEED, Home Energy Efficiency Database; HPC, High Performance Computing; HSEM, Housing Stock Energy Model; HVAC, Heating, Ventilation and Air Conditioning; idf, EnergyPlus Input Data File; KWt, Kruskal-Wallis *H* Test; LHS, Latin Hypercube Sampling; No-MASS, Nottingham Multi-Agent Stochastic Simulation; NUTS, Nomenclature of Territorial Units for Statistics; OAT, One-at-a-time; OOM, Object-Oriented Modelling; PCA, Principal Component Analysis; PAF, Postcode Address File; SA, Sensitivity Analysis; SOA, Super Output Area; TRY, Test Reference Year; UK, UK; UML, Unified Modelling Language; TFA, Total Floor Area.

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mand reduction are found in the domestic sector, where emissions have been maintained at almost the same level since 1990 [2].

In 2011, the domestic sector contributed $124MtCO_{2e}$ to the total emissions; two-fifths of these were caused by the generation of electrical energy in power stations and the remainder by direct combustion of fossil fuels. End-use energy demand in the domestic sector is attributed to four key services: 60% to space heating, 20% to domestic hot water (DHW), 17% to lighting and appliances, and 3% to cooking [4]. This highlights the importance of thermal energy flows in the development of Housing Stock Energy Model (HSEM).

Efforts have been made to improve the performance of the existing housing stock, but these have mostly been counteracted by the construction of new buildings, serving a larger population, comprised of smaller households. For this reason, a full understanding of the energy flow in dwellings, and the factors influencing them, is required to formulate robust policies and strategies [5,6] to achieve significant reductions in their carbon emission intensity. This requires further efforts on two fronts. On the one hand, the disaggregated measurement of end-use energy demand to complement existing surveys of housing characteristics for a representative sample of archetypes; and on the other, the formulation and calibration of suitable HSEMs, describing not only the performance of the existing stock, but also how this stock is likely to evolve in response to policy measures designed to reduce carbon intensity [7,8].

In their recent review, Sousa et al. [9] systematically evaluated, using a detailed matrix characterising their functionalities, usability and accessibility, the attributes of the 29 HSEMs that have hitherto been developed and deployed in the UK. From this they identified the Cambridge Housing Model (CHM) as being the most fully developed. They also concluded that a) the models should be transparent so that their underlying algorithms can be understood and evaluated, and be amenable to improvement; b) future HSEMs should have a modular architecture so that each module can be edited and additional modules can be added; c) their underlying thermal models should be dynamic, to support accurate prediction of indoor temperatures and comfort, and the associated operation of heating systems; and d) databases should track their sources and development, and be continually updated so they can maintain their validity. Furthermore, a successful *dynamic* HSEMs would ideally capitalise on available computing power, to support the rigorous and exhaustive testing of alternative decarbonisation hypotheses (concerning both design and energy using practices).

The Energy Hub (EnHub) platform has been developed in direct response to these observations. It is open and modular in structure, and enhances the virtues of existing HSEMs by dynamically simulating the performance of the building archetypes that comprise the UK housing stock; this latter requiring semantically attributed three-dimensional representations. EnHub also facilitates the straightforward testing of targeted housing stock decarbonisation scenarios, and is readily extensible to support the integration of models predicting household's investments to reduce their carbon intensity, and the associated impacts, in response to policies and strategies designed to stimulate these investments. By dynamically simulating the stock, it also facilitates the (future) study of how households apportion the co-benefits arising from these investments: reducing energy use and emissions on the one hand, and improving indoor thermal comfort and health on the other. Finally, EnHub improves on computational scalability using cloud and high performance computing technologies.

The processing of data to represent the housing stock is achieved using the statistical computing software `R` [10]. This is also used to construct dwelling archetypes, which are then simulated using the dynamic building simulation program `EnergyPlus` [11]. The platform creates geometrically simplified models constructed of contiguous cuboids, following the Domestic Ventilation Model (DOMVENT) [12] and Steadman's model [13]; assigning semantic attributes to these cuboids based on survey data (i.e. of envelope properties and household variables). Thus, the platform is able to derive more informative metrics than has hitherto been possible, including incidences of discomfort, the proportion of the stock that over- or under-heats, the heat gains per square metre of floor area, the disaggregation of energy demands, and the estimation of peak thermal and power demands.

The paper begins by describing, in Section 2, the basis of EnHub: its algorithms and data structures, and the workflow employed in its application. Then, in Section 3, a number of scenarios to decarbonise the domestic stock in the UK are tested and discussed in terms of their effectiveness. The paper closes by critically evaluating the utility of EnHub, and by identifying how its utility can be further enhanced to support the formulation, and the more rigorous testing, of alternative decarbonisation policies and strategies.

2. Methods: statistical analysis and engineering models

The structure of EnHub takes its inspiration from the CHM, which is at the core of the *Energy Consumption in the UK study* [4], *and has been identified as the most flexible and powerful of prior HSEMs* [9]. The principle data set underpinning both EnHub and CHM is derived from the English Housing Survey (EHS), which comprised 14,951 dwellings in its 2011 version, and is weighted to represent the 21 million houses in England. This data set is augmented by the Census and the Home Energy Efficiency Database.

The principle differences between EnHub and CHM, besides the more granular and transparent architecture of EnHub, are that:

i. EnHub utilises the dynamic simulation program `EnergyPlus` for energy performance predictions, while CHM uses the Building Research Establishment Domestic Energy Model(BREDEM), a simplified energy balance model.
ii. EnHub represents dwellings volumetrically, thus explicitly representing built form and adjacency (e.g. exposed or shared walls), and facilitating the more explicit modelling of thermal losses and solar gains, while CHM only scales the dwelling archetypes, limiting the analysis of envelope transfers.
iii. EnHub's archetypes represent the housing stock in a structured hierarchical way, which eases communication with its underlying data sets and facilitates convenient testing of modifications to their attributes, while CHM requires direct manipulation of models corresponding to individual EHS entries: testing modifications is far from convenient.
iv. EnHub's architecture is readily extensible to model households' responses to socio-economic drivers influencing investments and changes to behavioural practice that impact on net building energy demand.
v. EnHub employs a process of statistical data reduction to reduce the number of archetypes to simulate, while CHM evaluates every instance of the EHS data sets, with corresponding redundancy.

The steps involved in the application of EnHub are conceptually summarised in Fig. 1 and are described in detail in the following sub-sections. Once the main data set is integrated into the platform, the open-source statistical computing platform `R` is used to mine these data and to reduce the sample size by determining the most relevant archetypes contained in the original data set. Then, this reduced data set is re-weighted to match the original totals. The next step uses the archetypes to create a set of semantically enriched volumetric models that are used by `EnergyPlus` to simulate dynamic energy flows.