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Comparison of empirical and modelled energy performance across age-bands of three-bedroom dwellings in the UK

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ABSTRACT

Differences between measured and predicted energy demand of dwellings across construction age-bands are of interest since these categories mark changes in construction methods and building codes over time. This study compared empirical measures of gas consumption for three-bedroom dwellings in the UK with predictions from the Cambridge Housing Model (CHM), a bottom-up building physics model used for national energy statistics and government policy development. It used gas consumption data collected from 2008 to 2010 from a sample of 255 three-bedroom dwellings. For age-bands of dwellings built since 1919, empirical estimates of annual gas consumption in 2011 were slightly higher than the model predictions but the rate of decline across age bands matched the model closely. For dwellings built before 1919, which are characterised by solid wall construction, the empirical estimates were markedly lower than the model predictions both for annual gas consumption and the Power Temperature Gradient (W/K) – a first order estimate of energy performance from monthly data. These findings have implications both for development of energy models and for policy regarding energy efficiency programmes, since they suggest retrofit of older dwellings will result in lower energy saving than predicted by current building physics models.

1. Introduction and background

In addition to the construction of energy efficient new buildings, retrofit of the existing building stock is widely recognised as a key component of reducing energy demand to enable nations to meet their carbon emissions reduction targets [1]. In the UK, building codes have been progressively tightened over recent decades – particularly since the 1980s – to improve the thermal performance of the building shell and the efficiency of the heating system. Much of the building stock, however, was constructed prior to the introduction of these regulatory measures. Some previous studies of residential buildings in the UK and Europe suggest a divergence between the expected and measured energy consumption according to dwelling age, whereby newer dwellings tend to use more than model predictions and older dwellings less than expected [2]. Further empirical evidence is needed to quantify differences in energy consumption across dwelling age-bands, which correspond with changes in construction methods and building codes, and to investigate the factors that may explain patterns of divergence over time from predictions of energy demand models.

Older dwellings in the UK, with many of those built prior to 1919 having solid masonry wall construction, provide a primary example of the issues at stake. The Department for Energy and Climate Change (DECC) has identified these dwellings as a key target for energy efficiency retrofit due to their predicted poor thermal performance [3]. The retrofit of solid masonry dwellings requires internal or external wall insulation, in addition to other accompanying actions such as installing double-glazing, and is typically a more substantial and expensive intervention than that involved for insulating later dwellings with cavity-wall construction. Some recent studies have suggested that solid wall construction may provide better thermal performance than expected (i.e. a lower *U*-value than is assumed historically in energy demand models) [4] and occupants may operate their dwelling with lower indoor temperature than assumed as standard practice. Nevertheless, the DECC Energy Efficiency action plan has called for the retrofit of 1.5 million solid wall dwellings by 2020 [3]. With existing installations less than 1% of that number, this represents an ambitious target that equates to more than 5000 needing to be completed each week until that date. More broadly, accurate and robust estimates are

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needed for the expected reduction in energy demand post-retrofit of these and other dwellings; to guide and evaluate energy demand policy both at the stock level and for individual buildings, especially where such retrofit programmes rely on energy savings to finance their capital costs.

The conventional metrics of energy consumption and carbon emissions are framed around annual statistics. For instance, energy ratings for individual dwellings in the UK are defined according to range bands of estimated energy demand in kWh per annum, using estimates from the Standard Assessment Procedure (SAP) [5]. Similarly the UK Housing Energy Fact File [6] provides annual time series energy data obtained from the Cambridge Housing Model (CHM) and broken down by end-uses across broad categories of the dwelling stock [7]. The CHM is essentially a bottom-up building physics model based on SAP2009 that uses national housing survey data to aggregate up and generate estimates of energy demand of the residential stock [8]. Given the high seasonal variation, however, examination of energy consumption at higher resolution would enable a more detailed analysis of differences between measured and modelled energy demand for different age-bands of dwellings, and particularly the increase in space heating used across winter months. Fortunately estimates of monthly gas and electricity demand can be extracted for dwelling categories from the underlying calculation components of the CHM. Further, the evaluation can focus on gas consumption since electricity demand is estimated as unchanged across months for dwellings where gas is the primary source of heating.

In terms of empirical data, previous analysis of high-frequency metered energy data from the large scale DECC smart metering field trials in 2007–2010 has analysed the distribution of Power Temperature Gradient (PTG, W/K) for a large sample of dwellings [9]. PTG is based on the heating slope parameter of the Princeton Scorekeeping Method (PRISM) [10,11] and estimates the rate of increase in power demand as the external temperature declines below 15 °C. This simple empirical metric can be interpreted as a first order estimate of the effective rate of heat loss from the dwelling including through the building shell, ventilation losses, as well as efficiency losses from the heating system, all of which represent the main targets of energy efficiency related changes in building codes. Moreover, it was found that the PTG of gas consumption was almost identical to the PTG of total energy consumption [9], which therefore confirms that the bulk of increase in energy consumption in response to colder external conditions is accounted for by space heating and hot water demand (and to a much lesser extent increased gas cooking). Monthly gas demand therefore has the potential to provide more detailed information on the effect of changes with respect to the building shell on energy performance than figures for annual total energy consumption.

The aim of this study was to use empirical data from a sample of dwellings from the DECC smart metering trials [12] to compare estimated annual gas consumption and PTG values in 2011 across dwelling age-bands with predictions from the CHM and identify evidence for the energy related effects of changes in building codes over time.

2. Methods

2.1. Data sources

From 2007 to 2010, large-scale field trials were conducted in the UK by energy utilities on behalf of DECC to investigate the effectiveness of various types of demand response interventions related to feedback for householders on their energy use, that ranged from enhanced billing information to smart meters with displays sited within the home [12]. This study used metered gas and electricity data from three-bedroom dwellings from a sub-sample of 778 gas-heated dwellings from the set of smart meter field trials undertaken by the energy provider EDF UK. The study comprised a volunteer sample of participants with basic information on the characteristics of each household (including age and other sociodemographic data) and dwelling (including dwelling age-band, type, and size). Further details on the EDF sample have been published previously [9], from which the sample of 255 three-bedroom dwellings was extracted. As with the previous study, data for daily average external air temperature (°C) were obtained from data at 5×5 km grid points provided by the UK Meteorological office [13] with values matched according to the geographical location co-ordinates of the partial postcode provided for each dwelling.

Modelled estimates of gas consumption in 2011 for three-bedroom dwellings across age bands were produced from the CHM using building and occupant survey data for 15,000 representative dwelling 'cases' from the English Housing Survey [7]. This study uses 2011 monthly weather data from DECC for each region and does not include flats (multi-dwelling buildings, other than semi-detached dwellings).

2.2. Outcome variables

Annual gas consumption for 2011: as dwellings had various start and finish dates for energy monitoring (not necessarily corresponding to a complete year) spanning from 2008 to 2010, annual gas consumption for 2011 in each age-band was estimated in four steps:

(a) Each dwelling contributed a single data point for each month of gas consumption, which was then weighted according to representation of each dwelling in the residential stock (by dwelling type within each age-band).
(b) Linear regression parameters for monthly gas consumption (P_{gas}, power in kW) as a response to average external temperature T_{ex} over each month (that contributed data across multiple years) were obtained, where $T_{ex} < 15\,°C$.

$$P_{gas} = \alpha + \beta T_{ex}$$

(c) Regression parameters obtained in (b) above and 2011 monthly weather data were used to calculate gas consumption (kW) during the heating season. Data for population-weighted average monthly external temperature [14] for January 2011 to December 2011 were as follows: 3.9, 6.3, 6.8, 11.7, 12.3, 14.0, 15.3, 15.4, 15.1, 12.4, 9.5, 5.9, and 10.7 °C respectively.
(d) Average gas demand was used for months where $T_{ex} \geq 15\,°C$ (i.e. during the 'non-heating' season) which were used directly to obtain corresponding estimates of 2011 gas consumption.
(e) Annual gas consumption was calculated as the sum of each of the monthly estimates, after conversion to kWh (according to the number of days in each month).

This method to generate monthly data was selected after exploratory analysis of different approaches and timescales due to its relative simplicity and similarity to established methods, such as PRISM, and to provide as close a comparison as possible with CHM.

Power Temperature Gradient: PTG is the absolute value of the slope (β) parameter obtained from linear regression of monthly gas data against average external temperature as described above (and converted to W/K).