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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 subsample 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).

Table 1
Comparison of empirical estimates of gas consumption in 2011 across dwelling age-bands with those from the Cambridge Housing Model (CHM).

Sample age-band	N	Estimated 2011 gas consumption kWh (±Std. Error)	CHM age-band	CHM 2011 gas consumption kWh
			Pre-1900	21,230
Pre-1919	22	17,620 (±1650)	1900–1929	18,630
1919–1944	69	18,010 (±730)	1930–1949	16,990
1945–1964	74	16,910 (±710)	1950–1966	15,340
1965–1980	59	14,830 (±870)	1967–1982	14,280
Post-1980	31	13,190 (±1130)	Post-1982	11,490

3. Results

The study sample comprised of 255 three-bedroom dwellings, including 79 terraces, 101 semi-detached, 75 detached. Estimated annual gas consumption (weighted to match stock composition) for 2011 is shown in Table 1 While some CHM predictions of gas consumption in 2011 were within the standard error of the empirical estimates, they tended to track lower for dwellings built since 1920, particularly dwellings built since 1980 (Fig. 1). However, the main divergence evident was for dwellings built prior to 1900, where CHM predicts the highest annual gas consumption (21,230 kWh) relative to later dwellings and a linear decline thereafter, whereas the study sample estimates that pre-1919 dwellings have a *similar* gas consumption to those built 1919–1945 (lower but within the standard error). For age categories since 1919, both empirical and modelled estimates have a similar gradient of decline in annual gas demand: ~810 kWh/decade for the study sample and ~870 kWh/decade for the CHM (from linear regression).

For each age-band, the average monthly gas consumption figures over the heating season (October to March) show an approximately linear increase with decline in external temperature for both the study sample (Fig. 2) and the CHM (Fig. 3). Note that the CHM assumes no space heating requirements for June to September when predicted gas consumption is essentially the same across all dwelling age bands, whereas some space heating is evident during this period in the study sample. In the study sample, the pre-1919 dwellings have similar gas demand as the 1919–1945 dwellings, with demand tending to lower values in each month as the dwelling age decreases. Overall the study sample shows a markedly narrower and flatter wedge formed by the bounding regression lines on monthly data than for the equivalent area generated by the CHM (Fig. 3), particularly as a result of differences in the pre-1930 age-bands. But for dwellings built since 1945, absolute values of power consumption tend to be the same or higher for the empirical data for similar temperatures. For instance, the study sample has 1945–1964 dwellings using ~4.2 kW at 4 °C on average, compared with 4.0 kW for 1950–1966 dwellings from the CHM.

Based on slope obtained from regression of monthly data (as illustrated with the fitted lines shown for two age-bands in Fig. 2), the PTG values from the empirical data were consistently lower across age-bands than those obtained from the CHM (Fig. 4, Table 2). However, both again show a similar linear decline in both the empirical (18 W/K per decade) and modelled values (22 W/K per decade) for dwellings built since 1919. The outstanding difference remains that for dwellings constructed pre-1919, amounting to a divergence of ~40% from estimates for pre-1900 dwellings by CHM.

4. Discussion

This study has compared empirical and modelled estimates of gas consumption, a proxy for mainly space and hot water heating, across age-bands of UK dwellings and which would be expected to reflect improvements in energy performance over time due to changes in construction methods and building codes. Specifically, it has identified a number of key differences between estimates of gas consumption in 2011 based on empirical data from a large sample of three-bedroom dwellings and those predicted by a physically based model for three bedroom dwellings in the UK residential stock. The CHM model showed an approximately linear decline in annual gas consumption over each decade of ~850 kWh per decade, with pre-1900 dwellings predicted to have the highest gas consumption of almost 20,000 kWh/year. Estimates for 2011 gas consumption for post-1920 dwellings in the study sample were systematically higher than those from the CHM, but showed a similar gradient of change across these age-groups. However, the study sample shows a different overall relationship, with a peak in annual gas consumption for the 1919–1944 age-band and *slightly lower* (but within the standard error) gas consumption for the pre-1919 dwellings. This flattening of gas consumption for older dwellings was markedly below the consumption predicted by the CHM for pre-1900 dwellings, even though the version of the model has been modified to include updated *U*-values for solid walls (among other changes).

In contrast, the PTG, which reflects the heat loss and heating system efficiency of the dwelling as a function of external temperature, was consistently *lower* for the study sample than that

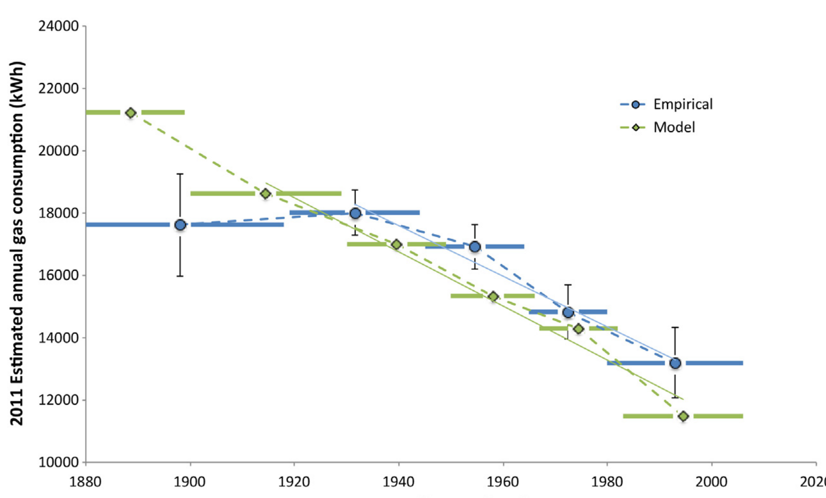

Fig. 1. Annual gas consumption in 2011 estimated from empirical data and the Cambridge Housing Model predictions by dwelling age-band (denoted by horizontal bars; standard errors shown as vertical bars), with linear regression fit shown for age-bands since 1919 ($R^2 > 0.9$).

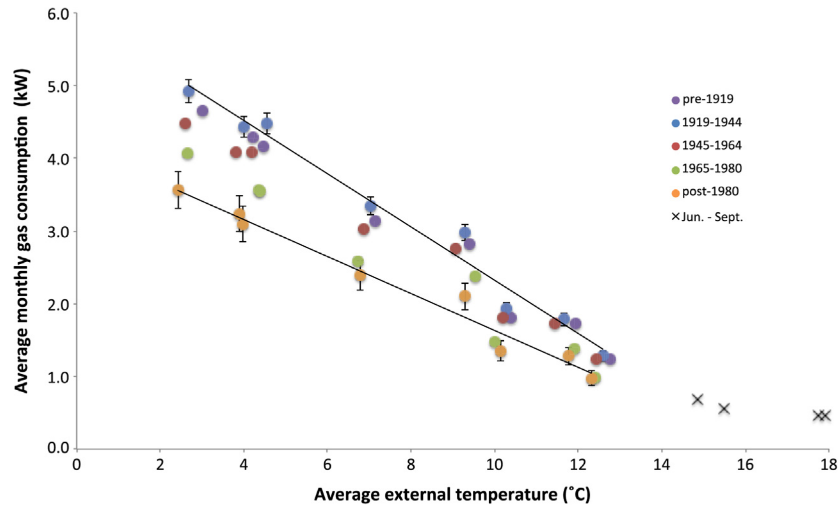

Fig. 2. Average monthly gas consumption during the "heating season" from the study sample 2008–2010 by dwelling age-band, with bounding linear regression lines shown for the 1919–1944 and the post-1980 age bands. (*Note*: for clarity June to September consumption data are denoted by "X" for all age bands as they are essentially the same; vertical error bars indicate the standard error for each month in the two bounding age-bands).

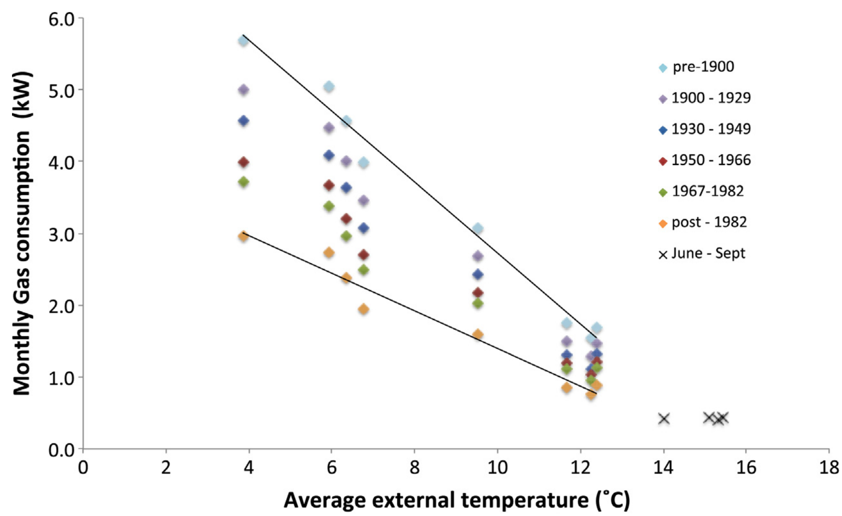

Fig. 3. Monthly gas consumption during the "heating season" from the CHM by dwelling age-band, with bounding linear regression lines shown for the pre-1900 and the post-1982 age-bands; (*Note*: June to September consumption data denoted by "X" for all age bands as they are essentially the same.

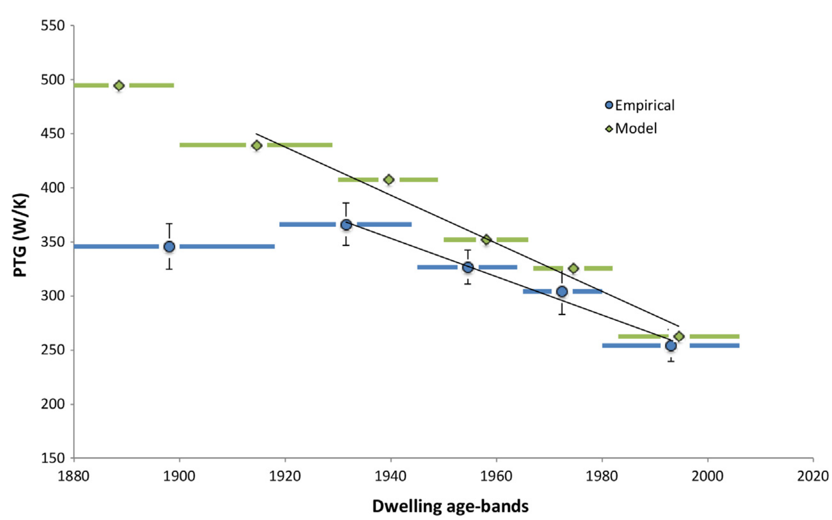

Fig. 4. Comparison of PTG from the CHM and the study sample by age band (top) and relative comparison (bottom) indexed to post 1980 (or for CHM post 1982) dwellings, with horizontal bars indicating the width of age categories and vertical bars the standard error.

Table 2
Gas consumption in 2011 estimated from empirical data and from the Cambridge Housing Model (CHM).

Sample age-band	Sample PTG W/K (±Std. Error)	CHM age-band	CHM PTG W/K
		Pre-1900	494
Pre-1919	346 (±21)	1900–1929	440
1919–1944	350 (±19)	1930–1949	407
1945–1964	315 (±15)	1950–1966	352
1965–1980	287 (±21)	1967–1982	325
Post-1980	242 (±14)	Post-1982	262

obtained from regression of the CHM monthly data. For instance, the PTG for 1965–1980 study sample dwellings was 290 W/K compared with 325 W/K for the 1967–1982 age-band from the CHM. However, the relative decline in PTG over time for dwellings built since 1919 was similar for empirical and modelled estimates, at ~22 W/K per decade. The outstanding deviation in PTG was again for the pre-1919 dwellings, compared with the pre-1929 dwellings in the CHM.

Although the sample size of this study is relatively small (for instance 22 dwellings in the pre-1919 age-band) the pattern of empirical results across age bands are broadly consistent with annual data from the National Energy Efficiency Database (NEED) [15], which shows a similar profile from 2008 to 2011 of almost flat annual gas consumption across dwellings built prior to 1919 compared with those built 1919–1944 (although all age bands do show a progressive reduction in gas demand since 2008, with consumption lower in 2011, a comparatively mild year). Further, the general pattern of higher energy consumption than expected in new dwellings and lower consumption in older dwellings is consistent with a review of data from across Europe, regarding lower than expected energy consumption in dwellings with low energy ratings and higher consumption that expected in new dwellings [2].

At least two distinct facets may explain the key difference between measured and modelled estimates of energy performance. First the large divergence in the pre-1919 dwellings suggests that basic assumptions about the characteristics of these dwellings, such as the heating patterns (e.g. lower set-point and average indoor temperatures and greater differential between zone) and the assumed thermal performance of the building shell model, need to be re-examined. Though it should be noted that the 2011 CHM model used in this study has already been updated with revised assumptions for the thermal conductivity of walls and indoor temperatures, based on other measured data obtained from a subsample of dwellings in the English Housing Survey and other sources. The CHM has recently been compared with large scale UK survey data (i.e. NEED) where the overestimation of annual gas consumption for pre-1919 dwellings was also evident [16].

Second, the similarity in *relative changes* in gas demand and PTG across age bands for dwellings built since 1919 suggests that the model calculation *is* capturing the broad changes in thermal performance of the building shell over subsequent decades. But to reconcile the higher empirical figures for annual gas demand and lower PTG's than the modelled estimates for these dwellings suggests that the heating season is longer than assumed (i.e. more than eight months of the year). This is supported in the monthly empirical data, which shows that gas use was already rising with declines in average external temperature even below 16 °C. It may also be the case that these heating patterns are not maintained as external temperatures decline, so that in colder months heat losses are closer to the expected values. In other words the model's use of a shorter heating season and higher PTG's may counteract the longer heating season but lower PTG's evident from the empirical data. This needs further detailed research and analysis in larger datasets, but underscores both the importance of moving away from annual consumption data in the evaluation of models and the lack of basic knowledge of the energy demand in the residential stock (such as understanding variations in the length of heating season and heating patterns in occupied dwellings).

With respect to the impact of building codes, the progressive decline across age bands in annual consumption for dwellings constructed since 1919, as well as in the PTG's, supports the notion that changes to the building shell and heating systems mandated by regulations or encouraged by energy efficiency initiatives over recent decades have led to improvements in energy performance. For instance, it would be hard to explain this pattern of "dose response" in the decline due to differences in social factors across occupants of dwellings in different age-bands. Where social factors do seem evident is in the broad and relatively sudden declines seen across all age bands the residential stock since 2007 that may reflect economic changes, such as increases in gas prices. Such price increases are absent from many models, including the CHM. It should be noted that the relationship observed (and accounted for in the model) includes a large proportion of dwellings in the older age-bands that would have some energy efficiency features installed, such as double glazing and cavity wall and loft insulation, with these expected to have lower consumption than equivalent dwellings in their original condition.

Although the general relationship of decline by age of building has been observed in annual energy consumption data, this is the first study to look also at the PTG with monthly data as an indicator the thermal performance of the building shell and heating system efficiency, while matched for dwelling size and composition of types to ensure as close to a direct comparison as possible. Again the relatively close agreement evident for the rate of decline in empirical and modelled estimates of energy consumption and PTG across dwellings age-bands since 1919 suggests that the building physics models are providing reasonable predictions of *change* due to the impact of progressive improvements in the energy performance of the building shell over recent decades. However, one of the issues with bottom-up physical models, which rely on normative settings for a multitude of parameters such as for the length of the heating season noted above, is that this can lead to systematic errors in the absolute values of energy performance predicted both across and within age-bands. Alternatively, if occupants tend to heat their dwellings less than the standard heating patterns assumed in the CHM, then this may lead to lower (and even declining) average indoor temperatures than predicted in response to colder external conditions, which manifest as lower rates of heat loss from the dwellings and hence lower than predicted PTGs. Further research on indoor temperatures is needed to investigate this possibility.

The most salient divergence between measured and modelled estimates, however, occurs with the pre-1919 dwellings, with PTG values ~50% lower then expected form the CHM. Clearly this suggests some substantial changes are needed in the modelling used for this age band, and such changes are likely to relate either directly or indirectly to the solid-wall masonry construction that characterises these dwellings. In addition to the previous note on changed made to account for in situ thermal performance (*U*-values) of solid walls, the heating systems may be constrained in their capacity to heat the homes to the level assumed (for instance due to radiator sizing), and in response occupants may just use single room heating rather than whole house or zoned heating. Whatever the case, empirical evidence is lacking as to exactly what is driving the lower than expected energy consumption in these dwellings. This serves to highlight the historical issue of using a normative model (with assumed standard heating patterns to allow fair comparison) as a predictor of actual potential energy savings, rather than a more statistical approach to model development, with interpretation informed by detailed empirical data, as would typically be adopted in disciplines such as health epidemiology.

As the pre-1919 dwellings represent a primary target for DECC's energy policy, the discrepancy has implications for reaching medium and long term objectives for carbon emissions reductions from the residential sector and initiatives, that use the same physics based models as the CHM for predictions of potential savings to offset the capital costs of energy efficiency retrofit of these dwellings. Findings do not necessarily undermine the case for retrofit of these dwellings, as there may be compelling social and health benefits (including cost reductions in health services use) that follow on from potentially reduced energy poverty and providing warmer indoor conditions [17]. Such benefits would support the continued targeting of older dwellings for energy efficiency retrofit, even if the expectation of energy savings from such interventions were reduced and required a broader economic model to justify the costs involved.

A key strength of this study is the use of high frequency measured data for a large sample of residential dwellings, with like-for-like comparison and metrics that attempt to focus on the energy performance of the building shell. However, a number of limitations need to be acknowledged, including the use of a volunteer sample from England that is not representative of UK dwellings or households, such as having only a few flats (multi-dwelling buildings) and underrepresentation of social housing. This was one reason why three-bedroom dwellings were selected as the group for comparison, as the vast majority of these dwellings are detached (including bungalows), semi-detached, and terraces. In a related point, the study data only have 'number of bedrooms' available as a proxy for dwelling floor area, whereas the size of three bedroom dwellings has tended to decline over time. The expected decline of energy consumption due to reduction in size, which represents a potential confounder for the impact of other energy efficiency improvements, was still accounted for in the CHM calculations for each age-band as this uses floor area in each of its representative dwelling 'cases'. The number of sample dwellings in the pre-1919 age from which the weighted estimate for 2011 gas consumption was obtained is relatively small. As noted, however, the gas consumption was consistent with that seen in NEED relative to other age-bands. Further, the flattening of gas consumption for the pre-1919 dwellings is also evident in NEED for both four and two bedroom dwellings. The latest age band category available in the empirical data is for post-1980 dwellings, which collapses a series of smaller age-bands that correspond to the series of changes in building regulations since 1980. Thus, for instance it is not possible to discern the relative performance of dwellings built under post-1996 or post-2003 regulations compared to the CHM predictions. The energy monitoring took place from 2008 through 2010, which as is indicated by national consumption data, was a period of rapid change in energy consumption in the residential sector that potential involved socioeconomic factors, such as the global financial crisis and rises in energy prices. Last, 2010 itself was also an exceptionally cold year – the coldest in 40 years – which also affected gas use in the study sample possibly beyond the scope of the temperature adjustment used to match to 2011 conditions.

5. Conclusion

For dwellings since 1919, results from energy meter data from UK dwellings show close agreement with the CHM regarding the rate of change in annual gas demand across age-bands. However empirical PTG and monthly data suggest that assumptions regarding the calculation of absolute dwelling heat loss and the length of the heating season need to be re-examined. In particular the large divergence for pre-1919 dwellings, which had markedly lower annual gas consumption compared with predictions from the CHM, requires further detailed research to advance understanding of the operational and energy related characteristics of these dwellings.

DECC's energy policies and mechanisms for supporting retrofit measures may also need to be revised to acknowledge what appears to be an existing weakness in estimating consumption and potential savings from pre-1919 homes. If further work and more dwelling-level data supports these findings the Department may need to develop a new approach to estimating consumption and possible savings from the oldest homes, including consideration of other social and health benefits. The use of sub-annual metrics, such as provided by the Power Temperature Gradient could be part of this new approach.

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