Validating Solid Wall Insulation Retrofits with In-Use Data

A. Hardy[a,*], D.Glew[a], C. Gorse[a], M. Fletcher[a]

[a]*Leeds Beckett University, Leeds, LS2 9EN*

Abstract

Improving the energy efficiency of the UK housing stock is important both to meet carbon emission reduction targets and to reduce fuel poverty. For this reason, domestic properties are frequently retrofitted with energy saving measures. This study looks at how the energy consumption, thermal properties and internal temperature of 14 dwellings change as a result of a solid wall insulation (SWI) retrofit. A decrease in heat transfer coefficient of $11^{+6}_{-7}\%$ was calculated for 2 dwellings, which is slightly lower than the previously modelled value of 18%. However, many houses displayed evidence that the full benefit of SWI was not being realised as, for example, energy savings were offset with increases in internal temperature. Future retrofit schemes should therefore consider supplementing the changes in fabric with increased guidance for the occupant.

Keywords: *Solid Wall Insulation, Retrofits, In-Use data*

1. Introduction

In 2015, the domestic sector accounted for 29% of UK total energy consumption [1] and of this percentage, space heating can account for around 60% [2]. The large amount of energy expended on domestic heating means that reduction strategies are vital if the UK government is to reach is target of cutting greenhouse gas emissions by 80% by the year 2050 [3]. Two of the simplest ways to reduce emissions from domestic heating are to ensure that houses are heated efficiently and to ensure they retain that heat well. Legislation is currently in place to work towards this, with the 1995 edition of the 1991 UK Building Regulations being the first that required step changes in energy efficiency requirements of new homes [4]. However, the English Housing Survey reports that over 80% of homes were built prior to this legislation coming into force and these homes are therefore expected to have generally poorer thermal performance [5]. This means that large scale retrofitting is crucial for increasing the efficiency of houses [6], and it has also been demonstrated that wider socio-economic health and community wide benefits can be achieved via retrofit policy [7, 8, 9].

Recent retrofit efforts including the Carbon Emissions Reduction Target (CERT), Renewable Heat Incentive (RHI), Community Energy Saving Programme (CESP) and the Energy Companion Obligation (ECO) have been relatively effective, as reflected in the fact that dwellings with A-C Energy Performance Certificate (EPC) ratings have risen from just 5% in 2005 to 28% in 2015 [5]. This also implies, however, that there is still a substantial way to go and it has been suggested that in order to meet the 5th UK Carbon Budget, the domestic sector is expected to cut emissions by a further 22% between 2015 and 2020 [10].

There are several options available when retrofitting a dwelling that can focus on the fabric or the services in the home. Of the 2 million measures installed via ECO, 38% were cavity wall insulation (CWI), 26% loft insulation and 21% boiler upgrades [11]. Government statistics on annualised gas data from a large number of homes show that these measures result in a saving of 8.4%, 2.1% and 8.3% respectively on average household fuel bills[12]. As a result, these three measures are often deemed to have the most carbon savings.

The benefits of solid wall insulation (SWI) are less well studied, with this lack of information due, at least in part, to the relatively low installation rate of SWI. This is a significant oversight since 34% of the UK housing stock is estimated to have solid walls, 98% of which remain uninsulated [13]. A summary of literature on the potential savings from SWI has been published by the BRE [13], and individual case studies often reveal that SWI can result in higher savings than CWI - upwards of 60% [14] or even 80% when part of a deep renovation [15]. However, assessment methods used to validate the effectiveness of retrofits on small numbers of dwellings, as in the case of SWI, inherently have low statistical power and high uncertainty. Conversely, savings for conventional measures are derived from samples of tens of thousands of homes [12].

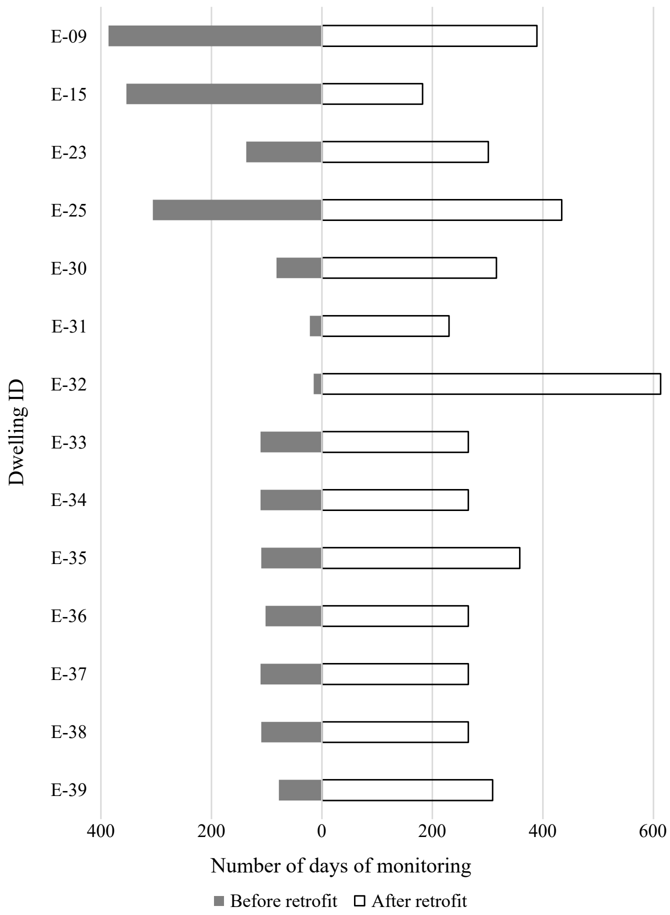
SWI may be applied as internal wall instulation (IWI) or external wall insulation (EWI), with installation approach typically dependent on local factors such as building geometry and local aesthetic. In general, SWI takes the form of EWI, as IWI requires more disruption to the household and reduces internal surface area. Previous es-

*Corresponding author
Email address: A.L.Hardy@leedsbeckett.ac.uk (A. Hardy)

timates for the effect of EWI suggest an 18% reduction in heat loss from the property [16]. However, owing to a lack of empirical data at the time, this figure was derived from building energy models which, in general, have been shown to overestimate the affect of improvements [7, 17]. The gap between the predicted and measured performance is due to a combination of factors, including the model's inability to fully incorporate all physical affects, its failure to reflect real-world insulation procedures and its reliance on standardised assumptions around occupant behaviour [18]. In-use factors are often used in an attempt to account for the occupant behaviour, but the uncertainty surrounding these adjustments is still high [13]

Gathering more data on SWI improvements is therefore of great importance to provide more certainty around costs and benefits of this measure, and will potentially allow more effective policy to be written. Similarly, it is important to develop robust assessment methods in order to understand how savings achieved from particular SWI projects compare to savings from more common methods such as cavity wall insulation. This study aims to achieve these two goals by presenting the results from long-term measurement of energy consumption and temperature in 14 solid wall dwellings in which SWI retrofits were undertaken. The project findings will provide insight into the 6.3 million solid wall dwellings in the UK that may in the future have a retrofit [5]. Given the substantial remaining potential and the fact that there will be minimum quotas for SWI in the Help to Heat policy [19], understanding the real improvements achieved by SWI installation is of particular importance in the UK and in other countries experiencing similar domestic energy policy challenges with large proportions of solid wall dwellings in their housing stock.

Figure 1: The number of days of data available either side of the retrofit. Some houses have minimal data taken before the retrofit took place.



2. Observations

Retrofit installers, Registered Social Landlords (RSLs) and Local Authorities (LAs) across the North of England who were taking part in government funded domestic retrofit programmes were invited to take part in this research. Securing samples proved challenging, but convenience sampling and snow ball sampling resulted in over 1,000 properties being invited to take part in the project from which 45 properties accepted. Of these 45 homes, 14 had retrofits suitable for inclusion in the study and took place within the research project time-scale. Within the sample of 14 properties, 10 had solid concrete walls (e.g. pre fab or no-fines) built between 1950 and 1970 and 4 had solid brick walls built pre 1910 (see table 1). These property ages are representative of a substantial proportion of solid walls dwellings in the UK housing stock, as 17% of homes in the UK were built before 1910, and 28% were built between 1945 and 1974 [20]. However, there is an over-representation of concrete walls in this sample compared to the UK housing stock, as approximately 86% of solid walls in the UK are masonry and only 14% are concrete [21].

In-use data was captured in each dwelling at half hourly intervals with Orsis sensors and included, where possible, gas (m^3), electricity (kWh), internal temperature (°C) for both upstairs and downstairs, and external temperature (°C). During the course of these measurements, SWI was installed in all of the properties. The installations were taking place independently to the research project and although the occupants were informed of the project, the installers were not. It is therefore anticipated the workmanship of the SWI was representative of a standard installation processes.

The observations and retrofits took place between 2013 and 2016 though the actual monitoring duration at each home differed according to when they had their monitoring installed and if there were delays in the retrofit occurring. How the measured data was distributed pre and post retrofit is shown in Figure 1.

Table 1: Summary of dwelling retrofits

Dwelling ID	House type	Wall type	Insulation measure	Primary heating type
E-9	Semi-detached	In-Situ Concrete	EWI	Gas
E-15	Semi-detached	Concrete	EWI	Gas
E-23	Semi-detached	Solid Brick	EWI	Electricity
E-25	Mid-terrace	No-fines concrete	EWI	Gas
E-30	Mid-terrace	Solid Brick	IWI to front, EWI to rear	Gas
E-31	Mid-terrace	Solid Brick	EWI to rear only	Electricity
E-32	Semi-detached	Concrete panel	EWI	Gas
E-33	End-terrace flat	No-fines concrete	EWI	Gas
E-34	Mid-terrace flat	No-fines concrete	EWI	Gas
E-35	End-terrace flat	No-fines concrete	EWI	Gas
E-36	End-terrace flat	No-fines concrete	EWI	Gas
E-37	Mid-terrace flat	No-fines concrete	EWI	Gas
E-38	Mid-terrace flat	No-fines concrete	EWI	Gas
E-39	Semi-detached	Solid Brick	EWI	Gas

3. Data pre-processing

Before the data could be analysed, it was first inspected to identify any possible errors. Given that the dataset included approximately eight million data-points, this pre-processing was largely automated and included the following producers;

First, it was noted that the raw data included many periods of "drop-out", in which no data was recorded or sent to the loggers. Data which suffered from these drop-outs was padded with timestamps containing NA values during the drop-out, so that each day contained the same number of data points for each sensor.

The data were further inspected for any error codes sent by the loggers themselves. For the sensors used, the error code corresponded to a reading of -2. As the minimum genuine value that the gas and electricity sensors could record was 0, any value of -2 in the electricity and gas data was certainly an error and was therefore replaced with an NA value. For the temperature sensors, however, it was possible that genuine values of -2 may have been recorded. Genuine values of -2 where therefore distinguished from error codes by searching for rapid temperature changes to -2 and back. Data points fitting this description were identified using methods of outlier detection in time series [22, 23], and flagged as potential errors.

Finally, it was observed that several periods of the electricity and gas data contained "flatlines" - periods of time over which the same non-zero value is recorded. The cause of these flatlines is not clear, but the resolution of the electricity and gas sensors (1kWh and 0.001m^3, respectively) is high enough that such constant readings over a prolonged period are unlikely to be genuine. Shorter periods of flat readings are potentially genuine, however, so we chose a dividing line of 3 hours to distinguish flatline errors. A rolling 3-hour window was applied to the data and any periods for which the readings were finite and constant were marked as a likely flatline errors.

The majority of the data did not raise any flags to indicate potential errors. Only $\sim$0.005 % of data points were identified as potential anomalies, and this low number allowed those error flags to be checked in person. Any confirmed errors were replaced with NA values.

4. Analysis

4.1. Changes in Electricity and Gas use

The first effect of the retrofit to be studied was that of any changes in the household electricity and gas consumption. Before this analysis was carried out, however, the consumption values were first weather corrected. A weather correction is often applied as, in addition to building improvements, weather can affect the energy consumption of a household. For example, a period of relatively warm weather after retrofit may result in a reduction in utility use due to the lower heating demand. A weather correction adjusts the utility consumption values in an attempt to remove the weather component and allow the affect of the retrofit to be isolated. The weather correction was achieved by multiplying the heating utility consumption values by the proportional difference in average heating degree day (HDD) between the periods of interest. One HDD was calculated from equation 1 [24].

$$HDD = \begin{cases} 0, & \text{for } \overline{t_{ext}} > 15.5 \\ 15.5 - \overline{t_{ext}}, & \text{for } \overline{t_{ext}} \leq 15.5 \end{cases} \tag{1}$$

where $\overline{t_{ext}}$ is the average external temperature of the day. For some houses, the difference in HDD's was sizeable, with a maximum of a 23% increase in the average HDD value before and after retrofit.

Figure 2: Comparison of the distribution means for gas (top) and electricity (bottom) before and after retrofit. A negative value for a change in the mean suggests a decrease in the use of that utility.

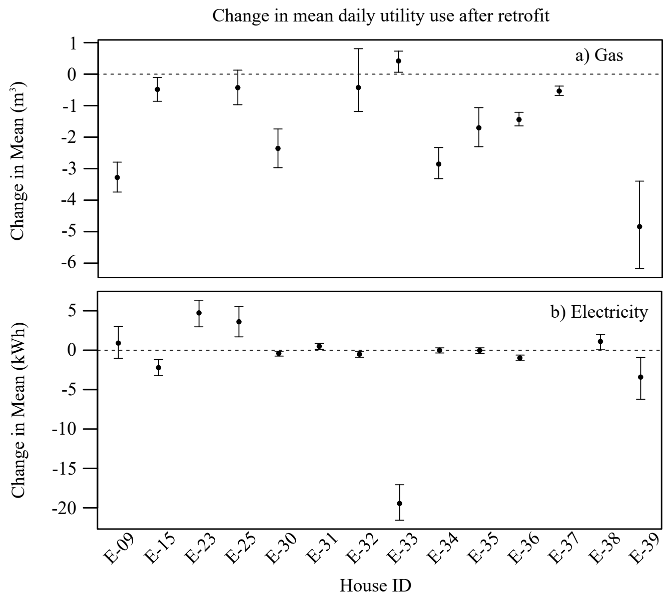
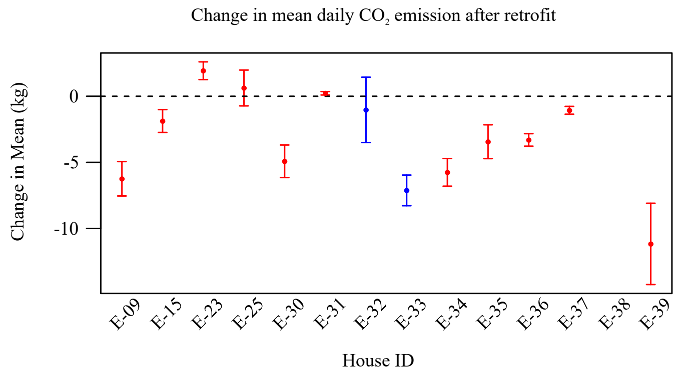


Figure 3: Change in the daily CO_2 emission associated with each properties energy use as a result of retrofit. The data are color coded, where red points denote houses which showed a general increase in internal temperature after retrofit, where blue points denote houses which showed a general decrease in internal temperature after retrofit.



The total daily electricity and gas consumption was then calculated for days in which heating was likely being used, defined as between the 1st of November and the of 1st of April. These months were chosen as they are typically the coldest 5 months of the year [25]. These daily consumption values were split into distributions before and after retrofit. In the cases where exact dates of the start or finish of the retrofit were not available, a one month window around the approximate date was used.

The distributions of gas and electricity consumption were non-normal, and a comparison of the two distributions was therefore achieved using a wilcoxon rank sum test. This test determines if there is a statistical difference in the mean of the two distributions, and the results of this test are plotted in figure 4.1. A negative value for the change in mean corresponds to a reduction in daily mean utility use, and any values whose error bars overlap 0 have no significant difference in their means at the 95% confidence level. Several houses are missing from these graphs due to data not being available. Houses E-23 and E-31 are missing gas data, but this is because they use electricity for heating. House E-38 does use gas, but a sensor fault caused the lack of gas data. Likewise, house E-37 uses electricity, but a sensor fault caused the lack of electricity data.

It is apparent from these data that 8 of the 14 houses display a significant decrease in their daily mean gas use. 2 houses have no significant change, and 1 house shows a significant increase in its daily gas use. For electricity, 6 of the houses have a significant decrease in their daily use (although the decrease is small in 3 of these cases), 3 have no significant change, and 4 show a significant increase. Combining the data displayed on these two graphs further gives insight into any changes in how a household is heated. In the most obvious example, E-33 reports a slight increase in gas use but a considerable drop in electricity use, suggesting occupants relied heavily on electric heating before the retrofit and now rely more on gas heat to their house.

To determine the effect of the retrofit on daily CO_2 emission, the values of daily gas and electricity were converted to associated values of CO_2 emission using UK government greenhouse gas conversion factors [26]. The results are displayed in figure 4.1. It is apparent from this figure that the increase in gas consumption for E-33 is compensated for by its decrease in electricity use. Indeed, the only houses which show an increase in associated daily CO_2 emission are the two properties which are heated electrically. The increase in utility use for these properties may be a manifestation of the rebound effect [27], in which gains in energy efficiency are offset by increased energy consumption after retrofit causing potential overheating. Likewise, it may be that they properties were suffering from the prebound effect [28], which describes a situations in which heating systems are under-used prior to retrofit due to their inefficiency. Removing this inefficiency therefore may result in increased use of the heating system. In either case, the rebound and prebound effects are both associated with increased internal temperatures. The internal temperature of the properties was therefore studied to offer further insight.

4.2. Changes in Internal Temperature

The change in mean internal temperature was calculated in the same manner to the electricity and gas data.

The results are displayed in figure 4. Many of the houses display an increase in internal temperature, suggesting that potential energy savings are at least partially offset by an increase in internal temperature. In five of these cases (E-31, E-34, E-35, E-37, E-39), the internal temperature was below the suggested value for thermal comfort of 18°C[29] before retrofit, and subsequently increased to within the comfortable region. These properties may therefore have been suffering from the prebound effect. E-31 is particularly interesting, as it shows a marginal increase in energy use after retrofit. Although the retrofit was not successful in reducing energy use, the increased tempearture has likely reduced the risk of ill-health, especially as the pre-retrofit survey data described the house as being particularly cold and damp.

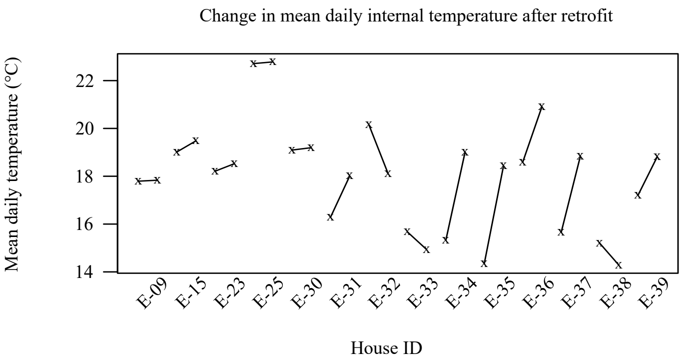
E-23 is the other instance in which an increase in utility use and associated CO_2 emission after retrofit was reported. The increase in internal temperature for E-23 is marginal, and both values are within a comfortable region. The increase in utility consumption for this property might therefore be due to increased occupancy, increased ventilation (with occupants opening more windows), or a combination of the two factors. E-32 is another instance where the data suggests increased ventilation after retrofit. E-32 shows no significant change in associated CO_2 emission, but a sizeable decrease in internal temperature. It may therefore be that the heating controls are unsuitable or misunderstood, and occupants now combat overheating of the property with open windows.

E-33 and E-38 show a temperature decrease and both values are below the normal ranges for comfort. Financial strain may be the reason for the lack of heating in these cases, and would also explain how such a large decrease in electricity was achieved for house E-33. If so, the retrofit might not be considered a success, as the reduction in CO_2 emission is partly due to increased fuel-poverty and the retrofit was unable to remedy this.

4.3. Grey-box Modelling

As a result of the rebound and prebound effects mentioned in section 4.1, reductions in utility use cannot be directly related to increases in building fabric performance. For example, a property might have its building fabric improved by 10% but show no reduction in utility use if occupants have chosen to increase the temperature of their property. To determine what the true fabric improvement is, grey-box modelling was therefore performed on the data. Grey-box modelling considers both the data on utility use and temperatures, and combines these with a physical model of the house. This technique has been shown to provide robust models for physical systems [30, 31] and, although other methods for the determination of building characteristics exist, other methods often have constraints such as the requirement that no heating be employed throughout the night period [32]. Grey-box modelling does not have these constraints, placing it amongst the most versatile methods available when modelling houses

Figure 4: Change in the daily average temperature as a result of retrofit. The first point for each house denotes the mean daily temperature before retrofit, and the second point the mean daily temperature after retrofit. A positive gradient in the connecting line therefore shows an increase in internal temperature between the time periods. The uncertainties on the points are negligible.



with differing heating patterns. A comparison of the optimal building models pre and post retrofit can then be used to trace how successful the retrofit was.

The building model employed treated building components as resistors and capacitors, where the values for thermal resistance and capacitance are the constants to be solved for. The change in internal temperature of the house, dT_i, was assumed to follow the relationship

$$dT_i = \frac{1}{C_i}[\frac{1}{R_i}(T_w - T_i) + H_p * I_{gas}]dt + \sigma_i d\omega_i(t) \qquad (2)$$

where C_i the thermal mass of the heated environment, R_i the resistance of the internal environment, T_w is the wall temperature, T_i the internal average temperature, H_p is a constant describing the conversion from gas consumption to heat output, I_{gas} the gas consumption due to heating, ω_i is a standard wiener process, describing the stochastic nature of the temperature changes and σ_i the scaling factor for the wiener process.

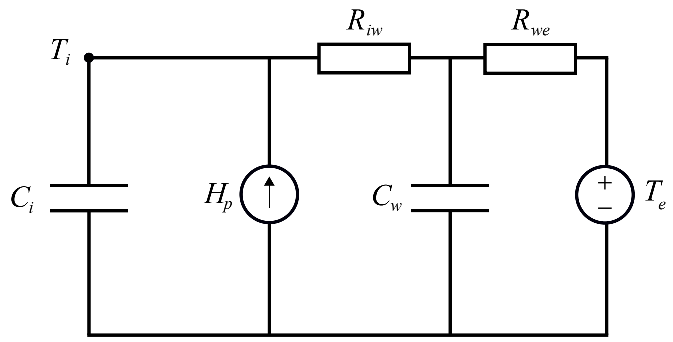
The wall temperature, T_w was not measured in this study, but the external temperature was measured. Another differential equation was therefore set up to describe the wall temperature:

$$dT_w = \frac{1}{C_w}[\frac{1}{R_i}(T_i - T_w) + \frac{1}{R_{we}}(T_e - T_w)]dt + \sigma_w d\omega_w(t) \qquad (3)$$

where C_w the thermal mass of the wall, R_e the resistance between the external environment and the walls and T_e is the external temperature. An RC diagram for the above system can be seen in figure 5.

The model was fit to the data of each house using the CTSM-R package [33]. The data before and after retrofit were fit separately. Again, only data within the

Figure 5: Physical model applied to the data pre and post retrofit. The values of thermal resistance of the fabric, R_{iw} and R_{we}, were of particular interest.



heating season were analysed, as these periods tend to include more heating and greater differences between internal and external temperatures which improves model estimates [34]. An example of data used in the model fitting procedure is displayed in figure 6. The modelled internal temperature can be seen to approximate the internal temperature well and the residuals approximate white noise. A term accounting for solar heating was not included in any models as these data were not available. However, the affect of solar should have a reduced affect within the winter months, and the residuals of the model fits do not indicate a solar term was lacking.

The final heat transfer coefficient (HTC) of the house was calculated as the inverse of the sum of the resistances in the model. The error in the HTC was estimated from the Jacobian of the resistance values. The proportional changes in the HTC pre and post retrofit were then calculated.

For the majority of the houses, the uncertainty in this proportional change in HTC was very large and, as such, no significant difference could be determined. The large uncertainties are perhaps because the model does not include non-linear effects such as wind, nor does it account for physical changes to the building envelope such as the opening of doors and windows. These factors could not be included as no data was available. A lack of data for some houses also contributed to their large uncertainties, as previous work has suggested at least 20 days of monitoring is required for accurate grey-box modelling [34], and 2 of the houses did not meet this requirement (see Figure 1.

The properties for which a significant reduction in HTC were found are listed in table 2. Dwelling E-39 does not have a well defined reduction meaning its utility is limited, but the value of HTC reduction for the remaining 2 dwellings have lower uncertainty and are in agreement with each other. The previously modelled value for the reduction in heat loss as a result of SWI is 18% [16], and the reduction in HTC found for these 2 properties does not agree with this value. The discrepancy between the modelled and measured values follows the established pattern found in other work [17], in which measured values of building fabric are generally worse than predicted values.

Table 2: Reduction in HTC for houses with significant model outputs

Dwelling ID	Reduction in HTC
E-9	$11^{+6}_{-7}\%$
E-35	$11^{+6}_{-7}\%$
E-39	$58^{+18}_{-57}\%$

5. Conclusions

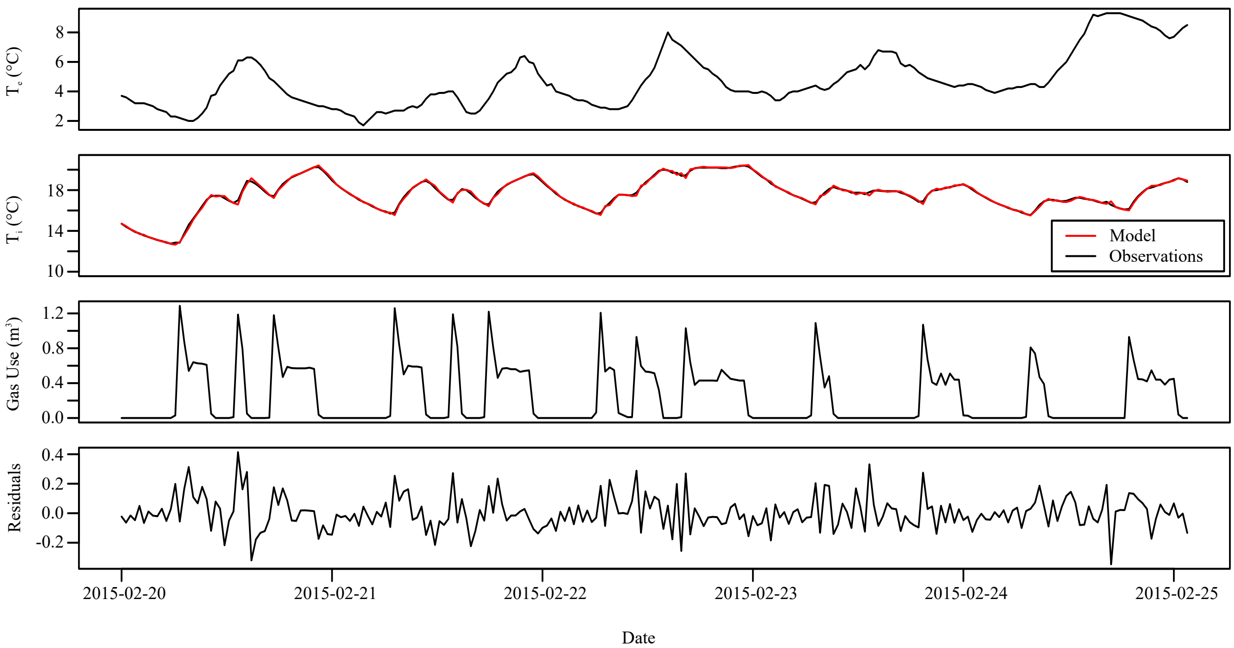
In-use electricity, gas and temperature readings were taken for 14 houses before and after a solid wall insulation (SWI) retrofit. Methods to clean these data were introduced as numerous errors were present. To determine the influence of the the SWI on the building fabric itself, grey-box modelling was performed on the data. A significant result was found for three of the houses, and the reduction in HTC found for two of these properties is less than modelled value of 18%. The remainder of the properties could not be fit accurately with a grey-box model, and additional information such as data on window-opening and weather data would likely assist in the analysis for these cases.

The CO_2 emission associated with the measured gas and electricity consumption was found to decrease for the majority of the houses in the study. However, there was considerable variation in the amount by which the CO_2 emission changed and, in many cases, this amount appeared to be strongly affected by changes in occupant behaviour. Many houses partially offset the potential reductions in utility use with increases in internal temperature in what are likely instances of the rebound or prebound effects. There were also additional non-ideal behaviours suggested by the data, such as the two houses which show a decrease in utility use but also a decrease in temperature, perhaps as a result of financial strain. Similarly, one house showed no significant change in utility use but a decrease in internal temperature, suggesting the occupants may be combating overheating of their houses with increased ventilation. Although the retrofitting generally resulted in lower carbon emissions and increased internal temperatures, educating occupants in how to efficiently use their newly retrofitted houses may be required to eradicate the more wasteful of these behaviours and allow the full benefit of SWI to be realised for each home, in terms of both carbon and financial savings.

Acknowledgements

This work was made possible thanks to funding from the department for business, energy and industrial strat-

Figure 6: Example of the time series data and model fit for house E-39. The top panel displays the external temperature, and below this the internal temperature (black for observed temperatures and red for modelled temperatures). The residuals for this model fit (bottom panel) are low and random suggesting the model is well fit. The gas use is also shown, allowing the effect of gas use on internal temperature to be seen.



egy (BEIS), formally the department for energy and climate change.

[1] BEIS, Energy consumption in the uk (2016).

[2] J. Palmer, I. Cooper, United kingdom housing energy fact file (2013).

[3] Climate Change Act, Climate change act chapter 27 (2008). URL http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf

[4] NBS, The building regulations 1991, approved document l1, conservation of fuel and power (1995).

[5] DCLG, English housing survey, headline report (2016).

[6] H. Elsharkawy, P. Rutherford, Retrofitting social housing in the uk: Home energy use and performance in a pre-community energy saving programme (cesp), Energy and Buildings 88 (2015) 25–33.

[7] S. H. Hong, T. Oreszczyn, I. Ridley, The impact of energy efficient refurbishment on the space heating fuel consumption in english dwellings, Energy and Buildings 38 (10) (2006) 1171–1181. doi:http://dx.doi.org/10.1016/j.enbuild.2006.01.007.

[8] A. Vilches, n. Barrios Padura, M. Molina Huelva, Retrofitting of homes for people in fuel poverty: Approach based on household thermal comfort, Energy Policy 100 (2017) 283–291. doi:http://dx.doi.org/10.1016/j.enpol.2016.10.016.

[9] Hansford, A report to the green construction board and government by the chief construction adviser, Report (2015).

[10] CCC, Meeting carbon budgets, 2016 progress report to parliament, Report (2016). URL https://www.theccc.org.uk/wp-content/uploads/2016/06/2016-CCC-Progress-Report-Executive-Summary.pdf

[11] DECC, Domestic green deal and energy company obligation in great britain, headline report (2015).

[12] DECC, Household energy efficiency national statistics (2016).

[13] BRE, Solid wall heat losses and the potential for energy saving, literature review, Report, Building Research Establishment (2014).

[14] A. Byrne, G. Byrne, G. ODonnell, A. Robinson, Case studies of cavity and external wall insulation retrofitted under the irish home energy saving scheme: Technical analysis and occupant perspectives, Energy and Buildings 130 (2016) 420–433. doi:http://dx.doi.org/10.1016/j.enbuild.2016.08.027.

[15] Innovate UK, Building performance evaluation programme: Findings from domestic projects (2016).

[16] BRE, A study of hard to treat homes using the english house condition survey, Defra and Energy Saving Trust, London.

[17] D. Johnston, D. Miles-Shenton, D. Farmer, Quantifying the domestic building fabric performance gap, Building Services Engineering Research and Technology 36 (5) (2015) 614–627.

[18] B. Bordass, R. Cohen, M. Standeven, A. Leaman, Assessing building performance in use 3: energy performance of the probe buildings, Building Research & Information 29 (2) (2001) 114–128. doi:10.1080/09613210010008036.

[19] BEIS, Energy company obligation: Flexible eligibility (2017).

[20] V. O. Agency, Council tax: stock of properties 2015 (2015).

[21] DCLG, English housing survey 2008, housing stock report (2008).

[22] C. Chen, L.-M. Liu, Joint estimation of model parameters and outlier effects in time series, Journal of the American Statistical Association 88 (421) (1993) 284–297.

[23] J. López, Detection of outliers in time series. URL https://cran.r-project.org/package=tsoutliers

[24] CIBSE, Tm41: Degree-days: theory and application, Report, The Chartered Institution of Building Services Engineers (2006).

[25] BRE, The governments standard assessment procedure for energy rating of dwellings 2012 edition, Report, BRE (2012).

[26] DECC, Greenhouse gas reporting - conversion factors 2016 (2016).

[27] J. D. Khazzoom, Economic implications of mandated efficiency in standards for household appliances, The energy journal 1 (4) (1980) 21–40.

[28] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: the gap between performance and actual energy consumption, Building Research & Information 40 (3) (2012) 260–273.

[29] WHO, The effects of the indoor housing climate on the health of the elderly: Report on a who working group (1984).

[30] R. Sonderegger, Diagnostic tests determining the thermal response of a house, Tech. rep., California Univ., Berkeley (USA). Lawrence Berkeley Lab. (1977).

[31] M. J. Jimenez, H. Madsen, Models for describing the thermal characteristics of building components, Building and Environment 43 (2) (2008) 152–162.

[32] A. Papafragkou, S. Ghosh, P. A. James, A. Rogers, A. S. Bahaj, A simple, scalable and low-cost method to generate thermal diagnostics of a domestic building, Applied Energy 134 (2014) 519–530.

[33] R. Juhl, N. R. Kristensen, P. Bacher, J. Kloppenborg, H. Madsen, Ctsm-r user guide, Technical University of Denmark 2.

[34] A.-H. Deconinck, S. Roels, Comparison of characterisation methods determining the thermal resistance of building components from onsite measurements, Energy and Buildings 130 (2016) 309 – 320. doi:http://dx.doi.org/10.1016/j.enbuild.2016.08.061.