Resilient Domestic Retrofit, Producing Real World Performance

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Abstract

This paper examines how deep carbon savings were achieved in a retrofit scheme in owner occupied houses in Greater Manchester. This programme operated within constraints that tested real-world at-scale conditions; modest capital budgets, homeowners in situ, and a 'mainstream' building contractor.

Post-works monitoring shows that the performance gap between design intentions and actual carbon emissions has been minimised. Environmental conditions have also improved, with householders reporting high degrees of satisfaction.

The paper explores the retrofit process, from assessment through design, construction and occupation. It uncovers what worked well, real world constraints, and potential areas for improvement. The authors are respectively the lead architect and a householder, giving a unique perspective from both sides of the process.

Keywords 'Retrofit' 'Performance Gap' 'Whole House'

1.0 Introduction

Whole house retrofit is a holistic approach to the application of deep energy efficiency measures. This needs to happen at scale and fast if the UK is to meet its carbon dioxide emissions reduction obligations (1). There are concerns about the quality of retrofit work carried out to date, and emerging evidence of a gap between predicted and actual performance (2-3). To address this we need to understand how significant this gap is and what causes it. This paper examines a single project, carrying out a detailed comparison of design intentions and built performance.

2.0 The Performance Gap

There is growing awareness of a mismatch between design intentions and actual performance in new homes (4), with fears of a loss of trust among householders, and implications for energy policy (5-6). If this is true of new-build housing, how much more is this likely to be apparent in retrofit, where direct comparisons between before and after experiences are possible, and work is often motivated by a direct desire to reduce energy use?

In the Retrofit for the Future programme, the majority of homes failed to meet the design targets (7). Data from mass-retrofit programmes indicates a significant performance gap, sometimes with no savings at all from retrofit works, or savings made but in cold homes (8-10). Modelling tools have been found to overestimate energy use in the pre-retrofit condition, with the identification of a 'pre-bound' effect (11), overstating the savings possible. Errors in implementation and assumption at each stage of the design and construction process then have a multiplying effect, further contributing to the size of the performance gap (12-13). (See Table 1).

Cause	Description
Inappropriate modelling tool / limited data entry	Whilst SAP (Standard Assessment Procedure - the UK's national energy calculation methodology) has often been criticised, it is relatively well understood and trusted as a steady state thermal modelling tool (12-13). RdSAP, a reduced data entry version, is the commonly used energy modelling tool for retrofit, introducing a greater number of potentially incorrect assumptions.
Climate and Weather	Weather varies from year to year. It is possible to control for this through a degree day analysis.
Incorrect assumptions about performance of existing fabric.	It can be difficult to determine the actual performance of existing constructions. For example, the thermal conductivity of existing brickwork. Energy models may be reliant on estimations that prove inaccurate.
Poor understanding of mechanisms by designers and poor buildability of design.	There is a limited understanding within the industry of the mechanisms that affect heat loss, and the importance of factors such as thermal bridging, air-tightness and system commissioning - leading to poor specifications. In addition it may not be possible to have a full understanding of existing conditions before construction work commences, resulting in details or specifications that cannot be achieved on site.
Energy model not reflecting proposed designs	Poor communication between designers and energy assessors, so the energy model does not reflect design intentions, leading to a gap in performance.

Poor installation and quality control in construction.	Builders making substitutions without realising the potential implications for performance (12-13). Poor quality control on site, resulting in poorly fitted insulation etc.
Incorrect assumptions with regards to user behaviour.	Building occupants are often blamed for failures in building performance (14). Comfort takeback is a particular concern in retrofit, where rather than saving energy, householders turn up the thermostat - though the evidence to support this is limited (15-17). Though the comfort preferences of occupants do have an impact on energy use, it may be possible to account for these at design stage.
Omission of unregulated energy use from design energy models.	A standard SAP assessment will not include unregulated energy uses - such as cooking and electrical appliances. This can result in a mismatch between reported projected and actual energy use.

Table 1 - Summary of potential causes of performance gap in retrofit.

3.0 Project Description

This paper examines a whole house retrofit scheme in 12 owner occupied homes in Greater Manchester. Funding was provided as a grant from Department of Energy and Climate Change (DECC) to cover set-up and design costs, whilst 0% interest loans were provided to householders for capital works. Some householders also contributed their own funds, and a small amount of subsidy was provided through the Energy Company Obligation (ECO).

The net construction budget for each house, informed by the assessment process and the householder's wishes, averaged £30,000 for fabric and services work, excluding PV installation. Householders applied for the project, with 12 selected from those who had expressed an interest and undergone an initial assessment, to provide a variety of house-types and locations throughout Greater Manchester. Design and pre-construction work was carried out in 2013, building works in the first half of 2014, and photo-voltaic panels were fitted to the houses in late 2014 and early 2015. A summary of the steps taken to minimise the performance gap in this project is given at Table 2.

The project brief was to achieve actual post-retrofit carbon emissions of $17kgCO_2/m^2$.a, and actual Space Heating Demand of $40-60kWh/m^2$.a (based on the requirements of the draft Greater Manchester Domestic Retrofit Strategy). During the design stage this was estimated using a spreadsheet energy model based on SAP 9.92. A pragmatic approach was taken, with modest budgets and householders remaining in situ during works. The designers learned lessons from their own experience of the Retrofit for the Future programme (18), taking a fabric first approach. Less obvious sources of heat loss were considered, such as loft hatches

and thermal bypass in chimneys and care was taken to address thermal bridging (see figure 5). A summary of the retrofit measures introduced is given in Table 3 below.

Since the whole house was not treated, it was not possible to create a new continuous air-tight layer around the whole dwelling. Instead, where invasive works were being carried out, such as the installation of internal wall insulation, tapes and membranes were used to create a good seal, with basic draught-proofing works in the remainder of the dwelling. Despite this, based on past experience, designers estimated that an air-permeability rating of $5m^3/m^2$.hr was achievable, cutting existing levels of air leakage by 50-75% - estimated using the SAP model.

Work was on site was generally carried out to a high standard, though the work took longer than planned (see figures 1-4). In interviews with householders, by both Salford University as part of DECC's programme evaluation, in work by independent researchers (19) and in internal project evaluations in which independent researchers were commissioned by the client to speak to householders, householders reported that whilst the construction process had been stressful and disruptive, their homes are now warmer and more comfortable, making it worthwhile.

Cause	Description
Inappropriate modelling tool and limited data entry	An assessment was carried out based on a full version of SAP 9.92 (21), so that a rich dataset was available for energy modelling. This was further augmented with a detailed householder questionnaire, and results were calibrated against actual pre-retrofit bill data.
Climate and Weather	Scheme to be monitored to enable degree day analysis so effects of weather could be accounted for.
Incorrect assumptions about performance of existing fabric.	A detailed survey of the existing fabric was undertaken, including investigation of wall and floor build ups with a borescope, and conservative assumptions were made about existing thermal performance. For example U-values of solid at 1.8 W/m^2.K, rather than the SAP default of 2.1 W/m^2.K
Poor understanding of mechanisms by designers and poor buildability of design.	The designers had extensive previous experience of whole house retrofit, which informed their fabric first approach and resulted in a full set of detailed construction design information. Dialogue was attempted with the chosen contractor, to improve buildability.
Energy model not reflecting proposed designs	The designers were also responsible for the energy modelling, minimising the opportunity for discrepancies between designs and modelled assumptions.
Poor installation and	A traditional contract was used, with high levels of oversight of

quality control in construction.	construction by the designers. Training was undertaken on site on the installation of solid wall insulation, which included an explanation of the significance of thermal bridging, and on the air-tight construction techniques.
Incorrect assumptions with regards to user behaviour.	Pre-retrofit modelling was calibrated against actual bills, so savings were not over-stated. Otherwise SAP assumptions were accepted.
Omission of unregulated energy use from design energy models.	An adjusted version of the standard SAP model was used, which included estimates of cooking and appliance energy use.

Table 2 - Outline of measures aimed at reducing performance gaps.

Property	Element	Existing Condition	Proposed	Implemented?
House 1: 114 sqm 4 bedroom end-terrace with room in roof early 1920s. 3 occupants.	Roof/Loft	Part-insulated room in roof and loft.	Loft top-up insulation	Yes
	Walls	Solid to gable and rear, uninsulated cavity to front. Single storey highly-insulated timber frame extension to rear.	140mm woodfibre external wall insulation to gable and rear. Cavity fill to front.	Yes.
	Floor	Uninsulated suspended timber at main house, uninsulated solid to kitchen, new solid insulated to extension.	200mm woodfibre insulation to suspended timber floor, perimeter insulation to solid kitchen floor.	Yes.
	Windows	Mix of double, single and secondary glazed.	Older double-glazed replaced with triple glazed.	Yes
	Doors	Solid timber front door	Insulated timber front door	Yes
	Ventilation	Intermittent extract.	Passive Stack	*Decentralised continuous mechanical extract.*
	Heating System	A-rated gas combination boiler with room thermostat, small room woodburner.	no change	-
	PV system	None	3kWp	3.27kWp
House 2 132 sqm 4 bedroom semi-detached 1920s. 4 occupants.	Roof/Loft	270mm loft insulation, new loft hatch.	400mm loft insulation and draught-proofing to loft-hatch.	Yes.
	Walls	Solid masonry, uninsulated.	80mm mineral wool Internal wall insulation (IWI) to front, 200mm external wall insulation (EWI) to side and rear.	Yes - with some changes in thickness of EWI to 100mm rear for reasons of space.
	Floor	Uninsulated suspended timber.	200mm woodfibre insulation.	Yes.
	Windows	Mix of single glazed, secondary glazed and double-glazed timber windows.	Single-glazed windows replaced with triple glazing.	Yes.
	Doors	Solid timber.	Draught-proofing to existing doors.	Yes.

	Ventilation	None.	Passive Stack Ventilation	Yes
	Heating System	A-rated gas combination boiler with room thermostat, small room woodburner.	No change	-
	PV system	None	3kWp	3.3kWp
House 3 *130sqm* *3 bedroom* *Mid-terrace* *Pre-1919* *1 occupant*	Roof/Loft	200mm loft insulation	400mm loft insulation	Yes
	Walls	Solid masonry, uninsulated.	80mm mineral wool Internal wall insulation (IWI) to front, 200mm external wall insulation (EWI) to rear.	Yes
	Floor	Uninsulated suspended timber.	No change	-
	Windows	Mix of recent timber double glazing and single glazing.	Replace single glazing with triple glazing.	Yes
	Doors	Uninsulated solid timber , front and rear.	Insulated timber, front and rear.	Yes
	Ventilation	Intermittent extract.	Passive stack ventilation.	Yes
	Heating System	A-rated gas combination boiler with room thermostat, small room woodburner.	No change	-
	PV system	None	2.33kWp	3.63kWp
House 4 *164 sq m* *4 bedrooms with recent single storey rear extension.* *Semi-detached.* *18th and 19th Century construction.* *2 occupants*	Roof/Loft	150mm loft insulation over majority, with some areas missing due to being inaccessible.	400mm loft insulation throughout.	Mostly - inaccessible area continued to be inaccessible, despite efforts of design and construction team.
	Walls	Solid masonry to front and rear, uninsulated cavity to gable (built when adjoining terrace demolished), insulated cavity to recent extension.	IWI to front, EWI to rear and side, with additional cavity fill to gable wall.	Yes.
	Floor	Uninsulated suspended timber to front, solid uninsulated to small area of kitchen, insulated solid to kitchen extension.	200mm woodfibre insulation to suspended timber floor.	Yes - though some areas in cellar omitted due to obstructions.
	Windows	Majority double glazed timber, single glazed timber to front.	Replace single glazed timber to front with triple glazed units.	Yes.
	Doors	Solid uninsulated timber.	Draught proofing to existing doors.	Yes
	Ventilation	Intermittent extract from kitchen only.	Passive stack ventilation added to bathroom.	Yes.
	Heating System	A-rated gas system boiler with hot water cylinder, large room woodburner.	No change.	-
	PV system	none	3.67kWp	3.96kWp

House 5 129 sq m 4 bedroom Semi-detached 1920s 2 occupants	Roof/Loft	Minimal loft insulation.	Top up loft insulation to 400mm.	Yes.
	Walls	Solid masonry.	80mm mineral wool Internal wall insulation (IWI) to front, 200mm external wall insulation (EWI) to side and rear.	Yes
	Floor	Uninsulated suspended timber, small uninsulated solid floor to utility room.	200mm woodfibre insulation to suspended timber floor, external perimeter insulation to solid floor.	Yes.
	Windows	Mix of single glazed timber and double glazed uPVC.	Most single glazed timber replaced with triple glazing, some with stained glass secondary glazed.	Yes.
	Doors	Solid uninsulated timber.	Rear door replaced with solid insulated timber door, front door draught-proofed.	Yes.
	Ventilation	None.	Passive Stack Ventilation.	Yes
	Heating System	G-rated gas boiler with cylinder and analogue room thermostat.	Replace with A-rated combination gas boiler with programmable room thermostat.	Yes.
	PV system	none	2.66kWp	2.61kWp

Table 3 - Summary of retrofit measures.

Figure 1 - On site training on thermal bridging and external wall insulation, showing insulation carried past internal floor level.

Figure 2 - Careful taping of air-tightness layer in internal wall insulation (IWI).

Figure 3 - Careful taping of air-tightness layer in installation of IWI at window reveal.

Figure 4 - High performance insulation to bridge between loft insulation and external wall insulation.
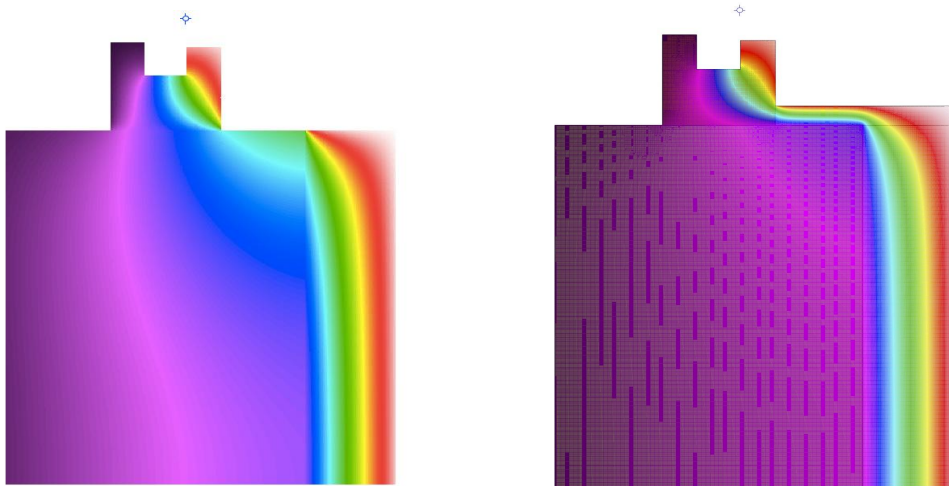

Figure 5 - Design stage modelling of thermal bridging. Image on left without reveal insulation, image on right with reveal insulation.

4.0 Performance Analysis

4.1. Household Energy and Environmental Data Collection

As a pilot project, properties were monitored post-completion to evaluate building performance. The data collected for this process is summarised below, and informs the analysis which follows. Of the 9 houses included in the contract studied here, 8 underwent a full whole house retrofit, and sufficient data for meaningful analysis is available for 5.

This analysis has been carried out by the lead architect for the project and one of the householders. This has given this work a unique perspective, in which both researchers have a thorough understanding of both the built and social context of the project.

Salford University data

The Salford University data used here covered a number of parameters including:

- Gas: pulse count on a 'Class 2' billing meter, +/-3% accuracy.
- Internal temperature and humidity (typically in 3 rooms): +/-3% relative humidity accuracy, +/-0.5^{o}C temperature accuracy.
- Electricity Use: off the shelf domestic CT clamp sensor (Current Cost), +/-3% accuracy (not able to monitor PV generation).
- Pre and post works building leakage tests, to determine air-permeability, conducted in accordance with EN13829, Type B.

The duration of the functioning data collection covered typically 280 days of data per household, but varied from 243 to 515 days between the different houses and within that there were some gaps in data (see Table 4). In particular it is noted that the pre-retrofit environmental data is very limited and covers almost none of the heating season before the retrofits taking place. Nevertheless, the resolution of the Salford University data was good with data available at 30 minute intervals.

Householder / Billing data

The householder data was collated by Dominic McCann as a collaborative process between the householders. The parameters collected were:

- Gas and electricity use quarterly data from meter readings.
- Quarterly PV generation Feed-in Tariff data.

This householder data covers at least 537 days of billing information (and over 5yrs in the case of most of the houses) with minimal gaps and as such represents a relatively complete set of data. The billing data was supplemented in some instances

by that originally collected in the initial URBED evaluations in terms of the pre-retrofit energy use.

Available data	Salford University Data (days)		Householder data (days)
	Gas data (no reliable elec data)	Temperature RH & CO2 data	Gas / Electricity billing data
House 1	505	515	5170
House 2	0	313	2501
House 3	366	366	3099
House 4	273	203	1790
House 5	243	574	537

Table 4 - Availability of household energy and indoor environmental data.

4.2 Building Performance

4.2.1 Air-tightness

Air-permeability	Before (m3/m2.hr @ 50pa)			After (m3/m2.hr @ 50pa)		
	Modelled (SAP)	Actual (Test to EN13829)	% difference	Modelled (SAP)	Actual (Test to EN13829)	% difference
House 1	13.60	9.43	31% better	5.00	9.22	84% worse
House 2	16.00	n/a	n/a	5.00	8.88	77% worse
House 3	15.40	n/a	n/a	5.00	10.18	103% worse
House 4	21.6	14.55	32% better	5.00	13.55	171% worse
House 5	18.4	16.71	9% better	5.00	11.69	133% worse

Table 5 - Air-permeability results (before and after)

Comparing the results for air permeability with the output of the model in Table 5 above shows that pre-retrofit air-tightness was underestimated to a significant degree, thereby over-estimating heat loss in the SAP model of the existing condition. This could be due to incorrect assumptions within the model itself, for example on the level of air-tightness achieved by different types of construction, or assessor errors in judgement, for example when noting what % of doors and windows draught-proofed. Unfortunately, the real-world tests came too late to inform the design modelling, being conducted just before construction work started. Post-works air-

permeability design targets were not achieved. This suggests over-optimism on the part of the designers, given the level of intervention possible.

4.2.2 Heating Energy Use

The main aim of the retrofit works was to reduce carbon emissions and improve comfort through reducing space heating demand. On a simple analysis, this has been achieved, with an overall reduction in gas use of 47% on average, and an estimated space heating demand reduction of 52%, as shown in Figure 6.
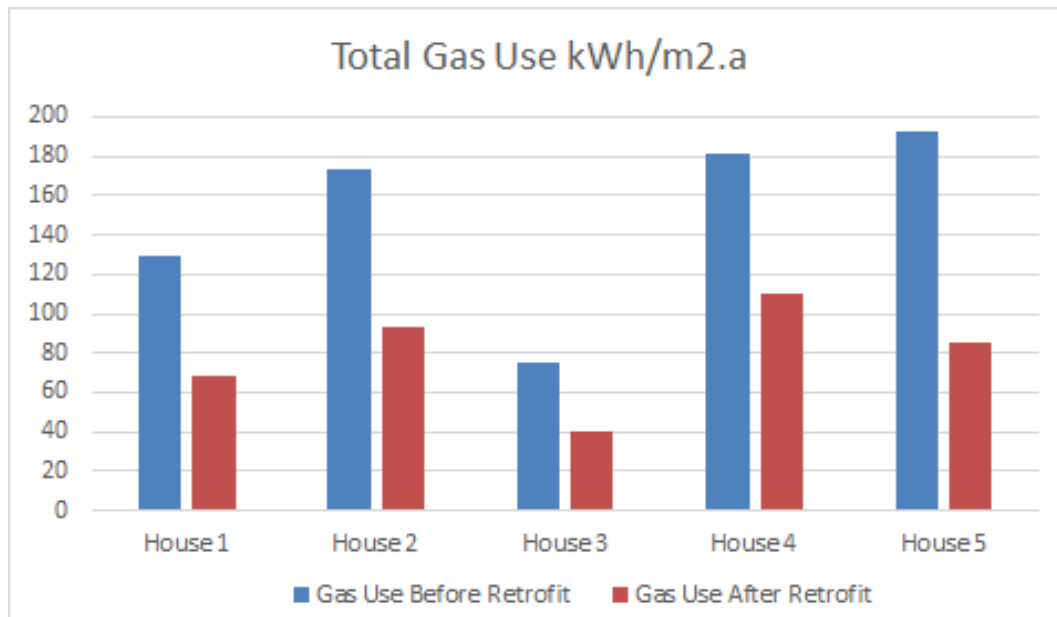
Figure 6 - Gas use before vs gas use after, by house

However looking simply at gas use doesn't provide the full picture. Carrying out a degree day analysis[1] isolates the variable of weather and demonstrates that gas use per degree of temperature difference between inside and outside has reduced by 39% (analysis limited to 3 houses for which a full set of Salford University data is available), as shown in Figure 7.

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[1] Degree day analysis based on base temperature of 15.5°C throughout. Met Office data for Manchester Airport used for external temperature.
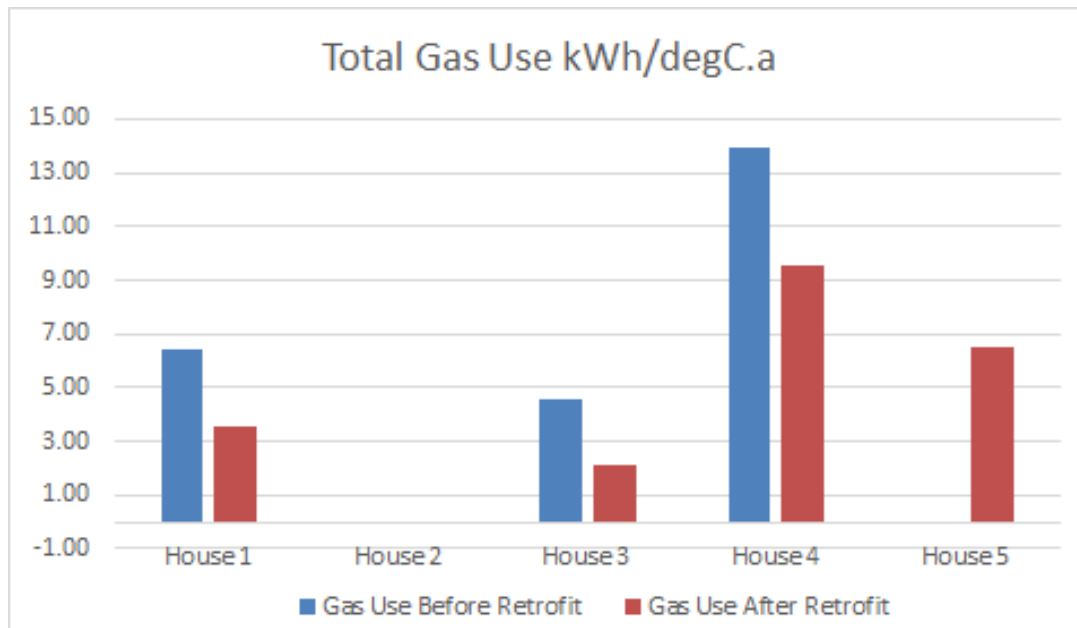
Figure 7 - Degree day analysis per house (Salford University Data: n.b. missing data House 2 before and after, House 5 before).

The design targets for the project were absolute, rather than relative. Whilst making a percentage reduction in energy use is of course welcome, it is important to understand whether design intentions for absolute outcomes have been achieved. Looking at this data demonstrates that there is significant variation from the outcomes predicted by the SAP model (Figures 8 and 9).
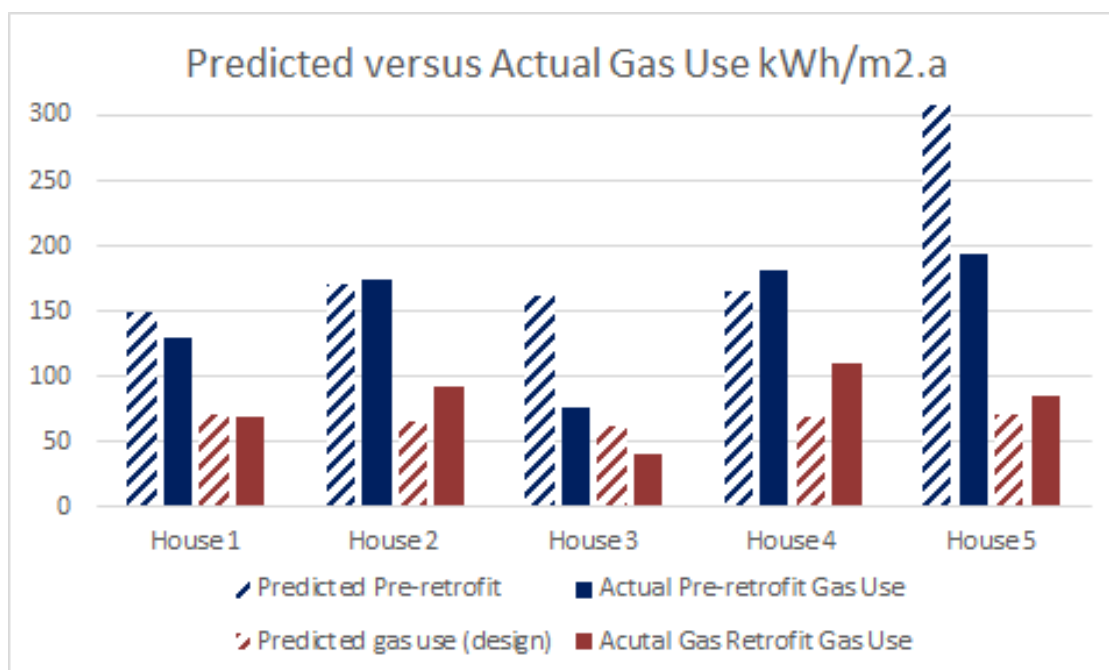

Figure 8 - Predicted vs actual gas use per house (before and after).
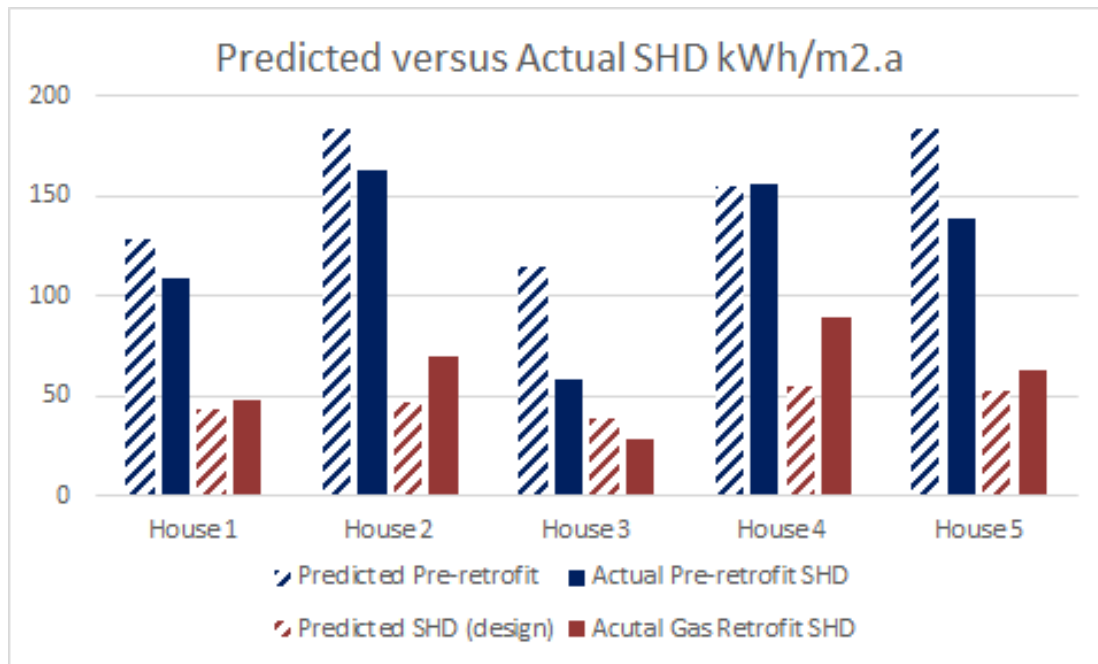
Figure 9 - Predicted vs actual SHD per house (before and after) (note: includes estimates of woodfuel use where applicable).

Space Heating Demand (SHD) in the analysis presented has not been directly measured, but rather has been derived from the gas use and solid fuel use data by a combination of scaling using the ratios in SAP for heating against hot water and other energy demands and estimates of the summer gas use demand outside the heating season.

Households were on average using less energy for heating before retrofit than was predicted. Since this was calibrated against actual bills, this is of lesser importance than whether post-retrofit targets were met. As can be seen in Figure 10, the SAP model is not correct in predicting Space Heating Demand outcomes, though not in a consistent direction.

We already know that the air-permeability values in the design model were not achieved. Running the model with air-permeability values corrected to those achieved on site closes this gap. This demonstrates the importance of air-tightness for energy performance, though it does not give the whole answer.
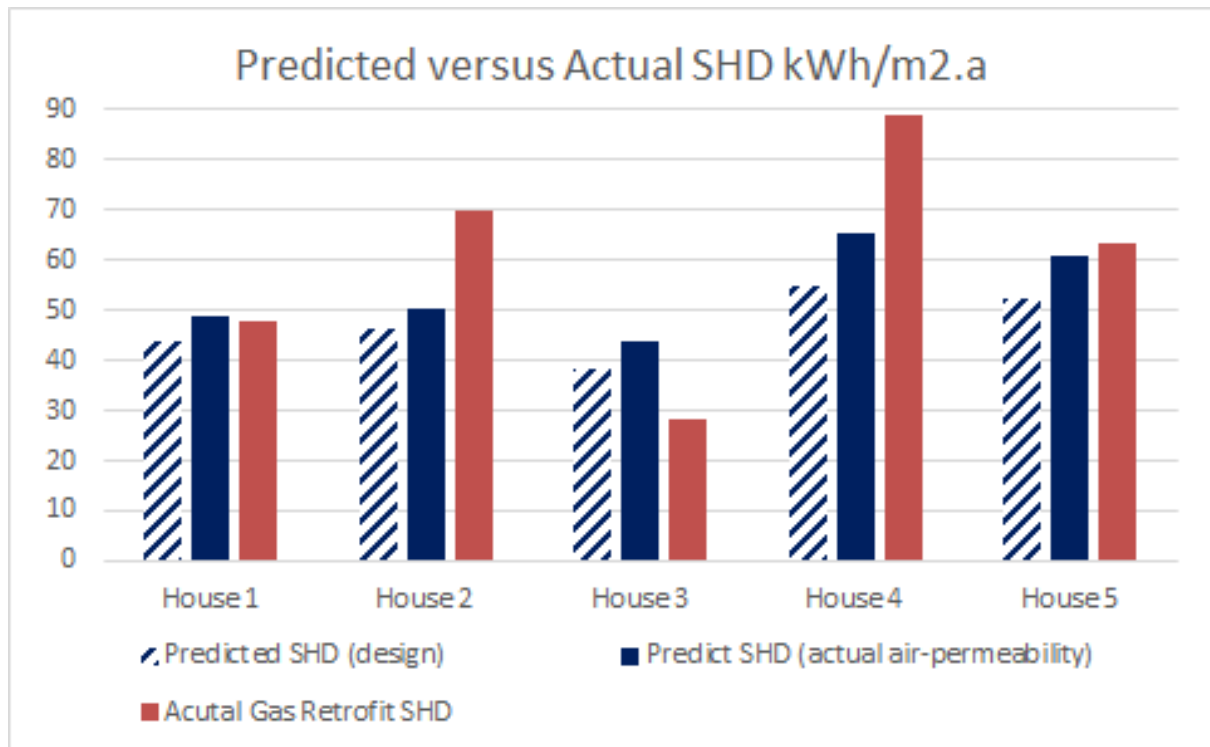
Figure 10 - Values for post-retrofit SHD, actual vs modelled adjusted for actual air-permeability value.

Assumptions about occupant behaviour and heating patterns need to be questioned. The average hours of heating is available only for the post-retrofit condition. This was based on the Salford University gas use data for February 2015. The methodology employed was: if the gas use was 0.5kWh or more in a 30min interval this was counted as "heating on". Clearly there may be slight errors in this if people ran a bath or took a long shower this might end up counted as heating; but represents a reasonable proxy in the absence of other monitoring. See Figure 11 below for house 1 for an illustration of this.
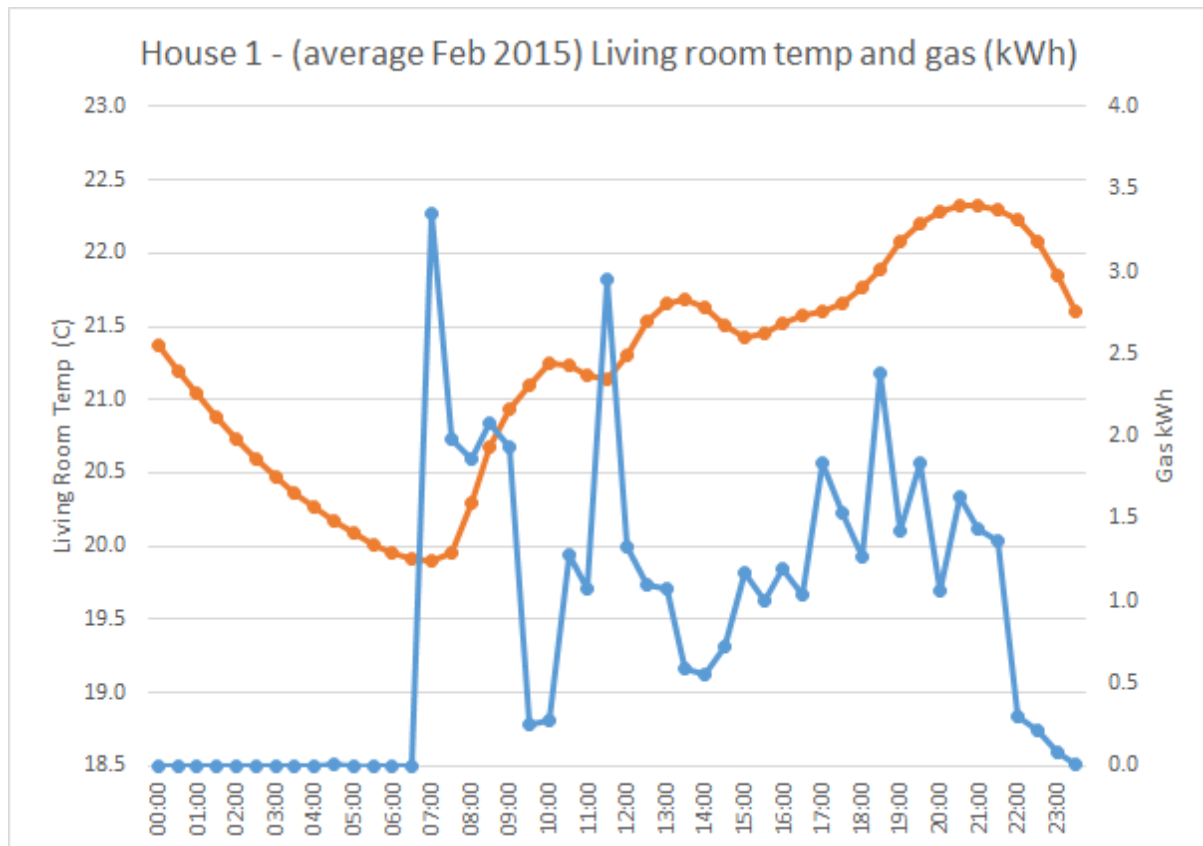
Figure 11 - Living Room Temperature and Gas Use in House 1.

Looking across the houses (Table 6) suggests that there is a close correlation between variation from predicted Space Heating Demand and actual hours of heating, with a direct and proportional effect on the amount of energy used.

	Estimated Hours of Daily Heating (Feb-2015)	SAP Assumption (weekday)	Difference
House 1	14	9	+5 hours
House 2	12	9	+3 hours
House 3	8	9	-1 hour
House 4	24	9	+15 hours
House 5	17.5	9	+8.5 hours

Table 6 - Hours of heating by house vs assumptions in SAP.

This is further supported by recent reported changes in House 4, where occupancy has changed and heating is now only on for 4 hours per day. Heating energy use has subsequently halved, bringing the actual consumption much closer to the modelled predictions (based on data from recently installed open energy monitors, supported by householder meter readings).

Another behavioural influence on energy use is hot water. Actual hot water demand was estimated by looking at gas use in non-heating summer periods, and is compared against predicted values in the graph below. There is a significant variation in hot water demand and no obvious pattern as to how this relates to predictions (Figure 12). This suggests that if SAP is to be used in estimating retrofit performance, a better way of assessing hot water demand is needed.
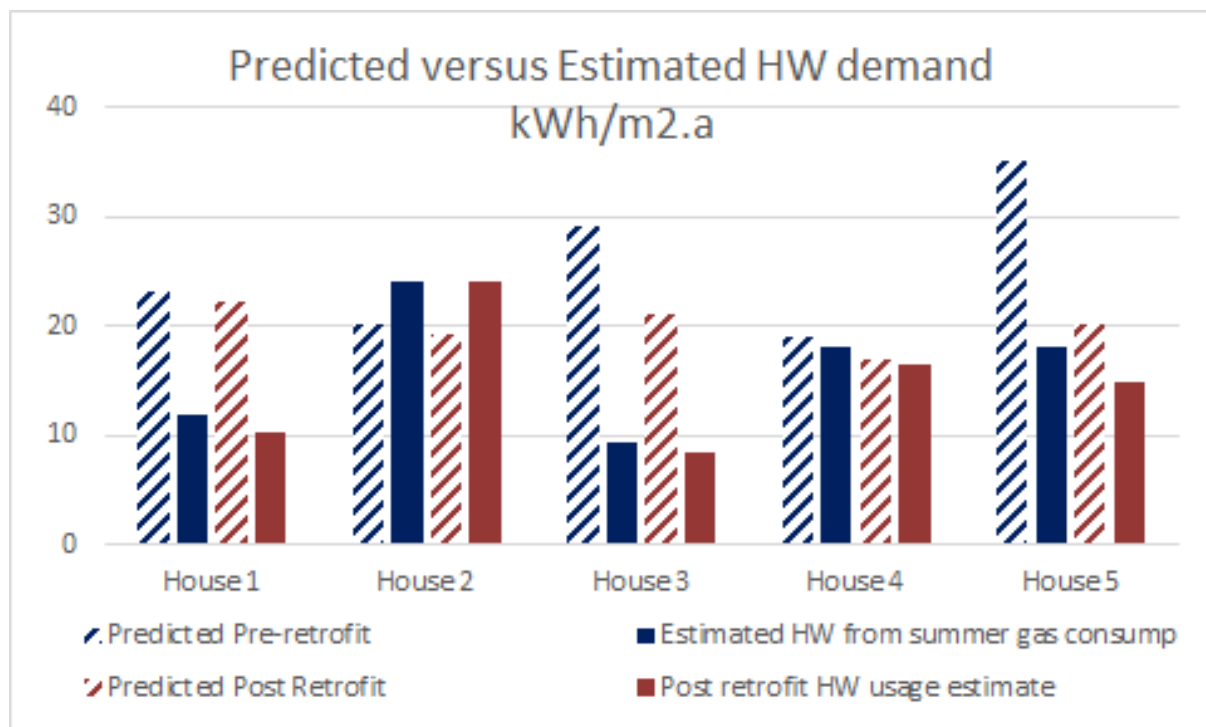

Figure 12 - Estimates of hot water use
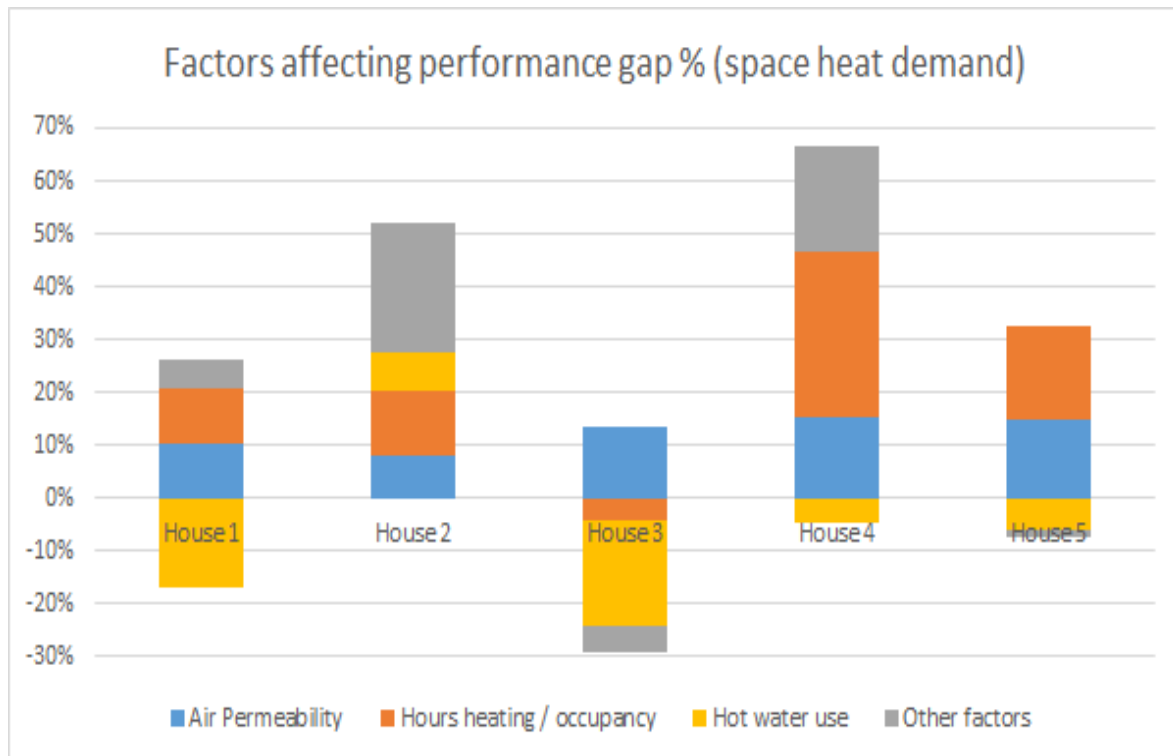
Figure 13 - Assessment of factors affecting the performance gap

The combination of worse than expected air permeability, variation in hours of heating / occupancy and hot water corrections to the performance gap can explain 18% of the 25% gap in the space heating demand. Thus the residual performance gap (other factors) is approximately 7% (Figure 13).

These other factors may include elevated internal temperatures, as compared with the assumptions within SAP, though there is insufficient data to confirm this at present. The above graph attempts to quantify the impact of each of these factors on the performance gap, and thereby suggests the areas that need to be addressed in future modelling of and design of whole house retrofits.

4.2.3 Environmental and Comfort Conditions

The performance gap is not just about energy use, but also meeting householders' comfort expectations and ensuring homes are healthy. Whilst anecdotally householders report they are warmer and more comfortable, we only have robust data for one house on temperature and humidity both pre and post retrofit. This shows that the retrofit has had a demonstrable effect on the internal environment by smoothing out internal temperature variations and increasing minimum temperatures (Figures 14-16). There appears to be no significant difference in relative humidity values, with the home maintaining an acceptable level of between 40 and 60% Relative Humidity.
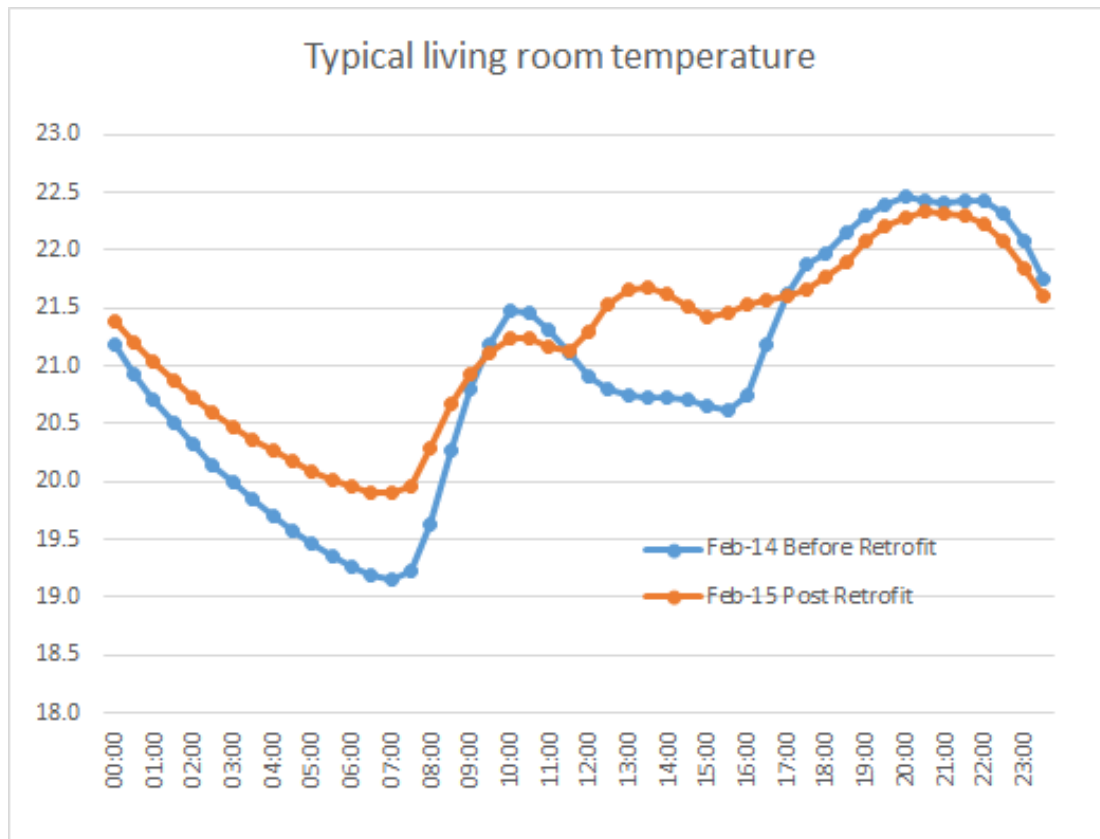
Figure 14 - Typical Internal temp before / after retrofit (House 1 only)

4.2.4 Electricity Use

Mains electricity is currently still a relatively carbon intensive fuel, and so householder's electricity use has a significant impact on the carbon emissions. Pre-retrofit, most of the houses already used significantly less electricity than predicted. This raises questions about the assumptions made at design stage. It is possible that the higher levels of environmental commitment of these volunteer households meant that they had already taken action - either behavioural or in choice of appliances - to reduce their electricity consumption.
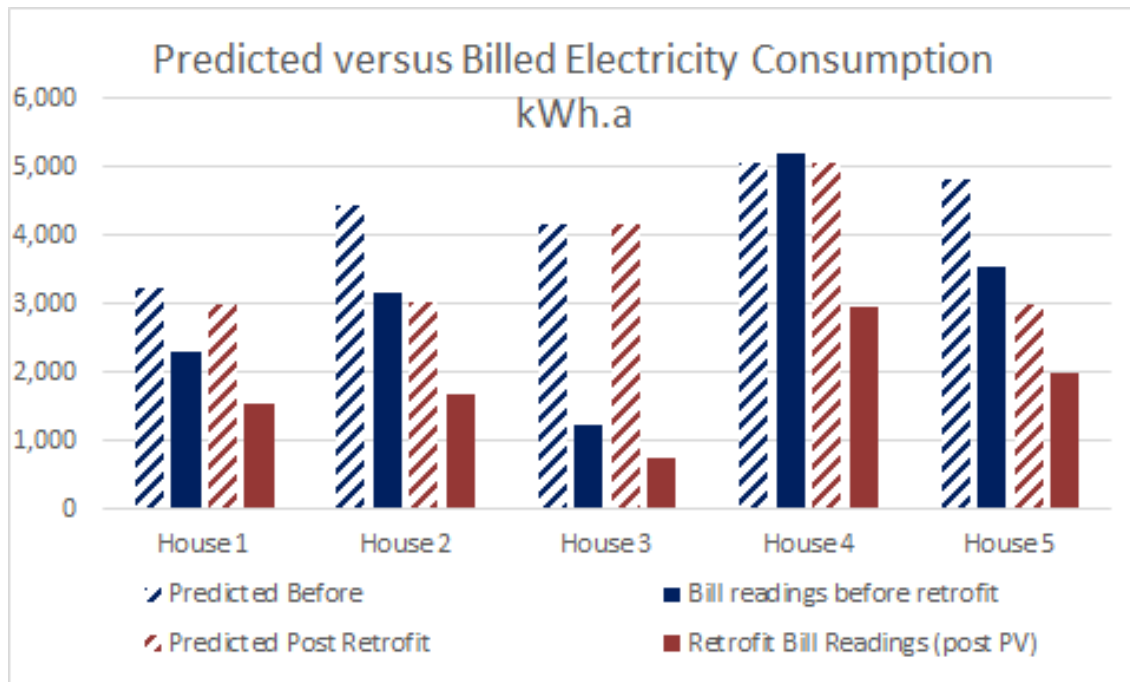
Figure 15 - Electricity Use, actual vs modelled (before and after).

Photovoltaic (PV) panels add another dimension to electricity use, which it has not been possible to monitor in a way that allows us to fully understand how much that was generated was used within the house, and how much exported. Several householders report anecdotally being more aware of their energy use, and modifying behaviour so that they use electricity for things like laundry during the day when panels are generating. Any electricity used directly from the panels like this would not be included in metered consumption figures for mains electricity above - providing a slightly skewed picture (Figure 17).

PV generation, taken from householder Feed in Tariff (FiT) (22) information is generally slightly better than originally modelled (Figure 18). The gap is minimal once adjusted for the actual systems installed. PV output was estimated at design stage in 2013, with detailed specification carried out in late 2014 by a specialist installer. In most cases this led to higher performance systems being installed - showing both the technological advancement occurring in PV, but also the benefit of specialist input.
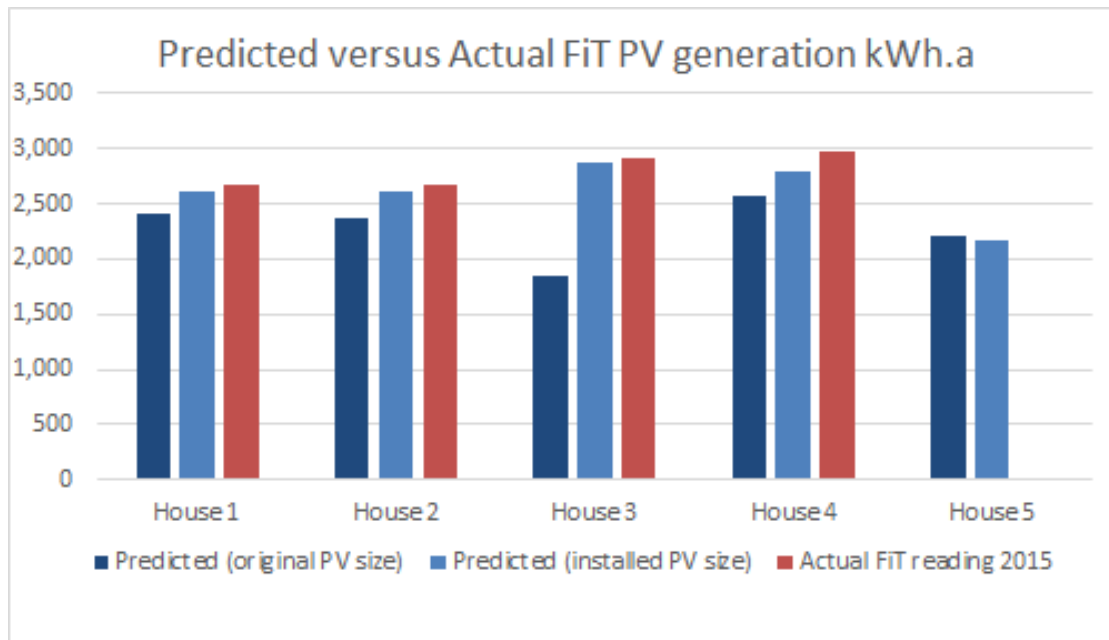
Figure 16 - PV generation modelled vs actual 2015 (note missing PV FiT data for house 5).

4.3 Carbon Dioxide Emissions

All of the above gas and electricity use and generation combine to result in the net carbon dioxide emissions from each property. Figure 19 shows the modelled target values, the values adjusted for actual air-tightness and PV installations, and the actual emissions achieved. Whilst the performance gap has not been eliminated, significant reductions in carbon emissions have been made. Houses are on average 67% below current UK average household emissions (23). Better than expected performance in the PV systems, and lower than expected electricity use, is in part compensating for worse than hoped for space heating demand. The resulting average carbon emissions rate achieved is 18kgCO$_2$/m^2.a - just one kilogram per square meter short of the original design target, or a 5% performance gap.
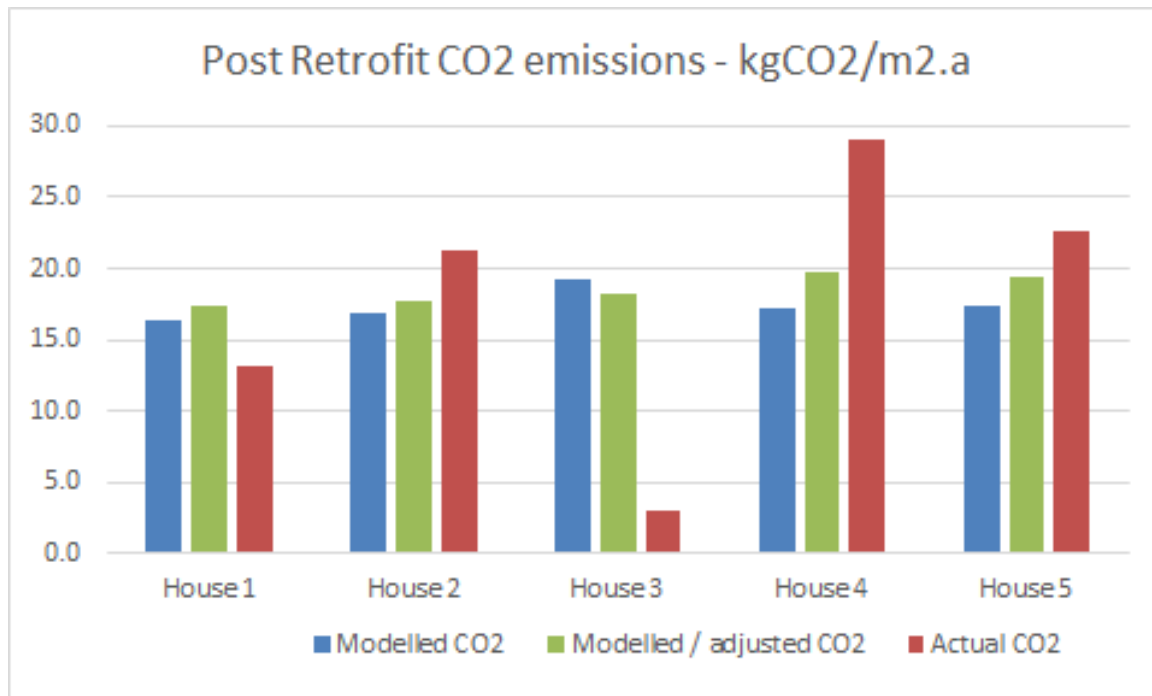
Figure 17 - Carbon dioxide emissions modelled vs modelled adjusted vs actual (after only, 2015).

5.0 Conclusions

A performance gap between designed and actual energy use has been observed in this project. However, by basing design stage modelling on full SAP, carrying out extensive surveys of both the houses and their occupiers, doing the modelling work alongside the design development, and paying close attention to issues of thermal performance in detailed design, the performance gap was mitigated at the design stage. By following through with training for site operatives and a high degree of quality assurance on site, there was a high degree of certainty that what had been designed was built, reducing the risk of a performance gap in construction.

Differences from modelled assumptions for air-tightness in the pre-retrofit condition provide a strong argument for including air-pressure tests as standard part of initial assessments. Designers proved to be overly optimistic about what was possible in terms of air-tightness performance in properties that were not being gutted, with some areas only tackled in a partial manner, and so air permeability values in all houses were significantly worse than design targets. This demonstrates the need to understand the significance of air-tightness to energy performance, but also to have a good understanding of it before work starts. On reflection, putting more effort into sealing areas such as floors and ceilings may be worthwhile - though disruption to householders would have increased. For example at loft level ceilings would either need to be replaced, or existing loft insulation removed, rather than just topped up, to allow a seal to be created.

Assumptions for heating patterns are clearly open to question. Heating patterns do appear to vary significantly from house to house, and even to change over time in individual houses. Being able to adjust modelling to take account of different heating patterns, whilst also being conservative in these assumptions, would be worthwhile in planning future whole house retrofits.

Assumptions about electricity and hot water use seem to be most open to question. Further research is required on this point, and more accurate assumptions of actual occupancy and behaviour at design stage may prove useful. In contrast, PV output is much closer to modelled assumptions. This should perhaps be expected, given the limited number of variables that influence this, and the absence of behavioral influence.

SAP is often criticised as a predictive energy modelling tool. However, it seems to be within acceptable predictive limits on thermal performance of fabric, provided the assumptions that go into it - on both construction quality and occupant behaviour - are reasonably correct. Where targets for energy use are stretching, with low absolute energy use and carbon emissions, a small degree of variation about this target could be argued to be of limited significance - given a percentage of 'not very much' is still 'not very much'. This emphasises the benefits of deep vs light touch retrofits in order to provide some certainty of achieving projected savings in energy use and carbon emissions.

Whilst the above case study of an individual project adds to the evidence base on the performance gap in retrofit, further research and development is required to better inform design and construction processes in retrofit. This study has highlighted the value of post-occupancy monitoring - though also some of the difficulties associated with obtaining data, and there are questions about how to achieve 'good enough' data to inform design teams that is accessible. However it has also provided some confidence to those involved in the project that the tools used at design stage have some value - on the basis that "all models are wrong, but some are useful" (24), provided their limitations are understood. It also points to areas in which to focus the future development of these tools.

The study has also further reinforced the importance of quality control and assurance throughout the design and construction process, to ensure modelled assumptions and aims are achieved in reality. How this level of oversight and attention to detail can be scaled up with the currently available resources to meet the enormity of the UK's retrofit task will require research, and also policy development.

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