Gupta, R, Gregg, M, Passmore, S and Stevens, G

Intent and outcomes from the Retrofit for the Future programme: key lessons

Gupta, R, Gregg, M, Passmore, S and Stevens, G (2015) Intent and outcomes from the Retrofit for the Future programme: key lessons. *Building Research and Information*, 43 (4). pp. 435-451.

doi: 10.1080/09613218.2015.1024042

Intent, outcomes and learnings from a national Retrofit for the Future programme

Professor Rajat Gupta[1] (corresponding author), Matt Gregg[1], Stephen Passmore[2], and Geoffrey Stevens[2]

[1]Low Carbon Building Group, Oxford Institute for Sustainable Development, School of Architecture, Oxford Brookes University, Oxford OX3 0BP, Email: rgupta@brookes.ac.uk and mgregg@brookes.ac.uk

[2]Energy Saving Trust, 21 Dartmouth Street, London SW1H 9BP,
Email: stephen.passmore@ecosequestrust.org and Geoffrey.Stevens@est.org.uk

Acknowledgements

The authors thank the project teams of the Retrofit for the Future programme, the Energy Saving Trust and the post-occupancy evaluation teams for their work in completing the projects, collating and analysing data. The authors are also grateful to Mariam Kapsali and Bob Irving for their assistance and contribution to the meta-analysis, and Laura Barnfield and the anonymous reviewers for reviewing the paper and providing helpful comments.

Abstract

The Retrofit for the Future programme, sponsored by UK Government's Technology Strategy Board from 2009-13, demonstrated innovative approaches to deep retrofitting of social housing, using a whole-house approach for achieving an 80% CO_2 reduction target. This paper critically examines the intent and outcomes of this programme (in which all authors participated) through a cross-project meta-study of the primary data, substantiated by insights from secondary sources. Given that only three (out of 45) projects met the expected CO_2 target in reality, despite generous funding and professional expertise, it suggests that decarbonizing existing housing will not be particularly easy. Important lessons are learnt from the formulation, target-setting, monitoring and evaluation procedures and feedback mechanisms of this initiative, which can inform the delivery and effectiveness of future national energy retrofit programmes. Furthermore, to support 'scaling up' of effective retrofit programmes and reduce the gap between intent and outcome, it is recommended that attention be moved from *what* level of CO_2 reductions are to be achieved, to *how* (delivery models) these radical reductions can be achieved, and by *whom* (supply chain). Such alternative delivery models to the 'whole-house' approach include, retrofit over time, city-scale retrofit and community-based energy retrofits.

Keywords: energy performance, household energy, dwelling, low-carbon buildings, retrofit, performance gap

1. Introduction

This paper uses a *cross-project meta-study* approach to critically examine the intent and outcomes of the UK Government's Technology Strategy Board's (TSB) (now Innovate UK) Retrofit for the Future (RfF) programme. It outlines what programme-level lessons in terms of set-up, delivery and evaluation could inform policy-making and help produce more successful energy retrofit initiatives in countries faced with the challenge of large-scale improvement of their building stock. The paper also debates whether a 'whole-house' low carbon retrofitting approach on a house-by-house level is an appropriate means to meet radical carbon dioxide (CO_2) targets, by undertaking a comparative cross-project analysis of primary data (covering the technical performance of retrofits) to reveal the gap between intent and outcome. The remit of the paper addresses a number of key questions raised by the special issue which include: *Are there instances where intended outcomes have been followed up and assessed in light of actual experience? What lessons could inform better policymaking and help produce more successful initiatives?* At the same time the approach adopted in the paper addresses the special issue theme of *linkages between policy formulation, objectives setting, monitoring, evaluation, validation and feedback.*

The paper is structured so that section 1 provides a contextualisation of the research through a review of evidence on national and international domestic retrofit programmes, followed by insights into the causes of the performance gap that can undermine the actual energy savings achieved by energy retrofits. Section 2 sets the scene by describing the intent of the RfF programme, the techniques used for monitoring and evaluation, and the data collected. Section 3 presents the meta-study by conducting a cross-project analysis of the primary data on energy consumption, air-tightness levels, ventilation systems and environmental conditions. Section 4 then extracts learnings from the RfF programme in terms of programme formulation, delivery and evaluation, while section 5 concludes the paper whilst using the learnings to construct wider lessons and recommendations for future initiatives and policy making on energy retrofits.

1.1 Energy retrofits and performance gap

Along with the European Union, the UK is required to cut greenhouse gas emissions (carbon dioxide emissions (CO_2) often used as proxy) by 80% over 1990 levels by 2050 (Department of Energy and

Climate Change (DECC), 2012a). To ensure incremental progress is made en route to meeting this goal, five-year carbon budgets have been established in the Climate Change Act, to which UK is legally committed (UK CCC, 2014). According to the 2011 UK Carbon Plan (HM Government, 2011), *by 2050 all buildings will need to have an emissions footprint close to zero*, and it is widely understood that the goal will not be achieved without significant energy retrofit of existing houses (Jones, Lannon and Patterson, 2013; Li *et al.*, 2014). This will unquestionably require a paradigm shift from existing approaches which tend to support the most cost-effective measures in worst-performing dwellings, as evidenced by some of the recommendations for meeting the next carbon budget, which include continual insulating of lofts and cavity walls and establishing of minimum energy performance standards for the private-rented sector (UK CCC, 2014). Even the Golden Rule[i] which is a key element of National Green Deal programme[ii] (DECC 2011), limits the size of the loan (and therefore, the extent of retrofit) to what can be repaid through savings (so as to protect the homeowner from financial burden). As such this rule has been observed to be a restriction on the level of obtainable CO_2 savings from whole-house retrofitting (Dowson *et al.*, 2012). Instead the approach of deep and whole-house energy retrofitting promotes the interaction of multiple measures to be considered (e.g. fabric, ventilation, heating, lighting and micro-generation) at the earliest stages, thereby improving the expected energy performance of the building from all end-uses of energy, by an average factor of four or within a range of between 65%-95% compared with pre-retrofit levels (National energy Foundation, 2014). From the German experience, it is realised that since economic benefits are never as great as predicted, deep retrofits should be encouraged through policy, using alternative motivators other than economic savings (Galvin, 2014a).

The success of any carbon reduction policy including an energy retrofit programme depends on achieving predicted energy reductions in practice (Summerfield, Oreszczyn, Pathan, and Hong, 2009). For this reason, recent policy initiatives such as UK Government's Electricity Demand Reduction Pilot[iii] and Government's Energy Savings Opportunity Scheme[iv] emphasize verification of energy savings in reality. However, an increasing body of research shows that large differences can occur between the predicted and measured energy performance of retrofits (Gupta and Gregg, 2012; Tweed, 2013; TSB, 2013; Chiu *et al.,* 2014; Galvin, 2014b). This energy performance gap can occur at any stage of retrofit delivery as described below:

- During *design and specification* stage, there can be a lack of understanding regarding the impact of early design decisions on energy performance, and lack of communication of design intent through all work stages. Also domestic energy modelling software, such as the Standard Assessment Procedure (SAP) in the UK, is reliant on the expertise of the user, quality of data input and appropriateness of the model to the particular context (Zero Carbon Hub, 2014). Energy models for retrofits must also consider the occurrence of under-heating in poorly insulated dwellings (Sunikka-Blank and Galvin, 2012) and higher temperatures in well-insulated dwellings (Kelly *et al.,* 2013).
- During *construction* stage, substitution of specified products with products of inferior performance due to supply chain issues and inadequate on-site understanding of performance implication of different products can be a cause behind the performance gap. This is further compounded by poor workmanship and lack of quality assurance procedures on-site (Gupta, Gregg and Cherian, 2013). In retrofit, during design and construction stages, an insufficient understanding of existing conditions can result in a failure to integrate new measures and technology appropriately.
- Finally at *handover*, delivery from the retrofit team is usually piecemeal with no formal aftercare arrangements, which lead to unfamiliarity amongst residents to operate, control and maintain new and unfamiliar technologies resulting in sub-optimal use, settings or unexpected behaviour (Summerfield *et al.*, 2009; Gupta and Kapsali, 2014). As a solution, Bartiaux, Gram-Hanssen, Fonseca, Ozolina and Christensen (2014) found that for retrofit work in Denmark, Portugal, Latvia and Belgium, knowledge networks were beneficial in providing advice and help for homeowners, both before and during the retrofit work.

For reasons such as these, policy-makers recognize the need to allow an offset for the performance gap in planning, therefore, the National Green Deal programme and the Energy Company Obligation (ECO)[v] include a set of 'in use' factors (Jones, Lannon and Patterson, 2013).

Recent research has also revealed a building fabric performance gap since the fabric is not as well understood and far less predictable than originally thought. Li *et al.* (2014) have shown that a large sample of solid wall U-values were found to be better (and covering a wide range) than the standard U-value used in energy estimation, suggesting that standard UK solid-wall U-values may be inappropriate for energy certification or for evaluating the investment economics of solid-wall insulation. This research has exposed the diversity in physical building characteristics as significant a source for anomalies as that which is commonly understood in occupant behaviour. Furthermore, as demonstrated in Elton and Turrent (2011), moisture ingress into the building fabric and resultant structural damage can be the result of misunderstood material relationships and poor construction quality. Research needs to address the lack of understanding regarding moisture movement through structures (particularly traditional solid wall structures) from inside and out, when they are insulated as this can potentially lead to rotting of embedded timbers. In recent years, English Heritage and the Sustainable Traditional Buildings Alliance have done much useful research in this area, given that the study of moisture management in buildings and fabric has its own modelling inaccuracies and complexities (English Heritage, 2014). Conclusively it is clear that whatever the reason, differences between measured and predicted performance of retrofits have the potential to seriously undermine national CO_2 reduction targets. It is against this context that the Retrofit for the future programme was developed and implemented.

2. Retrofit for the Future programme: intent

The Retrofit for the Future (RfF) programme was sponsored by UK Government's Technology Strategy Board (now called Innovate UK) from 2009-13 with £17million of funding to test and demonstrate innovative approaches to deep retrofitting[vi] of the UK's social housing stock, using a whole-house[vii] approach for achieving an 80% CO_2 emission reduction target. Through a two-stage process, 194 projects were awarded funding of up to £20 000 to develop a strategy towards meetings these targets in Phase 1, and about 86 projects (covering 119 dwellings) across the UK were awarded up to £150 000 each to demonstrate the effectiveness of their strategy in real homes during Phase 2. In order to set a single target across the programme independent of location, building type and condition, an estimated average emissions figure for the UK housing stock was used. Rather than a percentage reduction for each individual house, an absolute target was set for CO_2 emissions/m^2/yr, as a standard that would achieve an 80% reduction in CO_2 emissions against a 1990 baseline when averaged across the existing housing stock. This is because percentage reduction against individual dwelling baselines would have been relatively easy to achieve for a poorly-insulated home but considerably more difficult for more recent, better insulated, construction. The targets included all areas of energy consumption, including that for appliances and were based on emissions from a typical 80 m² semi-detached house. There were two CO_2 targets, both based on calculated emissions:

- 17 $kgCO_2/m^2$/year calculated using Standard Assessment Procedure 2005 with an extension worksheet to account for *unregulated* uses
- 20 $kgCO_2/m^2$/year calculated using Passive House Planning Package (PHPP)

The difference reflects the use of lower carbon intensities in SAP as compared with PHPP. There was also a primary energy target of 115 kWh/m^2/year. To assess the post-retrofit CO_2 performance, one year worth of electricity and heating fuel energy data were collected and normalized using floor area and common CO_2 metrics.

The RfF programme was designed to target the social housing sector (representing 20% of UK housing stock) which is relatively 'homogenous' with an established organisational structure of tenants and social landlords who were able to facilitate the delivery of retrofits and select suitable tenants. This does imply that the findings will not be completely representative of the private housing sector where householders have a stronger role in the decision-making process. However, the programme was a 'living lab' of many different experiments, and involved rigorous and systematic evaluation of each project, comprising short-term physical tests of building fabric; long-term physical monitoring of energy consumption and environmental conditions; standardized post-occupancy evaluation (POE) of occupant (primary resident) experiences; PCR of construction quality and holistic review of projects (TSB, 2014). Most of the primary data collected from the evaluation have been made available in the public domain through an interactive data platform called energy monitoring and building evaluation database (EMBED). Table 1 summarizes the types of data collected to evaluate the programme outcomes, the respective monitoring and evaluation technique deployed and the organisation responsible.

<Insert table 1 here>

Data generated by each method, apart from POE (work is ongoing to anonymize the POE data for analysis and release), are available through a range of primary and secondary sources, as listed in table 2.

<Insert table 2 here>

Overall a maximum of 86 dwellings had some level of data available that have been used for this meta-study. However depending on data availability, different aspects of data analysis are conducted on subsets of the 86 dwellings. For example, annual CO_2 emissions data (pre- and post-retrofit) are available for 45 dwellings, while only 36 dwellings have indoor monitored temperature and relative humidity data. In some cases the sample size becomes quite small; for instance, there are only 23 dwellings where pre- and post-retrofit electricity and gas figures can be compared. Another limitation of the dataset is that it represents only one retrofit programme located in the UK. Figure 1 identifies the built form and age ranges of the RfF dwellings. Since the RfF programme was competition-led, the sample is not exactly representative of the UK housing stock. Detached (including bungalows) dwellings are significantly underrepresented (at 1%) in the RfF dataset although they represent 24.5% of the UK stock. On the other hand semi-detached (UK: 28.4%), mid-terrace (UK: 18.7%) and end-terrace dwellings (UK: 10.3%) are over-represented in the RfF programme at 42%, 34% and 23% respectively. In addition, there are no flats in the dataset (UK: 20.1%) as the RfF programme focussed on retrofitting low-rise social housing dwellings (Data.Gov.UK, 2011; Department for Communities and Local Government, 2013; The Scottish Government, 2014).

<Insert figure 1 here>

Figure 1 Dwellings by built form and age

To achieve 80% (deep) carbon reductions through a ‘whole-house’ retrofit approach, a combination of energy saving measures and low/zero carbon technologies (LZTs) were adopted across the RfF projects such as super air-tight fabric in combination with mechanical ventilation with heat recovery (MVHR) systems, solar photovoltaics (PV), solar hot water systems (SHW), biomass boilers and heat pumps. As shown in figure 2, unsurprisingly fabric improvements were most popular wherein wall insulation was installed widely followed by roof/ loft insulation. While external wall insulation (EWI) was the most popular wall insulation strategy for all types of dwellings built post-1900 including post-1950s dwellings; internal wall insulation (IWI) was more prevalent in pre-1900 dwellings (historic) due to planning requirements, historic preservation, and/or aesthetic concerns. Although deployment of heat pumps was high, gas-fired boilers remained the most common heating system installed across two-thirds of dwellings because of resident familiarity. Due to high air-tightness levels, MVHR systems were installed in three-quarters of dwellings to provide background ventilation and good indoor air quality.

<Insert figure 2 here>

Figure 2 Distribution and count of energy saving strategies and LZTs in the RfF sample

3. Assessing outcomes through meta-study

The meta-study is conducted as a comparative analysis of RfF projects using primary datasets listed in Table 2, which are linked through unique identification numbers for each dwelling (TSB assigned identification numbers are not revealed in this paper). The appendix lists the dwellings included in the study along with characteristics and retrofit features. The main focus of the analysis is to examine the achievement of RfF targets in practice in terms of overall energy and CO_2 reduction, and also by fuel type. Since the ambitious targets set by the programme required high levels of insulation and airtightness, the meta-study investigates the effectiveness of significant improvements to the building fabric, through a comparison of measured pre- and post-retrofit air-tightness levels, and assessment of post-retrofit air-tightness levels against post-retrofit gas usage. Given the large uptake of MVHR systems (to provide reliable ventilation whilst minimising heat loss), in the RfF sample, the appropriateness of these systems and their performance (air flow rates) are also assessed. Finally indoor CO_2 levels, temperature and humidity as indicators of environmental conditions are also examined, albeit for a small sample of properties due to issues with data availability.

Of the 45 RfF dwellings with available data on post-retrofit measured CO_2 emissions, it is found that only three dwellings met the absolute RfF target of 17kgCO_2/m^2/year (and 20kgCO_2/m^2/year for dwellings modelled using PHPP). About 34 out of the 45 dwellings had data available for pre-retrofit modelled CO_2 emissions (figure 3), of which six dwellings achieved a reduction of less than 30%; five had a reduction of between 30-49%; eleven dwellings achieved a reduction of between 50%-69%; while nine achieved a reduction of between 70%-79.9%; and only three dwellings achieved a reduction of 80% or more as compared to pre-retrofit modelled CO_2 emissions. Given that most dwellings (20 out of 34) achieved CO_2 reductions from 50% to just above 70%, it raises questions about the level of CO_2 targets that should be set for future programmes so that they remain ambitious but achievable.

<Insert figure 3 here>

Figure 3 CO_2 emissions. *Note: (n) represents the number of dwellings with post-retrofit CO_2 emissions. Not all of these dwellings have pre-retrofit CO_2 emissions data.*

As was expected, achieving the absolute RfF target did not necessarily equate to 80% reduction over pre-retrofit modelled CO_2 emissions (baseline). For example, in one retrofit (H28), although CO_2 emissions were reduced by merely 55% over pre-retrofit modelled emissions (since it was a modern terrace with very low pre-retrofit emissions) the project was still able to meet the RfF target. This reinforces the need to establish clear and consistent absolute carbon targets (along with percentage reductions) in energy retrofit programmes, so as to avoid poorly-performing dwellings easily meeting ambitious percentage reductions, while dwellings with a low baseline (pre-retrofit) CO_2 emissions struggle to meet the same reductions.

Figure 4 compares the calculated pre-retrofit CO_2 emissions (calculated using SAP/PHPP along with a SAP extension worksheet to calculate CO_2 emissions from appliances and lighting) and measured (actual) post-retrofit CO_2 emissions for 43 dwellings (for which data was available) by retrofit wall type and heating system. While all the dwellings which achieved the RfF target had installed external wall insulation, dwellings with all kinds of heating systems (from gas boilers to heat pumps to biomass boilers) experienced significant reductions in CO_2 emissions. This indicates the influence of the most popular strategy adopted across the RfF projects, the ‘fabric first’ approach (minimising heat loss by prioritising insulation and air-tightness before generating more efficient heat) on reducing actual CO_2 emissions.

<Insert figure 4 here>

Figure 4 Predicted pre-retrofit and actual post-retrofit CO_2 emissions by wall insulation type and heating source. *Note: (n) represents the number of dwellings with post-retrofit CO_2 emissions and heating technology information.*

Out of the 45 dwellings, for a subset of 23 dwellings, pre-retrofit modelled and post-retrofit actual data for gas and electricity consumption were available as shown in figure 5. Although only one retrofitted dwelling experienced an increase in energy consumption and CO_2 emissions (indicated by an up arrow in Figure 5), about 15 dwellings with (gas) boiler improvements reduced mean measured annual gas consumption by 78%, though their mean annual electricity use increased by 44% suggesting possible addition of electricity-using equipment. Interestingly no association is found between the installation of an (always on) mechanical ventilation system and increase in electricity use. In eight dwellings with heat pump installations, there was an expected rise in annual electricity consumption due to fuel switching, which was equal to a mean increase of 178% in annual electricity use, although the proportion of electricity used for heating is not provided in the data. Though the heating fuel figures are not weather corrected, generally in the southeast (Heathrow weather station (Environmental Change Institute, 2015)), the period before retrofit was cooler than the period post-retrofit; however, both periods were warmer than average.

<Insert figure 5 here>

Figure 5 Electricity and gas consumption with CO_2 emissions. *Note: the first bar represents modelled pre-retrofit energy consumption and the second bar represents post-retrofit measured energy consumption.*

As seen in Figure 6, measured annual electricity use across all 23 dwellings (irrespective of the heating system) is greater than forecasted, implying that the difference between predicted and actual electricity use (rather than gas) is a significant factor in the energy performance gap. To add to this, only about half of the dwellings with gas fired boilers reduced gas consumption.

<Insert figure 6 here - landscape>

Figure 6 Forecasted and measured electricity and gas consumption with performance gap. *Note performance gap is calculated as measured value divided by forecast (Galvin, 2014b)*

Investigating post-retrofit electricity consumption further, figure 7 shows the change in electricity consumption for dwellings that had solar photovoltaic installations (PV) and those without. Within this sample, dwellings that had heat pumps and PV installed, are differentiated in the graph. It is expected that even with PV there would be a possible increase in electricity consumption for dwellings that installed heat pumps in place of gas boilers. However, of the 11 dwellings with only PV (no heat pumps), five reduced their electricity consumption. To add to this, most of the six PV only dwellings that experienced a rise in electricity use, increased it to a greater degree than those that had a reduction. Possible reasons for this could be a change in household compositions of these dwellings, underperformance of PV systems and/or increase in the use of electrical appliances.

<Insert figure 7 here>

Figure 7 Change in electricity consumption for dwellings with PV. *Note: the graph is scaled to a maximum increase in electricity consumption of 200%. H7 and H43 had increases above 200%; 312% and 937% respectively.*

To investigate the fabric performance of the RfF projects given the high levels of insulation that the programme necessitated, measured pre- and post-retrofit air-permeability rates (as indicator of air-tightness level) for 86 dwellings are compared as shown in figure 8. It is found that apart from eight dwellings, post-retrofit air-permeability is reduced (improved) across the remaining 78 dwellings representing 90.7% of the RfF sample, with an overall mean post-retrofit air-permeability of 5.5m^3/m^2/hr@50Pa. This is better than the 2006 Building Regulations required air-permeability of 10m^3/m^2/hour (Office of the Deputy Prime Minister, 2006) for new buildings that were effective during the RfF programme. Presently UK Building Regulations require air-permeability of 5m^3/m^2/hr@50Pa (HM Government, 2010) for new buildings and major alterations.

<Insert figure 8 here>

Figure 8 Measured air-tightness levels: pre- and post-retrofits

When measured (maximum, mean and minimum) air permeability is assessed against categories of built form, dwelling age or retrofit wall type, no obvious relationships are found. Interestingly, a weak correlation ($r = 0.3$) emerges between post-retrofit measured air-permeability rate and post-retrofit gas consumption (normalised by area) for a limited sample of 15 gas-heated dwellings (figure 9). (It is important to remember that a proportion of gas consumption is also used for domestic hot water and cooking). Within this sample, one dwelling (H14) with the lowest gas consumption had an air-permeability >12m^3/m^2/hr@50Pa. This is likely to be due to changes in household occupancy and composition. Based on these findings it is difficult to objectively infer the impact and effectiveness of building fabric improvements on energy consumption; however, it is obvious that in order to achieve the ambitious levels of improvements targeted by the RfF projects, all the elements of retrofit need to work sufficiently together.

<Insert figure 9 here>

Figure 9 Post-retrofit gas consumption and air-tightness results

It is recognised that high levels of air-tightness necessitates the use of mechanical ventilation (MV) systems for providing reliable ventilation whilst minimising heat loss. Mostly MVHR and sometimes decentralized mechanical extract ventilation (d-MEV) systems were installed in 66 RfF dwellings. However only 23 (out of the 66) dwellings achieved post-retrofit air permeability of 3m^3/m^2/hr@50pa or less, the level at which mechanical ventilation is recommended by Energy Saving Trust (EST 2007). The presence of MV systems (mainly MVHR) in dwellings (n=43) with higher air-permeability than recommended, suggests that MVHR was a redundant technology with an additional up-front cost (average cost of a domestic MVHR system was about £6 117 in the programme (Sweett, 2014)) that also added an ongoing parasitic electricity load due to its *always on* status. This trend of having MVHR in dwellings with inappropriate levels of air-tightness is happening in new-build social housing projects as well (Gupta *et al.,* 2013). Testing air-tightness midway (as undertaken by some RfF projects) during the retrofit works can help to identify and fix unforeseen areas of airflow effectively and relatively cheaply. When the performance of MVHR systems are further assessed using measured air flow data for 42 out of the 66 dwellings (Figure 10), vast discrepancy is found between the whole-house supply and extract rates, indicating system imbalance, possibly due to issues with the design, installation or commissioning of these systems. Many of the tested dwellings are over-ventilated which in turn increases space heating demand (Lowe and Johnston, 1997) and also electricity consumed by the MVHR systems.

<Insert figure 10 here>

Figure 10 Measured MVHR supply and extract air flow rates and corresponding Part F minimum.

The effect of air-permeability and ventilation systems on physical performance is assessed using measured internal environmental conditions within a selection of RfF dwellings. Figure 11 displays the minimum, mean and maximum indoor temperatures and relative humidity conditions (RH) observed in 36 dwellings. Looking at temperature to begin with, it is apparent that the annual mean indoor temperature of 22^{o}C is high and towards the warmer end of the recommended comfort range of 20^{o}-22^{o}C. Whilst on the one hand this illustrates the ability of well-insulated dwellings to provide whole-house comfort, such temperature levels have implications for heating energy consumption. Furthermore 21 out of 36 dwellings experience maximum temperatures above 26^{o}C and in some cases over 28^{o}C (in the living rooms) indicating very high demand temperatures. More detailed analysis of individual cases is necessary to establish the risk of overheating. On the other hand, 7 out of 36 dwellings also experience minimum indoor temperatures <16^{o}C and in some cases up to 14^{o}C, indicating design or control issues or unexpected patterns of use. The overall mean relative humidity (RH) is 52% across the 36 dwellings, with all the dwellings experiencing mean RH levels within the expected comfort range of 40%-70%. A few dwellings have minimum RH levels <30% which is likely to be due to high internal temperatures.

<Insert figure 11 here>

Figure 11 Minimum, mean and maximum indoor temperatures and relative humidity. Note: period length of measurement can vary widely and data are not weather corrected. Recommendations (CIBSE, 2006).

In assessing the internal conditions, it is important to consider the indoor CO_2 levels which are a good indicator of ventilation rates and indoor air quality. Figure 12 displays the CO_2 concentrations in living rooms of 12 dwellings allowing for comparative analysis. There is a general acceptance that CO_2 levels above 1000 ppm are indicative of poor ventilation rates (Sharpe, Porteous, Foster, and Shearer, 2014). Interestingly, though representing a small sample, two out of the three dwellings with the lowest mean CO_2 concentrations (<1000ppm) are naturally-ventilated. On the other hand, eight out of 10 MVHR dwellings have experienced CO_2 concentrations above 1000ppm while four of these experience concentrations greater than 1500ppm. Given the small sample, while it is not possible to associate poor indoor CO_2 levels with under-performance of MVHR systems, it re-emphasises the role of ventilation especially in dwellings with high air-tightness levels.

<Insert figure 12 here>

Figure 12 Minimum, mean and maximum indoor CO_2 concentrations. Recommendations (CIBSE, 2007).

4. Learnings from RfF programme

Findings of the meta-study provide useful insights and learnings for improving the formulation, delivery and evaluation of future energy retrofit initiatives.

4.1 Programme formulation and target-setting

The overall experience of the RfF programme shows how difficult it is to make deep cuts in energy consumption and CO_2 emissions from existing housing. One of the reasons for this is the dilemma that lies in the formulation of the programme itself, between the *intent* and *approach*. While on one hand, the programme was designed to deliver clear and ambitious CO_2 targets, on the other hand, it adopted an innovation-based approach, which led most projects to use effectively experimental (untested at that time) strategies to meet the goals. Whilst innovation should be encouraged, risk and uncertainty associated with innovation, and their impact on delivery of targets should also be considered during programme formulation. Furthermore innovation needs to sociotechnical, as research has shown that performance gap occurs where technological innovation takes place without social innovation (new ways of working with the user) (Usable Building Trust and BSRIA, 2009; Gill, Tierney, Pegg and Allan, 2010). Experimentation and innovation, however, are not the chosen policy route in the recent carbon budget for achieving the prescribed emissions reductions (UK CCC, 2014).

Whether future programmes adopt experimental or conventional measures or both, it is vital that the approach selected, is aligned with the intent of the programme, and integrated and effective supply chains are established for delivery.

The ‘whole-house’ approach adopted in the RfF programme was designed to address all end-uses of energy and associated CO_2 emissions as a whole, but in practice, this approach rarely delivered radical energy reductions, despite generous funding available for the implementation and involvement of committed and expert professionals (architects, engineers, constructors and university researchers). This indicates the complexity associated with the design and delivery of whole-house energy retrofits. Also the ‘whole-house’ approach was ‘technologically focussed’ and driven by physical energy models, while the human dimension was often omitted and not addressed through behavioural interventions. Future programmes must adopt a sociotechnical approach taking into account both the building itself and the occupants within, to address both physical and social factors that influence energy consumption, so that energy savings are realized and sustained over a long term, as observed in some recent community-led energy retrofit programmes (Gupta *et al.,* 2014).

The RfF analysis showed that a majority of the dwellings achieved around 50% CO_2 reductions (50% of the RfF baseline is roughly equivalent to 43kgCO_2/m^2/year), which coincidentally is the percentage target set (50% CO_2 reduction by 2025) for the fourth carbon budget (UK CCC, 2014). However, in initiatives where capital cost is a concern and deep low carbon retrofitting is likely unattainable, ambitious CO_2 cuts will be even more difficult to achieve. Galvin (2014a) has questioned whether the existing domestic sector should be even burdened with the same CO_2 reduction expectations as other sectors, given the history of inconsistency, unexpected results and complexity around the issue. Nevertheless, if the buildings sector does not deliver ambitious energy savings, meaningful CO_2 reduction targets will become very difficult to achieve nationally, since over 80% of existing homes will still be standing in 2050 (UK CCC, 2014). This then raises an important question for future programmes, whether *house-by-house* deep low carbon retrofitting is a viable route to reducing CO_2 emissions by 80%, or rather more localised area-based approaches need to be investigated, so that economies of scale can be used to drive down both capital costs and CO_2 emissions. Furthermore, even with CO_2 reduction as the goal, the majority of RfF projects in the programme consumed more electricity than predicted, exposing the challenges associated with cutting electricity use. To improve the uptake and effectiveness of electricity-saving interventions in future initiatives, it is necessary to develop a deeper understanding of the variety of ways in which electricity is used in existing homes across different tenures and why people react to particular electricity-saving interventions in the ways that they do. The recent Household Electricity Survey commissioned by the Government (Godoy-Shimizu, Palmer and Terry, 2014) provides insights into patterns of electricity use of owner-occupied houses, but needs to be expanded to include social housing and electrically-heated dwellings.

This leads to a discussion on whether CO_2 reduction should be considered as the main driver for retrofitting. Obviously for the UK government and the EU, reduction of CO_2 emissions has been the goal for deep retrofitting. But as Galvin (2014a) points out, the tunnel vision of achieving a specific emissions target has created policy measures that become barriers to homeowners potentially improving comfort on their own terms or reducing energy consumption incrementally in an affordable manner. Questioning drivers, Swan *et al.* (2013) interviewed social housing providers and found that fuel poverty and energy bills for residents were the top drivers for retrofitting. Chahal et al. (2012) interviewed social housing residents and found that energy costs and improved comfort were the leading drivers for interest in retrofitting. In both studies climate change as a driver received the least responses. As also shown by Tweed (2013) it was evident in some RfF projects (including authors' experience) that some residents prioritized comfort over greater energy or cost savings when afforded the ability to do so. Such findings imply that outcomes of energy retrofit programmes must be reframed, to focus on outcomes wider than energy or CO_2 reduction, such as comfort, indoor air quality, health and elimination of fuel poverty.

4.2 Monitoring and evaluation, and feedback

For the first time, from the outset, the RfF programme prescribed clear monitoring and evaluation (M&E) protocols for undertaking physical tests, co-incident energy and environmental monitoring over a long-term (12 months to 24 months) and social science surveys. Although physical tests such as air-permeability tests and thermal imaging surveys (for some projects) were conducted pre- and post-retrofits, the programme did not require the assessment of pre-retrofit measured energy consumption. Although the difficulty of obtaining consistent pre-retrofit energy data is acknowledged, such data could have helped in establishing baseline energy performance of the dwelling which could be used for validating energy models, providing a reference for measuring actual energy savings to verify the success of the retrofits, and most importantly, in revealing any unusual behavioural characteristics (such as excessive use of electric lighting or tumble dryer) that could be addressed through the retrofits. This is especially important for future energy programmes, given that collating reliable data about energy consumption is recognised to be a perennial problem internationally (Godoy-Shimizu, Palmer and Terry, 2014).

Despite the effort put into M&E and the experimental nature of the RfF programme, the feedback mechanisms to share the learning from the M&E were fragmented. Post-construction reviews were undertaken by third-party experts with almost no feedback provided to the project teams apart from an overall report. However in seven projects, post-construction (hindsight) interviews regarding perception of occupants' experience, lessons learnt and viability of technical solutions were undertaken as part of a separate European Regional Development Fund (ERDF) sponsored project on Facilitation, Learning and Sharing (FLASH) and published to identify future opportunities (Lowe, Chiu, Raslan, and Altamirano, 2013), but no feedback on the dwelling performance was provided to the residents. Occupancy surveys (comprising 90-minute interviews and walk-throughs) managed by EST served as a useful way to gather feedback from residents on their experiences with the retrofit process and technologies installed, but no feedback or advice was provided to the residents about managing and reducing their household energy consumption, or the project teams. In future programmes, retrofit project teams, housing associations and supply chains should be urged to integrate the lessons learnt from retrofit evaluation into their knowledge-management systems, so that mistakes revealed through the evaluation are not repeated elsewhere. This could be captured through a domestic variant of the Soft Landings[viii] approach (Usable building trust and BSRIA, 2009).

Given that M&E of retrofits is a form of action research (Oreszczyn and Lowe, 2010), it is vital that evaluation methods are integrated with occupant training, education and advice to avoid unintended consequences such as frequent window opening in dwellings with MVHR during winter for 'fresh air' which causes heat loss. In an ongoing project studying the impact of low carbon community groups, it has been found that *person to person* feedback through advice 'helped a lot' or was 'crucial' in informing residents on how to reduce energy consumption in their home (Gupta, Barnfield and Hipwood, 2014). Another method of feedback is through social learning which can involve local communities and networks to share occupant experiences of energy retrofits through home visits and open days for the wider community (Berry, Sharp, Hamilton and Killip, 2014). This would also enable greater diffusion of energy retrofits amongst the wider population.

5. Conclusions

Reducing energy consumption associated with buildings has long been identified as a key, relatively easy and cost-effective strategy, and as a focus for policy that can deliver a major impact in the next 30 years (CCC UK, 2014). However, evidence from the meta-study reinforces the finding by Oreszczyn and Lowe (2010) that it will not be particularly easy (and cheap) to reduce energy use in existing housing. Given that whole-house retrofits, as a route to achieving radical cuts in CO_2 emissions, did not deliver all that was intended, it might be more appropriate then to shift the focus of attention from *what* level of CO_2 reductions are to be achieved, to *how* (delivery models, implementation challenges) these radical reductions can be achieved, and by *whom* (supply chain, capacity in the system), in order to support 'scaling up' of effective retrofit programmes. While 'deep renovations' have political traction through the EU Energy Efficiency Directive (The European Parliament and the Council of the European Union, 2012), it is worth debating whether the 'whole-house' approach is the desired route, given that the scope of works in a whole-house retrofit is extremely challenging (high levels of insulation, mechanical ventilation, LZT etc.), involving a variety of suppliers and project management of multiple measures. Other alternative and complementary models for delivery of energy retrofits also need to be examined.

Given that physical changes to dwellings take place incrementally and, usually privately (Fawcett, 2013), models such as 'retrofit over time' (planned or emergent) are gaining recognition, given the experiences of owner-occupied *Superhomes* that have achieved 60% CO_2 reductions or more (Fawcett and Killip, 2014). Whilst individual action at building level remains important, an overemphasis at this scale risks fragmentation and overreliance on individual building owners and tenants (Dixon and Eames, 2013). This is why city-level (urban-scale) retrofit has gained prominence, operating across the building, neighbourhood and city-regional scales, and involving and motivating a range of stakeholders such as developers, financers and policy-makers (Dixon and Eames 2013). Even at a sub-city level, widespread upgrades to the UK housing stock can be achieved by involvement of local, community-based programmes that simultaneously address the social and technical issues of domestic energy consumption (Karvonen, 2013; DECC, 2014c; Gupta *et al*, 2014). Customised solutions to groups of dwellings can be developed, which can also be replicated in neighbouring areas. As observed in DECC's Low Carbon Communities Challenge (DECC, 2012b) and Local Energy Assessment Fund (DECC, 2013), community retrofit programmes could be community-led, local authority-led or even community/local authority partnership, but importantly they are able to engage with the owner-occupied (70% of stock) and private rented (10% of stock) sectors, that are vital for scaling up. As a corollary, it also brings local support for retrofit delivery, given that local planning was found to be an obstacle for many RfF projects despite the programme being Government funded (TSB, 2014).

Independent POE studies of 10 RfF projects by Institute for Sustainability (IfS, 2012) and 18 RfF projects by Energy Saving Trust (TSB, 2013) revealed that the type of lead organization influenced the integration of the project team and communication, as well as occupant satisfaction. It was found that dwellings with higher occupant satisfaction and team integration were led by project architects as opposed to Local Authority or housing associations. The occupants of these dwellings were found to be either *satisfied* or *very satisfied* with the handover process and claimed to understand how the technologies were operated, thereby implying the significant role of supply chains in the effective delivery and aftercare of energy retrofits. Although it is suggested that community groups and local authorities lead retrofit programmes in an umbrella sense, the role of integrated supply chains in delivering effective retrofits has to be emphasised. However, given the disjointed character of the retrofit industry (Clarke, 2006), this is a significant challenge to address and an area for further research.

Given the scale and scope of deep retrofits, success of these programmes will be dependent on resident experience. Whether or not the residents are decanted from homes during the retrofit process can impact the quality of work. In one example reported (TSB, 2014), when minimization of disruption was prioritized as residents remained in the home, opportunities to improve airtightness were not taken fully as the extra works were considered too disruptive. It is preferred that for deep retrofits, occupants should be decanted to achieve excellence in detailing the building envelope, specifically when internally wrapping the envelope and installing floor insulation (Baeli, 2013; TSB, 2013; Tweed, 2013). Further research is required to understand residents' responses to living amongst building works, and how their tolerance to disruption caused by retrofit works can be increased, as retrofit scales up and the private sector market grows (where moving people out temporarily will be more challenging). Active engagement of residents, right from the briefing and design stage, through construction, handover and aftercare will undoubtedly play an important role in this.

Jones *et al.* (2013) show that significant improvements are achievable at low costs, but as CO_2 savings go above 40% the costs rise steeply, while major cost increases begin to set in beyond 60% reduction. As experience in Germany shows, sometimes a simple cheap solution that does not meet the most advanced standards, can bring significant benefits and allowing these solutions could mobilize actions in low to medium income households (Galvin 2014a). On the other hand, mandatory and highly restrictive standards for thermal retrofitting of existing homes have had a negative impact, slowing the rate and depth of retrofitting required for achieving national goals in Germany. Energy retrofit policy should take account of the experience of the RfF projects in setting retrofit targets for existing housing that are acceptable to householders and are technically and financially viable, whilst recognising that costs will fall, construction standards will rise and technologies will be fine-tuned as a mass market develops.

Many of the wider lessons outlined in this section may seem obvious; however these issues are often overlooked even in large policy-based dwelling energy retrofit interventions. No doubt the RfF programme succeeds in capturing learning from projects by providing a repository of empirical evidence (though with varying data quality across projects) on the actual performance of deep retrofits. Until this programme, such a catalogue of empirical data on dwelling retrofit performance has been largely absent from the debate. Given the large differences that are found to occur between predicted and measured energy performance of deep energy retrofits, it is vital that such differences are captured through procedures similar to RfF, but it is also essential that the learning from such programmes is considered in the planning of incremental five-year carbon budgets, to bridge the gap between expectation (targets) and practice (delivery). Otherwise there is a risk that retrofits (deep or shallow) will save less energy than expected, and meaningful CO_2 reduction targets will become very difficult to achieve.

References

The Association for Environment Conscious Building (AECB) (2014) *Low energy building database.* Retrieved from: http://www.lowenergybuildings.org.uk/

Baeli, M. (2013). *Residential retrofit: 20 case studies.* London: RIBA Publishing.

Bartiaux, F., Gram-Hanssen, K., Fonseca, P., Ozolina, L. and Christensen, T. H. (2014). A practice-theory approach to homeowners' energy retrofits in four European areas. *Building Research & Information,* 42(4), 525-538.

Berry, S., Sharp, A., Hamilton, J. and Killip, G. (2014) Inspiring low-energy retrofits: the influence of 'open home' events, *Building Research & Information,* 42:4, 422-433

Chahal, S., Swan, W. and Brown, P. (2012). Tenant experiences of retrofit, in Swan, W. and Brown, P. (Eds), *Proceedings of Retrofit 2012* January 24th – 26th 2012, University of Salford, Salford.

Chiu, L. F., Lowe, R., Raslan, R., Altamirano-Medina, H., and Wingfield. J., (2014) A sociotechnical approach to post-occupancy evaluation: interactive adaptability in domestic retrofit, *Building Research & Information*, 42:5, 574-590

CIBSE (2007). *Environmental design: CIBSE Guide A.* 7th edition. London: The Chartered Institution of

Building Services Engineers.

Data.Gov.UK (2011). Living in Wales. Retrieved from: http://data.gov.uk/dataset/living_in_wales

Clarke, L. (2006). Valuing labour. *Building Research & Information*, 34(3), 246–256.

Department for Communities and Local Government (2013). *English Housing Survey: Headline Report 2012-13.* Retrieved from: www.gov.uk/

Department of Energy and Climate Change (DECC) (2012a). *Research report: How to explain the Green Deal.* Retrieved from: www.gov.uk

DECC (2012b). Low Carbon Communities Challenge: evaluation report. Retrieved from: www.gov.uk/

DECC (2013). *DECC LEAF Evaluation.* Undertaken by Databuild Research & Solutions Ltd. Retrieved from: www.gov.uk/

DECC (2014a). *Electricity Demand Reduction Pilot Scheme: Participant Handbook*. Retrieved from: www.gov.uk/

DECC (2014b). *Energy Savings Opportunity Scheme (ESOS).* Retrieved from: www.gov.uk/

DECC (2014c). *Community Energy Strategy: Full Report.* Retrieved from: www.gov.uk/

Dixon, T. and Eames, M. (2013). Scaling up: the challenges of urban retrofit. *Building Research & Information,* 41(5), 499-503.

Dowson, M., Poole, A., Harrison, D. and Susman, G. (2012). Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. *Energy Policy,* 50(2012), 294-305.

Elton, M. and Turrent, D. (2011). *Building opportunities for business: Improving the building fabric, guide 6*. Institute for Sustainability. Retrieved from: http://www.instituteforsustainability.co.uk/retrofitguides.html

Energy Saving Trust (EST) (2007). *CE248: Achieving airtightness in new dwellings: case studies.* Retrieved from: http://www.energysavingtrust.org.uk/content/download/2638/62023/version/1/file/CE248+-+Airtightness+Case+Studies.pdf

Energy Saving Trust (EST) (2014). *embed: building intelligence for innovation.* Retrieved from: https://est.amee.com/

Energy Saving Trust (EST) (no date a) *RftF property info availability* [Data set], Internal EST dataset, unpublished.

Energy Saving Trust (EST) (no date b) *Rff Technology Matrix* [Data set], Internal EST dataset, unpublished.

English Heritage (2014). External wall insulation in traditional buildings: Case studies of three large-scale projects in the North of England. North Yorkshire: NDM Heath Ltd.

Environmental Change Institute (2015). Degree Days for energy management. Retrieved from: http://www.eci.ox.ac.uk/research/energy/degreedays.php

The European Parliament and the Council of the European Union (2012). Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Retrieved from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN

Galvin, R. (2014a). Why German homeowners are reluctant to retrofit. *Building Research & Information,* 42(4), 398-408.

Galvin, R. (2014b). Making the ‘rebound effect’ more useful for performance evaluation of thermal retrofits of existing homes: Defining the ‘energy savings deficit’ and the ‘energy performance gap.’ *Energy and Buildings,* 69(2014), 515-524.

Gill, M., Tierney, M.J., Pegg, I.M. and Allan, N. (2010). Low-energy dwellings: the contribution of behaviours to actual performance. *Building Research & Information*, 38(5), 491-508.

Godoy-Shimizu, D., Palmer, J. and Terry, N, (2014). What can we learn from the household electricity survey? *Buildings*, 4(4), 737-761.

Gupta. R. and Chandiwala, S. (2010). Understanding occupants: feedback techniques for large-scale low-carbon domestic refurbishments. *Building Research & Information*, 38(5), 530-548.

Gupta, R., Barnfield, L. and Hipwood, T. (2014). Impacts of community-led energy retrofitting of owner-occupied dwellings. *Building Research & Information,* 42(4), 446-461.

Gupta, R. and Gregg, M. (2012). Using a building performance evaluation approach to achieve low-carbon retrofitting of a Victorian house in Oxford, In Amoêda, R., Lira, S and Pinheiro , C. (eds.) *Heritage 2012 - Heritage and Sustainable Development.* Green Lines Institute. 19-22 June 2012, Porto, Portugal.

Gupta, R., Gregg, M. and Cherian, R. (2013). Tackling the performance gap between design intent and actual outcomes of new low/zero carbon housing. *ECEEE 2013 Summer Study proceedings*, France, 1-6 June 2013.

Gupta, R. and Kapsali, M. (2014). Evaluating the 'as-built' performance of an exemplar eco-housing development in the UK. *CIBSE ASHRAE Technical Symposium Proc*., 3-4th April 2014, Dublin, Ireland

HM Government (2010). Building Regulations 2010: Approved Document F1: Means of ventilation, London, NBS. Retrieved from: http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partf/approved

Institute for Sustainability (IfS) (2012). *Retrofit insights: Perspectives for an emerging industry. Key Findings: Analysis of a selection of Retrofit for the Future projects*. Retrieved from: http://www.instituteforsustainability.co.uk

HM Government (2011). The carbon plan: Delivering our low carbon future. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf

Karvonen, A. (2013). Towards systemic retrofit: a social practices approach, *Building Research & Information* 41(5), 563-74.

Kelly, S., Shipworth, M., Shipworth, D., Gentry, M., Wright, A., Pollitt, M., . . . Lomas, K. (2013). Predicting the diversity of internal temperatures from the English residential sector using panel methods. *Applied Energy,*102(2013), 601–621.

Li, F., Smith, A., Biddulph, P., Hamilton, I., Lowe, R., Mavrogianni, A., … Oreszczyna, T. (2014). Solid-wall U-values: heat flux measurements compared with standard assumptions. Building Research & Information, 43(2), 238-252.

Low Carbon Communities Network (no date). *Resources.* Retrieved from: http://www.lowcarboncommunities.org/useful-resources/

Lowe, R. and Johnston, D. (1997). *A field trial of mechanical ventilation with heat recovery in local authority, low-rise housing.* Retrieved from: http://www.leedsbeckett.ac.uk/as/cebe/projects/derwentside.pdf

Lowe, R., Chiu, L. F., Raslan, R., & Altamirano, H. (2013). *Key findings report: Retrofit project team perspectives. London: Institute for Sustainability.* Retrieved from: http://www.instituteforsustainability.co.uk/uploads/File/KeyFindingRe ports_Retrofit.pdf

National Energy Foundation (NEF) (2014). *Breaking barriers: An industry review of the barriers to Whole House Energy Efficiency Retrofit and the creation of an industry action plan.* Retrieved from:

http://www.nef.org.uk/themes/site_themes/agile_records/images/uploads/BreakingBarriers_SummaryReport.pdf

Office of the Deputy Prime Minister (2006) Building Regulations 2000: Approved Document L1A: Conservation of fuel and power in new dwellings: 2006 edition, London, NBS. Retrieved from: http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/approved

Ofgem (2014a). *Energy Companies Obligation (ECO): Guidance for Suppliers (Version 1.1a).* Retrieved from: https://www.ofgem.gov.uk/

Ofgem (2014b)*. An introduction to the Domestic Renewable Heat Incentive scheme*. Retrieved from: https://www.ofgem.gov.uk/

Oreszczyn, T. and Lowe, R. (2010) Challenges for energy and buildings research: objectives, methods and funding mechanisms. *Building Research & Information*, 38(1), 107–122

Sharpe, T.R., Porteous, C.D.A, Foster, J. and Shearer, D. (2014). An assessment of environmental conditions in bedrooms of contemporary low energy houses in Scotland. *Indoor and Built Environment,* 0(0), 1-24.

Summerfield, A., Oreszczyn, T., Pathan, A., and Hong, S. (2009). Occupant Behaviour and Energy Use. In: Mumovic, D and Santamouris, M, (eds.) A Handbook of Sustainable Building Engineering and Design – An Integrated Approach to Energy, Health and Operational Performance of Buildings. 359 - 370 Earthscan Ltd.: London.

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

Swan, W., Ruddock, L. and Smith L. (2013). Low carbon retrofit: attitudes and readiness within the social housing sector. *Engineering, Construction and Architectural Management.* 20(5), 522-535.

Sweett (2014). *Retrofit for the future: Analysis of cost data*. Retrieved from: https://www.innovateuk.org/retrofit-analysis

Technology Strategy Board (TSB) (2013). *Retrofit revealed: The retrofit for the future projects – data analysis report.* Retrieved from: https://www.innovateuk.org/retrofit-analysis

Technology Strategy Board (TSB) (2014). *Retrofit for the future: Reducing energy use in existing homes: A guide to making retrofit work.* Retrieved from: https://www.innovateuk.org/retrofit-analysis

The Scottish Government (2014). *Scottish house condition survey.* Retrieved from: http://www.scotland.gov.uk/Topics/Statistics/SHCS/Downloads

Tweed, C. (2013). Socio-technical issues in dwelling retrofit. *Building Research and Environment,* 41(5), 551-562.

UK CCC. (2014). Meeting carbon budgets – 2014 Progress report to parliament. London: UK Committee on Climate Change.

Usable Building Trust and BSRIA (2009). *The Soft Landings Framework: for better briefing, handover and building performance in-use.* Retrieved from: https://www.bsria.co.uk/services/design/soft-landings/free-guidance/

Zero Carbon Hub (2014). *Closing the gap between design and as-built performance: Evidence review report.* Retrieved from: www.zerocarbonhub.org/

Tables

Table 1 Summary of RfF monitoring and evaluation methods and data collected

Data collected	Method	Undertaken by
Phase 1		
Basic building data / existing conditions • Built age • Built form • Existing systems	Pre-construction assessment / in some cases extended to pre-construction POE (Gupta and Chandiwala, 2010)	RfF project teams
Air tightness data and thermal imaging (pre-construction baseline)	Short term, one-off "spot" testing (required performance measurements)	Energy Saving Trust (EST)
Phase 2		
Air tightness data and thermal imaging (post-construction)	Short term, one-off "spot" testing (required performance measurements)	EST
Energy and environmental data • meters for gas, electricity, water and oil (where necessary) with remote data collection; • internal temperature and relative humidity in three locations – living room, hall, and principal bedroom; • external temperature and relative humidity; • indoor air quality: CO_2 (as a proxy for overall air quality);	Long term monitoring (required performance measurements)	RfF project teams / data collated by EST through EMBED
Occupant experience with the installation process / how the occupant(s) is interacting with the measures / occupant thermal and overall comfort	Post-occupancy evaluation (POE) (immediately after occupancy)	RfF project teams
Post-programme assessment led by Energy Saving Trust		
Occupant experience of the installation process / how the occupant(s) is interacting with the measures.	Post-occupancy evaluation (POE) (one year later)	EST, Oxford Brookes University, University College London, Databuild
Mechanical ventilation flow rates	Measured using a hooded anemometer	EST and industry experts
Site visit and walk-through inspection to review the following: • Inspect building fabric, installed technologies and measures. • Check and record delivery to the planned retrofits and comment on the appropriateness/effectiveness of any changes. • Comment on quality of works. • Record electrical appliances installed • Identify all defects and serious faults at the property which have arisen from the retrofit.	Post-construction review (PCR)	EST and industry experts

Table 2 Outputs produced by the RfF programme and data, methods and techniques covered

** Due to data privacy, a majority of POE results were not available for analysis.*

			Data, methods & techniques covered						
Publisher	**Source**	**Availability**	**Basic build info.**	**Method & tech. used**	**Energy & CO_2**	**Therm-ography**	**Air-tightness data**	**POE**	**Number of dwellings**
Primary source (datasets)									
EST	Property info list (Energy Saving Trust (EST), no date a)	not published	✓		✓		✓		123
	Tech. matrix (EST, no date b)	Not published	✓	✓					119
	Embed (EST, 2014)	Online	✓	✓	✓				69
	MVHR flow rate measurements	Not published		✓			✓		42
	Post construction reviews (PCR)	Not published		✓					44
	POE surveys	Not published		✓				✓	20*
AECB	Low Energy Buildings database (The Association for Environment Conscious Building, 2014)	Online	✓	✓	✓	✓	✓		88
Secondary source (reports)									
TSB	RfF guide (TSB, 2014)	Online		✓	✓			✓	40
	Retrofit revealed (TSB, 2013)				✓		✓		37
	Info-graphics (programme highlights)				✓			✓	23 / 24
TSB/ Sweett	Analysis of cost data (Sweett, 2014)			✓					70
RIBA	Residential retrofit: 20 case studies (Baeli, 2013)	Published	✓	✓	✓	✓	✓		20
Various	Various academic papers	Published	✓	✓				✓	Varies

Figures

Figure 1 Dwellings by built form and age

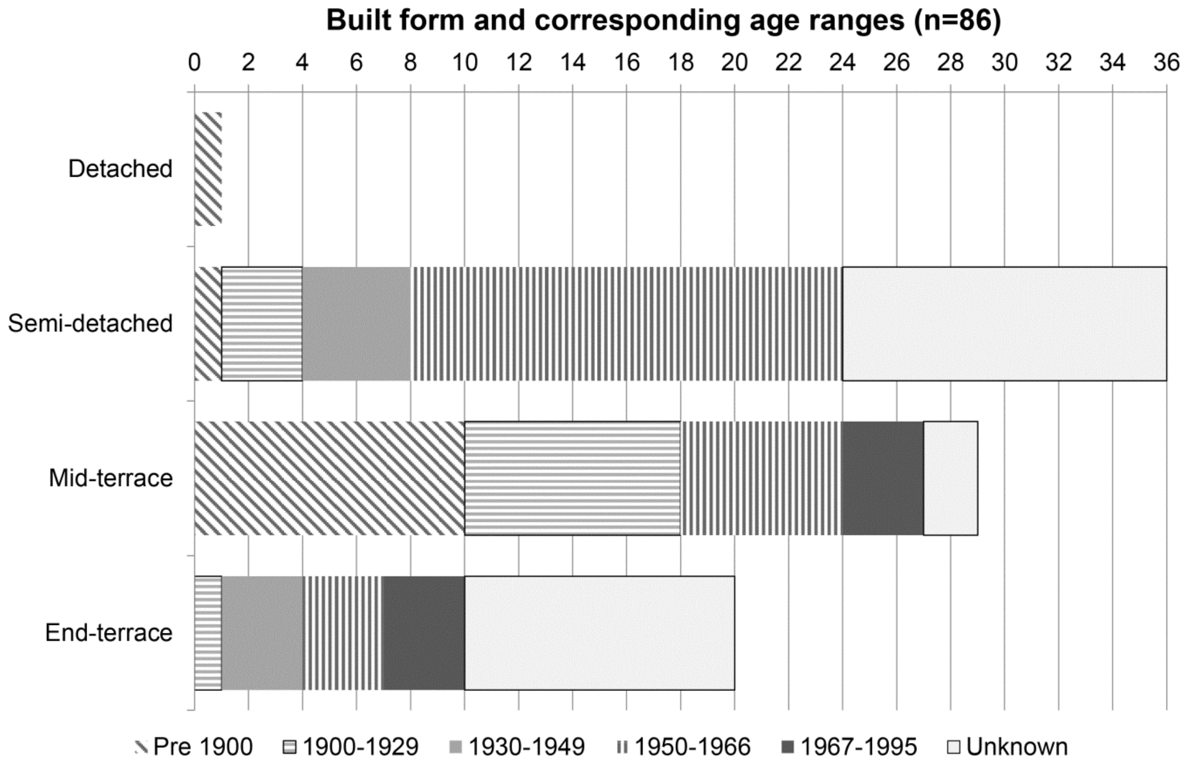


Figure 2 Distribution and count of energy saving strategies and LZTs in the RfF sample

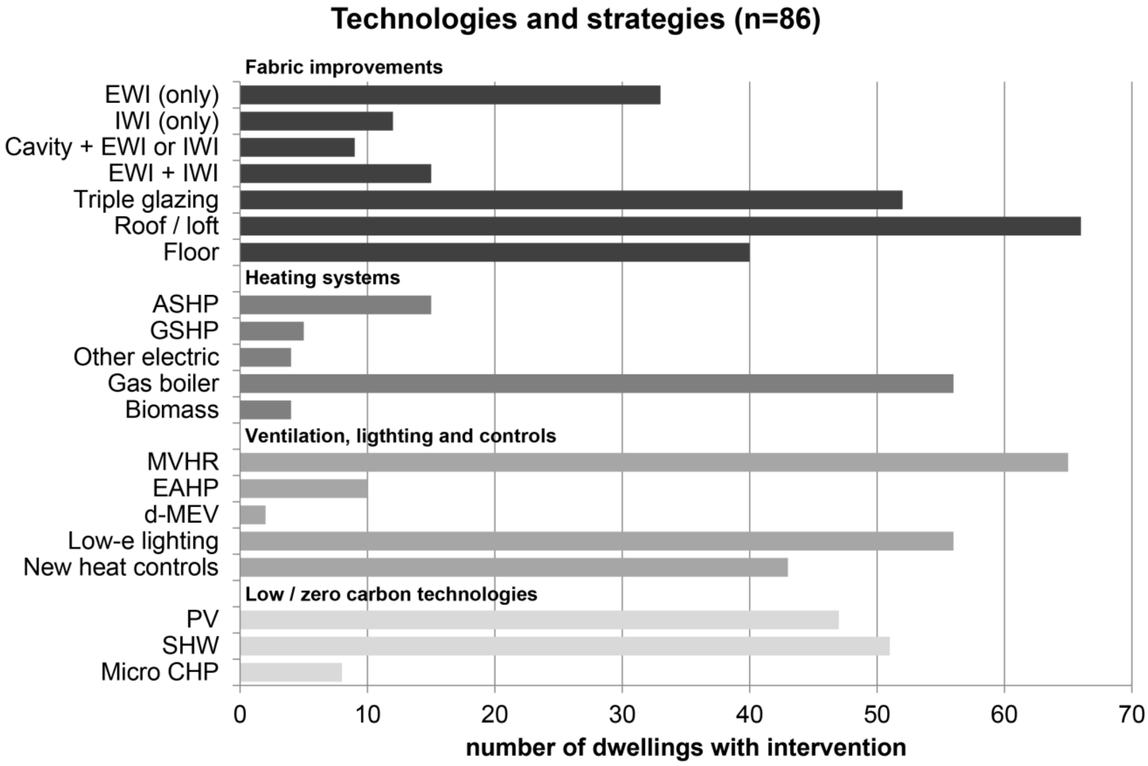


Figure 3 CO_2 emissions. *Note: (n) represents the number of dwellings with post-retrofit CO_2 emissions. Not all of these dwellings have pre-retrofit CO_2 emissions data.*

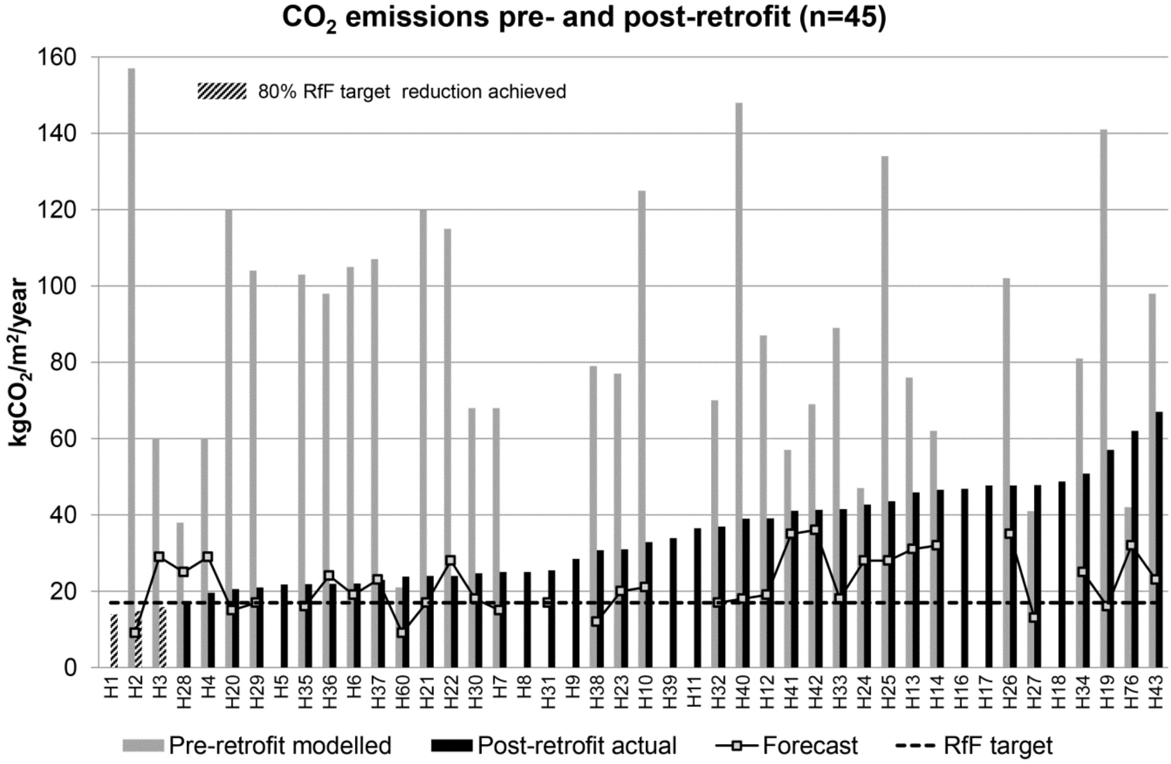
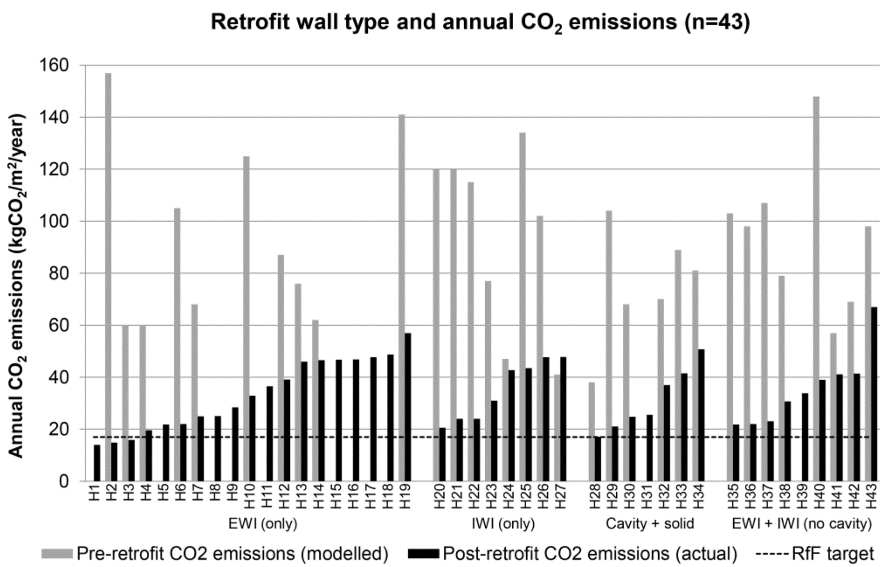


Figure 4 Predicted pre-retrofit and actual post-retrofit CO_2 emissions by wall insulation type and heating source. *Note: (n) represents the number of dwellings with post-retrofit CO_2 emissions and heating technology information.*



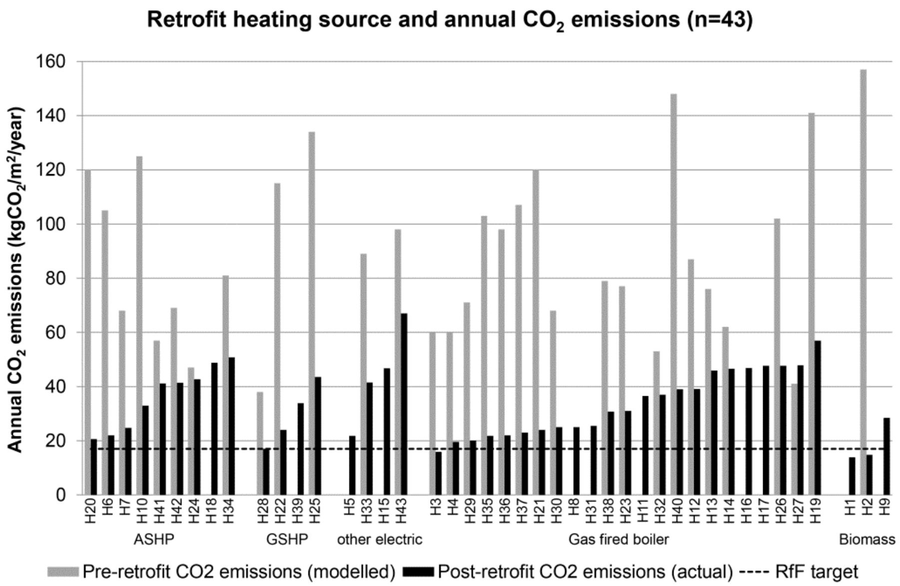


Figure 5 Electricity and gas consumption with CO_2 emissions. *Note: the first bar represents modelled pre-retrofit energy consumption and the second bar represents post-retrofit measured energy consumption. Heating fuel figures are not weather corrected.*

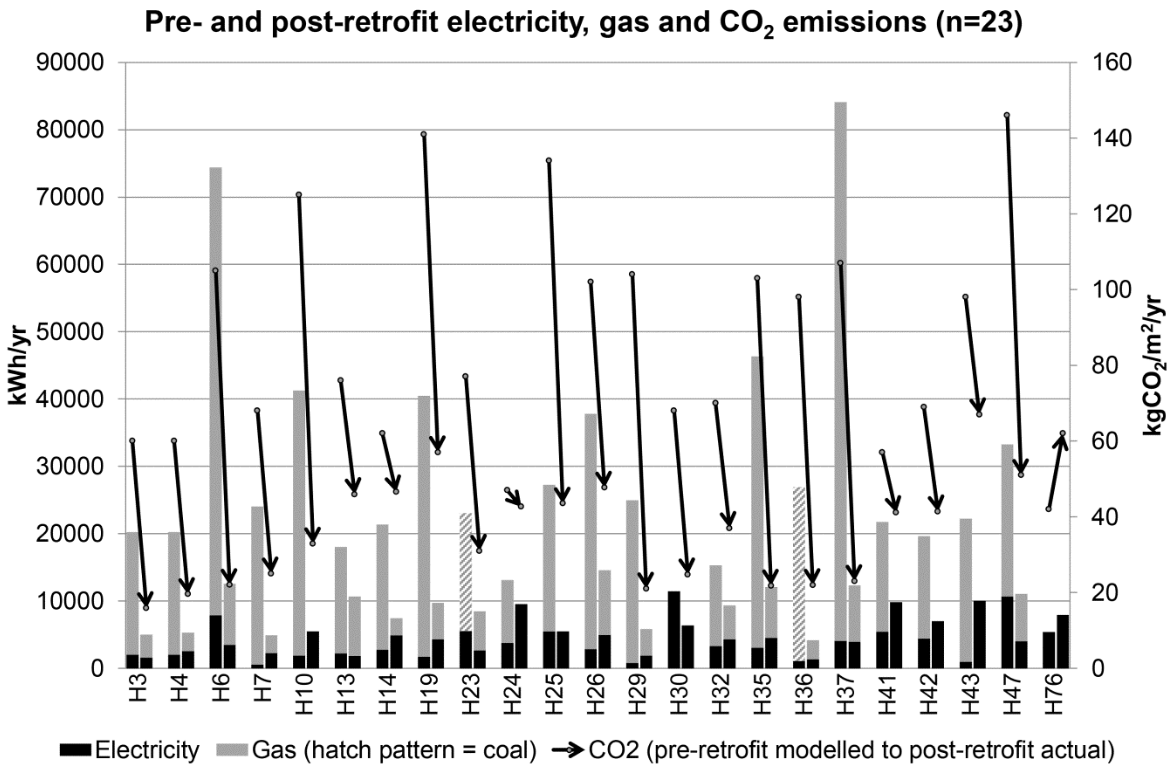


Figure 6 Forecasted and measured electricity and gas consumption with performance gap. *Note: performance gap is calculated as measured value divided by forecast (Galvin, 2014b)*

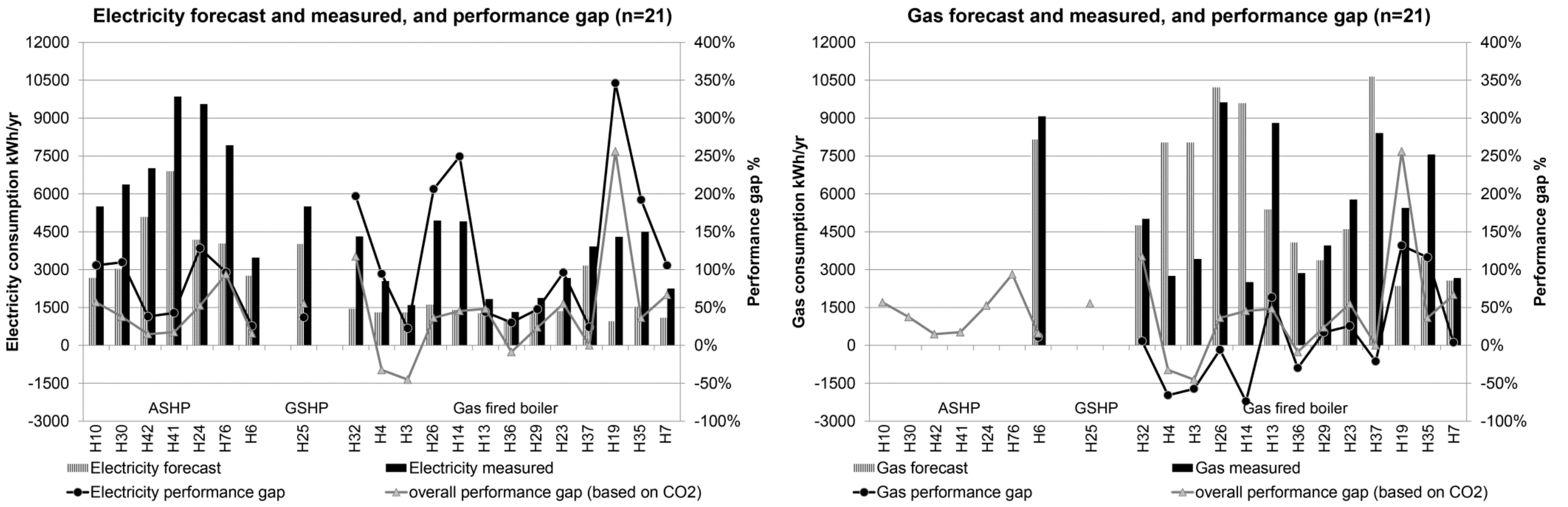


Figure 7 Change in electricity consumption for dwellings with PV. *Note: the graph is scaled to a maximum increase in electricity consumption of 200%. H7 and H43 had increases above 200%; 312% and 937% respectively.*

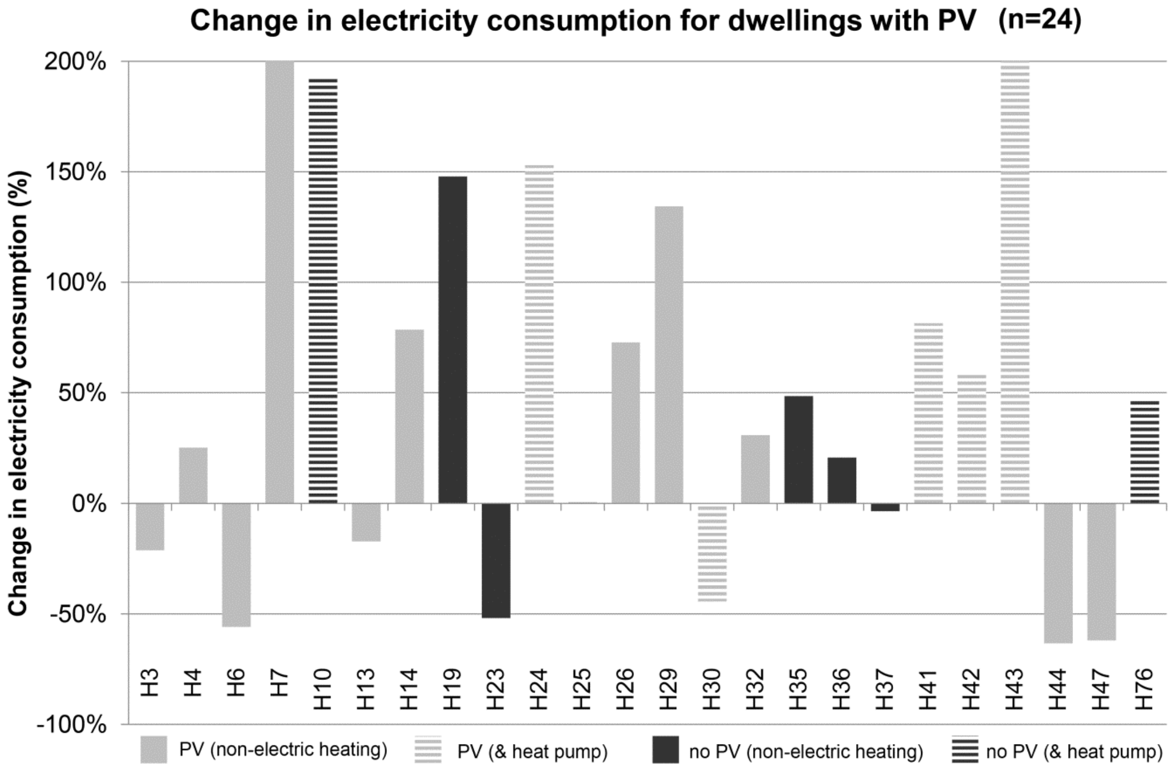


Figure 8 Measured air-tightness levels: pre- and post-retrofits

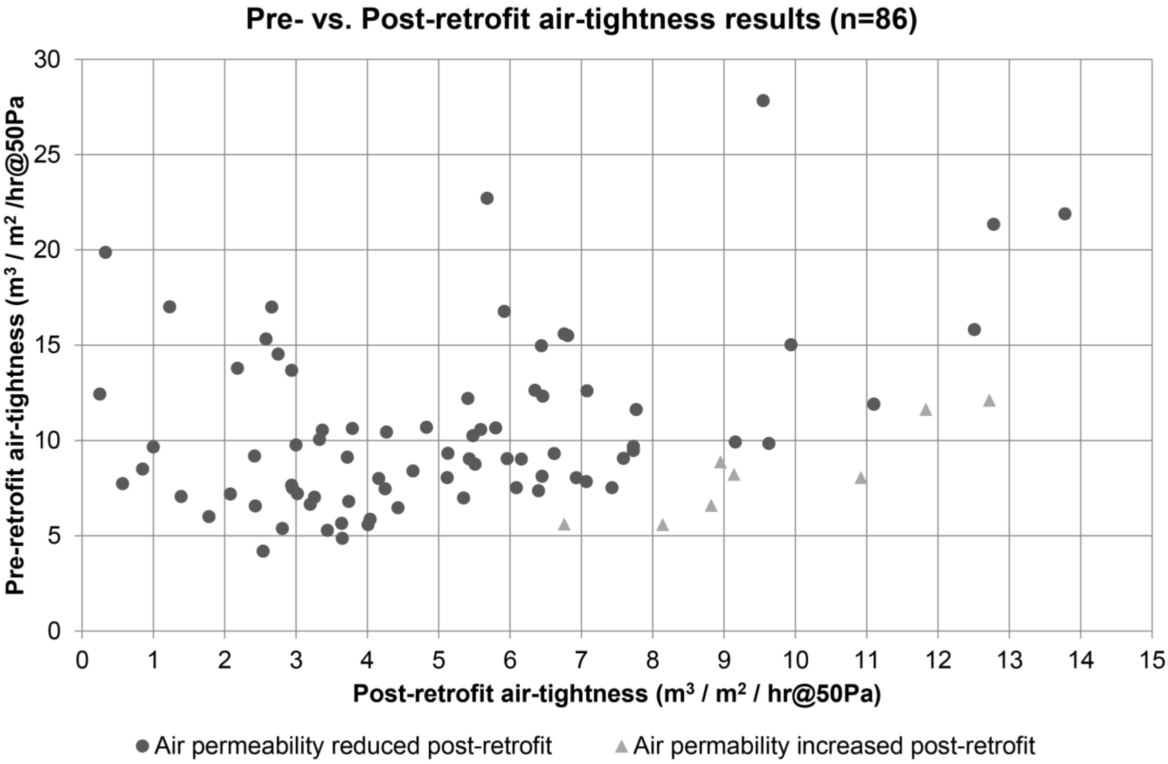


Figure 9 Post-retrofit gas consumption and air-tightness results

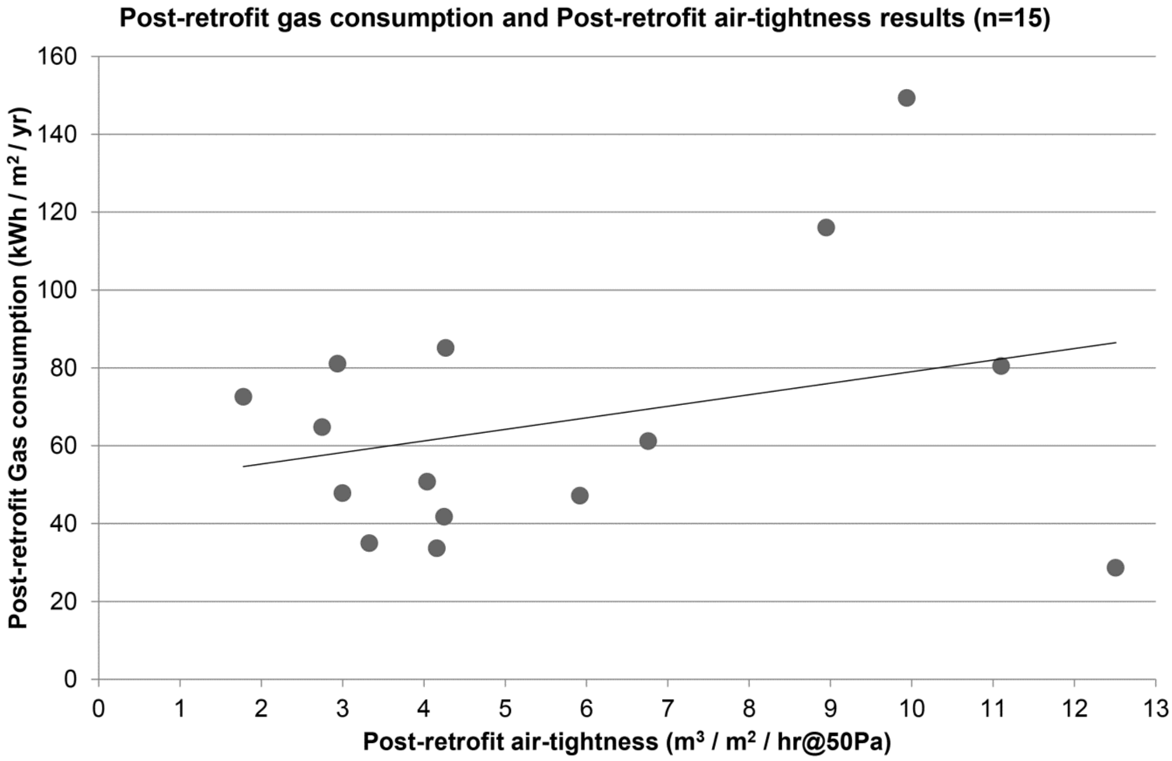


Figure 10 Measured MVHR supply and extract air flow rates and corresponding Part F minimum.

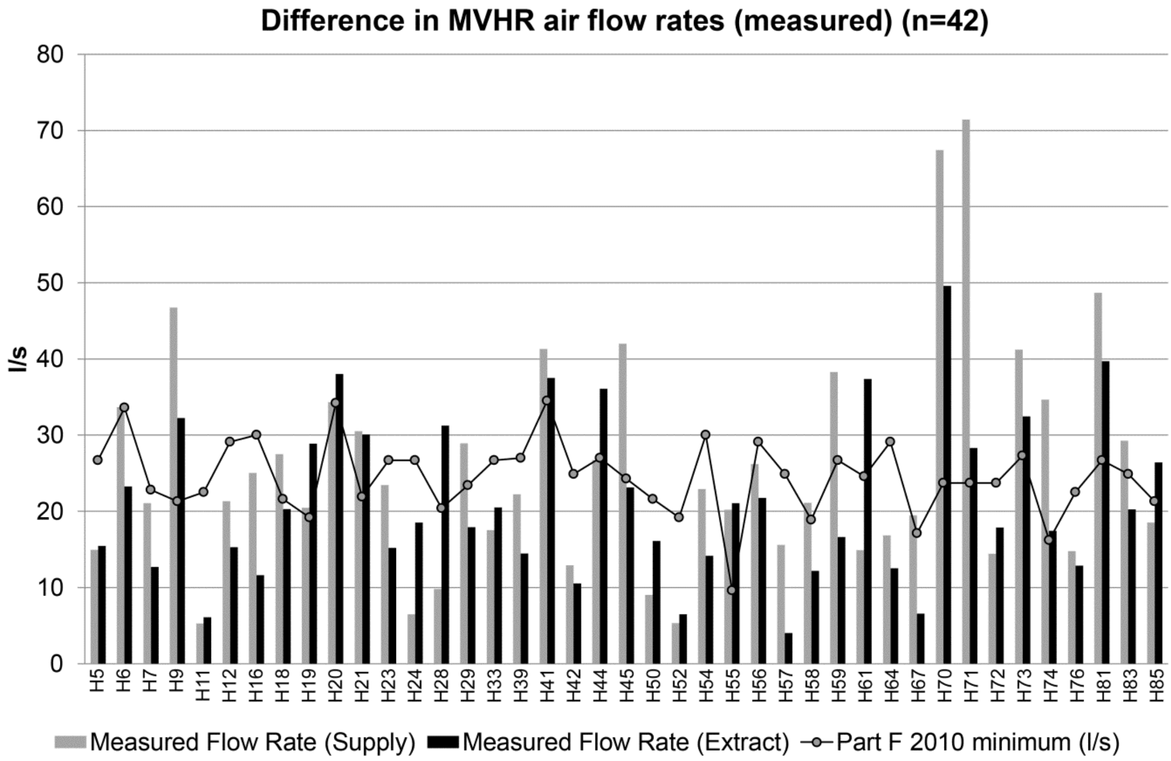


Figure 11 Minimum, mean and maximum indoor temperatures and relative humidity. Note: period length of measurement can vary widely and data are not weather corrected. Recommendations (CIBSE, 2006).

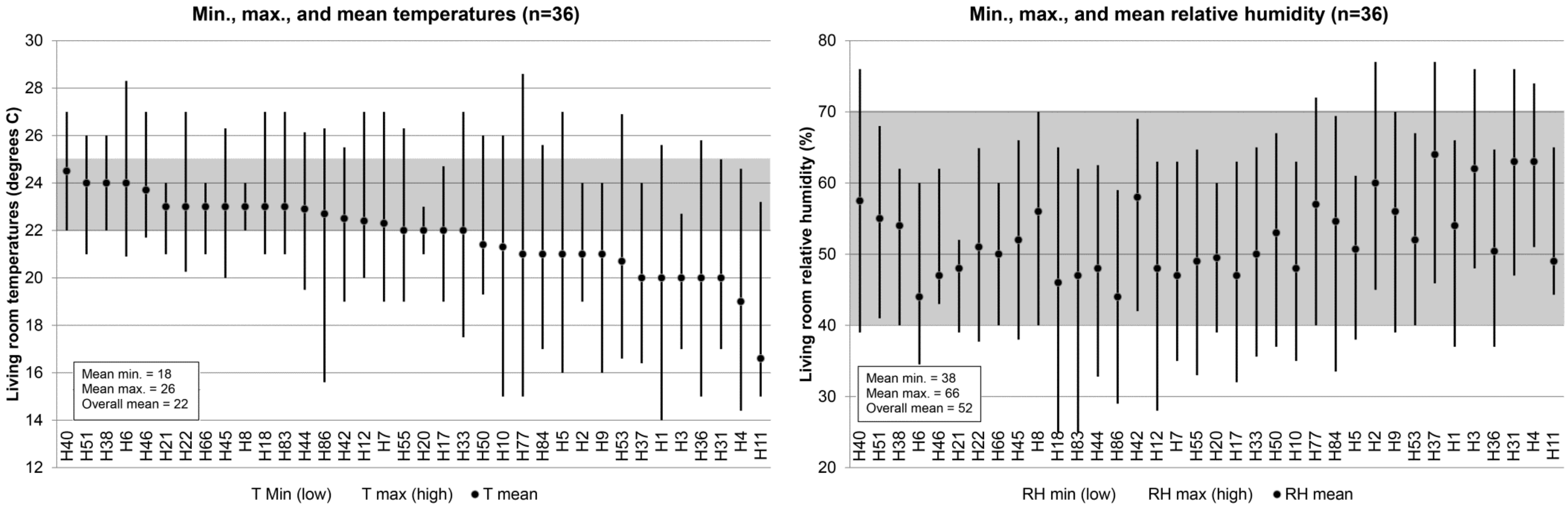
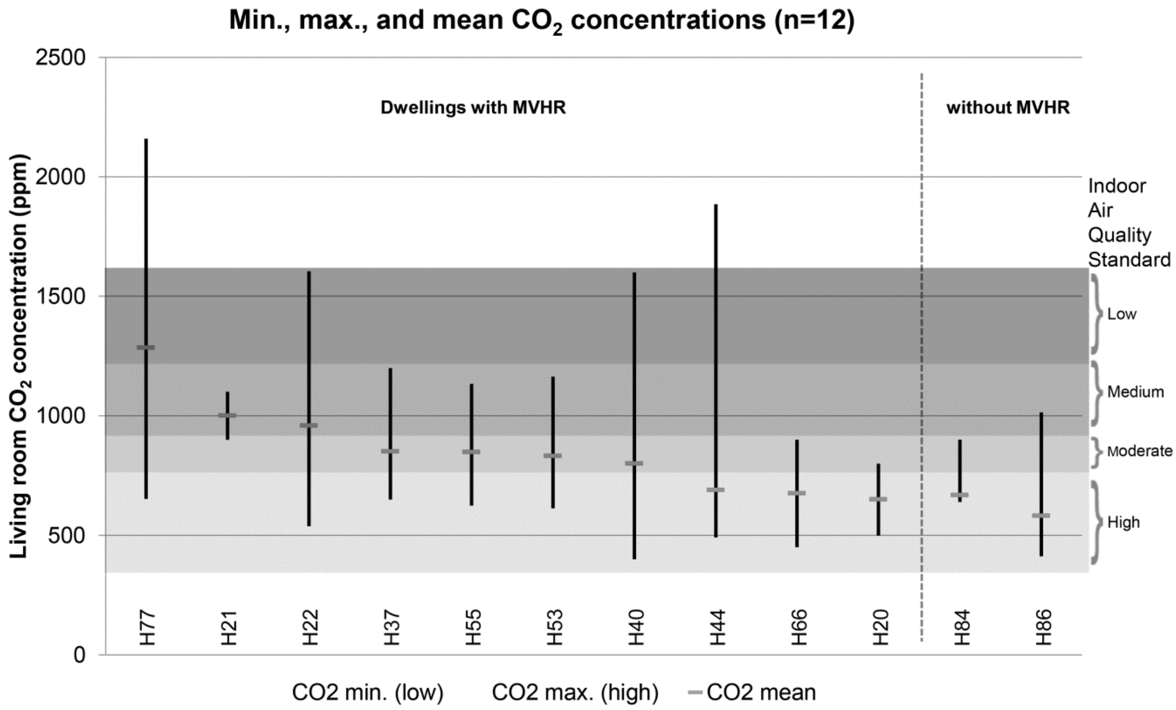


Figure 12 Minimum, maximum and mean CO_2 concentrations. Recommendations (CIBSE, 2006).



Endnotes

[i] The Golden Rule is the central mechanism for determining which measures can be financed by using the Green Deal. The rule: “Estimated savings must be greater than or equal to repayments.” The caveat: “Actual savings may be less than these repayments (if your energy use changes or if energy prices fall)” (DECC, 2012a).

[ii] The Green Deal is a UK Government initiated private investment in the carbon reduction of existing building stock. Energy efficiency improvements will be offered by the private sector to homeowners and businesses at little or no upfront cost with payment recouped through customers’ energy bills (DECC, 2012a).

[iii] Electricity Demand Reduction (EDR) summarizes electricity savings as a result of the installation of more efficient electrical equipment. Savings are calculated by comparing energy use before and after a project, whilst making appropriate adjustments (DECC, 2014a).

[iv] The Energy Savings Opportunity Scheme (ESOS) is a mandatory energy assessment and energy saving identification scheme for large ‘undertakings’ in the UK. Large undertakings are defined by either a large number of employees or large annual financial turnover and balance sheet (DECC, 2014b).

[v] The Energy Companies Obligation (ECO) operates alongside the Green Deal placing the obligation on larger energy suppliers to deliver energy efficiency measures to domestic premises of vulnerable consumer groups and hard-to-treat homes (Ofgem, 2014a).

[vi] A deep retrofit implies that interventions introduced will have a strong impact on the energy use and CO_2 emissions of the existing building, typically aiming for an 80% reduction in line with UK’s Climate Change Act target figure.

[vii] A whole-house approach means considering a household’s energy needs and CO_2 impacts as a whole, and establishing a comprehensive package of measures to reduce them.

[viii] Developed by the Usable Buildings Trust, the Soft Landings approach provides a five stage alternative to the conventional brief, design, build and occupy system, which aims to close the performance gap (Usable Building Trust and BSRIA, 2009). Though designed for non-domestic, the Soft Landings approach provides a methodical approach to improving review and communication of intent, assessment of knowledge and

understanding of construction team and appropriate handover and aftercare steps for the occupant which could all be applicable to construction in the domestic sector.

Case Study Ref.	Dwelling type	Dwelling Age	Wall upgrade	Heating system	Mech. Ventilation	Solar	PHPP	Pre air-perm.	Post air-perm	Pre-retrofit measured Electricity	Post-retrofit measured Electricity	Pre-retrofit measured gas	Post-retrofit measured gas	Pre-retrofit measured CO2	Post-retrofit measured CO2
								m3/m2/hr@50Pa		kWh/yr				kgCO2/m2/yr	
H1	MT	1950 - 1966	EWI	Biomass		Thermal		9.02	6.16						13.93
H2	SD	1930 - 1949	EWI	Biomass	MVHR		Y	8.5	0.85	18830		3130		157	14.8
H3	SD	1950 - 1966	EWI	Gas		PV		7.46	4.25	2033	1601	18213	3421	60	15.87
H4	SD	1950 - 1966	EWI	Gas		PV		8	4.16	2033	2545	18213	2756	60	19.57
H5	SD	1950 - 1966	EWI	Electric	MVHR			9.32	5.13						21.77
H6	ET		EWI	ASHP	MVHR	PV+ thermal		7.65	2.94	7895	3475	66507	9075	105	22
H7	ET	1976 - 1982	EWI	Gas	MVHR	PV+ thermal		10.05	3.33	547	2253	23490	2665	68	25
H8	ET	1991 - 1995	EWI	Gas	MVHR	PV		9.04	5.96						25.01
H9	SD	1930 - 1949	EWI	Biomass	MVHR		Y	9.66	1						28.44
H10	SD	1950 - 1966	EWI	ASHP	MVHR		Y		3.2	1885	5506	39377	0	125	32.9
H11			EWI	Gas	MVHR	PV+ thermal		11.9	11.1						36.51
H12	SD	1950 - 1966	EWI	Gas	MVHR	Thermal	Y	8.75	5.51	3337		29073		87	39.09
H13	MT		EWI	Gas	d-MEV	PV+ thermal		15.02	9.94	2223	1839	15811	8807	76	45.93
H14	SD	1950 - 1966	EWI	Gas		PV+ thermal		15.82	12.51	2751	4913	18587	2509	62	46.55
H15	MT		EWI	Electric	MVHR	PV+ thermal		8.89							46.71
H16	SD	1930-1949	EWI	Gas	MVHR	Thermal		12.32	6.46						46.83
H17	MT	1950 - 1966	EWI	Gas	MVHR	PV+ thermal		8.12	6.45						47.7
H18	SD	1950 - 1966	EWI	ASHP	EAHR	Thermal		7.52	6.09						48.76
H19	MT	pre 1900	EWI	Gas	MVHR	Thermal		10.44	4.27	1733	4296	38723	5446	141	57
H20	MT	pre 1900	IWI	ASHP	MVHR	Thermal	Y	19.87	0.33					120	20.57
H21	MT	pre 1900	IWI	Gas	MVHR	Thermal		15.32	2.58	2808		32860		120	24
H22	ET	1983 -	IWI	GSHP	MVHR	PV+		9.68	7.73	1505		28020		115	24

		1990				thermal									
H23	ET		IWI	Gas	MVHR	Thermal	Y	14.53	2.75	5550	2668	17500	5775	77	31
H24	MT	pre 1900	IWI	ASHP	EAHR	PV			4.22	3779	9558	9302	0	47	42.68
H25	MT	1900-1929	IWI	GSHP		PV+ thermal		8.06	10.92	5474	5503	21772	0	134	43.53
H26	MT	pre 1900	IWI	Gas	d-MEV	PV+ thermal		8.88	8.95	2861	4941	34933	9628	102	47.7
H27	MT	pre 1900	IWI	Gas	EAHR	PV+ thermal		9.47	7.73					41	47.83
H28	ET	1950 - 1966	CWI+SWI	GSHP	d-MEV	PV			5.25	2640		22946		38	17
H29	SD	pre 1900	CWI+SWI	Gas	MVHR	PV+ thermal		5.86	4.04	802	1879	24138	3957	104	21
H30	MT	1991 - 1995	CWI+SWI	ASHP	EAHR	PV+ thermal	Y	15.59	6.76	11451	6368	0	0	68	24.73
H31	SD	1950 - 1966	CWI+SWI	Gas	MVHR	Thermal		9.03	5.43						25.5
H32	MT	1991 - 1995	CWI+SWI	Gas	MVHR	PV+ thermal		5.62	6.76	3303	4319	11983	5016	70	36.96
H33	SD	1950 - 1966	CWI+SWI	Electric	MVHR			10.66	5.8	3241		27154		89	41.5
H34	MT	1950 - 1966	CWI+SWI	ASHP	EAHR	PV+ thermal		6.56	2.43	6593				81	50.79
H35	MT	1950 - 1966	EWI+IWI	Gas	MVHR	Thermal	Y	6	1.78	3029	4496	43306	7559	103	21.81
H36	MT	pre 1900	EWI+IWI	Gas	EAHR	Thermal		16.77	5.92	1097	1324	25810	2860	98	21.95
H37	D	pre 1900	EWI+IWI	Gas	MVHR	Thermal		9.76	3	4061	3915	80054	8407	107	23
H38	MT	1900-1929	EWI+IWI	Gas	MVHR	PV+ thermal		5.59	8.14	214		25987		79	30.7
H39	ET	1950-1966	EWI+IWI	GSHP	MVHR	PV+ thermal		4.86	3.65						33.88
H40	MT	1900-1929	EWI+IWI	Gas	MVHR	Thermal		17	2.66	2897		70164		148	39
H41	SD		EWI+IWI	ASHP	EAHR	PV	Y	13.79	2.18	5433	9858	16287	0	57	41.1
H42	SD	1930 - 1949	EWI+IWI	ASHP	MVHR	PV+ thermal		7.51	2.95	4412	7018	15212	0	69	41.37
H43	MT		EWI+IWI	Electric	MVHR	PV		7.02	3.26	968	10038	21283	0	98	67
H44	MT	pre 1900	IWI	Gas	MVHR	PV		12.43	0.25	7250	2657	22000		99	18
H45	SD	1900 - 1929	EWI	ASHP	EAHR	Thermal	Y	7.73	0.57	2155		59250		124	

H46	ET	1930 - 1949	EWI	Gas	MVHR	PV+ thermal		10.63	3.79	2010		40107		123	
H47	ET				MVHR	PV+ thermal		11.9	11.1	10669	4049	22565	7004	146	51
H48	ET	1950 - 1966						6.98	5.35						
H49	MT	1950 - 1966	EWI	Biomass		Thermal		9.92	9.16						
H50	SD	1950 - 1966	EWI	Gas	MVHR	Thermal		9.31	6.62						
H51	MT	1900-1929	EWI+IWI	Gas		Thermal		15.5	6.81	3151		63241		94	
H52	ET		IWI	Micro CHP	EAHR			7.19	2.08	1588		30115		114	
H53	ET	1930 - 1949	CWI+SWI	ASHP	MVHR	PV+ thermal		5.28	3.44	37554				435	
H54	SD	1950 - 1966	EWI+IWI	GSHP	MVHR	PV		4.19	2.54	37050				227	
H55	SD		CWI+SWI	Gas	MVHR	PV		6.8	3.74	16193				357	
H56	ET		EWI	Gas + Micro CHP	MVHR	PV		10.25	5.48	3977		17060		65	
H57	ET	1950 - 1966	EWI	Gas + Micro CHP	EAHR	PV		11.62	7.77	2968		27631		89	
H58	MT	pre 1900		Gas + Micro CHP	MVHR			13.68	2.94	2581		20980		99	
H59	ET		EWI	Gas	MVHR	PV+ thermal		6.6	8.82						
H60	SD			Gas				9.06	7.59	2029		2461		21	23.85
H61	ET		EWI+IWI	Gas + Micro CHP	EAHR	PV		5.65	3.64	1051		7411		28	
H62	SD			Gas				21.34	12.78	197		213		1	
H63	SD			Gas	MVHR		Y	5.38	2.81	1812		28659		109	
H64	SD	1900 - 1929	EWI	Gas	MVHR	PV+ thermal		7.36	6.4	2169		2651		21	
H65	ET	1930 - 1949		ASHP				12.63	6.35	16113		3439		143	
H66	MT	pre 1900	EWI+IWI	Gas	MVHR			17.01	1.23	2684		33051		79	
H67	ET	1900 - 1929	IWI	Gas	MVHR	PV+ thermal		11.64	11.83	980		27559		89	

H68	MT	pre 1900	EWI+IWI	Gas	MVHR	Thermal		12.6	7.08	18718		41541		169	
H69	SD	1950 - 1966		Gas		PV		8.05	5.12						
H70	MT	1950 - 1966		Gas	MVHR			9.12	3.72						
H71	MT	1900-1929	EWI	Gas	MVHR	PV+ thermal		7.84	7.07						
H72	SD			Gas	MVHR		Y	8.4	4.64	2190		49702		148	
H73	SD	1930 - 1949	EWI		MVHR	PV+ thermal		8.49		752.5		26803.9		78	
H74	ET	1950 - 1966	IWI	ASHP	MVHR	PV+ thermal		5.88		13060				120	
H75	SD		EWI	Gas	MVHR	Thermal	Y	7.21	3.02						
H76	SD			ASHP	MVHR	Thermal		27.83	9.55	5410	7928	0	0	42	62
H77	MT	1967 - 1975	CWI+SWI	Gas + Micro CHP	MVHR	PV+ thermal		12.2	5.41	3000		14000		63	
H78	SD			ASHP	MVHR	PV+ thermal		12.12	12.72	30121		11804		218	
H79	SD	1950 - 1966	IWI	ASHP	MVHR	PV+ thermal		9.18	2.42	17487		964		176	
H80	SD		EWI	ASHP	MVHR	PV+ thermal		9.84	9.63						
H81	ET		EWI	Gas	MVHR	PV+ thermal		8.23	9.14						
H82	MT	1900-1929	EWI	Gas				6.65	3.2						
H83	SD	1950 - 1966	EWI+IWI	Gas	MVHR	PV+ thermal	Y	7.06	1.39	2795		55234		155	
H84	SD	1930 - 1949	EWI	Biomass		PV+ thermal		7.37							
H85	SD		EWI	ASHP	MVHR	PV+ thermal			3.17	24635				168	
H86	MT	1900-1929		Gas		PV		14.97	6.44						