CP760
Airtightness measures
Ceredigion County Council

Technical Evaluation Report





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June 2018

Background

About National Energy Action

National Energy Action is the national fuel poverty charity working across England, Wales and Northern Ireland, and with sister charity Energy Action Scotland (EAS), to ensure that everyone can afford to live in a warm, dry home. In partnership with central and local government, fuel utilities, housing providers, consumer groups and voluntary organisations, it undertakes a range of activities to address the causes and treat the symptoms of fuel poverty. Its work encompasses all aspects of fuel poverty, but in particular emphasises the importance of greater investment in domestic energy efficiency.

About the Technical Innovation Fund

NEA believes that there is huge potential for new technologies to provide solutions for some of the 4 million UK households currently living in fuel poverty, particularly those residing in properties which have traditionally been considered too difficult or expensive to include in mandated fuel poverty and energy efficiency schemes. However, more robust monitoring and evaluation is needed to understand the application of these technologies and assess their suitability for inclusion in future schemes.

The Technical Innovation Fund (TIF) which was designed and administered by NEA, formed part of the larger £26.2m Health and Innovation Programme along with the Warm Zone Fund and Warm and Healthy Homes Fund.

TIF facilitated a number of trials to identify the suitability of a range of technologies in different household and property types and had two strands: a large measures programme to fund the installation and evaluation of technologies costing up to a maximum £7,400 per household, and a smaller measures programme with up to the value of £1,000 per household. It launched in May 2015, with expressions of interest sought from local authorities, housing associations, community organisations and charities wishing to deliver projects in England and Wales.

Over 200 initial expressions of interest were received and NEA invited 75 organisations to submit full proposals. Applications were assessed by a Technical Oversight Group, chaired by Chris Underwood, Professor of Energy Modelling in the Mechanical and Construction Engineering Department at Northumbria University who is also a trustee of NEA. In total, 44 projects were awarded funding to trial 19 different types of technologies and around 70 products (although this number reduced slightly as some products proved not to be suitable and were withdrawn).

More than 2,100 households have received some form of intervention under this programme that has resulted in a positive impact on either their warmth and wellbeing, or on energy bill savings. Of course the amount of benefit varies depending on the household make up and the measures installed. In a small number of instances, we removed the measures and took remedial action.

Technical monitoring and evaluation

NEA has been working with grant recipients to monitor the application of these technologies and assess performance, as well as understand householder experiences and impacts.

A sample of households from each TIF project was selected for monitoring purposes. Participation was entirely voluntary and householders were free to withdraw at any time. This involved the installation of various monitoring devices within the home which collected data for analysis by NEA's technical team. Some residents were also asked to take regular meter readings. In some instances, a control group of properties that had not received interventions under TIF were also recruited and monitored.

The technical product evaluation was conducted alongside a social impact evaluation to inform our understanding of actual energy behaviour changes, perceived comfort levels and energy bill savings, as well as any other reported benefits. Householders were asked to complete a questionnaire both before and after the installation of the measures which captured resident demographic data including any health conditions. Small incentives in the form of shopping vouchers were offered to maintain engagement over the course of the evaluation period.

The HIP fund was principally designed to fund capital measures to be installed into fuel poor households. A small proportion of the funding enabled NEA to conduct limited research and monitoring of products installed, and was restricted to ensure that the majority of funds were spent on the products. All products included in the trials were deemed to offer costs savings and energy efficient solutions as proposed by the delivery partners. The research and monitoring aimed to provide insights to inform future programme design and interested parties of the applicability of the product to a fuel poor household. We recognise that due to the limited number of households involved in the monitoring exercises and the limited period we were able to monitor a product's performance, we may recommend that further research is needed to better understand the application of these products in a wider range of circumstances over a longer period of time.

The research was conducted according to NEA's ethics policy, which adopts best practice as recommended by the Social Research Association (SRA) Ethical Guidelines 2002.

An accompanying programme of training and outreach work was also delivered to 292 frontline workers to increase local skills and capacity.

Individual project reports are being compiled and will be made available publicly on NEA's website from September 2017, along with a full Technical Innovation Fund Impact Report.

Acknowledgements

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NEA team:

Tomos Davies, initial Project Development Co-ordinator
Bryony Holroyd, Technical Project Development Co-ordinator
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Legal limitations and disclaimer

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Executive summary

Project overview

This project used airtightness tests to identify sources of uncontrolled ventilation and cold spots in poor energy efficiency (SAP bands D - G) properties in a rural area of Wales, highly exposed to sea winds, often solid-walled or other hard-to-treat (HTT) construction, and most not being served by mains gas. Results of the tests highlighted appropriate airtightness measures which could be installed to address and reduce uncontrolled air exchange, to provide energy savings and improved comfort to the residents, vulnerable to fuel poverty.

The project had the following aims:

- Identify and install appropriate measures required to address airtightness issues in poorly insulated homes in an exposed rural area of Wales – these were of a wide variety of construction types such as older solid-walled terraced properties, holiday bungalows converted to be homes, and some detached homes, all with low energy efficiency.
- Assess any change in residents' comfort – both reported in questionnaires, and measured using temperature and humidity monitors – after install of the airtightness measures,
- Monitor any change in energy use for heating, following airtightness measures,
- Monitor any change in air quality i.e. carbon monoxide and carbon dioxide levels in homes, to see if reducing ventilation by sealing up draughts might worsen air quality,
- Determine the effectiveness and cost-effectiveness of airtightness measures to improve energy efficiency and reduce fuel poverty in HTT properties.

Context

Ceredigion comprises of a series of isolated rural communities, with 82.4% of homes not served by mains gas – the highest number of off-gas properties in Wales. The area covered by this study to the north of Aberystwyth, mainly focussing on Borth – an area exposed to strong (south)-westerly sea winds, and not served by mains gas so where the majority of homes are electrically heated - is not classed as particularly deprived. However, many properties are of older construction, with solid walls, large rooms and (often single glazed) windows, and many some have rooms in the roof so there is no loft space to insulate. Others were bungalows built as holiday chalets, now lived in year-round. Properties focussed on were low SAP rated, bands D - G, so hard to keep their adequately warm affordably. In 2012, 30% of households in Wales were in fuel poverty.

These properties are defined as HTT as their often solid-wall construction, and high exposure to sea winds means the cheapest and most easily applied insulation methods may be unsuitable. Of the more expensive measures, fitting internal wall insulation is disruptive, and external wall insulation (EWI) and double glazing are often not possible due to high weather exposure, the presence of conservation areas or householder preference for heritage window frames. As 70% of homes in Wales are owner-occupied, the Welsh Government funds the Warm Homes Programme including Nest to provide energy efficiency advice and measures to qualifying private owners or occupiers of energy inefficient properties. Ceredigion County Council also run an Eco-Flex scheme to fully/partly fund the fitting of energy efficiency measures by qualifying private-sector households.

On average 10% of heat loss is through draughts, so airtightness measures may help to reduce heat losses where other insulation measures are not physically or financially possible. This would apply to homes across the UK, particularly those in exposed, rural off-gas areas with HTT homes.

The technology: Airtightness

Airtightness tests were carried out in all but one phase-1 properties (Jan-May 2017), and a sample of 4 of the phase 2 properties (May & June 2017), identifying various airtightness and insulation issues which the measures selected for each property aimed to address.

A variety of technologies were tested as required for each property: general sealant around floors, skirting boards, window-sills, chimneys, and entry points for utility pipes; QuattroSeal expandable sealant on windows, doors and loft hatches; door / window repairs or replacement; insulation around water tanks; secondary glazing; under-floor insulation; and heat recovery ventilation.

Airtightness tests were repeated after the measures were installed for the sample of 4 phase-2 properties to see the effect that the measures had made on the property's air permeability.

The project

Ceredigion Council contacted householders referred by Ymlaen Ceredigion - an organisation which provides energy saving advice to residents of electrically heated homes - inviting them to take part in this study. The homes all had low SAP ratings (D - G). 8 properties were selected for treatment in the initial phase, one upper-floor flat / maisonette, 3 bungalows, and 4 larger houses. Only one of the larger homes had gas central-heating, the remainder were heated by electric storage heaters, and/or or on-peak electric heaters. These properties had monitoring equipment placed on 5th July 2016, and their airtightness measures were installed from January – May 2017. As monitoring equipment batteries would expire, an interim visit was made to phase 1 properties in November 2017 to replace loggers and carry out an interim questionnaire. One property (the flat) withdrew from the monitoring at this point.

11 more modern properties which were better insulated (SAP ratings D - F) but suffered from draughts around windows due to sea winds. These windows were treated with QuattroSeal draught proofing product on windows, doors and loft hatches as necessary. These homes were treated in May 2017, and monitoring equipment was installed in June 2017, when airtightness tests were also carried out. A control group of 4 similar homes was recruited which did not receive measures, for comparison, where monitoring equipment was fitted at the same time.

All properties were monitored for temperature and humidity in various rooms (usually the living room, hall and main bedroom), and a sample of phase 1 homes were also analysed for carbon monoxide and carbon dioxide levels in the first year (all phase 1 homes were monitored for carbon monoxide in the second year). A current clamp was installed to record electricity use – usually installed on the properties incoming electrical supply cable. In the second year, phase 1 properties had 2 current clamps fitted, one each on the peak and off-peak circuits, to further break down usage. Residents were asked to record their electricity (and gas if present) meter readings every 2 weeks for the duration of the study, and if possible to provide bills showing previous consumption. Details were also requested of any other fuels used (oil, bottled gas, solid fuel). Initial questionnaires were carried out with residents when monitoring equipment was installed, to gather information on the household size and occupancy, energy using behaviours and cost, and satisfaction with the heating and insulation.

Monitoring continued until March 2018 when all equipment was collected, and a final questionnaire was carried out to gauge resident satisfaction with their heating and insulation after they had experienced a whole winter with the airtightness measures fitted.

Summary of findings:

Resident satisfaction and comfort

- Feedback indicated a general improvement in comfort: 13 of 14 householders previously had to wear extra warm clothes in the home to keep warm. By the end of the study, only 4 (of 14) said they needed to wear extra warm clothes in the house, a significant improvement. 4 of the 15 reported they could heat or comfortably use more rooms since the measures were fitted.
- 8 of 15 householders felt their home now kept the heat in better, 7 said it was warmer / more comfortable, while 5 felt their home got warmer faster. 6 identified reduced noise (wind, sea, roads and trains) as another key benefit. Others included being able to sit near windows for light without getting cold.
- Overall, resident satisfaction with their heating (control over heating, how easy the system is to use, how well the house keeps the heat in, and how warm it gets when it's cold out) improved from "neither satisfied or dissatisfied" to generally "satisfied". However, satisfaction with the costs of running their heating system did not improve.
- Those who felt the airtightness measures had made little difference were in either relatively modern and well-sealed homes, and/or those with other significant heat loss issues such as uninsulated solid walls and rooms in the roof.

Energy use and costs

- Residents' estimates of energy costs did not change noticeably after airtightness measures, or compared to the control group – possibly affected by price rises and the very cold winter in 2017-18. However, 4 of the 15 households who received measures felt their bills were cheaper, and another could afford to heat more of the home for the same cost. 4 said the measures had reduced any money worries a little, and one felt it had reduced them a lot. But the remainder felt the measures had not made a significant difference.
- Calculating heating costs from meter readings, electrically heated phase 1 properties saved on average 5.23% in terms of kWh used, and 10.55% in costs, but due to variability of savings, these were not statistically significant. Excluding property T-06 which received heat recovery ventilation that would use more electricity, savings were 6.93% in kWh terms and 12.7% in costs. The fact that cost savings were higher than electricity units saved is due to a reduction is in expensive "daytime" electricity use compared to the cheaper "off-peak" rate. This may be reduced use of supplementary electric plug-in heating used during the day. T-02, the mains-gas heated property saved 7.32% on gas.
- Electrically heated phase 2 properties saw a 2-3% increase in bills on average, this was likely to be associated with energy behaviour variability and 3 properties saw a significant increase in energy usage, but one householder had a new baby, one turned on an extra storage heater because of the cold winter, and one ASHP-heated property saw a significant increase in usage – as the heat pump worked less efficiently in cold weather. Other properties did save 6.65 - 22.82%, but due to this variability, no significant savings can be reported. In comparison, electrically-heated control properties did make a small saving of 3.35% in kWh terms and 5.82% in cost terms, significant to a 68.2% level.

Thermal comfort

- Despite winter 2017-18 being on average 1 degree colder per day than the previous winter, living room temperatures in the phase-1 properties increased slightly on average, so all but one were now within the recommended 18-21°C range for comfort and good health either over all 24hrs or during the evening heating period (6-10pm). Properties T-02 and T-07 saw large increases in living room temperature. Temperature variability also reduced slightly. Property T-01 had been heated to lower temperatures by the resident, who was advised to increase the temperature to prevent health effects. Bedroom and hall temperatures reduced very slightly.
- Phase 2 property temperatures were variable, but most were within the 18-21°C range. In comparison to control properties, homes which had airtightness measures' temperatures were 1°C warmer on average in living rooms, bedrooms were 0.72°C warmer, but halls were 0.8°C cooler than the controls.

Damp and humidity

- Prior to installation of airtightness measures, 4 of the 8 phase-1 properties' living room humidity levels were higher than the recommended 40-60% rh range. Humidity levels were better controlled after installation of the measures as 3 of these reduced to within or very close to this range. However, one home still had very high living room humidity levels after the measures, which could be due to increased occupation of the property. Hall and bedroom levels were mostly higher than the recommended range - hall levels were reduced slightly after the measures but bedroom levels increased. This suggests that some households may need to air cooler rooms more proactively, such as bedrooms by opening windows at the warmest time of day, now that uncontrolled ventilation has been reduced.
- Phase-2 properties had living room humidity levels within or close to the recommended range. Little difference was seen between treated and control group average values, but those which received measures had slightly lower living room and bedroom humidity. Average bedroom humidity levels were higher than recommended for both groups.

Air quality: carbon monoxide

- Other than a brief unexplained high peak in one property before measures were installed, there was no issue identified with carbon monoxide levels in the homes. None of the properties averaged more than 9 ppm above which long term effects may occur. Levels were highest in those homes using gas room fires or portable gas heaters, and where the logger was placed in a kitchen. Installation of airtightness measures therefore does not appear to worsen CO levels, though sampling was at different times of year. A few properties saw short duration spikes in CO concentration above the 9 ppm level, but these were for a small number of samples, and for reasons unknown, but do not suggest a long-term issue in the property.

Air quality: carbon dioxide

- All 4 properties monitored for CO_2 had average levels within the typical range for indoor air. Whilst all experienced levels between 1000-2000 ppm, which may result in drowsiness, only homes T-09 and T-01 saw samples above 2000 ppm which may result in headaches, poor concentration etc. For T-09 this occurred in the evenings, but for T-01 day and evening levels were pretty consistent, which may mean improved ventilation is required overall.

Electricity usage

- Monitoring of electricity usage using current clamps showed households' usage profile throughout the 24hr period. Despite being on an Economy 7 tariff, many households used a significant portion of their energy during the day – this is because they were on historical tariffs (no longer available) which offer some off-peak hours during the daytime.

Thermal Imaging

- Thermal imaging showed that draughts from windows, doors and loft hatches were eliminated or much reduced in phase 2 properties after treatment, though some small issues remained. In phase 1 properties, some issues did remain as points of heat loss, particularly areas which could not be treated / insulated without major works, either beyond the scope of this project, or which would cause too much disruption to the household to be carried out during the project.

Airtightness test results

- Airtightness measurements were not carried out after install of the measures in phase-1 homes. The small more modern bungalows already had relatively good airtightness, whereas T-09, the upper floor maisonette, and T-05, an old stone terraced house, were the leakiest. For the sample of phase-2 homes tested, the modern homes had relatively good airtightness prior to the works, with older properties being draughtier. All properties saw reductions in air permeability following treatment, though home T-65 did improve as much since it did not have much work done.

Customer care & other issues

- Householders were very satisfied with the installation of the measures, particularly phase 2, giving the installers good reviews, saying how quick and unobtrusive they were. A few had reliability issues: the only property receiving heat recovery ventilation feeling it was not effective, even after the installer returned to check it. One household said sealant on the loft hatch peeled off but hadn't reported this so it had not been replaced. Another said their windows and doors still needed regular tightening / maintenance after treatment as the wind made them loosen or "drop", and salt caused metal parts to corrode – this is likely to be the case for all residents in this highly exposed area.
- There was little change in project participants' concerns or actions around (saving) energy, but overall, residents agreed that they understood more about how they could save energy from taking part in the project.

Conclusions and recommendations

- Airtightness measures are quite quick and easy to install, and reduce uncontrolled ventilation so improving comfort and feelings of warmth, plus other benefits such as noise reduction.
- Despite some residents feeling that they had not saved money due to the measures, most phase-1 households had made a saving when data was corrected for external temperature.
- This measure may reduce energy bills, but this cannot be stated with statistical significance. It would therefore be recommended to combine airtightness work with other energy efficiency improvements, as part of whole-house treatment to address all issues, to ensure other more major measures' effectiveness is not reduced by heat losses via draughts. This would result in best cost-effectiveness, greatest resident comfort and biggest savings on energy. A separate study is recommended to monitor the effectiveness of this approach.
- Other issues which cause heat loss remained in some monitored properties, which may reduce the savings as heat can still be lost via these other pathways: single glazed slatted windows, draughty internal doors to unheated areas of the home, uninsulated rooms in the roof, external walls or flat roofs. These more major issues requiring resolution are likely to have a greater effect on heat loss than airtightness / draught-proofing measures.

- The provision of advice to residents - at the time of any installation - on the most effective and efficient use of energy in the home is always advised, to ensure residents are on the best energy tariff for their use, and that they are claiming all benefits for which they are eligible. In this off-gas area, advice on most effective use of Economy 7 tariffs, and safe use of portable gas heaters, if used, is also recommended.

1. Project overview

1.1 Introduction

This project, delivered by Ceredigion County Council, used airtightness tests to identify sources of uncontrolled ventilation and cold spots in poor energy efficiency (SAP bands D - G) properties in a rural area of Wales, highly exposed to sea winds, often solid-walled construction, and most not served by mains gas. Results of the tests suggested airtightness measures which could be installed to reduce uncontrolled air exchange, provide energy savings and improved comfort to the residents, who would be vulnerable to fuel poverty. The first phase of 8 properties were older generally less well-insulated properties with measures installed in January – May 2017. A second phase of 11 homes (generally more modern, better-insulated) had doors, windows and loft hatches treated with QuattroSeal[1] draught-proofing, which was installed in May & June of 2017.

NEA was assessing whether small relatively inexpensive airtightness measures could be a cost-effective way of improving energy efficiency and reducing heat loss from such HTT properties, thereby improving householders comfort and health.

The properties were owner-occupied homes (phase 1) and a mixture of owner-occupied and private rented homes in phase 2. Some control properties monitored were social housing of a similar type as those which were treated.

1.2 Aims

The project had the following aims:

- Identify and install necessary measures to address airtightness issues in low energy efficiency homes in an exposed rural area of Wales of a wide variety of construction types (older solid-walled properties, holiday chalets converted to be bungalows, some detached homes and more modern homes with draughty windows & doors).
- Assess any change in residents' comfort – both reported in questionnaires, and measured using temperature and humidity monitors – as a result of the airtightness measures,
- Monitor any change in energy use for heating following airtightness measures,
- Monitor any change in air quality i.e. carbon monoxide and carbon dioxide levels in homes, to see if reducing ventilation by sealing up draughts might worsen air quality,
- Determine the effectiveness and cost-effectiveness of airtightness measures to improve energy efficiency and reduce fuel poverty in HTT properties in this area mainly not connected to mains gas - information relevant to all types of property tenure.

1.3 Context

Rural Wales has very low levels of connection to the mains gas network, and Ceredigion Council has the lowest levels with only 9,000 connections – mainly around Aberystwyth and Lampeter. 82.4% of homes are not served by mains gas. Borth is in the dark blue area to the north of Aberystwyth, shown in Figure 1.1, with very low levels of gas connection[2].

The area covered by this study to the north of Aberystwyth, mainly focussing on Borth – an area exposed to strong (south)-westerly sea winds, where the majority of homes are electrically heated

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[1] http://www.theenergysavers.co.uk/ [Accessed 07/06/2018]

[2] www.nongasmap.org.uk, The non-gas map for the UK, [accessed 24/5/2018]

(some also use oil) - is not classed as particularly deprived. However, many properties are of older construction, with solid walls, large rooms and (often single glazed) windows, and some have rooms in the roof so there is no loft space to insulate. Others are bungalows built as holiday chalets but which are now lived in year-round. Properties targeted were low SAP band D - G, so hard to keep adequately warm affordably. In 2012, 30% of households in Wales were in fuel poverty[3]. Borth suffers from 14.8-16.1% fuel poverty as modelled from 2001 UK census data[4].

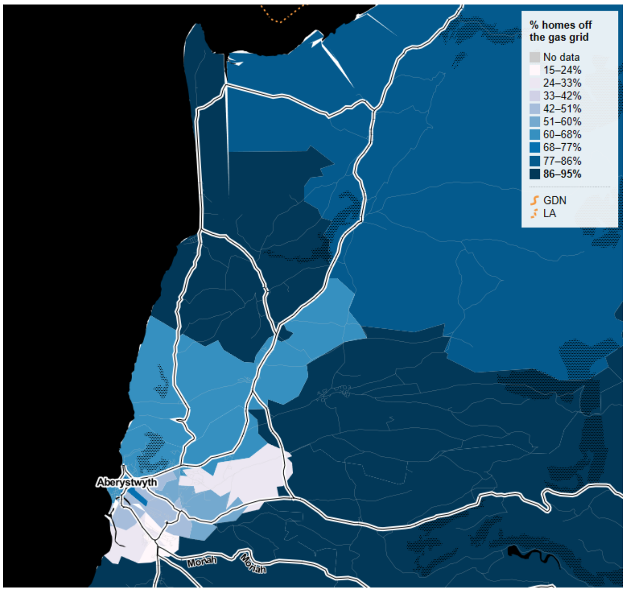

Figure 1.1 Off-gas map of the Aberystwyth & Borth areas

These properties are defined as HTT as their often solid-wall construction, and high exposure to sea winds and rain means the cheapest and most easily applied insulation methods are often unsuitable. Properties with cavity wall construction are likely to be unable to have the cavities insulated due to their level of exposure to wind-blown rain, which may cause the cavity to fail: allowing water to cross the cavity, resulting in penetrating damp and damage to the property. Of the more expensive measures, fitting internal wall insulation is disruptive, and EWI and double glazing are often not possible due to the presence of conservation areas, high exposure or (for windows) householder preference for traditional frames. As 70% of homes in Wales are owner-occupied, the Welsh Government funds the Warm Homes Programme including Nest to provide energy efficiency advice and measures to qualifying private owners or occupiers of energy inefficient properties. Ceredigion County Council also runs an ECO-Flex scheme to fully or partly fund the fitting of energy efficiency measures by qualifying private-sector households.

Buildings require a certain level of ventilation i.e. supply of fresh air, to maintain the health and comfort of the occupants. However, uncontrolled ventilation, known as air infiltration or leakage, can occur due to permeability of the building fabric, via gaps and cracks. This may lead to resident discomfort and a significant reduction in energy efficiency. According to an Energy Saving Trust study, ventilation heat losses can contribute up to 20% of total heat losses observed in existing buildings[5]. On average, 15% of heat loss is via draughts in an untreated property, so reducing the air leakage rate (i.e. improving air 'tightness') may help reduce heat loss hence decrease space heating requirements where other insulation measures are not physically or financially possible.

Installation of airtightness measures is not currently funded under any UK or Welsh Government programmes, mainly due to lack of academic study in the area and its low cost. Information from this project will support whether there is a need to include airtightness measures in future funding streams as a cost effective alternative measure to support households in fuel poverty. This would apply to homes across the UK, particularly those in exposed, rural off-gas areas with HTT homes.

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[3] Percentage of households living in fuel poverty (OU069), Welsh Government gov.wales/about/programmeforgov/data?code=OU069&lang=en

[4] gov.wales/docs/desh/policy/090129fuelmapceredigionen.pdf, Ceredigion fuel poverty map 2008, [accessed 23/5/2018]

[5] Energy Saving Trust (EST), *Good Practise Guide 268* - Energy Efficient Ventilation in Dwellings - *A Guide for Specifiers.* 2006 www.envirovent.com/images/uploads/files/GPG268-Energy-efficient-ventilation-in-dwellings(1).pdf

1.4 Project timeline

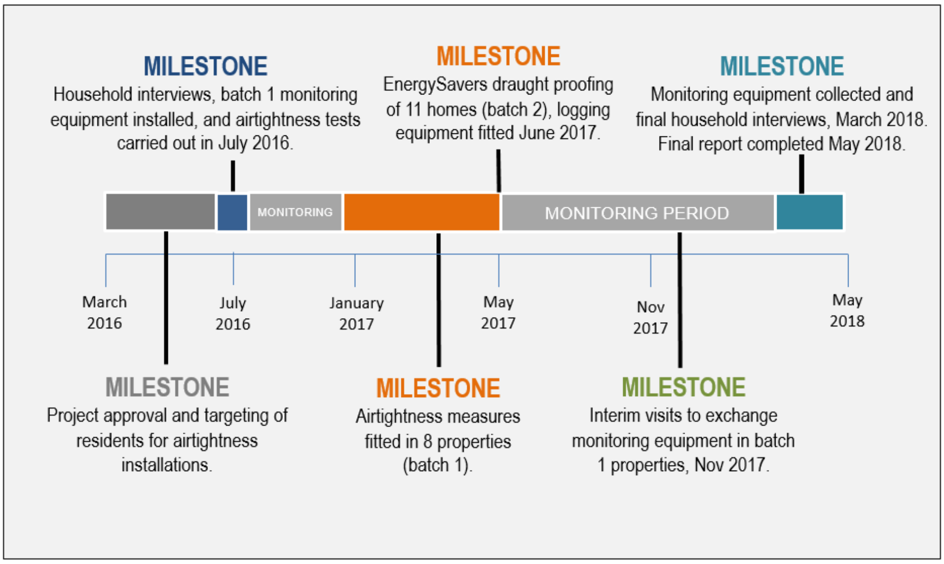


Figure 1.2 Project timeline

This project was agreed in March 2016, after which Ceredigion Council recruited participants for the study. Monitoring equipment was fitted, initial questionnaires and airtightness tests were carried out in the first phase of properties in July 2016.

Installation at each property took a different period of time depending on works required – where only sealant was applied this took only a few hours so work was completed within a day, where others may have taken a few days. Installations were carried out between January and May 2017. 8 households were treated and monitored in phase 1. However, one of these properties withdrew from monitoring in November leaving only 7 phase 1 properties monitored over the winter 2017-18.

For properties treated in phase 2, the draught-proofing installation works took only a few hours, and for each property this was completed over a period of 2-3 consecutive days in May-June 2017 (doors and windows could not be opened while the product cured, so not all could be treated on the same day to allow the home to be accessed). As these properties were not identified in time for prior monitoring to take place, a control group was required to compare against, whose monitoring equipment was fitted at the same time as for the treated properties in phase 2.

As batteries in monitoring equipment would expire, properties in phase 1 were visited in November 2017 to exchange data loggers and carry out a brief interim questionnaire. Monitoring continued until March 2018, when loggers were collected and final questionnaires were completed in all participating properties. This timeline is summarized in Figure 1.2.

1.5 Attracting beneficiaries and establishing a monitored group

Initial engagement was done by Ceredigion Council, who invited householders referred to them by Ymlaen Ceredigion - an organisation which provides energy saving advice to residents of electrically heated homes – to take part in this study. The study targeted a mix of coastal and rural towns and villages in properties with the lowest EPC ratings (D - G). 8 properties were selected for treatment in the initial phase, one upper-floor flat / maisonette, 3 bungalows and 4 larger houses. Only one of the larger homes had gas central-heating, the others were heated by electric storage heaters, and/or or on-peak electric heaters. These properties had monitoring equipment placed on 5th July 2016, and their airtightness measures were installed from January – May 2017. The properties were visited in November 2017 to exchange their data loggers (as their batteries would otherwise expire) and carry out an interim questionnaire. One property (the flat) withdrew from the monitoring at this point so their loggers were collected and a final questionnaire was carried out.

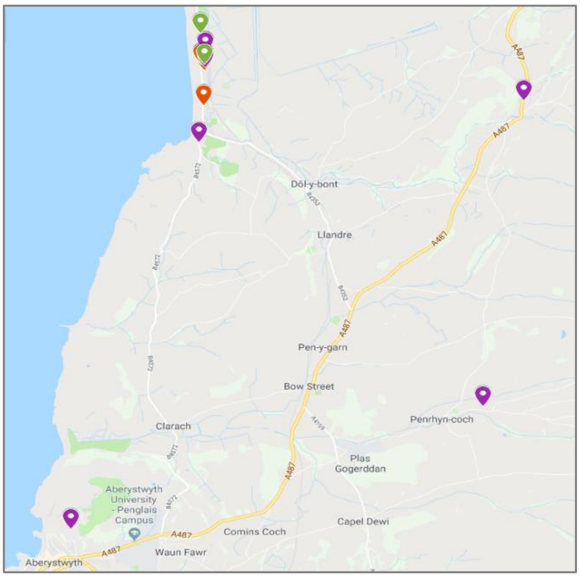


Figure 1.3 – Map of participants, mainly in Borth (top left), but also properties in Aberystwyth, Penrhyn-coch and Talybont (purple markers = phase 1, orange markers = phase 2, green markers = control properties)

A further 11 modern properties which were slightly more energy efficient (SAP ratings D - F) but suffered from draughts due to sea winds forcing their relatively new window and door frames inwards (causing gaps to develop along with associated air leakage), were treated with QuattroSeal draught proofing product on windows, doors and loft hatches as necessary. These homes were treated in May & June 2017, and monitoring equipment was installed in June 2017, when airtightness tests were also carried out. A control group was recruited, of 4 similar homes (which did not receive measures), for comparison, and in which monitoring equipment was fitted at the same time. A map of participant locations is shown in Figure 1.3.

Details of all the properties monitored are shown in Table 1.4, and example photographs of property types treated are shown in Figure 1.4. EPCs were not available for all properties as they had been owned or rented long-term since before EPCs were required, so indicative SAP values from nearby similar properties are shown. The SAP values of the properties treated in phase 1 varied from 16 (G) to 65 (D), phase 2 from 29 (F) to 66 (D), and those of the control properties

Tech ref.	House type	Storeys	Bed-rooms	SAP rating	Heating system	Wall type	Replace Window	Secondary Glazing	Repair Window	Replace Door	Door Repair	Floor Seal & Insulate	Replace Extractor Fans (Self Closing)	General Sealing (Mastic)	Service Pipe Holes Sealed	Small Scale Insulation	Loft Hatch Repair	Loft Hatch Seal	Energy Savers Door Seals	Energy Savers Window seals
T-01	Semi-detached bungalow	1	2	52 (E)	Elec storage	Cavity					✓			✓	✓	✓				
T-06	Semi-detached bungalow	1	2	46 (E)	Elec storage	Cavity	✓		✓	✓			✓	✓						
T-04	Mid-terrace bungalow	1	2	57 (D)	Elec storage	Cavity								✓	✓	✓				
T-03	End-terrace house	3	4	16 (G)	Elec storage	Solid			✓					✓						
T-07	Detached house	2	4	22 (F)	Elec storage	Cavity								✓			✓			
T-02	Detached house	2	4	65 (D)	Gas CH	Cavity						✓		✓						
T-05	Mid-terrace house	3	3	29 (F)	Elec heaters	Solid		✓									✓	✓		
T-09	Mid-terrace maisonnette	2	3	39 (E)	Elec storage	Solid			✓					✓	✓					
T-82	End-terrace house	2	3	63 (D)#	Elec storage	Cavity												✓	✓	✓
T-55	Mid-terrace house	2	3	66 (D)#	Elec storage	Cavity												✓	✓	✓
T-56	Mid-terrace house	2	3	66 (D)#	Elec storage	Cavity												✓	✓	✓
T-71	Mid-terrace house	2	3	40 (E)	Elec storage~	Cavity												✓	✓	✓
T-51	End-terrace house	2	3	40 (E)#	Elec storage	Cavity													✓	✓
T-65	Semi-detached house	4	4	41 (E)#	Oil CH	Solid								✓					✓	
T-58	Detached house	2	5	29 (F)	ASHP	Solid													✓	✓
C-59	Semi-detached house	2	2	68 (D)	Elec storage*	Cavity														
C-80	Semi-detached house	2	3	64 (D)	Elec storage	Cavity														
C-73	Mid-terrace house	2	2	69 (C)	Elec storage	Cavity														
C-54	Mid-terrace house	3	7	41 (E)#	Oil CH	Solid														
	# based on nearby similar property			* = but elec on-peak heaters used				~ = but Calor gas heater used												

varied from 41 (E) and 69 (C).

Table 1.4 – Type and size details of monitored properties

In order to maintain anonymity for study participants, all properties are reported using allocated Technical reference numbers, as shown in Table 1.4.

Examples of the technologies tested – as detailed in Table 1.4 - are shown in Figure 1.5

Figure 1.5 – Examples of airtightness measures installed: sealing around pipe inlets, under window-sills, secondary glazing, and EnergySaver window and door sealant

All properties were monitored for temperature and humidity, in various rooms of the property (usually the living room, hall and main bedroom), and a sample of phase 1 homes were also analysed for carbon monoxide and carbon dioxide levels in the first year (all phase 1 properties were monitored for carbon monoxide in the second year). A current clamp was installed to record electricity use – this was normally on the main electrical cable, or where this was not possible, it was attempted to locate the off-peak heating circuit to monitor. In the second year, phase 1 properties had 2 current clamps installed, one on the peak and one on the off-peak circuit, to further break down usage. Residents were asked to record their electricity (and gas where relevant) meter readings every 2 weeks for the duration of the study, and if possible to provide bills detailing previous consumption. Details were also requested for any other fuels used such as oil, bottled gas, and solid fuels. Initial questionnaires were carried out with residents at the time that monitoring equipment was installed, to gather information on the household occupancy, energy using behaviours and costs, and satisfaction with the heating and insulation.

Monitoring continued until March 2018 when all equipment was collected, and a final questionnaire was carried out to gauge resident satisfaction with their heating and insulation after they had experienced a whole winter with the airtightness measures fitted.

Examples of properties treated in this study are shown in Figure 1.6, and exposure levels of Borth properties to south-westerly sea winds and rain is suggested in photos on the cover of this report.

Figure 1.6 – Types of properties treated: (a) phase 1 properties (b) phase 2 properties (c) control properties

a) bungalows, solid-walled stone terraced properties (and flats within),

more modern but exposed detached homes

b) Modern but exposed sea-front homes

c) Similar modern homes, some had solar PV panels

Home-type part of both phase 2 of installation and control group: Close behind seafront houses.

1.6 Factors affecting the planned evaluation methodology

Issue	Description and mitigation
Staffing and Time Management	Ceredigion Council's contact responsible for project delivery worked only 3 days per week and supported this project alongside another TIF project (CP754) and other work commitments. At certain times delivery was compromised: timeframes for installation of phase 1 measures slipped
Identification of properties for install	It was difficult to recruit participants for the study. Identifying a sufficient sample to treat took longer than expected.
Airtightness testing and installation of measures	Ceredigion Council found it difficult to employ suitable airtightness testers and contractors via their procurement framework as intended, leading to significant delays in delivery. Phase 1 installation was meant to be complete by February 2017 but did not begin until January 2017, and was not completed until May 2017. There were issues with the length of time taken and quality of installation by the contractor in phase 1, factors which contributed to the extension of the monitoring of this project until Spring 2018. Hence for phase 2, Ceredigion County Council employed a company specialising in installation of their own airtightness measures, based in Scotland.
Size of monitoring group	All 8 phase-1 properties took part in monitoring over winter 2016-17, but one withdrew in Nov 2017, leaving only 7 properties monitored over winter 2017-18. 8 of the 11 phase-2 properties were monitored, but residents of one property moved in October 2017 (before the winter heating period) so only 7 phase-2 homes were analysed. 4 similar control properties were also monitored for comparison. All 15 monitored properties and 4 control properties, are assessed for their questionnaire responses.
Start of monitoring	Monitoring equipment was placed in the initial 8 properties in July 2016. Due to delays in installs, monitoring was for almost the whole winter prior to installation of the measures, so requiring extension of the project to monitor properties for a full winter after install. Phase 2 monitoring started for both monitored and control group householders in June 2017.
Meter readings	Meter readings were obtained for all properties from energy log books, bills or energy company records for the period prior to and after install, including for the phase 2 properties which did not have monitoring equipment fitted during the winter before their measures were installed. However, less detailed information was available for use of other fuels such as oil, bottled gas and solid fuels as these are often purchased long before their use, and recollections may be erroneous.
Failure of monitoring equipment	A small number of data loggers did not record data for unknown reasons. One logger's battery corroded / leaked (possibly due to salty damp sea air) and damaged the logger so that any data recorded was unreadable. These are noted in the relevant sections of the data analysis.
Other factors	This sample contains very different property types, which were treated with different measures as necessary for the issues present in that home. This must be taken into account when analysing both impacts on bills, and questionnaire feedback about the measures.

Table 1.6 - Issues experienced which may affect the monitoring and evaluation of this project

2. Social evaluation and impacts

2.1 Qualitative feedback from initial questionnaire

The 15 monitored householders were interviewed at the start of the monitoring period – for 8 of these this was in July 2016 (phase 1), 7 more were interviewed in June 2017 shortly after their draught-proofing measures had been fitted (phase 2) and residents of the 4 control properties were interviewed at the same time. 6 phase 1 households completed a short interim questionnaire in the November 2017 (after the measures had been installed), when the household which withdrew completed a final questionnaire. Residents of all 14 monitored households and 4 control properties were interviewed at the end of the project in March 2018. These questionnaires aimed to identify key aspects of the property's type, occupancy and resident behaviour which may affect energy use at the outset; and identify any changes, benefits and other effects at the end of the project. This section sets out the results of the questionnaires regarding residents' views, acceptance of the measures etc. and any immediate findings.

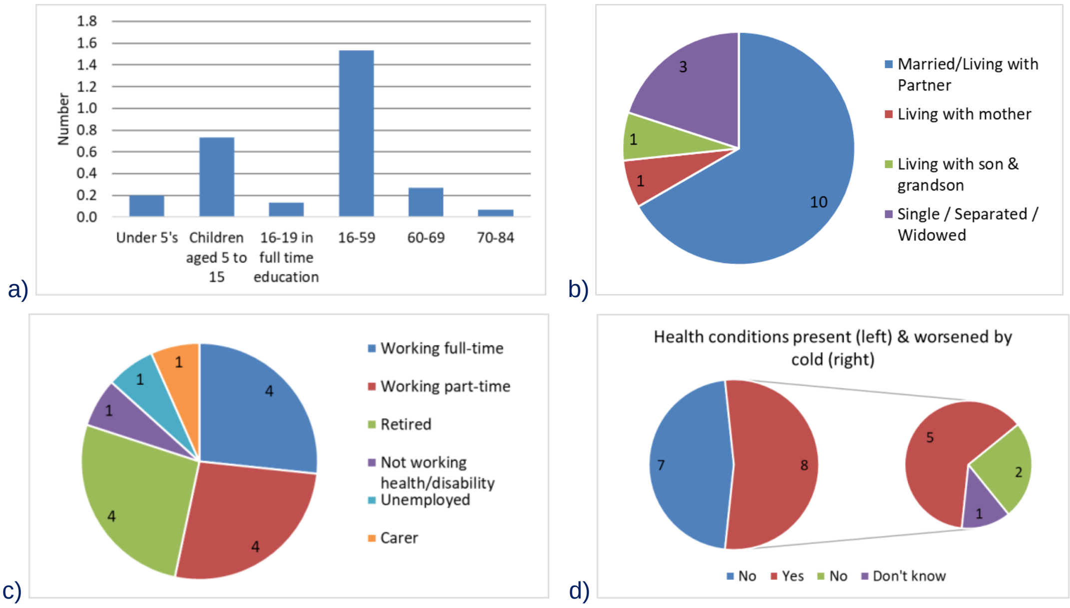
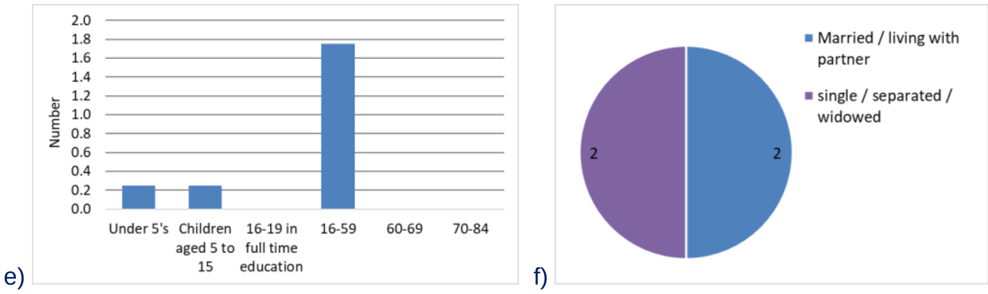
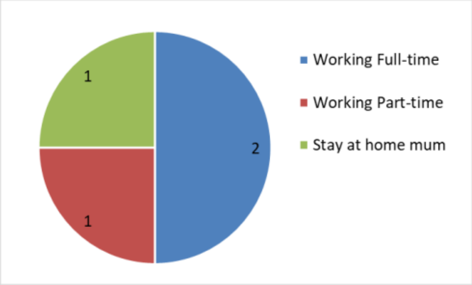
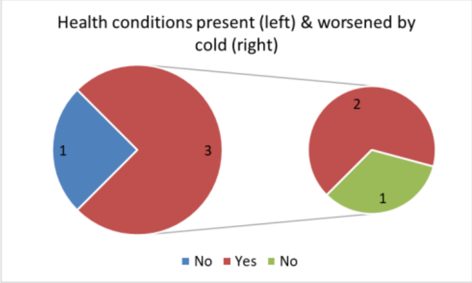


Figure 2.1 (a) Household age distribution, (b) How the bills are managed / paid, (c) Occupation, (d) Health conditions, for households receiving measures (both phases 1 and 2) above, and (e-h) the same charts for the control group below.





g)



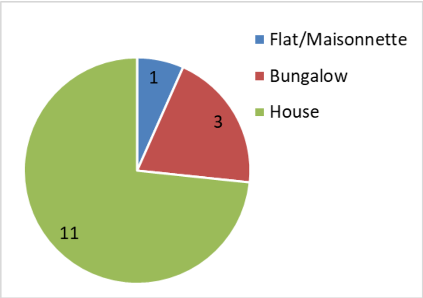
h)

Figure 2.1(a) shows that there was a wide distribution of resident ages in the monitored properties – the majority were of working age, but there were a significant number of children (though mainly older than 5), and also older people. Whether householders are able to share responsibility for energy bills can be a useful guide to vulnerability to high energy costs. Figure 2.1(b) shows that residents in 12 of the 15 households were able to share responsibility for energy bills with another household member – only 3 of the householders were the sole adult in the home. 4 of the 15 households reported that the main bill payer was working full-time, Fig 2.1(c), 4 working part-time, 4 were retired and 3 were not working for various reasons including their own health issues, unemployment, or being a carer for another household member, which may indicate a more limited income. Figure 2.1(d) shows that 8 of the 15 households contained at least one resident with health issues, 5 of which were reported to be made worse by living in a cold home (so for best health they needed to keep the home warm). One did not know, but given illnesses present were circulatory, keeping their home warm would be advised. Health issues present included arthritis, COPD, asthma, sleep apnoea, allergic reactions, diabetes, depression, heart condition (fibrillation), high blood pressure, cancer, osteoporosis, nerve injuries and, fibromyalgia.

In comparison, the control group contained mainly younger residents with working-age adults and a lower proportion of children. 2 shared the bills and 2 were the sole bill-paying adult. 2 of the control group worked full-time, one worked part-time and one was a stay-at-home mum, suggesting a limited income. 3 of the control households contained people with health issues, 2 of which were worsened if the home was cold. This implies that the groups which received measures contain more groups which are likely to be in the home for longer periods during the day, so may require more heating. The proportion who manage their household bills alone is higher in the control group, so they may be more vulnerable to energy price shocks.

The type of property is listed in Table 1.4 (page 15) which shows there was large variation in the type, size and format of the homes treated varying between 1-3 storey (most, 9 of the 15 treated, were 2 storey). These are displayed in Figure 2.2 below. In comparison, all of the control properties were houses, 3 of the 4 were 2-storey homes, and one was 3-storey; two were 2-bed, one had 3 and one had 7 bedrooms; and 2 were semi-detached while 2 were mid-terrace.

a)



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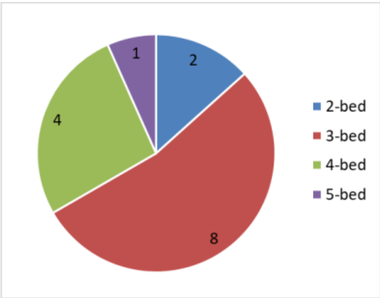

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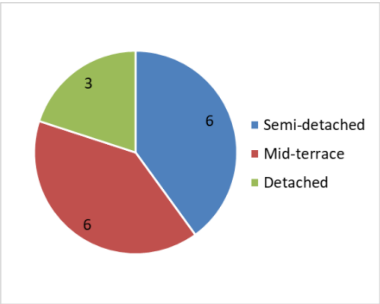


Figure 2.2 Energy using appliances present in (a) group receiving measures (b) control group properties

11 homes which received measures were heated by electric storage heaters, see Figure 2.3, and 4

used other methods: on-peak electric heaters, air-source heat pump, oil or gas central heating. One storage heated property preferred to use only a Calor gas heater instead. 3 of the 4 control group had storage heaters and one had oil central heating – but one with storage heaters reported that they did not use them, preferring to use plug-in on-peak electric heaters.

Unsurprisingly, hot water heating methods were similar, as shown in Figure 2.4. One electric storage-heated property had a mini immersion tank (as no bath present), and the home using on-peak electric heaters had immersion tank(s) for hot water.

Figure 2.3 Heating installed in (a) group receiving measures, (b) control group

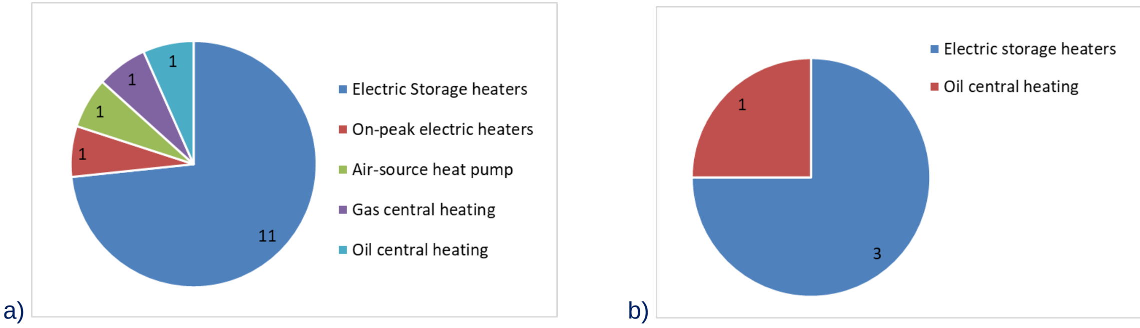
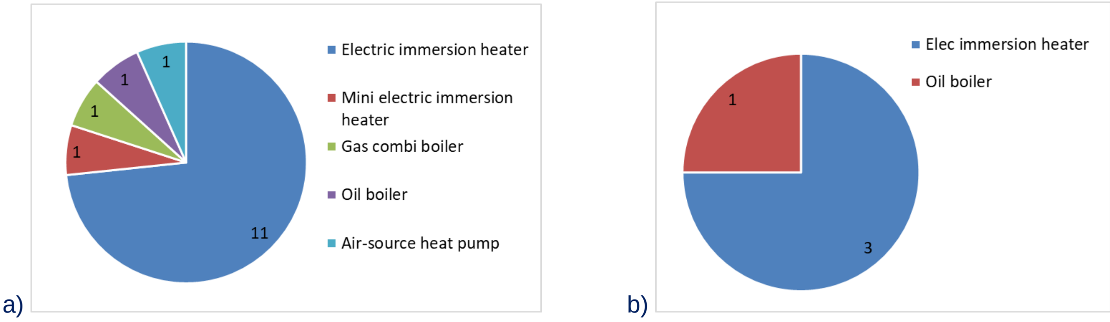


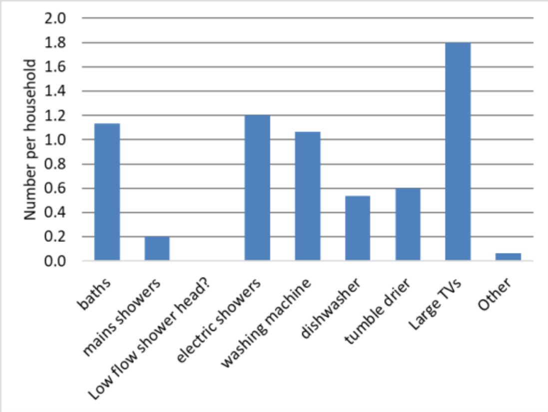
Figure 2.4 Hot water heating installed in (a) group receiving measures, (b) control group



6 of the properties which received measures reported also using supplementary heating daily, 3 said they used it seasonally, and 2 further reported using it occasionally: these included Calor / bottled gas heaters, or gas (mains / bottled) room fires, two households had multi-fuel stoves which they used to top up the main heating in the evenings, and various types of electric fan, bar or oil-filled heaters were used. Two properties used only supplementary electric heating, one having no other heating fitted, another had electric storage heaters but preferred to use a Calor gas room heater. In other properties, supplementary heating was used in parts of the home where no storage heaters were fitted (e.g. bedrooms), or to top up heat in the evenings. In the control properties, one household had electric storage heaters fitted, but used only electric supplementary heating, while another used a Calor gas heater to warm rooms which did not have storage heaters.

13 of the 15 properties receiving measures were double-glazed, one had a mixture of double and single glazing, while another was fully single glazed. All control properties were double glazed.

Figure 2.5 Energy using appliances present in (a) group receiving measures (b) control group properties a)



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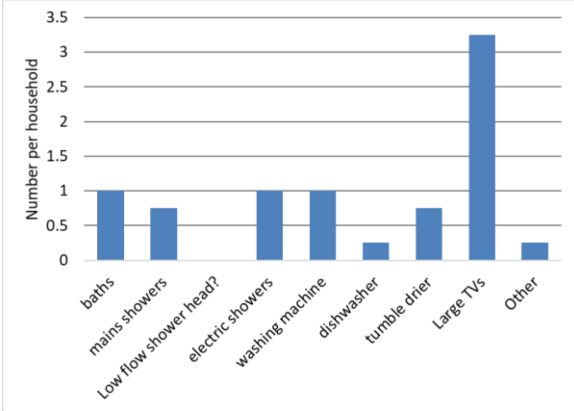


Energy-using appliances present in the households are shown in Figure 2.5 – on average, all had a washing machine fitted, and a bath and shower, either mains and/or electric. 9 of the 15 treated homes had a tumble drier and 8 had a dishwasher. For the control group, only 1 of the 4 had a dishwasher while 3 had a tumble drier. The most frequent appliances were large TVs, with an average of 1.8 per property receiving measures, but 3 per property in the control group. Other high energy-using appliances reported were dehumidifiers and a large fridge-freezer.

Most properties did not know their normal room temperatures as a thermostat was only present in 2 of the treated properties, however 7 households thought they normally heated their living room to 16-18°C, 5 said they heated it to 18-21°C range, while the remaining 3 did not know their room temperature. All those in the control properties reported their normal living room temperature as 18-21°C, but again, only one of these properties had a thermostat fitted.

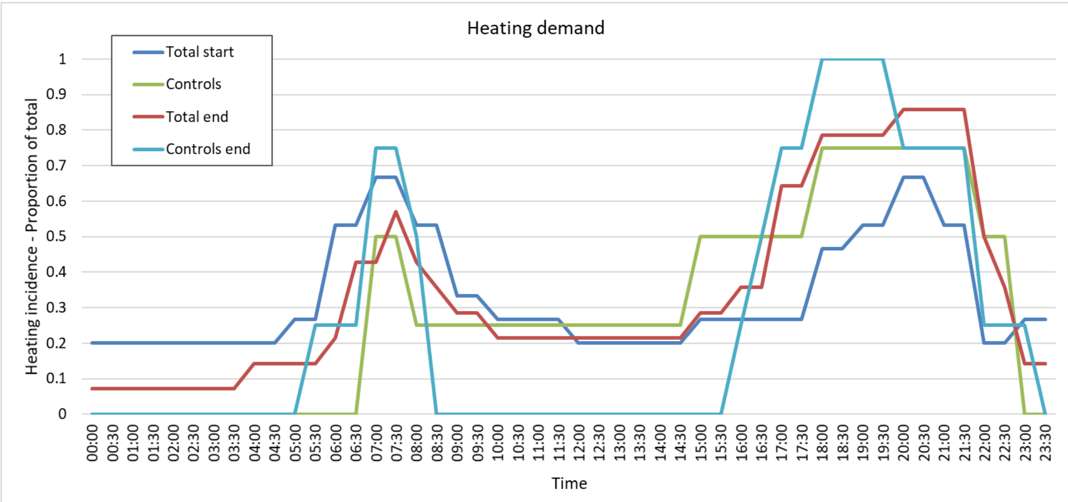


Figure 2.6 Times when residents stated it was important for them to have a warm home

Householders were asked what time(s) of day it was important for them to have a warm home, at both the start and end of the project. The resulting heating demand profile, Figure 2.6, divided into half hour blocks over a 24hr time period, was used in the technical monitoring to assess whether homes achieved warm and safe temperatures during the peak desire time period(s), in this case 6-10pm was when all group desire line peaks overlapped. The “Total” line represents the sum of all phase 1 and phase 2 properties which received airtightness measures.

2.2 Affordability of energy bills

In each questionnaire, residents were asked to estimate how much they paid for energy bills, and at what interval. This was used to estimate an annual total. Although this method is known to be inaccurate (due to incorrect recollection, rounding, accounts in debt / credit, delays in energy companies amending direct debit payments) it is useful as a measure of residents' perception of their heating costs. Not all residents knew their bill payments, and some properties heated by other means e.g. oil, bottled gas or solid fuel, only reported on their regular electricity payments, not their other fuel costs. Initially, householders in 12 of the 15 treated homes reported their payments, which averaged £1,223 per year, or £1,303 if the oil-heated property which did not report their oil costs is excluded. This varied between a minimum of £336 (the oil-heated property) or £720 (ASHP heated home) and a maximum of £2,080, with a median of £1,102. For the control properties, the average was £1,220 per year, but the median was £990 indicating that most spent less (minimum £800 per year) with the average skewed up by one large property spending £2,100 per year on oil and electricity.

Only phase-1 households completed the interim questionnaire - phase 2 households and controls were not visited - so it is not useful to make comparisons. At the end of the study, energy payments reported averaged £1,299 per year (including costs of as many different fuels used as possible), varying between £540 - £2,190. In comparison, control properties' heating costs were reported as £1,157 per year on average – again skewed by one high user, as the median was £955 per year, with a minimum of £820 and maximum of £1,900. This suggests very little change in energy cost during the period of the study for both groups. Energy price rises occurred during the study period which will confound estimates, and winter 2017-18 was particularly cold, so more heating was required, which may explain any increase – efforts were also made to ask about all fuel types used at the final visit, which may also mean these are taken into account for the first time. Some homes had known reasons for increases in costs e.g. ill health so residents felt the cold or were at home more, a new baby, or oil boiler breakdown meaning the electric immersion heater was used.

We also asked residents for their perception of whether their energy bills had reduced or not. At the interim questionnaire (November 2017), all phase 1 households questioned felt that their bills were about the same as previously. However, as shown in Figure 2.7 (a), by the end of the study (March 2018), of the 15 respondents, 4 felt that their bills were cheaper, though the remainder felt they had not changed, and one did not know due to billing issues. One did comment that their bills may have gone up slightly because it had been so cold, and another stated that he now got the benefit of more heat / comfort for the same money and felt it was worth heating more areas of the home.

Figure 2.7 Effect of measures on (a) heating bills (b) money worries at interim visit, (c) at end of monitoring period.

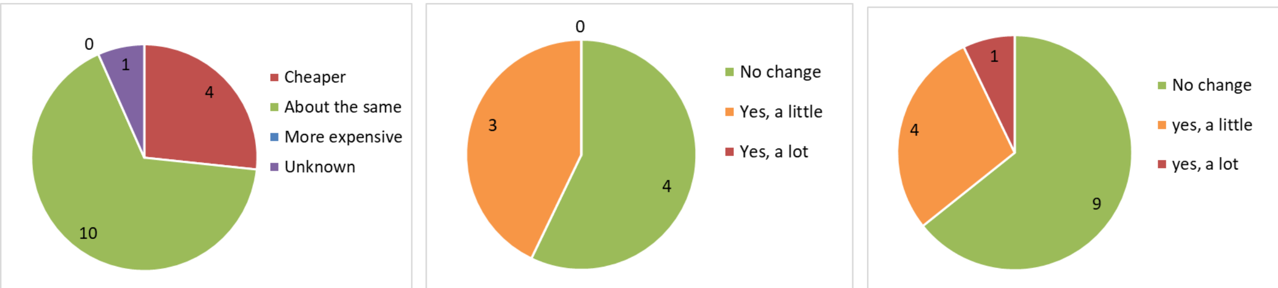


Figure 2.7 (b) and (c) shows residents' views on whether the measures had reduced any money worries they had. At the interim visit, 3 of the 7 phase-1 respondents questioned reported that the airtightness measures had reduced their money worries a little, and at the end of the study, 4 of the 15 respondents felt the measures had reduced their worries a little, and 1 felt it had reduced their money worries a lot. However, the majority felt that there had been little noticeable financial impact.

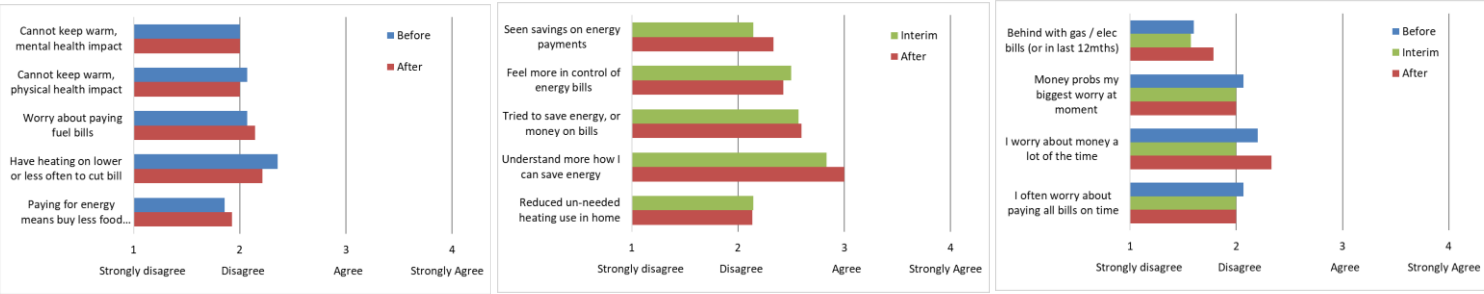


Figure 2.8 Impact of the study on (a) energy affordability concerns, (b) energy saving issues, (c) general money worries.

a) b) c)

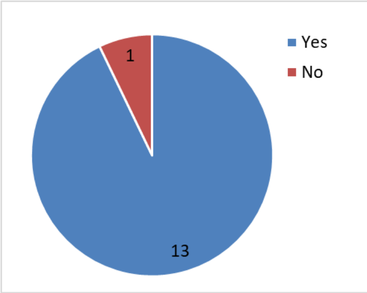
Respondents were asked how much they agreed or disagreed with a series of statements relating to energy affordability issues, feelings of control over energy bills, and money concerns in general. Responses were allocated a score of 1 for strongly disagree, 2 for disagree, 3 for agree and 4 for strongly agree. Responses were averaged across all respondents for each questionnaire period so any change in opinions over time can be seen – results are displayed in Figure 2.8. Statements in (a) and (c) were negatively phrased, so a lower score is better in fuel poverty terms, whereas in (b) the statements were positively phrased, so a higher score shows better feelings of control.

All these charts show that concerns and actions to reduce energy bills have changed little between the start and end of the study period. If anything, a slight increase was seen in agreement that residents were behind with their energy bills, or had been recently. This was a small change so may not be significant. The greatest concerns were with residents worrying about money a lot of the time, though most residents still disagreed with the statement. There was also agreement that householders knew more about how they can save energy. 8 residents said that they had received energy saving advice as part of the project, but only 4 had already taken action to make changes as a result of that advice.

There was little change in respondents' views on the influence of the measures or their behaviour over their energy bills, Fig 2.8 (b), between the interim and end questionnaires – variations are likely to be due to a smaller number of phase 1 householders only questioned. Lowest agreement was seen with the suggestion that paying for energy meant buying less of other essentials such as food - Fig 2.8 (a), and that residents were behind with their energy bills Fig 2.8 (c), showing that most householders prioritised paying for these as a priority over other purchases.

2.3 Perceived comfort and benefits

In the initial questionnaire, participants were asked about their comfort with their existing heating & insulation arrangements, before installation of the airtightness measures. The same questions were asked as part of the final questionnaire to see whether there had been any improvement. A relatively high proportion, 10 of the 15 householders, felt they could mostly keep comfortably warm enough at home before draught-proofing, and after install this increased only slightly to 11 of the 15. The measures alone have not resulted in a major improvement where there are other issues.

a) 

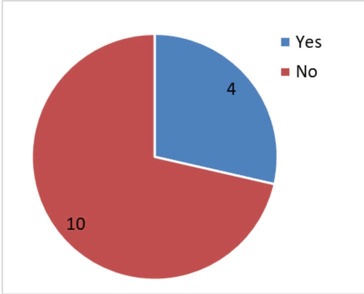
b) 

Figure 2.9 Householders reporting that they needed to wear extra-warm clothes in the home to keep warm enough (a) before, and (b) after installation of the airtightness measures

Respondents were asked about whether they ever needed to wear extra warm clothes in the home e.g. blankets, dressing gown, coat or multiple jumpers over clothes, in order to keep warm, with responses shown in Figure 2.9. This showed a significant change, with only one householder of 14 who responded to the question reporting that they did not need to wear warm clothes in the house. By end of the study period, only 4 householders now reported that they needed to wear warm clothes in the house to keep warm.

Residents were also asked whether they felt they could heat or comfortably use more rooms since airtightness measures were fitted, at both the intermediate and end questionnaires. Only one of the 7 phase-1 householders questioned at the interim visits said they could comfortably heat / use more rooms. Of the full group at the end of the study, 4 of the 15 householders stated that they could heat or comfortably use more rooms in the property since the measures were fitted.

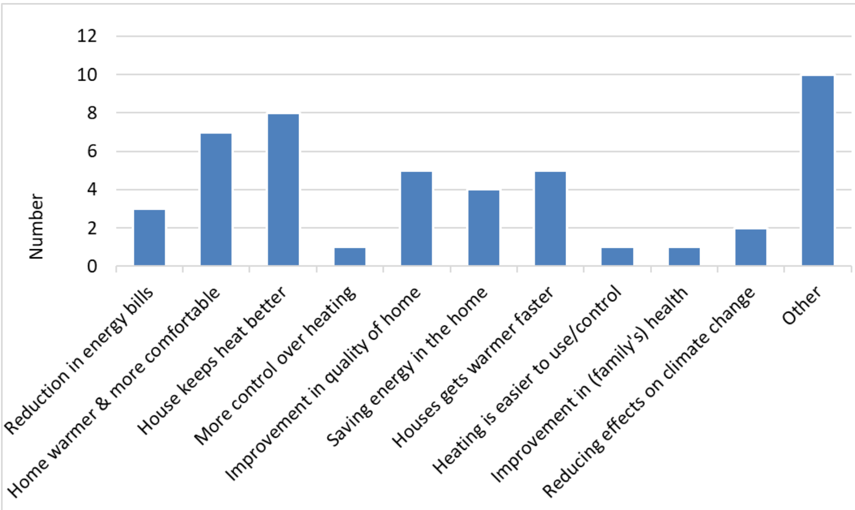


Figure 2.10 Benefits perceived by residents after installation of the draught-proofing

Figure 2.10 shows the number of householders identifying benefits as a result of the air-tightness measures fitted, at the end of the study. 8 of the 15 stated that their home kept the heat in better and 7 felt it was warmer and more comfortable. 5 reported that their home gets warmer faster, and that the measures have improved the quality of the home. 4 feel the measures are saving them energy in the home, though only 3 have seen a reduction in energy bills. 10 comments were made about other benefits, including 6 reporting reduced noise of wind, sea, nearby trains or roads, and fewer draughts, 3 reported either needing a lower storage heater setting for the same warmth, or being able to heat more rooms for the same cost, 2 mentioned needing fewer clothes & blankets to keep warm, and the ability to sit near windows to use the light without getting cold. Other benefits mentioned were reduced ingress of unpleasant smells from outside (road and farmyard smells); one resident had suffered from (allergic) rhinitis in winter but this had not recurred since the measures were fitted; another said flapping blinds due to draughty windows used to knock ornaments off window-ledges, but that this no longer happened!

Other benefits identified related to damp, condensation and mould in the home, if this was present. Householders were asked whether the measures had made any change to it, the results shown in Figure 2.11.

3 properties did not report suffering any damp issues, and 9 which did have moisture issues had seen no improvement, but 2 reported that mould problems had improved (even if not completely gone), or not recurred after the last treatment.

One resident reported that damp issues had got worse in an upstairs unheated bedroom: this is likely to be linked to a reduction in uncontrolled ventilation into the property: they were advised to open windows to air the room for an hour at the warmest time of day (and / or heat the room a little).

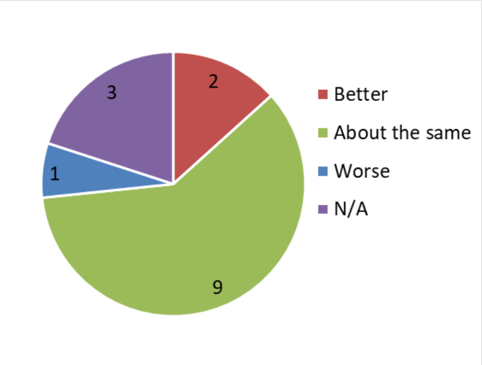


Figure 2.11 Impact of measures on damp / condensation / mould

9 households used supplementary heating daily or seasonally at the start of the study. This had not reduced by the end of the project with 12 reporting using supplementary heating: 2 using it alone, 1 for areas of the house not fitted with storage heaters, and the rest in addition to the main heating. However, 4 of these now stated that they only use the extra heating in particularly cold weather.

2.4 Resident acceptance and satisfaction

Given the nature of the measures installed, few responded to questions on ease of use as they did not "use" their airtightness measures – but the few who responded felt they understood how the measures worked and found them easy to use. The measures caused no negative issues, even for those who felt they hadn't made much / any difference to their heating costs or comfort.

Householders were asked about their satisfaction with different aspects of their home heating and insulation in the start, interim and end questionnaires. Similar to the questions where residents were asked how much they agreed or disagreed with statements, a response of very satisfied was allocated a value of 100, satisfied with 75, neither satisfied nor dissatisfied with 50, dissatisfied with 25, and very dissatisfied was valued at zero. These values were averaged across all respondents to see if overall opinions changed during the study period. Results are displayed in Figure 2.12. It should be re-emphasised that only 7 of the 8 phase-1 properties were interviewed in the interim questionnaire – whereas the before and after samples contain all 15 monitored households - so some differences may result from this being a different sample.

This shows that there was little change in satisfaction with the cost of running the system (a slight increase at the interim questionnaire but this had reduced again by the final interview): residents were overall "neither satisfied nor dissatisfied" with the cost of running their heating system. But in all other aspects, residents' satisfaction with the amount of control, ease of use of the system, how warm the home got when it was cold outside, and how well the house kept the heat in improved, from being close to "middling" prior to the installation, to being satisfied afterwards. Draught-proofing / air-tightness measures alone have not solved all the heating & insulation issues with these HTT properties, so some are still not satisfied, but the measures have improved satisfaction.

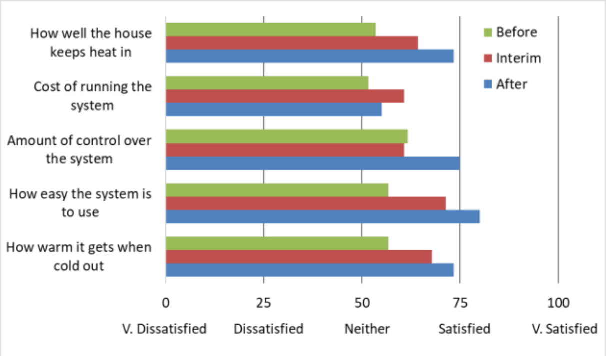


Figure 2.12 Resident satisfaction with aspects of their heating system & insulation

However, residents of 4 properties didn't feel the measures had made any significant difference, generally those that were relatively well-sealed already, and the larger properties with significant other heat-loss issues such as large areas of (un-insulated) solid external wall, and un-insulated rooms in the roof. Also, as winter 2017-18 was so cold with strong winter storms, some residents may not have perceived that the measures made a difference to their comfort or heating costs (despite our energy monitoring potentially indicating that they were not having to spend as much per degree day of heating required - see section 3.3).

5 of the 15 respondents' comments suggested they felt very positive about using their heating now they had received airtightness measures, and 5 were mildly positive. 5 who felt they had not seen a noticeable improvement were indifferent about the measures. None felt negatively about them.

2.5 Ease of use and reliability

Given that these measures were installed under windowsills, in doors and windows etc., most were not physically "used" by the residents, as the property's heating system was used as normal. One household had heat recovery ventilation fitted in their kitchen and bathroom, with a simple pull-cord or switch to turn them on and off. One of the fans was not felt to be effective – the resident stated that it could be left on for hours and the bathroom was still misty. The installer returned but the issue was never fixed to the householder's satisfaction. However, the property was over-occupied, (2 adults and 3 children in a small 2-bedroom bungalow) so the large number of residents using an internal bathroom (no window to open) would have worsened the issue. Another issue was with loft hatch sealant which in one case peeled off and could not be stuck back, but the householder had not reported this issue so it had not had the opportunity to be resolved. One resident reported that window & door mechanisms still needed regular tightening even after treatment, as the salty wind caused them to loosen and "drop", and corroded the metal parts. Another reported that it was still cold in their bay window despite the measures, however this is likely to be a case of over-expectation as windows will always be less insulating than walls.

6 of the 15 participants reported general maintenance issues in the initial questionnaire related to their heating, insulation, moisture or mould and which caused them concern with keeping warm, or increased their bills. 6 of 15 – but not necessarily the same residents - also reported such issues at the final questionnaire. These covered issues such as mould and damp issues, storage heaters not working (well), or insufficient storage heaters fitted to heat all of the property – particularly upstairs. Initially, draughty doors and windows were reported, but also lack of insulation to some areas of properties. All issues were reported to Ceredigion County Council. However, most households are owner occupiers so there is little they can do to assist in these improvements – all those which may be eligible were sent details of the ECO-Flex scheme when it became available in Ceredigion.

2.6 Customer service and installation issues

Comments about the installation process were requested and residents noted how quick, un-obtrusive and tidy the installers were. One resident said that the phase 1 installer had sometimes not kept to his appointment times, but reports on phase 2 installers were overwhelmingly positive.

Residents were asked about their satisfaction with the project communications and installation. As previously, the responses were averaged across the whole group, displayed in Figure 2.13. Householders' opinions were very good – there was some minor issue with whether residents had been kept informed about delays or changes to the project – but given the significant delays this project suffered, the responses are overwhelmingly positive. Residents were asked about support received: whether they were shown how to use the measures, if they knew how they worked etc. Most of these questions were not relevant as the measures did not require any active input.

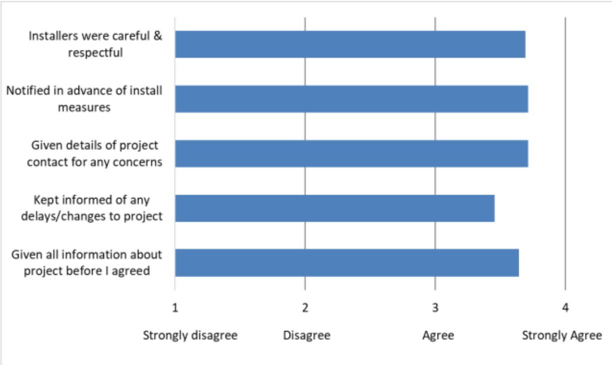


Figure 2.13 Resident satisfaction with aspects of their heating system & insulation

3. Technical evaluation and results

3.1 Overview of technology

Airtightness pressure testing was conducted in a sample of properties pre- and post-installation of draught-proofing measures, using a fan-pressurisation test. This uses a fan mounted into a temporary door to induce positive or negative pressure differences across the building envelope while measuring the air flow through the fan, see Figure 3.1. The air leakage rate in or out of the dwelling can then be calculated for a standard 50 Pa pressure difference ($m^3/h/m^2$), quoted 'air permeability'. Maximum air permeability rates are 5 $m^3/h/m^2$ for good practise, and 3 $m^3/h/m^2$ for best practise[4].

Phase 1 properties were tested for airtightness pre-installation in November 2016 and post-installation in May 2017. Airtightness testing for phase 2 occurred on 1st June 2017 before installation of the measures, then on 17th June 2017 post-installation of measures.

Figure 3.1 Airtightness testing of a property

Results of the airtightness tests identified specific airtightness and minor insulation issues which required addressing, and hence which measures were suitable in each property. This resulted in installation of the measures detailed in Table 1.4 (page 15), examples of measures installed are also shown in Figure 1.5 (page 16).

Given the wide variety of measures installed in phase 1, these were ordered by the contractor as required and further details of specific products used are not known. General mastic sealant was used for sealing draughts where required.

The Energy Savers product was Quattro Seal, a mastic sealing system that is claimed to stop draughts from all styles of window, including uPVC. Residents reported that it was used on windows, doors, loft hatches and any other identified sources of draughts on half of the property. These could not be opened for 24 hours while the product expanded to the space available and cured. The installers then tidied up any excess sealant, treated the remaining sources of draughts in the home the following day, again returning to tidy up the cured sealant on the third day.

3.2 Technological monitoring

To assess the performance of the airtightness / draught-proofing measures, the following monitoring equipment was placed in the properties, both those receiving measures and controls:

Thermal & humidity data loggers

Two or three Lascar EasyLog USB-2 loggers[6] were placed in different rooms of each monitored property, usually the living room (or main living area), hall and bedroom. These recorded temperature and humidity in the property every hour. Ideally, they were positioned in a discreet location, away from direct heat, cold or draughts. At interim visits in Nov 2017, replacement loggers were placed, set to record temperature every 20 minutes (phase 1 properties only).

One TinyTag Plus 2 external temperature logger[7] was installed under the eaves of an outbuilding at a phase-1 property, to verify against external temperatures obtained from a nearby weather station.

Carbon monoxide (CO) data loggers

One Lascar EasyLog USB-CO logger[8] was placed in the main living area of each phase 1 property from July 2016, and replaced with a new logger during the second winter. They record carbon monoxide levels in the property every 5 minutes. With only a 3-month data capacity, these monitored from July – October 2016. Replacement loggers placed in November 2017 monitored from November 2017 to March 2018. Phase 2 and control properties were not monitored for CO.

Carbon dioxide (CO_2) data loggers

Cumulate FB201 CO_2 data loggers[9] were installed in the main living area of 4 sample phase-1 properties. They logged CO_2, as well as temperature and humidity, every 10 minutes. Data from these was unable to be downloaded at interim visits so they were left in position until the final visit.

Current clamps

TinyTag View 2 current clamps[10] were placed on the main electricity cable feeding each of 5 phase 1 properties and each phase 2 property to monitor electricity consumption every 20 minutes. Where this was not possible (in some cases the main cable was wired directly into the meter) it was attempted to place the current clamp on the heating circuit of electric storage-heated properties to monitor heating energy usage. At visits to phase 1 properties in November 2017, for households with Economy 7 wiring, the TinyTag logger was replaced by two Lascar ACT current clamps[11], one on the peak and one on the off-peak cable. Where only a single rate meter was present, one Lascar ACT logger was placed on the main cable. These loggers monitor and log electrical current every 5 minutes.

Energy meter readings / usage

Residents were requested to record their electricity (and gas if present) meter readings regularly, usually every 2 weeks, during the study period, in a log book provided. A text message was sent every fortnight to householders (where they consented to this) to remind them to take a meter

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[6] Lascar EasyLog USB-2 product details: www.lascarelectronics.com/easylog-data-logger-el-usb-2, [Accessed 11/04/2018]

[7] TinyTag Plus 2 temperature logger details: https://www.geminidataloggers.com/data-loggers/tinytag-plus-2/tgp-4017 [Accessed 30/5/2018]

[8] Lascar EasyLog USB-CO product details: www.lascarelectronics.com/easylog-data-logger-el-usb-co, [Accessed 11/04/2018]

[9] Cumulate FB201 CO2 logger details: www.tradekey.com/product-free/Cumulate-Fb201-Carbon-Dioxide-co2-Indoor-Air-Quality-Monitor-With-Data-Logger-8303811.html [Accessed 30/5/2018]

[10] TinyTag View 2 Current data logger details: https://www.geminidataloggers.com/data-loggers/tinytag-view-2/tv-4804 [Accessed 30/5/2018]

[11] Lascar EasyLog USB-ACT product details https://www.lascarelectronics.com/easylog-data-logger-el-usb-act [Accessed 30/5/2018]

reading. Householders were also asked to retain energy bills or statements received from the winter prior to, and during the monitoring period. Many allowed NEA staff to phone their energy company during visits to obtain meter readings, or they signed consent forms to allow NEA to contact energy suppliers to request meter readings held on their account.

Details of other fuels used in the property were also requested – oil, bottled gas, and solid fuels, however accurate information on usage of these was harder to obtain as they are not metered in-situ and are often purchased (when receipts / invoices may be available) in advance of usage.

3.3 Cost

This analysis uses the regular meter readings recorded by householders, and others obtained from bills or energy suppliers. Meter readings from before the start of the study were used to calculate previous energy usage – these could be obtained for all householders for electricity costs, but particularly for households using other fuels, this was not always available or accurate enough to allow for a full comparison of savings. Previous usage was compared against usage for the period after the measures were installed (generally studying only the winter heating period), to see if the measures had helped the households to make savings. Questionnaire responses indicated that many households used electric or other supplementary heating in addition to (or instead of) their main heating.

For all homes, standardised Economy 7 electricity costs of 18p/kWh were used for peak / daytime usage, and 7p/kWh for night-time / off-peak usage. For the few properties using single rate electricity, a cost of 16p/kWh were used, and for the household supplied with mains gas, a cost of 5p/kWh was used for cost calculations – these are all slightly higher than common tariff rates as they include an element for standing charges etc. Cost comparisons are displayed in Table 3.3 (a) and (b) on the next page.

To properly analyse energy use for space heating, account must be taken of the weather, as it is poor practice to compare the heating costs for two periods without compensating for different outdoor temperatures during the periods – particularly as winter 2017-18 was so cold. An external temperature of 15.5°C is accepted by energy specialists as the outdoor temperature below which heating is normally required, and above which no heating is needed. Degree days (dd) are the heating requirement i.e. the number of degrees below 15.5°C that the average temperature falls, for each day. For example, if the average outside temperature is 14.5°C, this is recorded as 1 degree-day. Degree days are summed over the required period, to give a total number in the period. Different periods can then be compared for their energy consumption and the results used to predict energy consumption on a normalised basis, accounting for outside temperature in the different periods[12]. Degree day data was obtained from weather station 3503, Trawscoed, WLS, GB (3.95W,52.34N)[13] as this is relatively close to the area in which the properties are located and had good quality data for many years. 20-year average degree day values are only available on a regional basis: Wales experiences 1999.77 degree days per year on average.

For electricity costs, those households on a single-rate tariff are highlighted in pale yellow, all others have a white background. Those marked * do not use electricity as their main heating fuel, so should be excluded for the purposes of this heating costs analysis, as any costs shown will be for powering appliances (use of supplementary electric heating was not reported in these homes).

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[12] www.carbontrust.com/resources/guides/energy-efficiency/degree-days [Accessed 11/04/2018]

[13] Degree Days.net: www.degreedays.net [Accessed 01/05/2018]

a)

20 year average degree-day comparison of savings

Region: Wales | 20 year average: 1999.8

Tech Ref	"Before" period: Period	Days	Total Period (kWh)	Cost per 30 days	Degree days	kWh per Degree Day	Estimated annual cost#	"After" period: Period	Days	Total Period (kWh)	Cost per 30 days	Degree days	kWh per Degree Day	Estimated annual cost#	Comparison: Estimated Saving kWh#	Estimated Saving cost#
T-05	20/9/2016 - 3/4/2017	195	9,095.0	£223.88	1,495.90	6.080	£1,945.36	9/9/2017 - 20/3/2018	192	8,927.0	£223.18	1,539.40	5.799	£1,855.47	4.62%	4.62%
T-02*	8/11/2016 - 9/5/2017	182	1,250.0	£32.97	1,471.50	0.849	£271.80	20/10/2017 - 20/3/2018	151	1,117.0	£35.51	1,430.60	0.781	£249.82	8.09%	8.09%
T-07	25/9/2016 - 19/3/2017	175	7,698.7	£188.15	1,389.00	5.543	£1,580.12	15/10/2017 - 20/3/2018	156	8,315.8	£215.11	1,445.30	5.754	£1,547.67	-3.81%	2.05%
T-04	10/7/15-5/7/16, 13/9/16-16/1/17	486	10,574.0	£70.15	2,834.70	3.730	£801.76	16/1 - 1/5/17, 27/9/17 - 21/3/18	280	6,440.0	£62.75	2,324.40	2.771	£503.87	25.72%	37.16%
T-06	16/12/15 - 31/3/2017	461	8,944.0	£54.82	2,853.30	3.135	£590.44	12/9/2017 - 19/3/2018	188	4,996.0	£73.22	1,518.60	3.290	£604.22	-4.95%	-2.33%
T-01	16/8/2015 - 18/1/2017	521	6,321.0	£52.18	2,845.30	2.222	£636.93	18/1 - 26/4/17, 27/9/17 - 19/3/18	271	4,428.0	£53.75	2,242.60	1.974	£432.95	11.12%	32.03%
T-03	12/9/2014 - 20/2/2017	892	52,155.0	£144.41	5,261.40	9.913	£1,631.96	4/3 - 29/4/17, 4/11/17 - 27/4/18	230	19,921.0	£198.95	2,024.70	9.839	£1,506.48	0.74%	7.69%
T-09	30/7/2014 - 24/3/2017	968	23,380.0	£70.80	5,591.30	4.181	£817.04	7/4-4/5/2017, 2/8 - 22/11/2017	139	2,261.0	£52.85	558.30	4.050	£877.09	3.15%	-7.35%
Average, Phase 1 properties						4.457	£1,034.43						4.282	£947.20	5.59%	10.24%
Average, Phase 1 properties, elec heating only						4.972	£1,143.37						4.782	£1,046.82	5.23%	10.55%
T-58	30/5/2016 - 14/6/2017	380	8,510.6	£107.50	1,951.10	4.362	£1,395.66	15/9/2017 - 20/3/2018	186	9,546.7	£246.37	1,522.50	6.270	£2,006.30	-43.75%	-43.75%
T-65*	8/10/15-23/3/16, 20/9/16-28/3/17	356	1,175.0	£15.84	2,703.10	0.435	£139.08	7/9/2017 - 20/1/2018	135	1,983.0	£70.51	901.70	2.199	£703.66	-405.92%	-405.92%
T-82	11/10/16 - 1/5/17	202	9,270.0	£177.48	1,625.50	5.703	£1,470.21	26/10/17 - 30/4/18	186	8,064.0	£184.85	1,709.90	4.716	£1,340.33	17.30%	8.83%
T-55	7/2 - 24/5/17	106	2,966.0	£120.59	709.60	4.180	£1,200.76	21/10/2017 - 21/3/2018	151	6,659.5	£180.39	1,440.20	4.624	£1,260.78	-10.63%	-5.00%
T-56	12/10/15-27/4/16, 27/9/16-10/5/17	414	10,202.0	£86.67	3,154.70	3.234	£758.18	16/10/2017 - 21/3/2018	156	4,398.9	£97.03	1,457.20	3.019	£692.44	6.65%	8.67%
T-71	9/1-4/4/16, 17/11/16 - 29/4/17	249	7,947.0	£129.06	2,191.30	3.627	£977.57	27/10/2017 - 22/3/2018	146	4,012.6	£115.88	1,433.60	2.799	£786.69	22.82%	19.53%
T-51	26/10/2016 - 1/4/2017	157	5,094.0	£117.05	1,318.70	3.863	£928.91	15/10/2017 - 22/3/2018	158	6,015.8	£138.68	1,470.10	4.092	£993.52	-5.93%	-6.96%
Average, Phase 2 properties						3.629	£981.48						3.960	£1,111.96	-59.92%	-60.66%
Average, Phase 2 properties, elec heating only						4.161	£1,121.88						4.253	£1,180.01	-2.26%	-3.11%
C-80	12/10/15-4/4/16, 1/10/16-14/6/17	431	10,761.0	£73.54	3,119.00	3.450	£677.41	11/9/2017 - 22/3/2018	192	5,043.0	£74.65	1,559.00	3.235	£612.82	6.24%	9.53%
C-59	22/1 - 21/5/17, 14/9/16 - 27/4/17	345	7,932.0	£105.01	2,651.40	2.992	£910.85	19/9/2017 - 3/4/2018	186	4,812.0	£119.51	1,618.00	2.974	£915.82	0.59%	-0.55%
C-73	16/9/2016 -7/2/2017~	144	4,236.0	£79.08	1,088.30	3.892	£697.47	4/9/2017 - 19/3/2018	196	5,763.5	£74.76	1,529.90	3.767	£638.41	3.21%	8.47%
C-54*	4/10/14 - 14/6/2017	984	16,850.0	£82.20	5,832.70	2.889	£924.34	8/9/2017 - 26/4/2018	230	3,499.0	£73.02	1,804.90	1.939	£620.28	32.89%	32.89%
Average, control properties						3.306	£1,057.72						2.979	£953.06	10.73%	12.59%
Average, control properties, elec heating only						3.445	£1,102.18						3.325	£1,063.99	3.35%	5.82%
Average						3.909	984.219						3.964	975.418	-16.66%	-14.58%

single rate tariff, so these costs used in calculations * Does not use electricity as main heating fuel ~ may be from different address # 12 month estimated costs based on 20 year average degree-day value for region stated

b)

20 year average degree-day comparison of savings

Region: Wales | 20 year average: 1999.8

Tech Ref	"Before" period: Period	Days	Total Period (kWh)	Cost per 30 days	Degree days	kWh per Degree Day	Estimated annual cost#	"After" period: Period	Days	Total Period (kWh)	Cost per 30 days	Degree days	kWh per Degree Day	Estimated annual cost#	Comparison: Estimated Saving#
T-02	15/12/14-19/3/15, 15/12/15-14/6/16, 9/11/16-21/4/17	433	24,921.0	£86.33	3,558.10	7.004	£700.32	20/10/2017 - 20/3/2018	151	9,286.8	£92.25	1,430.60	6.492	£649.08	7.32%
T-65	1/3 - 21/7/2017	142	9,635.9	£87.00	593.30	16.241	£1,387.97	21/7 - 20/12/2017	152	6,955.2	£58.66	685.50	10.146	£867.09	37.53%
C-54								1/6/17 - 30/4/2018	333	24,115.5	£92.84	1,977.70	12.194	£1,042.08	

12 month estimated costs based on 20 year degree-day value for the region stated

Table 3.3 Analysis of (a) electricity and (b) gas & heating oil costs before and after air-tightness measures were fitted

Cost analysis is separated out into phase 1, phase 2 and control properties. The row coloured grey is the household which withdrew from monitoring in November 2017 – the data available from this property is analysed to see if any conclusions can be drawn.

Excluding property T-02 which does not use electricity for heating, average savings between the before and after periods for phase 1 properties were 5.23% in energy terms (kWh used) and 10.55% in cost terms (due to a change in the balance between peak and off-peak energy usage) as this figure is higher than the amount of energy units saved, it indicates that a greater proportion of peak-rate electricity is being saved than off-peak. This may suggest that for storage heated properties, the storage heaters are providing more of the heating with less requirement for top-up supplementary electric heating on peak-rate tariff during the day or evening. Property T-06, which did not make savings in either cost or kWh energy used terms, received heat-recovery ventilation which the householders reported was not effective so had to be left on for long periods. Extra electricity may have been used to power the fans, or the small increases in use seen may be the result of other changes in household energy use.

To assess the significance of these reported savings, the standard deviation (SD or σ) of the savings was calculated – this is an indication of the spread of results around the average, as displayed in Figure 3.4. Savings are significant with 68.2% certainty when σ is added to or subtracted from the mean (denoted ±σ) and the value remains greater than zero, and significant with 95.4% certainty when mean savings are greater than zero ±2σ. In social studies, it is rare to meet the 3σ requirement for a 99.6% level of significance.

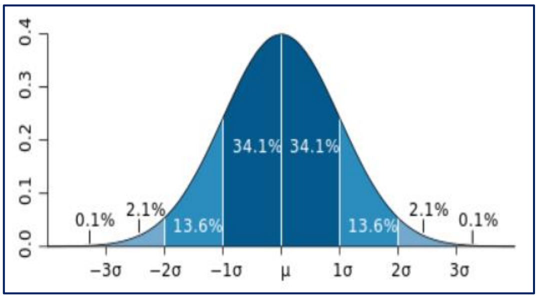


Figure 3.4 Illustration of mean (μ) and standard deviation (σ) in a normal distribution

Since there is wide variability is savings within the sample group, the standard deviation of the electricity savings if T-02 is excluded, is 10.53% in terms of kWh electricity saved, and 17.18% in terms of cost saving. As the reported average saving in energy terms of 5.23% ± 10.53% will not always be greater than zero, these savings therefore cannot be said to be significant, even to the lowest 68.2% significance level. Similarly, the average cost saving of 10.55% ± 17.18% will not always be greater than zero, so cannot be said to be significant.

For phase 2 properties, excluding property T-65 which normally used oil for heating (the oil boiler breakdown necessitated use of the electric immersion heater for hot water, hence a large increase in electricity use), average savings were -2.26% in kWh energy use, and -3.11% in cost terms, i.e. slight increases in electricity usage and costs on average for these properties. House T-51 had a new baby occupant, and T-55 reported that due to the cold weather they had to turn on the storage heater in their kitchen which was not normally used, both of which may result in an increase in electricity use even after degree-day correction. Property T-58 which has ASHP heating also saw a significant increase in electricity use and costs: it may be that over winter 2017-18 cold air temperatures caused this to work less efficiently, the settings were changed, or that the year's comparison period prior to the measures being fitted (all that can be used from meter readings available) is not comparable to the winter period after the measures were installed. We do not know the cause. However, 3 other properties made energy savings of 6.65 – 22.82% in terms of kWh used, so the draught-proofing measures may result in savings, but we cannot exclude the properties which saw increases in electricity use from analysis without known reasons to do so.

In comparison, control properties which were electrically heated made savings of 3.35% in terms of kWh electricity used, and 5.82% in cost terms between the before and after periods, even though they had no measures installed. With standard deviations of 2.83% and 5.54% respectively, these savings are even significant!

In terms of those properties which used another fuel for their main space heating, these are analysed in Figure 3.3 (b). Property T-02 was connected to mains gas, and made a 7.32% saving on energy use compared to previous winters. Calculation of oil usage is harder to do – firstly heating oil prices have varied significantly over the past 2 years, see Figure 3.5 below. A standard / average price of 50p/L was used for all calculations, and a calorific value of 10.35kWh/litre was used for kerosene 28 heating oil[14].

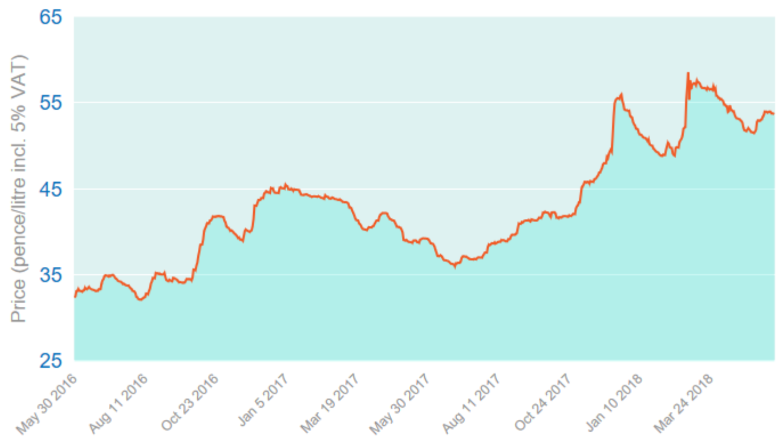


Figure 3.5 Variation in heating oil prices over the past 2 years, from BoilerJuice website[15]

Only one of the households which used heating oil, T-65, provided exact dates, costs and volumes of heating oil purchased, whereas the other, C-54, relied on recollection – which is notoriously unreliable – for the most recent winter only. The residents of property T-65 suffered a few boiler breakdowns during winter 2017-18, which may have resulted in savings on oil but necessitated increased electricity (immersion) use as previously mentioned. They then moved out of the home in Dec-Jan 2018, only visiting at weekends after this (with low heating on a timer between visits), which would have reduced oil usage compared to the previous winter, so no conclusions can be drawn from either of these properties as far as any energy savings after the airtightness measures. These households use 10.1–16.2 kWh per day for heating – higher than the other properties in the study, however these are both large 3-storey seafront houses with uninsulated roof rooms, similar-sized to property T-03 which used 9.8-9.9 kWh per day in electric storage heating, plus bottled gas.

Three properties had multi-fuel / log-burner stoves fitted. Only T-01 could estimate their solid fuel use of £6 per week, but did not think this had changed since their measures were installed. T-02 said that they needed to use the stove less often than before the measures were fitted, but could not estimate their usage as it was relatively infrequent. T-65 said their wood-burning stove felt more efficient, presumably as more heat was retained within the home.

[14] Calorific values used for comparison of domestic heating costs, Monikie https://monikie.org.uk/fuel-calorific-values.htm [Accessed 30/5/2018]

[15] BoilerJuice Average home heating oil prices: www.boilerjuice.com/heating-oil-prices [Accessed 30/5/18]

Details of the amount of bottled gas used in the properties were not requested unless it formed a major part of the heating system – property T-71 reported that they did not use the storage heaters at all, and only used their bottled gas heater when it was very cold as they did not like it warm. They had previously used a 15 kg gas bottle per winter, but in winter 2017-18 after the measures were fitted, they had only needed a 7 kg bottle. Residents of property T-03 had suffered significant health issues, and felt the cold a lot more – so had increased their bottled gas heater use, reporting using one 12 kg (approx. £30) bottle every 5 days! This was clearly not because of the airtightness measures, but the estimated cost of this was included in the social evaluation in Section 2.2. Property T-07 had only one storage heater working, and used an LPG room fire in the living room, buying 2 x £52 standard sized LPG tanks per year, which reportedly had not changed since the measures were fitted. Properties T-82 and C-73 (had) also used bottled gas heaters for some period during the monitoring, but this was more minor usage so was not recorded.

We investigated whether energy use in the properties was better controlled, in terms of being more closely related to the number of degree days of heating required, since the airtightness measures were installed. Regular meter readings were used to plot energy usage over shorter periods during the monitored winters both before and after installation of the measures and plotted against degree days in these periods. Energy usage in most properties was well-correlated with degree days of heat required, however no noticeable improvement was evident. The properties which were less well-correlated included T-06 where electricity was used to power only one working storage heater and the immersion tank, so a greater proportion was made up by appliances and supplementary electric heaters, T-01 where storage heaters were only used on low, and a multi-fuel stove was used to top up heat in the evenings, and T-56 did not correlate for unknown reasons.

3.4 Temperature and thermal comfort

Temperature and humidity loggers were placed in 2-3 locations as appropriate in the monitored properties, generally the main living room/area, the main bedroom, and the hall or landing. Data loggers were in position from July 2016 for phase 1 properties. Phase 2 properties had loggers installed in June 2017, shortly after installation of their measures, so we do not have temperature data from prior to installation of the measures. We therefore also installed data loggers in control properties for comparison. Data loggers installed over the first winter (phase 1 properties) were exchanged in November 2017. One property, T-09, withdrew from the monitoring at this interim visit, when their data loggers were collected. Data loggers were collected from all properties in March 2018. Some loggers were not functioning at certain times, for unknown reasons.

Different periods were therefore selected over which to analyse temperatures, a before and after winter period for the phase 1 properties, and only one after period over which to compare the phase 2 and control properties. The "Before" period in winter 1 covered 1/11/16 when the winter started to get cold until 14/1/17, after which the measures started to be installed in properties. This was a period of 74 days, during which 677.6 degree days of heating need were experienced, averaging 9.03 dd/day. (In comparison, the external temperature monitor located at property T-02 measured a total of 598.87 degree days – calculated by deducting the temperature measured from 15.5°C and substituting any negative values for zero – an average of 7.98 dd/day, 1.05 dd / day lower on average than the weather station data). As the last measures were not installed into properties until May, there could be no "After" period for phase 1 during the first winter – it therefore started on 23/11/17 (after all properties had their data loggers changed at interim visits) and ran until the day before one of the data loggers stopped working: 8/2/2018, a period of 77 days during which 782.7 degree days were experienced, 10.03 dd/day. (Again, for comparison, the external temperature logger recorded 723.36 degree days, an average of 9.27 dd/day, 0.76 dd/day lower than the weather station data – this indicates that the temperatures experienced were slightly milder than those recorded at the Trawscoed weather station, but are broadly in line with them. It also shows that winter 2017-18 was more severe, on average 1 degree colder each day than winter 2016-17. Table 3.6(a) & Figure 3.6(b) display temperatures recorded over these periods.

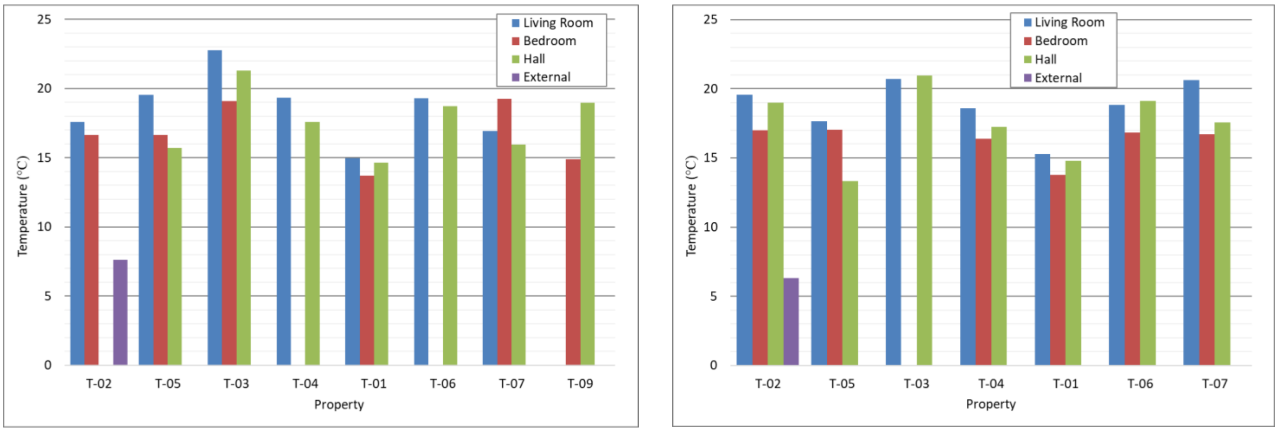
The letters after the property codes indicate the type of room in which the data logger was placed: L for a living room; K-L is a kitchen which was used as the main living area of the home; B is a bedroom; and H is a hallway. For property T-05, the kitchen was used as the main living area. For logger locations or periods where no data was available, either as no logger was installed, it malfunctioned or was lost, "-" is shown. Property T-09 withdrew from the second winter monitoring. The first two columns show average (mean) temperature: the first (orange) for the 6-10pm heating period – identified from questionnaire responses as the time at which most of the monitored households desired heating (see Figure 2.6), and the second column displays the whole 24hr period average. SD is the standard deviation, the variability of the data around the mean.

Before, winter 1							
1/11/16 - 14/01/17	Temperature analysis						
Property ref.	6 - 10pm	24hr	Median	Mode	Min	Max	SD
T-02 L	17.57	17.15	17.00	16.00	14.50	22.00	1.55
T-05 K-L	19.56	19.69	19.00	17.50	15.00	30.50	2.72
T-03 L	22.75	22.47	22.50	22.50	15.50	27.00	2.15
T-04 L	19.32	18.22	18.00	18.50	13.50	25.00	1.53
T-01 L	14.96	14.66	14.50	14.00	9.00	26.00	2.37
T-06 L	19.31	18.00	18.00	18.00	13.50	23.50	1.56
T-07 L	16.91	16.62	17.00	16.50	12.00	19.50	1.42
Living Room avg.	18.63	18.12	18.00	17.57	13.29	24.79	1.90
T-02 B	16.66	16.18	16.00	15.00	13.50	21.50	1.47
T-05 B	16.66	17.19	17.00	14.50	13.00	25.50	2.20
T-03 B	19.07	18.99	18.50	17.50	15.50	23.50	1.75
T-04 B	-	-	-	-	-	-	-
T-01 B	13.71	14.00	14.00	13.00	9.00	18.50	1.85
T-06 B	-	-	-	-	-	-	-
T-07 B	19.27	18.00	17.50	17.50	10.50	36.50	3.80
T-09 B	14.88	14.78	15.00	14.50	9.00	19.00	1.82
Bedroom average	16.71	16.52	16.33	15.33	11.75	24.08	2.15
T-02 H	-	-	-	-	-	-	-
T-05 H	15.69	15.54	15.50	15.00	13.50	20.50	1.13
T-03 H	21.31	21.11	21.00	22.00	16.50	27.50	1.63
T-04 H	17.60	17.10	17.00	17.00	13.00	21.00	1.38
T-01 H	14.63	14.50	14.50	14.50	9.50	23.00	2.08
T-06 H	18.73	18.64	18.50	18.50	16.50	20.50	0.85
T-07 H	15.94	15.69	16.00	15.50	9.50	19.50	1.99
T-09 H	18.98	18.89	19.00	19.50	16.00	21.50	1.01
Hall average	17.55	17.35	17.36	17.43	13.50	21.93	1.44
Average indoor	17.68	17.37	17.28	16.85	12.90	23.58	1.81
T-02 ext	7.63	7.52	7.55	7.48	0.06	15.30	2.70

After, winter 2							
23/11/17 - 8/2/18	Temperature analysis						
Property ref.	6 - 10pm	24hr	Median	Mode	Min	Max	SD
T-02 L	19.58	18.59	18.50	18.00	14.50	23.50	1.49
T-05 K-L	17.66	19.11	18.50	17.00	12.00	26.50	2.61
T-03 L	20.69	20.87	21.50	22.00	14.50	25.50	2.15
T-04 L	18.61	17.41	17.50	17.50	13.50	24.00	1.60
T-01 L	15.29	15.63	16.00	16.00	9.50	22.50	2.09
T-06 L	18.84	17.88	18.00	18.00	14.50	22.50	1.25
T-07 L	20.61	19.08	18.50	18.50	14.50	27.00	1.94
Living Room avg.	18.75	18.37	18.36	18.14	13.29	24.50	1.87
T-02 B	17.01	16.47	16.50	16.00	13.00	21.00	1.25
T-05 B	17.04	17.07	17.00	16.00	11.00	24.50	2.00
T-03 B	-	-	-	-	-	-	-
T-04 B	16.38	16.13	16.50	17.50	11.50	22.50	1.82
T-01 B	13.79	14.01	14.00	13.50	8.00	18.50	1.84
T-06 B	16.83	16.26	16.50	17.00	13.00	19.50	1.18
T-07 B	16.70	16.07	16.00	15.00	12.50	21.00	1.47
T-09 B	-	-	-	-	-	-	-
Bedroom average	16.29	16.00	16.08	15.83	11.50	21.17	1.59
T-02 H	19.01	18.26	18.00	18.00	14.50	22.50	1.14
T-05 H	13.33	13.24	13.50	14.00	9.50	16.00	1.20
T-03 H	20.96	20.72	20.50	21.00	16.00	27.50	1.76
T-04 H	17.23	16.62	16.50	17.00	12.50	21.50	1.47
T-01 H	14.81	14.92	15.00	14.50	9.00	19.50	1.84
T-06 H	19.11	18.71	18.50	19.00	16.00	22.00	0.91
T-07 H	17.55	17.19	17.00	17.00	14.00	21.00	1.08
T-09 H	-	-	-	-	-	-	-
Hall average	17.43	17.10	17.00	17.21	13.07	21.43	1.34
Average indoor	17.55	17.21	17.20	17.13	12.68	22.43	1.60
T-02 ext	6.33	6.23	6.24	6.16	-0.58	12.67	2.56

Table 3.6 (a) Temperature in monitored properties (i) before and (ii) after installation of airtightness measures

Figure 3.6 (b) Graphs based on Table 3.6(a) for 6-10pm heating period average temps (i) before and (ii) after measures



This shows that temperatures during the evening heating period are generally slightly higher than

24hr average temperatures, though this is not always the case. Most living room average temperatures fell into the recommended range of 18-21°C at this time, T-02 is slightly lower than this range, but temperatures in properties T-01 and T-07 are significantly lower. As a resident of T-07 is a childminder – at home much of the time, with many small children in the property – this would be of concern. The retired householder at T-01 had consciously kept his temperatures low and has now (at the end of the study) been advised of the recommended temperature range for comfort and good health. Property T-03 contained elderly residents with health conditions, hence their need for higher temperatures.

Bedrooms were generally cooler than living rooms and halls, except for property T-07 where in winter 1 the bedroom was the warmest room monitored – though this was no longer the case by winter 2. This room was warmed by electric heaters so it may be that they were not well controlled as a very high maximum temperature is recorded by this logger. Only 2 properties' bedrooms achieved the 18-21°C temperature range. Halls were often a similar but slightly lower temperature to living rooms, except in property T-05 where the unheated hall was the coldest area monitored.

The median temperature is the middle of the list when sorted into size order, and the mode is the most frequently recorded temperature – looking at these different types of average can identify whether the temperature of a property is relatively even or if it is skewed towards high or low temperatures. The standard deviation indicates if the temperature fluctuates significantly around the mean. For most properties, the three types of average are relatively consistent, but in properties T-02, T-07 and T-05 the mean > median > mode which indicates that the temperatures are generally low but with the mean pulled upwards by spikes of higher temperatures.

Looking at the maximum and minimum temperatures, the minima are very low for properties T-01, T-07 and T-09. For T-01 the lowest temperatures generally coincided with when the householder was away so may have left storage heaters only on low, or completely off - the maxima show that high temperature levels can be achieved when the heating is on (and the home's multi-fuel stove is used in the evenings). The other properties did not note if / when they were away. Very high maximum temperatures are noted in many properties, especially in the living rooms, and bedroom of property T-07 as already mentioned. This is likely to be due use of supplementary heating which does not have thermostatic control – residents could save money by using a temperature card or thermometer and turning the heater down or off when the room is warm e.g. 23°C.

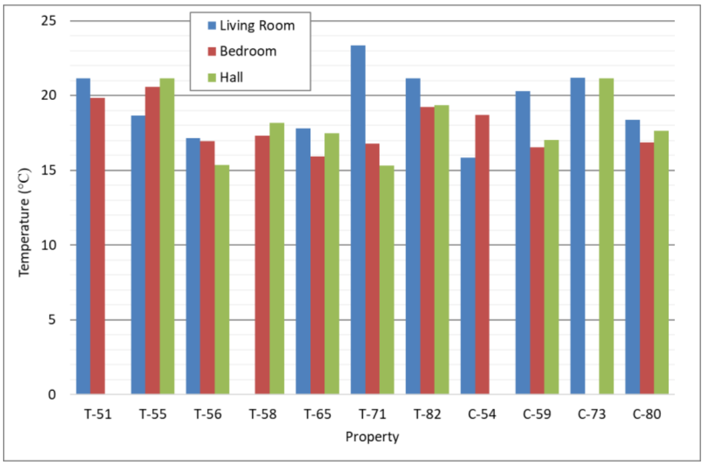
Following installation of the airtightness measures, temperatures in most households remained quite consistent, despite the 1 degree colder external temperatures. Properties T-02 and T-07 saw sizeable increases in their living room temperature, T-01 saw a small increase, while others saw small decreases. T-03's average temperature fell but from a high start point, so the average is now within the recommended 18-21°C range. T-04's average temperature fell slightly but remains within the recommended range. Both property T-02 and T-07's mean, median and mode averages are now quite close, showing that their temperatures are more even. As home T-05 is heated by supplementary electric heaters, these only release heat when the resident turns them on, so temperatures in this property remain quite variable. Overall, a slight increase was seen in living room temperatures, while the hall and bedroom temperatures dropped slightly – however all these changes were very small so are unlikely to be significant. The reduction in temperature in the bedroom of property T-07 – due to a reduction in maximum temperatures from supplementary heaters – may explain why they now suffer mould in that room. They may need to increase heating a little and ventilate the room at the warmest time of day.

For phase 2 and control properties, a period from 30th Oct 2017, when it started to get cold for the winter, to 25th December 2017 was selected for analysis, as after this one logger was moved to a window-ledge, outside the heated part of the monitored room. This is a period of 56 days, during which 496.5 degree days were experienced, an average of 8.71 dd/day.

Again, living rooms were usually the warmest, with bedrooms cooler, and hall temperature between the two (some "hall" loggers were located on the upstairs landing in this sample). This was reversed in property T-55 where the householder only used one storage heater in the living room, leaving the door open to allow the heat to rise upstairs – so the hall (upstairs landing) and bedroom loggers were warmer.

Table 3.7 (a) Temperature during the winter after airtightness treatment of phase 2 properties, and in control properties, and Graph 3.7 (b), right, plotting temperatures during the evening heating period for these homes

After, winter 2							
30/10/17 - 25/12/17	Temperature analysis						
Property ref.	6 - 10pm	24hr	Median	Mode	Min	Max	SD
T-51 L	21.16	20.71	21.00	21.00	16.50	31.50	1.68
T-55 L	18.67	18.66	19.00	19.50	13.50	21.50	1.45
T-56 L	17.14	16.93	17.00	16.50	12.00	22.00	2.06
T-58 L	-	-	-	-	-	-	-
T-65 L	17.80	17.07	17.00	17.00	10.50	23.00	2.31
T-71 L	23.34	21.47	21.50	21.00	17.00	26.50	1.87
T-82 L	21.16	20.11	20.00	20.50	16.00	24.00	1.25
Living Room average	19.88	19.16	19.25	19.25	14.25	24.75	1.77
T-51 B	19.85	19.57	19.50	20.00	14.50	24.00	1.44
T-55 B	20.56	20.70	21.00	21.00	16.50	24.00	1.46
T-56 B	16.96	17.55	17.50	17.00	12.00	21.50	1.72
T-58 B	17.31	16.47	16.50	17.50	11.00	20.00	1.89
T-65 B	15.91	15.18	15.50	16.00	9.00	21.00	2.49
T-71 B	16.77	16.77	17.00	17.50	12.00	21.00	1.90
T-82 B	19.23	19.15	19.00	18.50	16.00	22.00	1.20
Bedroom average	18.08	17.91	18.00	18.21	13.00	21.93	1.73
T-51 H	-	-	-	-	-	-	-
T-55 H	21.15	21.34	21.50	22.00	17.50	24.50	1.35
T-56 H	15.34	15.33	15.50	15.50	9.50	20.00	1.95
T-58 H	18.18	17.05	17.00	18.50	11.50	20.50	1.67
T-65 H	17.48	16.97	17.50	17.50	10.50	23.50	2.56
T-71 H	15.31	15.46	15.50	16.00	12.00	18.50	1.15
T-82 H	19.36	19.14	19.00	18.50	15.50	22.00	1.21
Hall/Landing average	17.80	17.55	17.67	18.00	12.75	21.50	1.65
Average Energysavers	18.56	18.19	18.29	18.47	13.32	22.68	1.72
C-54 L	15.85	15.84	16.00	16.00	13.00	18.50	0.93
C-59 L	20.31	19.45	19.50	19.00	14.00	24.50	2.00
C-73 L	21.17	21.02	21.00	21.00	17.00	23.50	1.30
C-80 L	18.36	18.32	18.50	17.50	15.00	21.50	1.39
Living Room average	18.92	18.66	18.75	18.38	14.75	22.00	1.40
C-54 B	18.69	18.35	18.00	18.00	14.50	24.50	1.63
C-59 B	16.53	16.38	16.50	17.00	12.00	22.00	1.41
C-73 B	-	-	-	-	-	-	-
C-80 B	16.87	17.29	17.50	18.00	14.00	20.50	1.44
Bedroom average	17.36	17.34	17.33	17.67	13.50	22.33	1.49
C-54 H	-	-	-	-	-	-	-
C-59 H	17.02	17.03	17.00	17.50	13.00	21.50	1.23
C-73 H	21.15	21.21	21.00	21.00	16.50	24.00	1.44
C-80 H	17.62	18.15	18.00	18.50	14.50	21.50	1.39
Hall/Landing average	18.60	18.80	18.67	19.00	14.67	22.33	1.35
Average Controls	18.36	18.30	18.30	18.35	14.35	22.20	1.42



There was wide variation in temperatures seen within the phase 2 property sample, and between the control properties. Most achieved living room temperatures of 18-21°C, and the remaining 2 were less than a degree lower during the evening heating period. The warmest living room temperatures were seen in property T-71 which reported only using a bottled gas room heater in cold weather – the rest of the house was not heated which would explain the temperature profile in this property. T-56 saw the lowest temperatures within the treated group – this property also only heated the living room and left doors open to circulate the heat to the rest of the house, but the storage radiator may not have been on its highest setting. Property C-54 had the lowest living room temperatures in the control group – the only one not to achieve the 18-21°C temperature range, possibly as its living room seemed little used (there was also a seating area in the kitchen) and was open to the large hall.

The average living room and bedroom temperatures were 1°C and 0.72°C warmer respectively in homes which had received airtightness measures compared to the control properties, although hall temperatures were 0.8°C lower than in the control properties.

3.5 Humidity

Water vapour in the air is usually referred to as relative humidity (RH) and quantifies the percentage of water vapour held by the air when compared to the saturation level (the highest quantity of water able to be supported by the air at a given temperature). Since this is dependent on temperature, relative humidity is a function of both moisture content and temperature. Relative Humidity is derived from the associated Temperature and Dew Point for the indicated sample. The higher the value of RH, the more water vapour is contained in the air.

Humidity is not usually considered to be an indoor contaminant or a cause of health problems. In fact, some level of humidity is necessary for comfort. Conversely, the relative humidity of indoor environments (over the range of normal indoor temperatures of 19 to 27°C), has both direct and indirect effects on health and comfort. The direct effects are the result of the effect of relative humidity on physiological processes, whereas the indirect effects result from the impact of humidity on pathogenic organisms or chemicals which may affect health. High values of RH are problematic as they can cause damage to building fabric and furnishings, mould growth and associated health problems. From the Building regulations part F[16]; the suggested average monthly maximum humidity levels for domestic dwellings during the heating season is 65%.

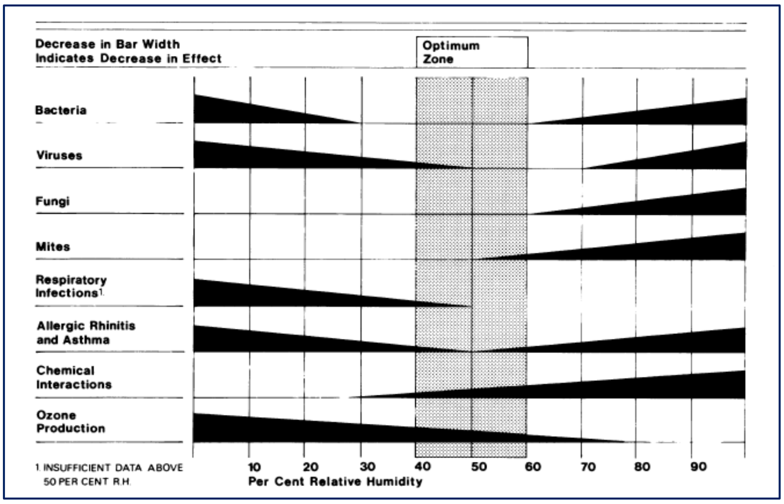


Figure 3.8 Optimum humidity levels to reduce indirect effects from pathogenic organisms or chemicals

Figure 3.8 illustrates the optimum humidity levels as cited by Arundel et al[17]. The study concluded that maintaining relative humidity levels between 40% and 60% would minimise adverse health effects relating to relative humidity.

Humidity data for the properties, over the same analysis periods as for the thermal loggers (explained in section 3.4), is shown in Table 3.9(a) for phase 1 properties, and presented in graph form in Figure 3.9(b) where error bars show one standard deviation around the mean. There is a complex relationship between humidity and evening heating period: relative humidity is inversely proportional to temperature, so in some rooms the humidity decreases, possibly due to an increase in heating, whereas in others, presumably those which are occupied (breathing releases moisture), and where other activities which release moisture such as cooking or bathing is taking place, humidity increases. The whole 24-hour average is therefore the best period to analyse for humidity. This shows that many of the properties' average humidity levels before installation of the measures

[16] Available from www.gov.uk/government/uploads/system/uploads/attachment_data/file/468871/ADF_LOCKED.pdf [Accessed 21/03/2017]
[17] Anthony V. Arundel, Elia M. Sterling, Judith H. Biggin, and Theodor D. Sterling: Indirect Health Effects of Relative Humidity in Indoor Environments: available at www.ncbi.nlm.nih.gov/pmc/articles/PMC1474709/ [Accessed 21/03/2017]

are higher than the recommended 40-60% range for good health. Properties which have the highest average temperatures usually tend to have lower relative humidity, however this is not always the case here. Properties T-01, T-04 and T-06 are bungalows built on low-lying ground (previously marsh), which may explain their high levels of humidity despite adequate temperatures. Property T-06 is also over-occupied, with 2 adults and 3 children occupying the small 2-bedroom bungalow. Bedrooms and halls generally experienced higher humidity levels than living rooms.

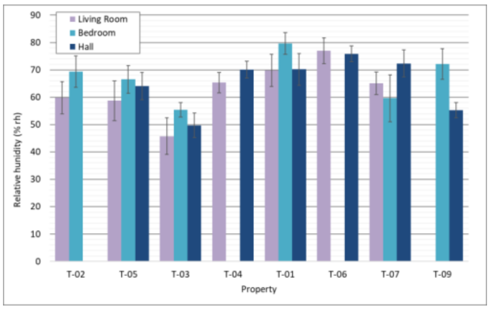
After installation of the measures, a reduction in relative humidity levels was seen in living rooms of most properties, with 24hr average humidity levels now within the recommended range except for homes T-01 and T-04 which were only slightly over 60% humidity on average. This suggests that airtightness measures can help to control excess humidity. Unfortunately, humidity levels in property T-06 increased, with their minimum levels now over 60%, so this is not always the case.

There was little change in humidity in halls, but on average humidity increased in bedrooms: this may be due to data from different loggers being in the sample during the two monitoring periods, also residents may not previously have had to actively air rooms due to uncontrolled ventilation, so may need to form a habit of opening windows at the warmest time of day to air (cooler) rooms.

Before, winter 1							
1/11/16 - 14/01/17	Humidity analysis						
Property ref.	6 - 10pm	24hr	Median	Mode	Min	Max	SD
T-02 L	59.60	59.77	59.50	59.00	43.00	74.00	5.90
T-05 K-L	58.93	58.74	59.00	61.00	37.00	77.00	7.30
T-03 L	45.75	45.76	44.00	43.00	36.00	66.50	6.68
T-04 L	64.51	65.37	66.00	66.00	44.50	79.00	3.76
T-01 L	69.25	69.83	70.50	67.50	44.50	86.00	5.88
T-06 L	74.71	77.01	77.25	77.50	59.50	88.50	4.69
T-07 L	65.19	65.12	66.00	66.50	51.00	84.50	4.13
Living Room avg.	62.56	63.09	63.18	62.93	45.07	79.36	5.48
T-02 B	67.27	69.34	69.50	70.50	52.50	83.50	5.77
T-05 B	66.94	66.51	66.50	65.00	51.00	80.00	5.02
T-03 B	55.01	55.41	55.50	56.00	48.50	80.50	2.60
T-04 B	-	-	-	-	-	-	-
T-01 B	78.45	79.60	79.50	78.50	61.00	91.00	3.96
T-06 B	-	-	-	-	-	-	-
T-07 B	59.11	59.62	61.50	67.00	31.50	77.50	8.56
T-09 B	71.46	72.18	72.00	73.50	56.50	86.50	5.54
Bedroom average	66.37	67.11	67.42	68.42	50.17	83.17	5.24
T-02 H	-	-	-	-	-	-	-
T-05 H	64.73	64.13	65.00	69.00	44.00	75.50	5.00
T-03 H	49.87	49.70	49.00	48.50	37.00	64.50	4.47
T-04 H	70.05	70.03	70.25	71.00	59.50	87.00	3.09
T-01 H	69.81	70.18	70.50	71.00	47.50	87.50	5.76
T-06 H	76.36	75.89	76.00	77.00	67.00	89.00	2.81
T-07 H	69.91	72.35	73.00	73.00	52.50	81.00	4.91
T-09 H	55.72	55.26	56.00	57.00	45.00	65.00	2.72
Hall average	65.21	65.36	65.68	66.64	50.36	78.50	4.11
Average indoor	64.63	65.09	65.33	65.88	48.45	80.20	4.93

After, winter 2							
23/11/17 - 8/2/18	Humidity analysis						
Property ref.	6 - 10pm	24hr	Median	Mode	Min	Max	SD
T-02 L	51.84	52.57	52.50	52.00	40.00	65.50	4.15
T-05 K-L	57.22	54.83	55.00	54.00	39.00	75.50	6.01
T-03 L	48.95	48.36	46.50	44.50	36.50	63.00	5.87
T-04 L	61.52	62.00	62.00	62.00	49.00	79.50	3.15
T-01 L	62.85	61.73	61.50	60.00	46.50	84.00	5.06
T-06 L	77.32	78.60	79.00	79.50	65.50	89.50	3.81
T-07 L	53.85	54.02	53.50	52.00	42.50	69.50	4.68
Living Room avg.	59.08	58.87	58.57	57.71	45.57	75.21	4.68
T-02 B	61.84	63.26	63.00	61.00	52.00	79.50	4.74
T-05 B	62.13	63.49	64.00	67.50	43.50	76.50	4.92
T-03 B	-	-	-	-	-	-	-
T-04 B	66.35	66.03	66.00	64.00	48.00	88.50	5.60
T-01 B	75.68	77.14	77.00	76.00	58.50	89.50	3.61
T-06 B	88.16	89.42	89.50	90.50	81.00	96.50	2.31
T-07 B	67.70	70.94	71.00	72.00	57.00	83.00	4.64
T-09 B	-	-	-	-	-	-	-
Bedroom average	70.31	71.71	71.75	71.83	56.67	85.58	4.30
T-02 H	54.90	54.76	54.00	54.00	43.00	73.00	4.37
T-05 H	70.68	70.42	71.00	72.00	60.00	78.50	3.71
T-03 H	50.00	50.28	50.50	51.50	38.50	61.50	4.49
T-04 H	63.53	63.67	64.00	64.00	49.50	91.00	3.98
T-01 H	67.18	66.78	66.50	66.00	52.50	89.50	4.68
T-06 H	75.94	75.51	76.00	77.00	67.50	89.50	2.86
T-07 H	62.69	62.20	61.50	60.50	52.00	78.00	3.93
T-09 H	-	-	-	-	-	-	-
Hall average	63.56	63.37	63.36	63.57	51.86	80.14	4.00
Average indoor	64.02	64.30	64.20	64.00	51.10	80.05	4.33

Table 3.9 (a) Table showing relative humidity (RH) in properties (i) before and (ii) after fitting of airtightness measures



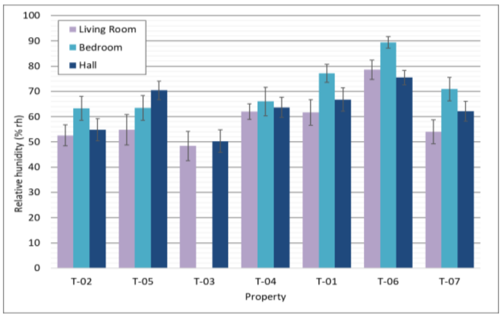
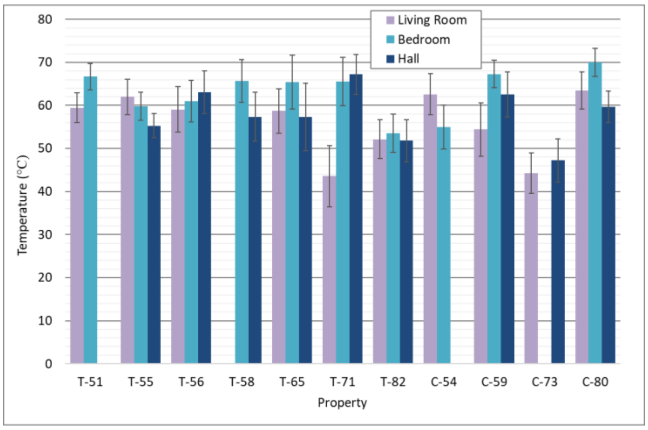


Figure 3.9 (b) Graph based on Table 3.9(a) for the 24-hour average relative humidities, (i) before and (ii) after measures

Table 3.10 (a) Temperature during the winter after airtightness treatment of phase 2 properties, and in control properties,

After, winter 2							
30/10/17 - 25/12/17	Relative humidity analysis						
Property ref.	6 - 10pm	24hr	Median	Mode	Min	Max	SD
T-51 L	58.75	59.45	59.50	60.00	38.00	71.50	3.50
T-55 L	61.88	61.96	62.00	62.00	49.00	72.50	4.07
T-56 L	59.11	59.06	59.50	56.00	44.00	75.50	5.33
T-58 L	-	-	-	-	-	-	-
T-65 L	58.86	58.73	59.50	62.00	43.50	70.50	5.14
T-71 L	43.21	43.56	44.00	47.00	26.50	63.50	7.08
T-82 L	51.81	52.12	52.50	56.50	37.00	65.00	4.52
Living Room average	55.60	55.81	56.17	57.25	39.67	69.75	4.94
T-51 B	65.69	66.70	67.00	67.00	57.00	76.00	3.07
T-55 B	58.33	59.82	60.00	62.50	50.50	68.00	3.30
T-56 B	59.41	61.00	60.50	62.00	47.50	75.00	4.84
T-58 B	65.38	65.67	66.50	66.50	55.00	76.50	4.93
T-65 B	64.64	65.37	66.50	67.50	44.50	78.00	6.27
T-71 B	64.15	65.53	65.50	63.50	50.50	85.50	5.66
T-82 B	54.57	53.52	54.00	57.00	42.50	65.00	4.47
Bedroom average	61.74	62.51	62.86	63.71	49.64	74.86	4.65
T-51 H	-	-	-	-	-	-	-
T-55 H	54.55	55.27	55.00	55.00	45.50	62.50	2.77
T-56 H	62.06	63.08	63.00	62.50	51.00	76.50	4.93
T-58 H	56.65	57.36	57.25	56.50	43.50	78.50	5.72
T-65 H	57.06	57.36	59.00	63.50	33.50	74.50	7.85
T-71 H	67.13	67.22	67.50	70.00	52.50	81.50	4.62
T-82 H	52.77	51.80	52.50	55.00	39.00	72.00	4.86
Hall/Landing average	58.37	58.68	59.04	60.42	44.17	74.25	5.12
Average Energysavers	58.74	59.19	59.54	60.63	44.76	73.05	4.89
C-54 L	63.05	62.60	63.00	62.50	51.50	76.50	4.74
C-59 L	54.65	54.42	55.00	55.00	35.50	70.50	6.21
C-73 L	43.97	44.27	44.50	45.50	31.00	55.50	4.72
C-80 L	63.94	63.44	63.50	65.50	51.50	78.50	4.27
Living Room average	56.41	56.19	56.50	57.13	42.38	70.25	4.99
C-54 B	54.60	55.03	55.50	59.00	41.00	67.00	5.09
C-59 B	67.19	67.30	67.50	69.50	58.00	75.00	3.25
C-73 B	-	-	-	-	-	-	-
C-80 B	67.70	70.01	70.00	70.50	62.00	78.00	3.23
Bedroom average	63.16	64.11	64.33	66.33	53.67	73.33	3.86
C-54 H	-	-	-	-	-	-	-
C-59 H	64.03	62.53	63.50	65.00	47.00	73.00	5.25
C-73 H	46.94	47.21	47.50	48.00	34.00	61.50	5.05
C-80 H	59.56	59.65	60.00	61.00	47.50	68.50	3.69
Hall/Landing average	56.84	56.46	57.00	58.00	42.83	67.67	4.66
Average Controls	58.56	58.65	59.00	60.15	45.90	70.40	4.55



and Graph 3.10 (b), right, plotting temperatures during the evening heating period for these homes

Results for humidity analysis of phase 2 and control properties is shown in Table 3.10(a) and Graph 3.10(b). For phase 2 properties, all but one household, T-55, had 24-hour average humidity levels in the recommended range of 40-60%, and T-55's average levels were only just higher than this.

Bedroom humidity levels were generally higher, with only 2 properties' levels falling into the recommended range, another was slightly higher than the recommended range, and within the range during the evening heating period. Halls generally had humidity levels within the recommended range apart from in two properties where levels were higher – in property T-71 where only the living room was heated this would explain why humidity in other areas of the house is much higher, where the temperature is lower.

Control properties' humidity levels were very variable – only 2 of the 4 properties had levels within the recommended range. The peak-electrically heated property C-59 had humidity within the recommended range in the living room but other areas of the house which were barely heated had much higher humidity. Property C-73 which had storage heaters downstairs but not upstairs had humidity levels within the range in the living room and hall, but bedroom levels were higher. However in C-80 which used the same storage heaters, humidity was slightly high in all rooms but the hall. Oil-heated C-54 had slightly high humidity in their (possibly unused) living room, but bedroom levels were lower, where it was warmer.

Little difference is seen between the average values for the two groups, but those receiving phase 2 airtightness measures had humidity levels slightly lower than those properties which did not. Average humidity levels in bedrooms was slightly higher than the recommended range of 40-60% for both groups.

3.6 Air quality: carbon monoxide and carbon dioxide levels

Carbon monoxide (CO) is the toxic product of incomplete combustion of carbon-containing fuels. This can occur where appliances such as gas, oil or multi-fuel stoves, ovens, water heaters and boilers malfunction, or are inadequately ventilated so insufficient oxygen reaches them e.g. blocked flues. The health effects of different levels of CO are shown in Table 3.11.

Level of CO	Health Effects, and Other Information
0.1 PPM	Natural atmospheric levels in normal, fresh air.
0.5-5 PPM	Average level in homes without indoor sources.
5-15 PPM	Near properly adjusted gas stoves in the home.
9 PPM	Maximum recommended prolonged indoor CO level (ASHRAE).
10-24 PPM	Possible health effects with long-term exposure.
25 PPM	Max TWA Exposure for 8 hour work-day (ACGIH).
50 PPM	Maximum permissible exposure in workplace (OSHA) and safety level specified by HSE in the UK
100 PPM	Slight headache after 1-2 hours.
200 PPM	Dizziness, nausea, fatigue, headache after 2-3 hours of exposure.
400 PPM	Headache and nausea after 1-2 hours of exposure. Life threatening in 3 hours.
800 PPM	Headache, nausea, and dizziness after 45 minutes; collapse and unconsciousness after 1 hour of exposure. Death within 2-3 hours.
1000 PPM	Loss of consciousness after 1 hour of exposure.
1600 PPM	Headache, nausea, and dizziness after 20 minutes of exposure. Death within 1-2 hours.
3200 PPM	Headache, nausea, and dizziness after 5-10 minutes; collapse and unconsciousness after 30 minutes of exposure. Death within 1 hour.
6400 PPM	Death within 30 minutes.
12,800 PPM	Immediate physiological effects, unconsciousness. Death within 1-3 minutes of exposure.

Table 3.11 Health effects of various concentrations of carbon monoxide (from detectcarbonmonoxide.com)

As draughts provide uncontrolled ventilation which could reduce danger should high carbon monoxide levels be present, it was important to verify that reducing such ventilation by applying airtightness measures did not exacerbate any problems. Whilst only one property had a mains gas boiler, questionnaire responses indicated that some other homes also contained potential sources of carbon monoxide: one had an oil boiler, 3 had a multi-fuel stove fitted, 2 had gas room fires (mains or bottled), and others used portable bottled gas heaters. Other indoor sources of carbon monoxide might include burning of candles and smoking.

The CO loggers record carbon monoxide concentrations at minimum of 5-minute intervals, giving a maximum capacity for 3 months of monitoring data. These therefore required changing during the monitoring period. Due to the remoteness of this area from project personnel, repeated visits were not possible for frequent equipment changeout, so data is only available for summer-autumn before install of the measures, and November 2017 – March 2018. Periods were selected within this when all loggers were installed and recording data:

- Period 1: 6/7 – 11/10/16, before airtightness measures installed, summer-autumn.
- Period 2: 30/11/17 – 18/03/18, after measures installed, winter.

As shown in Table 3.11, there are various levels of CO which may cause concern, both individual spikes of high CO concentrations over 50 ppm, and long-term average exposure of above 10 ppm. Table 3.12 presents average levels, and numbers of incidences of concentrations over 50 ppm in the homes monitored for CO. This shows that none of the average levels experienced cause concern for resident safety. However, property T-04 experienced a very high maximum CO concentration during the period before installation of the airtightness measures, higher than the 50ppm safety level specified by the HSE in the UK – however, this was recorded by only 3 samples (i.e. over a period of 15 minutes), with levels having returned below 9ppm by the time the next sample was taken. This was also the only property to record sample levels higher than 9ppm during this period. However, there were no known CO sources identified within this property. The resident did state that they had a dishwasher removed, so a possible explanation is that the van which removed this was left running – with exhaust gases containing CO entering the property – during the time that this was carried out, but it is not known whether this was the actual cause. The fact that levels are otherwise relatively low and the peak did not recur during the sample period suggests that there is not a problem with carbon monoxide in this property.

Summer-autumn / 1st period									
	CO concentration analysis (ppm)							No. samples over 9 ppm	No. samples over 50 ppm
Property	Evening	24hr	Median	Mode	Min	Max	SD		
T-04	0.60	0.61	0.50	0.00	0.00	380.50	3.02	12	3
T-07	0.52	0.48	0.50	0.50	0.00	5.50	0.47	0	0
T-01	0.00	0.00	0.00	0.00	0.00	0.50	0.01	0	0
T-05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
T-06	0.50	0.43	0.50	0.50	0.00	4.00	0.40	0	0
T-03	2.68	1.46	1.00	0.00	0.00	8.50	1.71	0	0
T-02	0.02	0.01	0.00	0.00	0.00	6.00	0.19	0	0
T-09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
Winter / 2nd period									
	CO concentration analysis (ppm)							No. samples over 9 ppm	No. samples over 50 ppm
Property	Evening	24hr	Median	Mode	Min	Max	SD		
T-04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
T-07	3.80	1.93	1.00	0.50	0.00	11.00	1.94	48	0
T-01	0.00	0.00	0.00	0.00	0.00	8.50	0.05	0	0
T-05	0.22	0.32	0.00	0.00	0.00	10.50	0.82	28	0
T-06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0
T-03	1.50	0.96	0.00	0.00	0.00	8.50	1.51	0	0
T-02	0.00	0.00	0.00	0.00	0.00	0.50	0.01	0	0

Table 3.12 Average carbon monoxide concentrations in properties over periods (a) before (b) after

Property T-03 – which uses a bottled gas portable heater – experienced the highest average CO levels of all the monitored properties during the first monitored period, however maximum levels are still lower than the 9 ppm level at which long-term health issues may be caused. Levels remain high in this property in the second monitored period, with the same maximum concentration seen of 8.5 ppm, but again no samples are detected higher than the 9 ppm level. (The resident has since ceased use of this gas heater having found that it caused coughing, so CO levels in this property should reduce now that an electric heater is being used in its place.)

In two properties, a small number of samples above a 9 ppm CO concentration were detected. T-07 has an unvented LPG room fire, which had previously been condemned but was repaired so it was in use again. Due to this room fire, potential airtightness measures (insulation, heat recovery ventilation and replacement of the slatted windows present) were not applied to the room in which the fire was located. The maximum 11 ppm CO concentrations detected here are still low, and the average levels should not be a cause for concern. In property T-05 the logger was placed in the kitchen, as it was used as the main living area in the house, and although CO levels were generally low at 0.22 ppm on average, this property saw maximum peak(s) of 10.5 ppm, possibly as a result of cooking. Property T-01 also had a multi-fuel stove, but apart from maximum levels of 8.5ppm, overall averages in this property were very low. No properties experienced CO levels above the 50 ppm safety limit in the second period.

No trend can be observed between monitoring periods 1 and 2, especially as they were from different times of year, but this monitoring suggests that other than a short-term but unexplained high peak in one property, all CO concentrations are at levels which do not arouse concern.

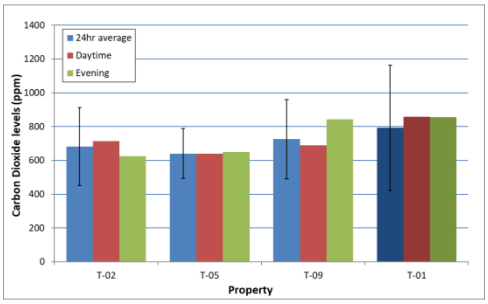
Four sample properties were also monitored for carbon dioxide – this is a colourless, odourless gas that is the product of human and animal respiration, and a by-product of complete combustion of carbon-containing fuels. Since CO_2 is heavier than air, fatalities from asphyxiation have occurred when high concentrations have entered confined spaces such as tanks, sumps or cellars and displaced oxygen[18], but CO_2 is not usually found at hazardous levels in the indoor environment. However, its levels are often used as an indicator of the number of occupants, and the adequacy of ventilation in a building, which may lead to the build-up of other contaminants.

250-450 ppm	Normal background concentration in outdoor ambient air
350-1,000 ppm	Concentrations typical of occupied indoor spaces with good air exchange
1,000-2,000 ppm	Complaints of drowsiness and poor air.
2,000-5,000 ppm	Headaches, sleepiness and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present. Impaired cognitive performance and energy levels
5,000 ppm	Long-term exposure limit (8-hr reference period) in most jurisdictions including HSE (UK)
15,000 ppm	Short-term exposure limit (15 minute reference period) by HSE (UK)
35,000 ppm	OSHA (USA) exposure limit for 15 minutes - levels above this likely to cause loss of consciousness (fainting)
>40,000 ppm	Exposure may lead to serious oxygen deprivation resulting in permanent brain damage, coma, even death.

Table 3.13 Health effects of various concentrations of carbon dioxide (from Wikipedia[19] and Kane[20])

Loggers were placed in properties in July 2016, and left for the duration of the whole study. Three data loggers reached capacity in July 2017, however one in property T-01 rolled over (overwriting previous data) so we were able to obtain data on the second winter only. The same date period was selected of 10th Oct – 18th March during both winters, but samples from properties T-02, T-05 and T-09 are from the first winter (2016-17) only, and T-01 is from winter 2017-18. Table 3.14 (a)

CO2 levels analysis										No. samples > 1000 ppm	No. samples > 2000 ppm
Property	Period	Day	Evening	24hr	Median	Mode	Min	Max	SD		
T-02	1: 10 Oct 2016 - 18 Mar 2017	714.6	625.9	681.8	646.5	399.0	376.0	1798.0	229.9	387	0
T-05	1: 10 Oct 2016 - 18 Mar 2017	639.2	650.4	640.6	633.0	537.0	371.0	1340.0	147.7	45	0
T-09	1: 10 Oct 2016 - 18 Mar 2017	690.1	842.8	725.7	679.0	553.0	330.0	2024.0	235.0	480	2
T-01	2: 10 Oct 2017 - 18 Mar 2018	859.1	855.5	792.5	712.0	394.0	380.0	2538.0	371.6	937	27
Average		725.7	743.6	710.1	667.6	470.8	364.3	1925.0	246.0	462.3	7.3



and Graph 3.14(b) summarise the levels monitored. Error bars indicate one standard deviation.

Table 3.14(a) Carbon dioxide levels in properties over periods monitored and Graph 3.14(d) based on this.

Average concentrations recorded were within the typical range for indoor air. All 4 properties experienced CO_2 levels higher than 1000 ppm, for property T-05 this was only 46 incidences and neither they nor property T-05 ever saw levels higher than 2000 ppm. Two >2000 ppm samples were recorded in property T-09, which may have led to sleepiness and the sensation of stale, stuffy air. Their evening (5-11pm) CO_2 levels were higher than during the day (8am–5pm), suggesting that some aspect of their evening routine is linked to high levels. Highest CO_2 levels were recorded in property T-01: this household has a multi-fuel stove, used daily in the evenings to warm the property. However, no difference in CO_2 levels is seen between day and evening concentrations, so this may not be the cause of the high levels. The large error bar on this property indicates large variations in CO_2 levels in this home. 27 samples were above 2000 ppm, so the resident of this property may improve their wellbeing by improving ventilation.

[18] HSE information on carbon dioxide www.hse.gov.uk/carboncapture/carbondioxide.htm [Accessed 14/5/2018]

[19] Wikipedia, Indoor air quality, carbon dioxide https://en.wikipedia.org/wiki/Indoor_air_quality#Carbon_dioxide [Accessed 14/5/2018]

[20] Kane, Safe levels of CO_2 in rooms www.kane.co.uk/knowledge-centre/what-are-safe-levels-of-co-and-co2-in-rooms [Accessed 14/5/2018]

3.7 Electricity usage analysis

5 of the phase 1 properties had current clamps fitted onto their mains cable to monitor electricity use over the first winter. These were swapped in November 2017 for replacement current clamps which monitored both peak and off-peak circuits separately where these were available (main cable only where only single rate electricity was present). Over the first winter the households' electricity use was monitored from 10th October 2016 – 30th April 2017, a period of 202 days during which 1,635.1 degree days were experienced, an average of 8.09 dd / day. Over the second winter, properties' electricity use was monitored from 31st Oct 2017 – 18th March 2018, a period of 138 days during which 1,368.3 degree days were experienced, an average of 9.92 dd / day. The results are shown in Figure 3.15 below.

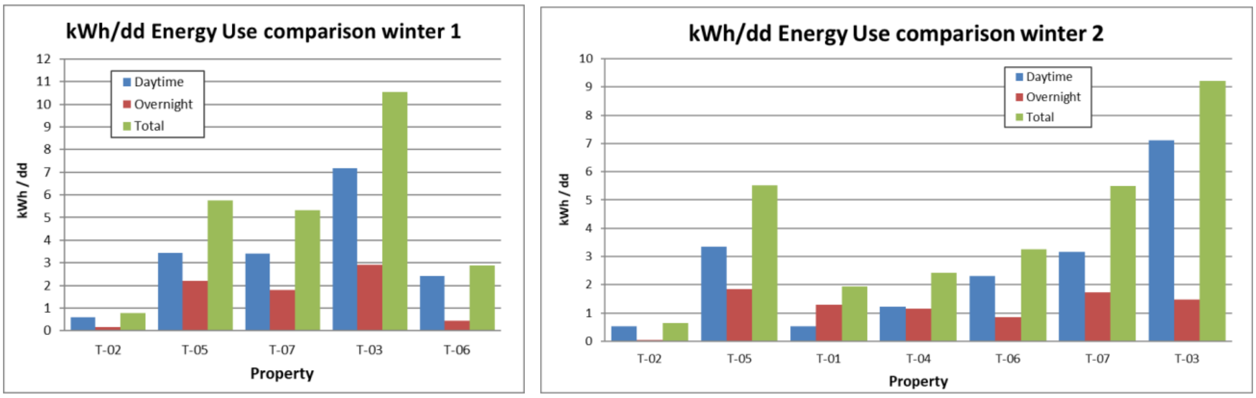


Figure 3.15 Electricity use for phase 1 properties over the winters (a) before and (b) after airtightness measures.

Property T-02 – a mains gas-heated property unsurprisingly has the lowest electricity use per degree day of the phase 1 homes monitored over both winters. T-03 has the highest electricity use, as this was a large property containing elderly residents with health conditions who require warmer room temperatures than normal. Note that many properties – despite being on Economy 7 – use a significant proportion of their electricity during the day (8-30am – 11.30pm). This is because homes T-03, T-04 and T-06 had a variety of relic economy 7 tariffs where a proportion of the off-peak rate hours occur during the afternoon. This means that storage & immersion heaters are topped up, and cooking / washing etc. could also be done during this period for a cheaper rate. For example, despite the usage profile above, 90% of T-03's electricity use was on their off-peak rate.

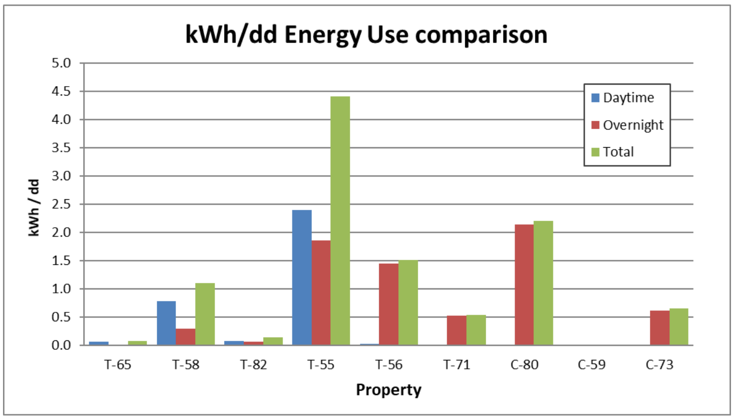
Comparing the two periods, T-03's usage reduced a little, especially overnight (midnight – 8am), T-07 and T-05's usage remained very similar – the latter is of note since this household reported that they could now afford to heat more of the property since they had secondary glazing installed, and T-06's overnight usage increased slightly.

All phase 2 and control properties had a single current clamp fitted, however - unusually - in many of the properties, the main cable was wired directly into the electricity meter as soon as it was split into live and neutral (and this was boxed in), so the whole of the circuit could not be monitored using one clamp. The heating circuit was therefore monitored where possible.

Comparisons of electricity usage are shown in Figure 3.16. It is known that the current clamp at property T-82 did not function correctly as it was not closed properly around the cable. Very low usage was also recorded at properties T-65 and C-59, so these may also have malfunctioned.

Property T-58 was heated by an air-source heat pump, so it is interesting that their electricity consumption is relatively low compared to those heated by storage heaters. This may also be due to T-58 having solar PV panels installed, which are likely to cover some of the daytime electricity

Figure 3.16 Electricity use in phase 2 and control properties over the winter after airtightness measures.



consumption. In property T-55 the whole circuit was monitored as the current clamp was placed on the neutral cable – this property uses the most electricity of all the phase 2 mainly well-insulated properties, and with less than half of the electricity consumption occurring in the overnight off-peak period. This household did report using a tumble drier quite frequently which may explain this high usage. All other properties had only their off-peak circuit monitored hence why no daytime usage is recorded. As off-peak time periods in this area appear to be 1.30 – 8.30am, this would explain why total usage is slightly higher than overnight usage, set as midnight to 8am. T-56 uses slightly less than T-55 for its heating. In comparison, T-71 uses much less – this household did not use the storage heaters – preferring to use a portable gas heater in the living room only – but did use their immersion tank to heat hot water. Property C-80 uses the most electricity of the control properties, similar in level to T-55 and T-56 (as explained previously, the logger in C-59 may have malfunctioned), with C-73 using a relatively low amount. This is similar in magnitude to usage in property T-71, however property C-73 did use their storage heaters. They also had solar PV panels fitted, but these are unlikely to have reduced the overnight off-peak electricity usage as the sun will not be up overnight. It is possible that this household does not use their immersion tank.

3.8 Thermal Imaging

During interim visits to the monitored properties in November 2017, a thermal imaging camera was used to assess a sample of properties' fabric temperatures for any remaining cold / draughty spots which may affect comfort: via doors, windows, walls, draughts etc. Figure 3.17 shows the resulting thermal images. Many of these issues will cause heat to be lost, increasing heating need and resulting in temperature variations within the property, possibly reducing comfort levels

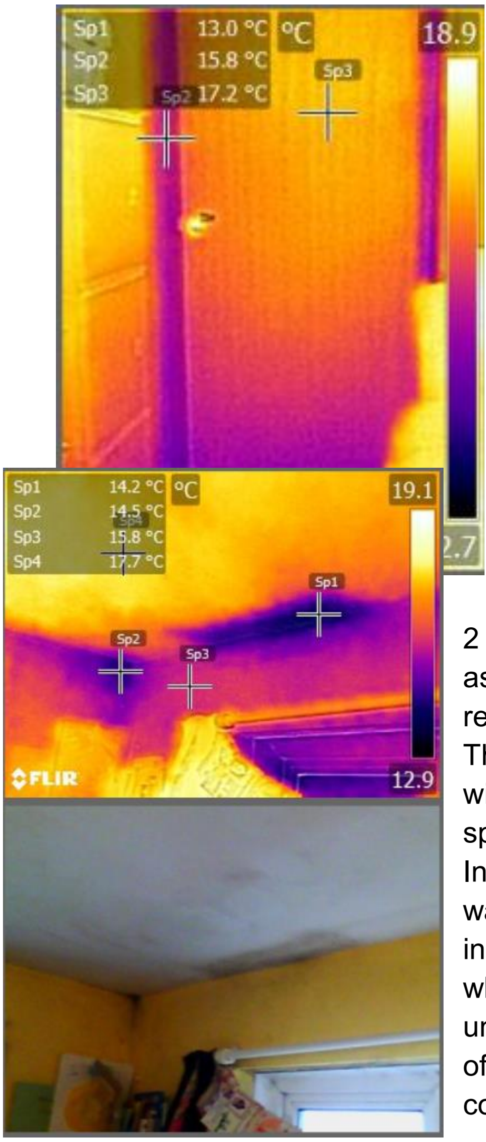
In property T-02, some draughts remain under doors to unheated areas of the property such as the corridor to outbuildings, and front porch. The main part of the living room floor which was sealed and insulated is evenly warm, however the steps up to the hall-area (open plan to this room) show cold patches where insulation and/or sealing could still be improved.

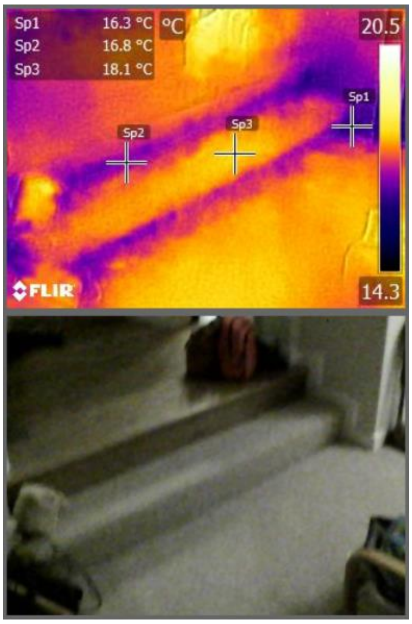
In property T-06, areas with poor insulation, or where insulation had failed, were evident: on ceilings and lintel areas above windows. As this property also had high humidity these cold patches frequently suffered mould and/or caused wallpaper to peel.

Property T-07 had a single-skinned back part to the living room – particularly the joins of walls and ceilings suffered colder temperatures. Significantly lower temperatures were also noted at or around skirting boards at floor level – it is not known if this is due to damp, draughts or thermal bridging.

Figure 3.17 Thermal images of phase 1 properties, taken in November 2017 after airtightness measures.

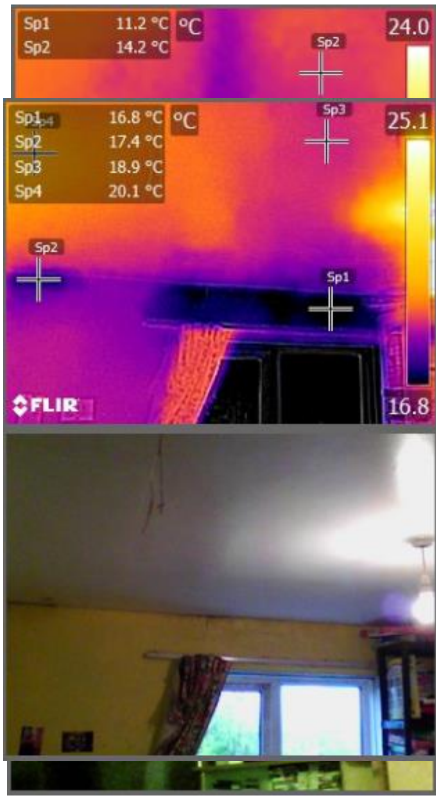
a) Property T-02





b) Property T-06

c) Property T-07 (below)

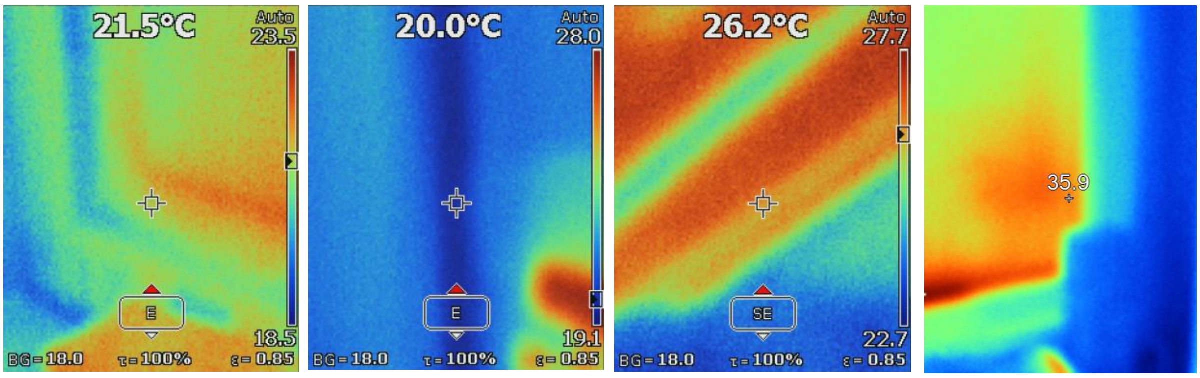


Phase 2 properties also had thermal images taken as part of their airtightness testing, with the resulting images shown in Figure 3.18. These identified leaks of cold air around windows (a) and doors (b) as well as other specific leak points around pipes, wires etc. In properties with rooms in the roof, the roof was often identified as having little insulation, being warm on the summer day when visits were carried out (c) – unfortunately roof room insulation was not offered in phase 2 of this project, so this could not be rectified.

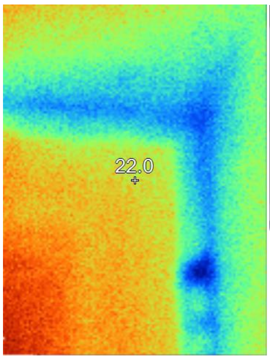
Thermal images taken in June, following the measures, showed no remaining draughts around windows (d, red shown in this image is the sun reflecting off the window's metal spacer bar, no leaks present). A few showed small remaining leaks around doors (e, blue patch of cold air) or loft hatches (f, red, warm air from loft on a sunny day) but this was much better than previously.

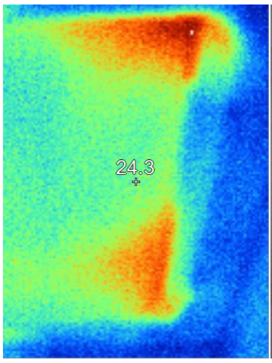
Figure 3.18 Thermal images of phase 2 properties, taken in May (a & b, before) and June 2017 (c, after measures).

a) b) c) d)



e)





f)

3.8 Airtightness tests

Airtightness tests were carried out by external contractors as part of this project. All but one phase-1 property had one airtightness test in July 2016, prior to installation of their measures. A sample of 4 phase-2 properties received two airtightness tests, one on 31st May 2017 prior to - and again on 16th June 2017 after - installation of their measures. Results of the tests are presented in Tables 3.19. As different contractors carried out the two sets of tests, the test results / reports provide different information – more detail is provided for the phase 2 properties, which is presented.

Before	05/07/2016
Property	Air Permeability at 50 Pa ($m^3/(h.m^2)$)
T-05	11.1
T-09	9.97
T-01	7.27
T-07	7.15
T-03	5.78
T-06	6.17
T-04	6.33

			Before	31/05/2017	After	14/06/2017
Property	Net floor area (m^2)	Volume (m^3)	Air Permeability at 50 Pa ($m^3/(h.m^2)$)	Air changes per hour ($m^3/(h/m^3)$)	Air Permeability at 50 Pa ($m^3/(h.m^2)$)	Air changes per hour ($m^3/(h/m^3)$)
T-82	38.5	193.9	5.62	6.11	4.79	5.21
T-58	95.9	356.2	13.82	13.98	12.19	12.33
T-71	34.8	178.3	4.81	5.26	4.26	4.65
T-65	48	460.3	9.57	7.69	9.41	7.57

Tables 3.19 Airtightness values (a) for Phase 1 properties before treatment and (b) Phase 2 properties both before and after the installation of airtightness measures

For phase 1 properties, the small bungalows T-01, T-04 and T-06 were quite airtight. Surprisingly, so were the large property T-03, and the detached property T-07. The least airtight properties were T-09 (the upper floor maisonette) and T-05, the terraced stone property with single glazing.

For phase 2 properties, the small modern properties such as T-71 and T-82 were relatively airtight prior to treatment, and the air permeability was reduced further by the sealant works carried out. Properties T-65 and T-58 were much older and leakier. Air permeability of T-65 reduced by very little as few works were able to be carried out in this property due to the type of windows present. Air permeability of property T-58 improved, but was still relatively high after treatment – so further treatment of the entrance porch loft hatch was recommended (this could not be carried out as part of the works due to no recess present against which the sealant could form a seal).

4. Conclusions and recommendations

4.1 Conclusions

The project's aims were to identify issues present, and fit the necessary measures to improve airtightness in HTT properties in this remote, mainly off-gas and exposed area of Ceredigion, and:

- Assess any change in residents' comfort – both reported in questionnaires, and measured using temperature and humidity monitors,
- Monitor any change in energy use for heating,
- Monitor any change in air-quality i.e. carbon monoxide and dioxide levels in homes, to ensure reducing ventilation by sealing up draughts does not worsen health & safety,
- Determine the effectiveness and cost-effectiveness of draught-proofing / airtightness measures to reduce fuel poverty in HTT properties where other improvement measures may not be possible or appropriate.

Summary of results

- Residents' feedback indicated a general improvement in comfort: only 1 of 14 householders previously did not need to wear extra warm clothes at home to keep warm. By the end of the study, only 4 (of 14) respondents said they needed to wear extra warm clothes in the house, a significant improvement. 4 of the 15 householders reported they could heat or comfortably use more rooms in the property since the measures were installed.
- 8 of 15 householders felt their home now kept the heat in better and 7 said it was warmer and more comfortable, while 5 felt their home got warmer faster. 6 identified reduced noise (from wind, sea, roads and trains) as another key benefit. Others included being able to sit near windows for light without getting cold.
- Overall, resident satisfaction with their heating (control over heating, how easy the system is to use, how well the house keeps the heat in, and how warm it gets when it's cold out) improved from "neither satisfied or dissatisfied" to generally "satisfied". However, satisfaction with the costs of running their heating system did not improve.
- 2 of 9 households which had previously suffered with damp felt the issue had improved, but one said it had got worse. This may have been due to less need for supplementary heating in the bedroom, and reduced uncontrolled ventilation (plus the very cold winter), so active ventilation – opening windows at the warmest time of day – of the room was recommended.
- Residents' estimates of energy costs did not change noticeably after airtightness measures, or compared to the control group – possibly affected by price rises and the very cold winter in 2017-18. However, 4 of the 15 households who received measures felt their bills were cheaper, and another could afford to heat more of the home for the same cost. 4 said the measures had reduced any money worries a little, and one felt it had reduced them a lot. But the remainder felt the measures had not made a significant difference.
- Calculating heating costs from meter readings, electrically heated phase 1 properties saved on average 5.23% in terms of kWh used, and 10.55% in costs, but due to variability of savings, these were not statistically significant. Excluding property T-06 (which received heat recovery ventilation), savings were 6.93% in kWh terms and 12.7% in costs. The fact that cost savings were higher than electricity units saved shows more of the reduction is in expensive – daytime – rate than in the off-peak rate, maybe use of less electric plug-in heating. T-02, the mains-gas heated property saved 7.32% on gas.

- Electrically heated phase 2 properties saw a 2-3% increase in bills on average, this was likely to be associated with 3 properties which had a new baby, one turned on an extra storage heater because of the cold winter, and one ASHP-heated property saw a significant increase in usage – possibly the heat pump worked less efficiently in cold weather, or a change in the programmer. Other properties did save 6.65 - 22.82%, but due to this variability, no significant savings can be reported. In comparison, control properties which were electrically heated did make a small saving of 3.35% in kWh terms and 5.82% in cost terms, significant to a 68.2% level.
- Despite winter 2017-18 being 1 degree colder per day than the previous winter, living room temperatures in the phase-1 properties increased slightly on average, so all but one were now within the recommended 18-21°C range for comfort and good health either over all 24hrs or during the evening heating period. Properties T-02 and T-07 saw large increases in living room temperature. Temperature variability also reduced slightly. Property T-01 had been heated to lower temperatures by the resident, who was advised to increase the temperature to prevent health effects. Bedroom and hall temperatures reduced very slightly.
- Phase 2 property temperatures were variable, but most were within the 18-21°C range. In comparison to control properties, homes which had airtightness measures' temperatures were 1°C warmer on average in living rooms, bedrooms were 0.72°C warmer, but halls were 0.8°C cooler than the controls.
- Prior to installation of airtightness measures, 4 of the 8 phase-1 properties' living room humidity levels were higher than the recommended 40-60% rh range. Humidity levels were better controlled after installation of the measures as 3 of these reduced to within or very close to this range. However, one home still had very high living room humidity levels after the measures, which could be due to over-occupation of the property. Hall and bedroom levels were mostly higher than the recommended range - hall levels were reduced slightly after the measures but bedroom levels increased. This suggests that some households may need to form the habit of actively airing cooler rooms like bedrooms by opening windows at the warmest time of day, now that uncontrolled ventilation has been reduced.
- Phase-2 properties had living room humidity levels within or close to the recommended range. Little difference was seen between treated and control group average values, but those which received measures had slightly lower living room and bedroom humidity. Average bedroom humidity levels were higher than recommended for both groups.
- Other than a brief unexplained high peak in one property before measures were installed, there was no issue identified with carbon monoxide levels in the homes. None of the properties averaged more than 9 ppm above which long term effects may occur. Installation of airtightness measures therefore does not appear to worsen this, though sampling was at different times of year. Levels were highest in those homes using gas room fires or portable gas heaters, and where the logger was placed in a kitchen. A few properties saw spikes in CO concentration above the 9ppm level, but these were for a small number of samples - reasons for these are unknown, but do not suggest a long-term issue in the property.
- All 4 properties monitored for CO_2 had average levels within the typical range for indoor air. Whilst all experienced levels between 1000-2000 ppm, which may result in drowsiness, only homes T-09 and T-01 saw samples above 2000 ppm which may result in headaches, poor concentration etc. For T-09 this occurred in the evenings, but for T-01 day and evening levels were fairly consistent, which may mean improved ventilation is required.

- Monitoring of electricity usage using current clamps showed households' usage profile throughout the 24hr period. Despite being on an Economy 7 tariff, many households used a significant portion of their energy during the day – this is because they were on old tariffs (no longer available) which offer some off-peak hours during the daytime.
- Thermal imaging showed that draughts from windows, doors and loft hatches were eliminated or much reduced in phase 2 properties after treatment, though some small issues remained. In phase 1 properties, some issues did remain as points of heat loss, particularly areas which could not be treated / insulated without major works, either beyond the scope of this project, or which would cause too much disruption to the household to be carried out during the period of the project.
- Airtightness measurements were not carried out after install of the measures in phase-1 homes. The small more modern bungalows already had relatively good airtightness, whereas T-09, the upper floor maisonette, and T-05, an old stone terraced house, were the leakiest. For the sample of phase-2 homes tested, the modern homes had relatively good airtightness prior to the works, with older properties being draughtier. All properties saw reductions in air permeability following treatment, though home T-65 did improve as much since it did not have much work done.
- Householders were very satisfied with the installation of the measures, particularly phase 2, giving the installers good reviews, saying how quick and unobtrusive they were. A few had reliability issues: the only property receiving heat recovery ventilation feeling it was not effective, even after the installer returned to check it. One household said sealant on the loft hatch peeled off but hadn't reported this so it had not been replaced. Another said their windows and doors still needed regular tightening / maintenance after treatment as the wind made them loosen or "drop", and salt caused metal parts to corrode – this is likely to be the case for all residents in this highly exposed area.
- Those who felt the airtightness measures had made little difference were in either relatively modern and well-sealed homes, and/or those with other significant heat loss issues such as uninsulated solid walls and rooms in the roof.
- There was little change in project participants' concerns or actions around (saving) energy, but overall, residents agreed that they understood more about how they could save energy from taking part in the project.

4.2 Recommendations for potential future installations

Identifying suitable properties was a difficult process – those in the worst insulated properties may not be in a position to have works carried out e.g. tenants of private rented properties, or private owners with other / conflicting priorities. It would therefore be advisable to have a wide range of measures available to install, and identify those measures required as appropriate.

To prevent the effects of airtightness measures being reduced by draughts and/or heat loss from elsewhere in a property, ideally they should be carried out as part of 'whole-house' treatment, also addressing any other issues such as single-glazing, draughty internal doors to unheated areas of the property, insufficient insulation, insulation of rooms in the roof and external solid walls, where these measures are possible. A separate study is recommended to monitor the effectiveness of this approach.

Advice should always be provided to all residents at the time of installation, on how to use energy most cheaply, effectively and efficiently in the home, to reduce supplementary heating use in favour of whole-house heating, ensure residents are claiming all benefits for which they are eligible, and that they are on the best energy tariff for their use. Support should also be offered to resolve any billing issues present, as some were discovered as part of this study. In areas off the mains gas network such as this, advice on use of portable bottled gas heaters is also recommended to minimise risks of carbon monoxide poisoning and damp from the moisture they produce.

Ongoing maintenance may be required to maintain the integrity / effectiveness of draught-proofing measures over a longer period, particularly in very exposed areas suffering salty sea winds, as otherwise the useful lifetime of some of these products may be relatively short – cost effectively this might need to be an annual phone call to trigger any checks or works required.

4.3 Impact on fuel poverty

These measures appear to aid efforts against fuel poverty:

- Reducing heating bills by £97 per year on average for phase 1 properties, though savings cannot be reported for phase 2 properties due to variability of costs within the sample;
- Only 4 of the 14 respondents now needed to wear extra warm clothes in the home to keep warm, compared to 13 of 14 at the outset;
- 8 of the 15 householders surveyed said their home now keeps the heat in better, 7 warmer and/or more comfortable, 5 said the house gets warmer faster. A variety of other benefits were mentioned including less noise from outside, and ability to sit near windows for light;
- 4 of the 15 felt their energy bills had reduced, and one further reported being able to heat more of the property for the same money. This had reduced money worries a lot for 1 of the 15 residents questioned, and a little for 4 more;
- 2 of 9 who had suffered any damp, condensation or mould issues felt that were better after the measures were installed. One reported this was worse in a bedroom, this may be due to reduced heating (need), and reduced uncontrolled ventilation so was advised to air the room at the warmest time of the day;
- The impact of these measures could be improved in the future by undertaking a more comprehensive review of the property to identify other improvement measures for whole-house treatment to eliminate all draughts, cold-patches, insulate rooms in the roof and solid walls, replace single glazing or fit secondary glazing.

4.4 Performance comparison against manufacturer's claims

Products from a variety of manufacturers were installed, and neither manufacturers nor installers made specific claims for savings from airtightness measures, therefore this aspect was not tested.

4.5 Economic business case for installation of measures

Table 4.1 below shows the business case for installation of airtightness measures:

Measure	Capital cost	Installation costs	Annual energy saving (this study)	Indicative annual payback	Assumptions
Air-tightness measures	£1,247.5 per property (phase 1) £406.84 per property (phase 2)	Included	£97 Cannot be reported	12.86 yrs Cannot be reported	• No savings were noted in solid fuel, heating oil, and very limited savings in bottled gas costs by households which use these.

Table 4.1 Summary of business case

As savings could only be reported for phase 1 properties – due to wide variability in savings (or otherwise) for phase 2 properties, a payback period can only be calculated for phase 1 treatments. On average a cost saving was calculated for electrically heated properties of £97 for a year which experienced the average number of degree days. This would result in a payback period from these measures of 12.86 years.

The payback period would be longer for properties heated by cheaper mains gas, for example the only mains gas property in this sample made savings of £50.40 when degree-day corrected, but this should not be extrapolated from measurements of only one household.

Savings would be greater if also combined with other measures to improve the insulation, and controllability of ventilation, of these HTT properties – especially those which may attract government ECO (-Flex) or other Welsh government funding.

Appendix 1: Glossary of Terms

CO	Carbon monoxide, toxic gas, product of incomplete combustion of carbon fuels
CO_2	Carbon dioxide, product of respiration and complete combustion of carbon fuels
DD (or dd)	Degree Days
ECO	Energy Company Obligation (scheme requiring energy companies to fund energy efficiency improvements)
ECO-Flex	As above, ECO funding which Councils may apply for to vary the terms so as to better assist with improving the homes of their fuel poor residents
EPC	Energy Performance Certificate
EWI	External Wall Insulation
HIP	Health and innovation Programme
HTT	Hard-to-treat – properties for which the easiest and cheapest insulation measures are unsuitable / cannot be applied.
NEA	National Energy Action – the National Fuel Poverty Charity
RH	Relative Humidity
SAP	Standard Assessment Procedure (for assessing home energy efficiency)
TIF	Technological Innovation Fund
TRV	Thermostatic Radiator Valve

Appendix 2: Health and Innovation Programme 2015 – 2017

The Health and Innovation Programme (HIP) was a £26.2 million programme to bring affordable warmth to fuel poor and vulnerable households in England, Scotland and Wales.
The programme launched in April 2015 and was designed and administered by fuel poverty charity National Energy Action as part of an agreement with Ofgem and energy companies to make redress for non-compliance of licence conditions/obligations. To date, it remains the biggest GB-wide programme implemented by a charity which puts fuel poverty alleviation at its heart.

The programme comprised 3 funds

- **Warm and Healthy Homes Fund (WHHF):** to provide heating, insulation and energy efficiency measures for households most at risk of fuel poverty or cold-related illness through health and housing partnerships and home improvement agencies

- **Technical Innovation Fund (TIF)**: to fund and investigate the impact on fuel poverty of a range of new technologies

- **Warm Zones Fund (WZF):** to install heating and insulation and provide an income maximisation service to households in or at risk of fuel poverty, delivered cost-effectively through partnership arrangements managed by NEA's not-for-profit subsidiary Warm Zones Community Interest Company

What it involved

- **Grant programmes** to facilitate the delivery of a range of heating and insulation measures and associated support. Grant recipients were encouraged to source match and/or gap funding to increase the number of households assisted and to enhance the support provided to them
- **Free training** to equip frontline workers with the skills needed to support clients in fuel poverty
- **Outreach work and community engagement** to provide direct advice to householders on how to manage their energy use and keep warm in their homes

In addition we undertook substantial **monitoring and evaluation** work, to assess the effectiveness and measure the performance of the technologies, and to understand the social impacts of the programme. Our **communications programme** helped partners to promote their schemes locally as well as share best practice with others. The programme generated a considerable amount of **knowledge and insight** which will be made freely available to help support future policy and delivery.

Proper investment of advanced payments allowed us to generate interest which, along with efficiency savings, was reinvested back into the programme in the form of additional grants and support which helped us further exceed our targets.

For more information see www.nea.org.uk/hip

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Action for Warm Homes