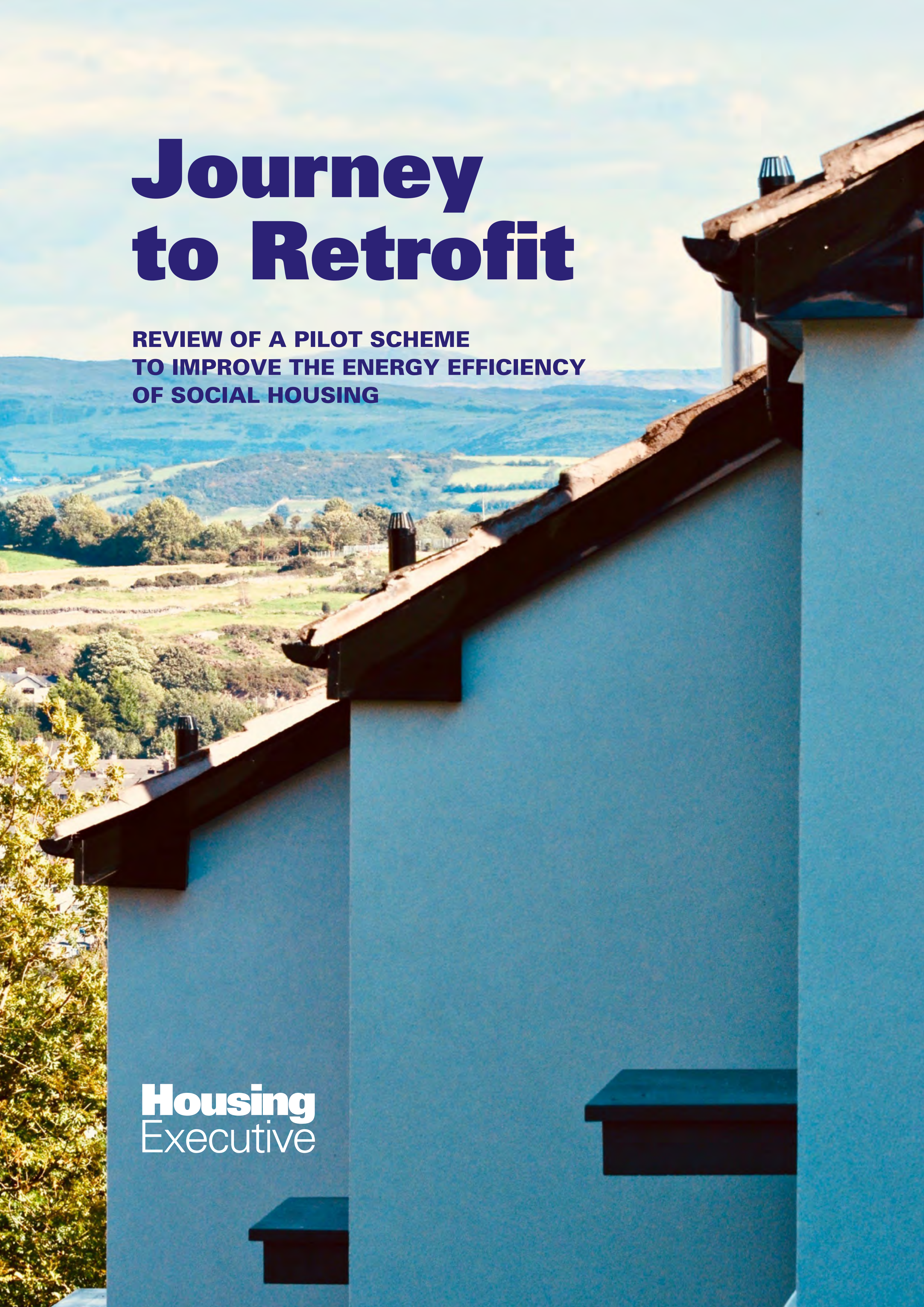

Journey to Retrofit

REVIEW OF A PILOT SCHEME TO IMPROVE THE ENERGY EFFICIENCY OF SOCIAL HOUSING

Housing Executive

Acknowledgements

The Housing Executive wishes to express thanks to the following organisations for their input and assistance throughout the development of this pilot scheme:

MosArt - Passive House specialists

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BlueBuild Developments - Main contractors

Bryson Energy - sponsors of the privately owned property

Foreword

This report, produced by the Northern Ireland Housing Executive (NIHE), gives an account of a retrofit pilot project to improve five houses to different energy efficiency standards. The scheme was completed in 2018, followed by two years of post-occupancy evaluation. The purpose of the pilot was to understand the benefits and challenges of implementing various retrofit measures, which would then inform the strategy for future retrofit schemes on a much larger scale. The aim of this report is to disseminate the lessons learned to stakeholders who may be considering, or are currently undertaking similar retrofit work, perhaps for the first time. This may include, but is not limited to Housing Associations, homeowners, designers, students, policy makers and government bodies. The report describes the process from its very early, ambitious beginnings, to the detailed and target-driven approach finally delivered.

In summary, the five houses were chosen for their similarities in terms of location, orientation, size and layout, making them suitable for comparative purposes to demonstrate the impact of applying different packages of measures. The Standard Assessment Procedure (SAP) was the method of calculation to determine the pre and post-retrofit energy efficiency rating, with one house required to meet a high SAP B, one low SAP B, one high SAP C, one low SAP C and finally a privately owned property that was to meet a SAP C of any level.

The measures implemented include external wall insulation, loft insulation, gas boilers, heating controls, new windows and doors, improved construction detailing to reduce thermal bridges at critical locations, an airtightness strategy, and innovative ventilation systems.

The following is an overview of the outcomes of the scheme, of which more detail can be found in the body of the report.

The house is always warm. Very comfortable.

New tenant

75.5%
average reduction on CO_2 emissions rate

45.3%
average decrease in total fabric heat loss

195%
average improvement on pre-retrofit SAP scores

This project places the Housing Executive in a good position to meet the requirement of nearly Zero Energy Building.

Steven Stenlund, BRE

20.3°
average post retrofit temperature (3.4° increase on pre retrofit)

£748
average reduction in fuel bills

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Introduction

Introduction

Nine years prior to the UK's commitment to reach net zero greenhouse gas emissions (GHG) by 2050, the Housing Executive embarked on a pilot project to improve the efficiency of its typical housing stock far beyond statutory requirements. At the time, deep retrofit to existing buildings was a relatively new concept, particularly in Northern Ireland. Subsequently in Britain, there have been major failures in retrofitting within 'Green Deal' and 'Energy Company Obligation' schemes, resulting in damp and unhealthy homes. A notable omission from the Green Deal, but included in this project, was ventilation provision. Retrofitting carries inherent risks, but initiatives such as the Bonfield review "Each Home Counts" have since attempted to provide guidance on best practice, paving the way for more successful retrofit programmes.

Over 25% of GHG emissions are attributed to domestic energy use in the UK, which suggests that significant improvements could be made to reduce carbon emissions within this sector. The construction industry uses many standards and assessment methods through which sustainable buildings can be designed, assessed and delivered, such as the Code for Sustainable Homes, Passive House and SAP. These assessment tools are most commonly used for new-build scenarios, however achieving similar standards in a retrofit situation is a more challenging task. In fact, the complex nature of upgrading existing buildings has led to the development of new, more tolerant assessments such as EnerPHit and BREEAM Domestic Refurbishment, specifically designed to achieve the best results possible within the limitations of an existing structure.

As the largest Landlord in Northern Ireland, responsible for properties built mostly before 1990, the Housing Executive is conscious of the responsibility it faces to reduce emissions in the social housing sector, and in its 'Home Energy Conservation' role, in resolving appropriate upgrades for private homes. Whilst fuel costs and low incomes remain the major causes of fuel poverty, these factors cannot be readily influenced by Landlords. To improve matters and protect occupants against any future rise in fuel costs, it is necessary to investigate ways to conserve energy and reduce heat loss in conjunction with the integration of innovative systems and renewable energy resources. A deeper, future-proofed approach to retrofit embedded into planned maintenance schemes would provide more cost effective, long-term benefits to both occupant and Landlord. By improving energy efficiency, we can provide warmer, healthier homes and prolong their useful life, potentially reducing the frequency and duration of void properties, rent arrears and housing management costs.

This pilot project was one of the Housing Executive's first systematic explorations into energy efficient retrofit, which evolved over time until its completion in the summer of 2018. Through this, it has become apparent that the "Fabric First" approach adopted here, wrapping the outside of the heavy walls with insulation, is also compatible with storing and benefitting from more heat produced by local wind and sunshine, and with limiting the costs of electricity system investments. The project has fuelled the organisation's drive for continuous improvement through sustainability and innovation. It has provided real-world experience and evidence-based information that has elevated the Housing Executive as an industry leader in domestic retrofit, and influenced its strategic approach to climate change.

2 Scheme objectives

2.0 Scheme Objectives

When this pilot was first initiated, there was arguably a less established retrofit industry in Northern Ireland compared with the rest of the UK. The level of design expertise and tradesperson skills required to execute intricate low-energy construction detailing was not widely available in Northern Ireland, particularly in the social housing sector. The pilot scheme afforded the Housing Executive experience in navigating this supply issue to deliver cost effective energy efficient retrofit measures.

The main objective of the scheme was to trial a variety of energy improvement measures that would reduce the likelihood of fuel poverty and increase comfort, to ultimately reduce heat loss and energy costs, and improve indoor air quality. Although Social Landlords can benefit from reduced housing management costs in more energy efficient homes, as well as increased capital values, the occupants are the main beneficiaries of such investments.

The objectives:

1. To inform the NIHE 10 year Energy Efficiency Strategy by identifying the most economically viable approach to maximise energy savings, reduce heating bills and improve the thermal comfort and air quality of our housing stock.
2. Upgrade properties to the Commonly Adopted Standard (CAS) as a minimum.
3. To broaden the understanding of sustainable building practices across the local construction industry to improve construction standards and tradesperson skills.
4. To raise the profile of the NIHE and its commitment to reducing fuel poverty, and to establish itself as a leader in innovation and sustainable construction in the social housing sector.

The completion of each objective has been assessed through measureable targets referenced throughout this review. The focus is to demonstrate a tangible improvement between the pre and post retrofit status of the houses in terms of SAP scores, temperature and relative humidity levels and fuel costs. The research also investigates the benefit of each measure against its cost, taking into consideration heat-loss reduction and carbon savings.

3 Project background

3.0 Project Background

This project dates back to 2010 when it was originally submitted as a bid for funding through the Technology Strategy Board (TSB), now Innovate UK. The bid was unsuccessful due to an oversubscribed number of applicants. However, the Housing Executive recognised the benefits of such a scheme and agreed to self-fund the project instead. The concept was to retrofit a terrace row of five almost identical houses in Newry to increasing levels of energy efficiency. The houses were perfect for research and comparative purposes, being of similar design, construction and orientation.

Initial designs included the refurbishment of one house to the Passive House EnerPHit standard and one to the BREEAM Domestic Refurbishment Standard, amounting to a construction cost of approximately £400,000. MosArt architects and Passive House specialists were commissioned to design the EnerPHit solution in one property that would have required major renovations including the addition of a new south facing living space to maximise advantageous solar gain (Fig. 3.1). The project team felt it would be imbalanced to offer an extension to one property and not to the others, but adding this to all properties significantly increased the cost of the scheme, making it unfeasible.

Regretfully, as the scheme would be funded mainly through the public purse, the extent of the content had to be value-engineered, essentially ruling out a truly deep retrofit package. Consequently, this resulted in a proposal that better represents the scope of works the Housing Executive could realistically afford to implement at scale.

Fig. 3.1: Southfacing extensions

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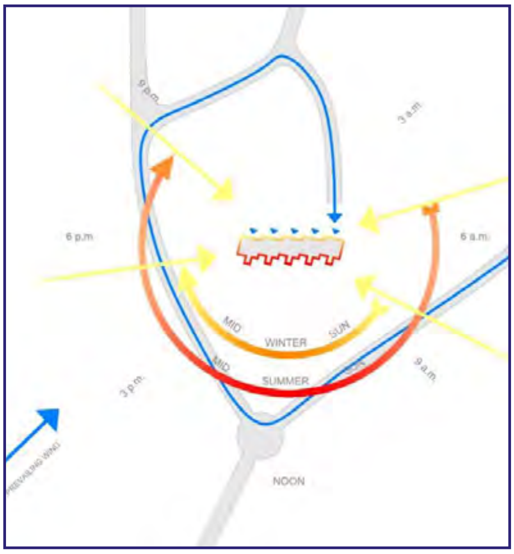
Scheme proposals

4.0 Scheme Proposals

The original concept to renovate the properties to increasing levels of energy performance targets was upheld, so that they could be compared to one another in terms of improved energy performance and cost. More modest target SAP scores were set and the packages of work were designed to maximise the impact of the reduced budget. The pre-retrofit properties started with a SAP score of 41-42 E and the target SAP scores aimed to achieve a High B (86+), a Low B (81-85), a Low C (69-74) and two properties achieving a High C (75-80).

Designing different measures for each house allowed the project team to evaluate the most beneficial energy improvement methods in terms of construction costs and potential energy savings. This offered a unique opportunity to compare the performance of each approach across the five almost identical houses, against current market prices, which could be used to project future expenditure. The proposals included a broad range of 'fabric first' solutions as well as energy saving and renewable technologies. In addition to the reduction of carbon emissions and fuel costs, the effect of the retrofit on the occupant's comfort levels would also be monitored in terms of internal temperature and humidity. Before upgrades, occupants who would normally struggle to afford sufficient heating may be forced to suffer uncomfortable conditions during the coldest months. The pilot scheme would test the theory that occupants should experience an increase in the number of comfortable days throughout the year where the houses are warmer (18° - 21°) and dryer for longer, requiring little or no heating.



4.1 Site Analysis

During the conception phase of the scheme, the Housing Executive's Corporate Services Division was asked to participate in the Greater Newry Vision - Sustainable Energy Group, as part of the Newry Sustainable Energy Zone. Conceived by Newry and Mourne District Council in 2009, the group designated a sustainable energy zone in the heart of Newry City. Its aim was to collaborate with government departments, agencies, private businesses, commercial, voluntary sectors and local residents to examine ways of creating a sustainable energy environment within the zone. The group's target to increase the amount of heat and electricity produced by renewable sources to 20% aligned with the objectives of our proposed scheme so it seemed fitting to identify a row of Housing Executive properties within the Newry Sustainable Zone to act as subjects for the research. The chosen site had other benefits such as good access from the main road and plenty of open space for builders' compounds and storage. The houses have south facing gardens and excellent views over Carlingford Lough, and they have mostly enjoyed long-term tenancies. However, it is also an elevated and exposed site, and the occupants would regularly comment on how difficult and costly they were to heat.

4.2 Pre-retrofit Dwellings

The subject dwellings are very typical of the majority of Housing Executive stock, meaning that any solutions resolved through this pilot could be replicated at scale. There are three mid terraces and two end terraces, all with three bedrooms, a living room and a kitchen/dining room. For the purposes of this report the five houses are referred to as House A, B, C, D & E. They are constructed of rendered blockwork with cavities filled with mineral fibre, which was found to be inconsistent in density. Before the retrofit, the houses had double-glazed windows with timber frames, oil-fired central heating and a number of inherent thermal-bridges, particularly at the eaves where a concrete boot lintel spans the cavity, creating cold spots on the inside.

Four of the houses belong to the Housing Executive, while the fifth is privately owned. The work to the private dwelling was funded jointly by grant aid from Bryson House and external funds held by the Housing Executive's Energy Conservation Unit, consisting of accumulated interest on previous EU funding. The funding for the private property enabled thermal continuity around the entire block, as well as a complete aesthetic transformation of the terraced row.

5

Energy upgrade measures

5.0 Energy Upgrade Measures

The scope of works for each house was built up gradually to meet its proposed target SAP score. This was based on the expected energy improvement of each measure calculated in SAP and a 'shopping list' of corresponding tendered rates gleaned from the procurement of the original scheme.

At the beginning of the project all houses were occupied, meaning the extent of work was restricted to avoid major disruption to occupants. When one house in the terraced row became unoccupied during the design phase, it was agreed to retain it as a void property for the duration of the works so that intrusive measures could be implemented without major disruption to occupants. The extent of works to this house was increased to meet the high SAP B target, including increased EWI thickness, improved thermal bridge detailing and a whole-house air tightness strategy. The remaining houses were still occupied and decanting[1] arrangements had to be made for a period of approximately 1-2 months during construction. Without decanting, the scheme would have become a lot more complex and prolonged.

The types of measures applied to the houses fell into two categories, 'Fabric First' and 'Technology and Renewable Energy', though the main focus was to upgrade the fabric to reduce the space heating demand.

The scope of work differed from house to house as described in the following sections, but generally included external wall insulation, new gas heating, new windows and doors, upgraded loft and eaves insulation, ventilation, airtightness measures and new downstairs sanitary accommodation. The final works content applied to each individual house can be found in Appendix B.

1. Temporary relocation of occupants during the construction period.

5.1 Fabric First

The fabric first measures included external wall insulation wrapped around the entire terrace, with 130mm expanded polystyrene fitted to Houses A, B, C & E, and 210mm fitted to House D. The cavities, which were poorly filled with mineral fibre insulation, were topped up to the recommended density, including party walls, which were found to be empty[2]. Additional loft insulation was installed, with additional PIR insulation inserted between rafters at the wall to roof junction to address the thermal bridge at this point. Other areas of thermal bridging were also addressed, such as the window heads, jambs and sills. Existing concrete window sills were either over-clad or replaced with EPS insulated Passive Sills, and new Energy 'A' rated double glazed windows and GRP doors were installed. Two of the houses had specific airtightness measures applied, which are discussed in more detail in section 6.2 Air Permeability.

5.2 Technology and Renewable Energy

The renewable energy measures included a solar hot water system to House B and a 1.7kW PV system to House D. Higher SAP ratings could have been achieved by using more renewable energy in the other houses however, the cost of on-going maintenance is a major concern for Landlords, particularly if such measures are to be installed at scale. Improving the building fabric reduces the overall heat load, making the houses more suitable for heat pumps, which could eventually replace the gas boilers.

Other technologies installed includes two whole-house ventilation systems in Houses C and D, and a smart thermostat in all Housing Executive houses that operates the heating and hot water.

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2. In most situations topping up mineral fibre insulation would not be recommended, but in this instance, with the walls protected by EWI and render, it was the simplest way to mitigate thermal bypass in the cavity.

5.3 Retrofit Detailing

When developing this scheme there was a strong emphasis on designing out thermal bridges that would potentially lose more heat as the wall insulation thickness increased. In their pre-retrofit state, the thermal bridges in some cases were actually lower than the SAP 2012 approved psi value because the heat loss from the wall, floor and roof was so great. Increasing insulation to each element intensifies heat loss at any unresolved thermal bridges, so in order to assess possible solutions to this, multiple variations of the weakest junctions were developed and applied to each house. THERM software was used to calculate the psi values at eaves, lintels, jambs, sills and ground/ floor wall junctions. The result of this research is discussed in detail in the section 6.4 Thermal Bridges.

5.4 Ventilation

The UK retrofit movement has learned a lot from experience, and ventilation has emerged as an essential retrofit measure, particularly when insulation is being upgraded. Social housing stock in Northern Ireland suffers from the same moisture related issues as those across the UK and Ireland, with notably increasing cases of severe mould and condensation in recent years. The current standard in Housing Executive properties is to install intermittent extract fans in kitchens and bathrooms as per Building Regulations. These may prove ineffective when properties are heavily insulated and made more airtight. Positive input ventilation units are often installed in the loft when there are complaints about mould and condensation with varying success, often being disabled by the occupant due to cold drafts, but proving effective in other cases.

This pilot aimed to investigate alternative means of ventilation that are easily installed, operated and maintained, in a practical and affordable way. There are many different systems available and perhaps the most restricting factor is the availability of space within the houses. Mechanical ventilation heat recovery (MVHR) could save energy, although it is challenging to accommodate duct routes in the typically small rooms and low ceilings within social housing. MVHR also requires very low air permeability to work effectively, which can be costly and disruptive to achieve in existing, occupied houses. Ducted systems are only as good as the installation, and are susceptible to higher than expected energy consumption and inadequate indoor air quality when poorly installed.

Demand-controlled mechanical extract ventilation was considered an energy efficient alternative that would adapt to the needs of the occupants to avoid under or over-ventilation. The scheme trialled two different types of demand-controlled ventilation: a centralised system and a de-centralised system.

5.4.1 Centralised Mechanical Extract Ventilation - CMEV

This is an Aereco system that consists of a centralised fan unit installed in the loft of House D. It requires ducting for extraction only, and demand-controlled supply inlets in each habitable room. These are provided in the form of trickle vents in this case, although wall mounted vents can also be used. The system utilises Aereco's Hygro control sensor that exploits the expansion

and contraction of a nylon strip when exposed to moisture, offering a natural and energy-free method of controlling the aperture size of ventilation grilles. Openings increase in size as humidity rises, allowing more fresh air when it is needed. Equally, the ventilation unit increases the rate of ventilation as it senses an increase in humidity. The unit has washable filters, so there is no expense in regularly replacing these, though as the unit is in the loft, access can be a problem. The performance does not depend on low air permeability and acoustically the unit is designed to operate at low noise levels (33dB(A) @ 40m^3/h) to address the concern that occupants may find it a nuisance and have it disconnected.

Throughout the duration of the monitoring period, the occupants of House D have been very happy with the ventilation system. They have little interaction with it and allow it to operate as required. There was one incident recorded when the fan unit stopped working due to a blown fuse, and there are issues regarding who exactly is responsible for the regular maintenance to clean the filter. This is something that will need to be addressed in future schemes prior to the specification of similarly non-typical items.

5.4.2 De-centralised Whole House Smart Ventilation - D-WHSV

In House C, a de-centralised smart ventilation system called Think.Air was installed, which has been designed locally in Northern Ireland. Think.Air is a whole-house, balanced ventilation system that operates without ducting, supplies fresh filtered air into habitable rooms and extracts polluted air from the wet rooms.

This prototype technology has recently been awarded BEIS Net Zero disruptive innovation funding to further develop its capabilities and bring it to market. The BEIS project will include developing artificial intelligence that enables the ventilation system to interact with the heating system to create a whole system approach to reduce energy and CO_2 emissions.

As this is a prototype, real-life testing has enabled the developers to adjust and improve the system. The first installation proved the concept of airflow utilising re-purposed fans from proprietary ventilation units, with sensors incorporated to measure temperature and relative humidity. Initially, the system was connected to the cloud via the occupant's broadband router so that indoor environmental conditions could be displayed on a web-based dashboard. Problems with intermittent data transfer between the occupant's broadband router and the cloud were detected, so to bypass the need for the household to have broadband, cloud connection is now available via 4G and LoRaWAN.

From the outset, the occupants expressed an interest in trialling the ventilation system and gave valuable feedback, which led to adjustments and the development of new aspects and functions. The occupants reported fan noise from the first installation, so a new fan was developed and 3D printed which improved the balance of the impellers and reduced the noise. Another problem encountered was that the occupants would block off the ventilation units to prevent excessive, cooler, fresh air being supplied into the house, particularly during times of high wind speed. This is a common problem with ventilation systems and the developers of Think.Air have designed an automated air valve to address this problem.

The data logging capability was also upgraded with CO_2, VOC and IAQ sensors in each room and a flow sensor has been developed that raises an alert on the dashboard if the fan has been disabled.

The dashboard has become more user-friendly since the first installation and now operates a traffic light system to indicate whether levels of pollutants are considered safe or harmful. In future, a Health Prompt facility will alert the occupant to indoor pollution levels, the source from which the pollution originates, the impact this could have on health and the recommended mitigation measures.

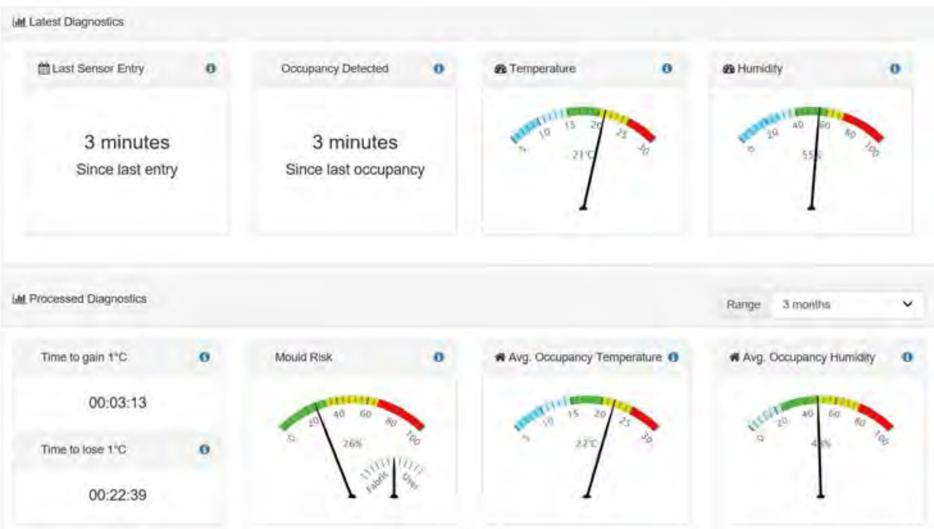
5.5 Smart Heating Controls and Monitoring

In the four Housing Executive homes, a Switchee Smart Thermostat was installed. This is an autonomous space and hot water heating controller that learns the occupant's routines over time. It has a simple, easy to use interface, it records temperature and humidity at the unit itself and it displays the data it gathers via an on-line dashboard (Fig. 5.1). Information is displayed on the dashboard for each property such as how quickly the house gains or loses 1°C, the risk of mould and the average temperature and humidity, as well as the latest sensor reading. The home page of the dashboard displays comparative information for all houses where the client has Switchee units installed. It ranks the properties in terms of the highest mould risk, most at risk of fuel poverty, highest humidity and the most at risk of overheating.

This data allows Landlords to see at a glance if there are any issues, so they can be dealt with in a timely manner and before any severe, moisture-related defects emerge. Coupled with the ability to contact the occupant to arrange visits and even to test the boiler remotely, having access to internal sensor data in this way is a great step towards the smart management of fuel consumption, improving occupant comfort levels and Landlord's maintenance obligations.

Perhaps the most intuitive aspect of the Switchee is the inter-dependence between data collection and heating controls. This addresses problems of occupant interference that Landlords face when introducing any new technology into their homes. Occupants are less likely to disable a system connected to the heating controls than if it was a standalone system, thus increasing the chances of gathering continuous data.

Figure 5.1: Switchee Dashboard



6 Measured improvements

6.0 Measured Improvements

To demonstrate the impact of the retrofit on each property the improvements have been measured and analysed in respect of SAP results, air permeability, temperature and humidity, and thermal bridge calculations.

6.1 SAP Results

Table 6.1 shows the improvement made to the SAP score of each house, indicating that all targets were met and the energy performance of each property improved by between 36 to 46 SAP points. The energy assessment also provides the CO_2 emission rate, which fell by 71% to 84%, and the total fabric heat loss, which fell by 40% to 51%.

Table 6.1: SAP, Carbon Emissions and Total Fabric Heat Loss Per Property

SAP (2012)	House A	House B	House C	House D	House E
Pre Retrofit (SAP E)	42	41	41	41	42
Target	Low C (69-74)	Low B (81-85)	High C (75-80)	High B (86 +)	C (69-80)
Post Retrofit	78	81	79	87	78
IMPROVEMENT (% increase)	186%	198%	193%	212%	186%

Total CO_2 Emission Rate kg/yr/m²	House A	House B	House C	House D	House E
Pre Retrofit	87.75	90.85	90.85	90.85	87.75
Post Retrofit	24.94	20.26	23.33	14.33	26.43
IMPROVEMENT (% decrease)	71.58%	77.70%	74.32%	84.23%	69.88%

Total Fabric Heat Loss W/K	House A	House B	House C	House D	House E
Pre Retrofit	171.74	166.99	166.99	166.99	171.74
Post Retrofit	102.29	89.24	88.71	81.36	100.54
IMPROVEMENT (% decrease)	40.44%	46.56%	46.88%	51.28%	41.46%

6.2 Air Permeability

The air permeability of the pre-retrofit houses had an average value of 17 m³/(h.m²). This was based on two tests carried out to House A and House C using the blower door method. When the test to House C was carried out there was damage to the first floor ceiling which was not sealed, which accounts for the very high value. It was agreed this could not be a true reflection of the typical air permeability and so the value recorded for House A was applied to the remaining houses. The improved target value was set at 5 m³/(h.m²) for Houses A, B & C, 10 m³/(h.m²) for House E, the privately owned home, and 3 m³/(h.m²) for House D where the full airtightness strategy would be implemented. The experience gained from this pilot has proven how difficult it can be to achieve anything more than a 10 m³/(h.m²) improvement on pre-retrofit air permeability without severe disruption, and this is reflected in our post retrofit results.

Table 6.2: Air Permeability Per Property

Air Permeability $m^3/(h.m^2)$	House A	House B	House C	House D	House E
Pre Retrofit	15.76	15.76	22.14	15.76	15.76
Target	5	5	5	3	10
Post Retrofit	7.81	8.57	7.63	2.66	7.08
IMPROVEMENT (% decrease)	50.44%	45.62%	65.54%	83.12%	55.08%

Table 6.2 shows the target was met in two of the houses, most notably House D where the air permeability fell by 83% to 2.66 $m^3/(h.m^2)$. This was achieved by using airtightness tapes around openings, a membrane at 1st floor level, a plaster parge coat on the inside face of the external walls, and through targeting typically leaky areas such as around 1st floor joist ends and at ground floor to wall junctions. This intrusive work was only made possible by the fact this was a void property at the time. The remaining properties achieved an average of 7.8 $m^3/(h.m^2)$, ranging from 7.08 to 8.57 $m^3/(h.m^2)$. This is noteworthy as Houses A, B and E had no specific airtightness measures, meaning the reduction in air permeability was achieved purely through the application of the EWI and installation of new windows and doors. Whereas House C received airtight tape around openings, but did not result in significantly lower air permeability compared to the others. This result could suggest it is unnecessary to apply tape around windows and doors during cyclical schemes. However, doing this as an incremental measure when the opportunity arises, such as when windows and doors are replaced, would contribute to a long-term strategy for the overall improvement of air tightness. This may involve membranes, plaster coats and joist-end taping, carried out when practical, such as during changes of tenancy, multi-element improvement schemes, or when fire or water damage occurs.

6.3 Monitoring Results

The primary objective for this pilot scheme was to identify the most economically viable approach to maximise energy savings, reduce heating bills and improve the comfort of our housing stock. The temperature and relative humidity (RH) of an indoor space play a pivotal role in ensuring the health and comfort of the occupants. Typically, temperatures need to be between 18°C and 21°C and RH should be between 40% and 70%. Air that is lower than 40% RH is too dry and will generally cause discomfort such as a dry throat or may aggravate existing respiratory conditions, whereas RH above 70% could lead to surface condensation and mould growth, especially when insulation is lacking.

The Building Research Establishment (BRE) analysed the temperatures and relative humidity in the five houses, based on pre and post-retrofit data. The purpose of this was to bring to light any change in comfort levels experienced by the occupants after the work was complete. BRE used data loggers to record both temperature and relative humidity in the kitchen, living room and master bedroom of each house. The pre retrofit data was recorded between 21st December 2014 and 31st May 2015 at 30-minute intervals. The full pre-retrofit report from BRE can be found in Appendix C. In summary, each house suffered from under-heating, particularly in the bedrooms, with some experiencing intermittent instances of very high humidity. The report highlights that these conditions could cause condensation and mould growth, although there was also evidence that windows were being opened which would alleviate this. In some instances, it was clear the occupants chose to heat one room in the house the majority of the time rather than heat the whole house. These findings are consistent with complaints from the occupants who reported the houses had poor heat retention, leading to high fuel bills which they struggled to afford.

Following the completion of the retrofit scheme, a further data set was recorded between 13th October 2018 and 11th March 2019. Data loggers were placed in the kitchens, living rooms and master bedrooms of all houses and readings were again recorded at 30-minute intervals. BRE analysed the recordings against the pre-retrofit data, focusing on the percentage of time the rooms maintained the preferred temperatures of 18-21°C and acceptable relative humidity of 40-70%. Fig 6.1 and Fig. 6.2 show the post retrofit data and the difference between this and the pre-retrofit data. The commentary for each house from BRE is summarised below and the full report from BRE can be found in Appendix C.

House A

The average temperature of each room ranged between 20°C to 21.2°C and the average humidity sat between 49%-58.5%. There are few instances of over-heating; however, the living room showed signs of under-heating for a proportion of the time, indicating significant swings in temperature. On average across the three rooms, temperatures fell within the 15-25°C acceptable range for 97.1% of the time. In terms of humidity, there were a few instances when less than 40% RH was recorded in the living room and most notably in the kitchen, though generally the relative humidity was within the 40-70% acceptable range for 96.1% of the time. Unfortunately, this property was not included in the pre-retrofit monitoring and therefore a comparison cannot be made between the pre and post-retrofit results.

House B

The average temperature of each room ranged between 20.1°C to 20.7°C and the average humidity sat between 55.5%-61%. There was negligible overheating, occurring less than 2% of the time. Compared with the pre-retrofit data, this property experienced substantially less under-heating in the bedroom (0.1%), demonstrating an improvement of 17.5%. On average across the three rooms, temperatures fell within the acceptable range of 15-25°C for 99.3% of the time, up from 93.1% pre-retrofit.

The living room and kitchen also exhibited significant improvements in terms of humidity. Prior to refurbishment their relative humidity was outside the acceptable level of 40-70% for around 20% of the time, whereas following refurbishment the relative humidity of all three rooms fell within optimal levels for 99.7% of the time, up from 62.3% of the time pre-retrofit.

House C

Data from House C shows almost no overheating above 25°C aside from a small amount in the living room, and no significant under-heating. This contrasts with significant under-heating prior to refurbishment, especially in the living room, which was under-heated for almost one fifth of the time. On average across the three rooms, post-refurbishment temperatures sat within the acceptable range of 15-25°C for 98.2% of the time, up from 85.6% pre-refurbishment. Humidity also sat within an acceptable range of 40-70% for the majority of the time.

House D

This dwelling exhibited no significant over or under-heating and all rooms were within the acceptable range of 15°C to 25°C 100% of the time, up from 60.4% before the retrofit. The kitchen and bedroom displayed good humidity characteristics, though the relative humidity of the living room did rise above 70% for a small portion of the time. The percentage of time that relative humidity sat within the acceptable range of 40-70% rose from an average of 52.1% RH to 94.4% post-refurbishment across the three rooms. The data suggests this property enjoys substantially improved indoor air quality compared with pre-retrofit conditions, when the property was under-heated for much of the time and the living room was often above 70% RH.

House E

Although this dwelling did not display many instances of significant over or under-heating, there were some significant temperature fluctuations, both spatially and temporally. The living room was heated to between 18-21°C for around two thirds of the time, above 21°C approximately a quarter of the time, with small proportions of time spent above 25°C and below 18°C. The kitchen was adequately heated for almost all of the time studied, but varies slightly from the living room in that it was heated above 21°C for less time and below 18°C for more time. The bedroom was also not significantly over or under-heated, but was mostly below 18°C, with the remainder spent at 18-21°C, and virtually no time above 21°C. The data shows great improvement compared with the pre-retrofit situation, which had an average temperature ranging from 14.6°C in the kitchen to 16.2°C in the living room, which was significantly under-heated much of the time. On average across the three rooms, temperatures sat within the acceptable range of 15-21°C for 97.7% of the time, up from 61.2% pre-retrofit.

Relative humidity very rarely sat outside of the acceptable range of 40-70%, which was largely the case prior to retrofit, except in the bedroom, which was above 70% RH for 16.5% of the time prior to refurbishment and then 1.1% of the time after refurbishment.

Fig 6.1: Difference between Pre and Post Retrofit Temperature

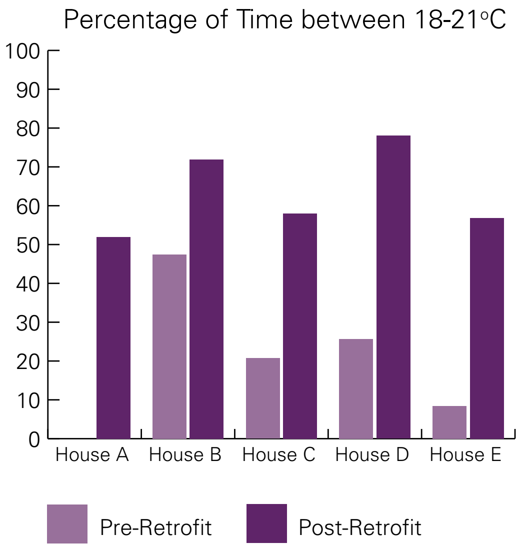
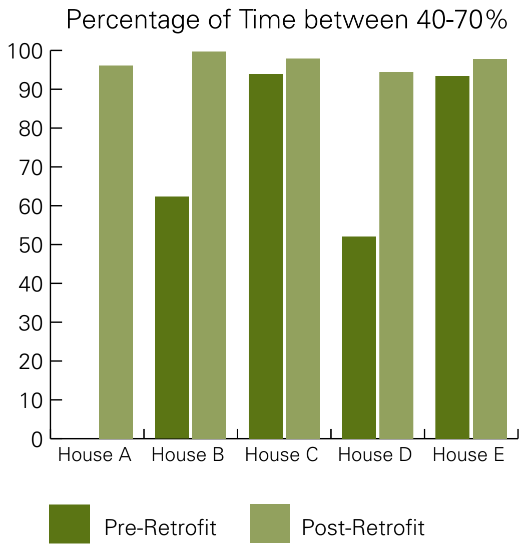


Fig 6.2: Difference between Pre and Post Retrofit Relative Humidity



The graphs show the performance of each property. Overall, the houses spent an average of 63.3% of time between 18-21°C, an improvement of 37.8%. The humidity levels sat between 40-70% for 97.2% of the time, a 22% improvement on the pre-retrofit data.

Referring specifically to House D, this property experienced the greatest improvement in relative humidity with an increase of 42.3% in the time spent within the desired parameters. Notably, there was a change of tenancy between pre-retrofit and post-retrofit monitoring. Differences in occupant behaviours may have contributed somewhat to the change in humidity levels, but this is unlikely to have had as great an impact. Considering the air permeability of this house has decreased by 13m³/(h.m²), the amount of uncontrolled air infiltration has been significantly reduced. This potentially could have resulted in high humidity levels and moisture problems if left unaddressed, but has been mitigated by introducing the demand-controlled ventilation, which manages the moisture and maintains a comfortable humidity level.

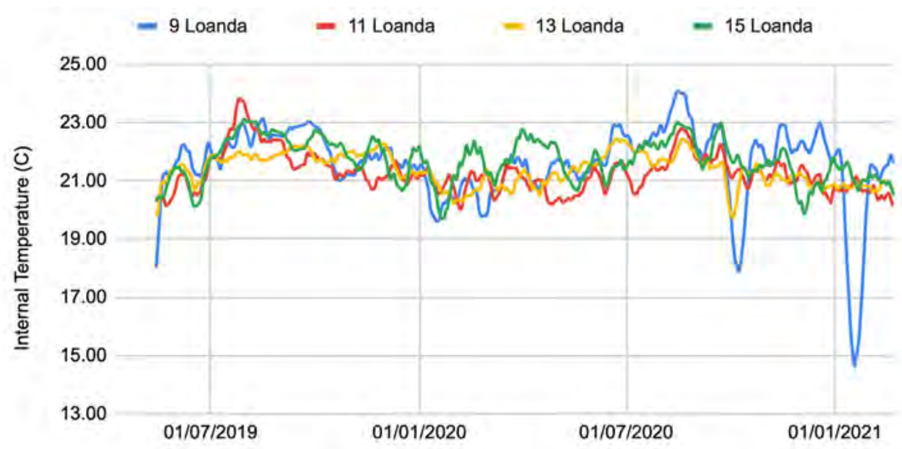
6.3.2 Continued Monitoring

In addition to the monitoring by BRE, Houses A, B, C & D continue to be monitored by the Switchee smart thermostat installed in the hallway of each property. This provides live data on the temperature and humidity of each house and alerts the Landlord to any issues that occur.

The graphs in Fig. 6.3 have been generated from data collected by the Switchee unit from July 2019 to January 2021, and these along with additional graphs and comparisons drawn between House B and House D can be found in Appendix D.

Fig. 6.3 Switchee Data - Temperature and Humidity

Internal Temperature (C)



Relative Humidity (%)

The Switchee Analyst has drawn the following conclusions from data analysed:

House B has comfortably the lowest absolute and relative humidity across the year and in winter. This could be because they use their heating the most in winter.

House D uses the heating the least in winter (91 minutes per day - over 50% less than House B) yet its internal temperature in winter is the highest (21.4C).

Meanwhile, House B, which uses its heating the most in winter (200 minutes), has the lowest avg. internal temperature. This is almost two hours extra heating per day in winter, for 1.54% less heat.

The internal temperatures of the properties remain remarkably similar in winter compared to the rest of the year, suggesting the homes are well insulated.

6.3.3 Conclusion

The results undoubtedly show a substantial improvement to both the performance of the properties and the indoor comfort conditions. Unsurprisingly, House D enjoys the greatest transformation with an increase of 46 SAP points, an 84% reduction in CO_2 emissions and a decrease in air permeability of 13 $m^3/(h.m^2)$.

Monitoring temperature and humidity before and after retrofit works gives a more accurate indication of the actual performance of the property compared with SAP calculations. SAP is based on standardised criteria and focuses on predicting fuel usage and expenditure based on assumptions relating to occupancy numbers and time-periods that generate estimates for heating, hot water and electricity usage. Other factors that influence indoor air quality that have not been monitored in this scheme such as CO_2, VOC's, and radon that can have a serious impact on health and well-being, would be worthwhile monitoring in future schemes.

6.4 Thermal Bridges

Aside from reducing heat loss through walls, floors and roofs, the interfaces between different materials and elements need to be considered. If left unprotected, junctions around openings and at ground and ceiling level will contribute to the overall heat loss of a building. An expected output from this pilot scheme was to develop standard retrofit details that could be integrated into planned maintenance schemes and repeated at scale. To achieve this, different solutions for typical junctions were modelled using THERM software to calculate the heat loss and lowest internal surface temperature at the junctions. Each detail was analysed in terms of both energy performance and ease of installation on site. The following sections describe the various approaches taken to address the eaves, lintel, jamb, sill and ground floor/wall junctions, highlighting what worked well and could realistically be carried forward as standard procedure in future schemes.

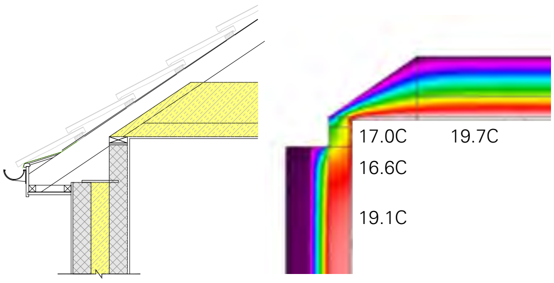
6.4.1 Retrofit Detailing - Eaves

The pre-retrofit eaves detail suffered from two main issues, the concrete boot lintel above the windows that spans the cavity, and the narrow gap between the wall plate and the roof that restricts the thickness of insulation where the ceiling meets the wall. In houses of this era, the interface between the wall and the ceiling commonly presents with mould, as warm, moist air rises and travels towards areas of lower temperatures. In this scheme, two solutions were installed with different types and thicknesses of higher performing insulation.

The pre-retrofit status essentially relied on mineral fibre loft insulation being pushed down from the loft as far as possible, and due to the stagger between the inner and outer leaf of blockwork restricting access, it is difficult to fill the gap to connect with the cavity wall insulation. Fig 6.4 shows the thermal model and internal surface temperatures of the pre-retrofit detail, and proposed Options A and B.

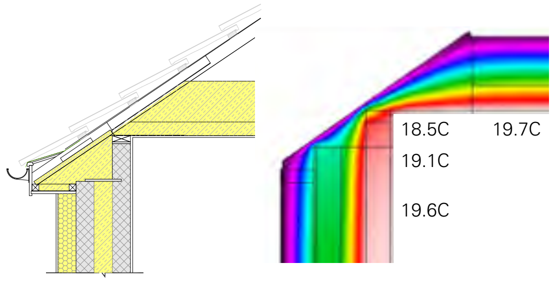
Fig. 6.4 Eaves Details and Corresponding Thermal Models

Pre-retrofit Eaves Detail: 0.38 W/mK



The pre-retrofit construction consists of 300mm mineral wool loft insulation and cavity wall insulation.

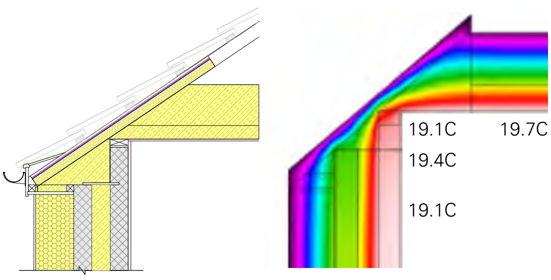
Proposed Option A: 0.13 W/mK



Houses A, B, C & E - 25mm PIR, Mineral Fibre Insulation

This option was designed to avoid the need to remove the bottom four rows of tiles by inserting a 25mm board of additional PIR insulation board between rafters via the soffit. However, this proved impractical on site and the contractor very quickly opted to gain access from the roof tiles above.

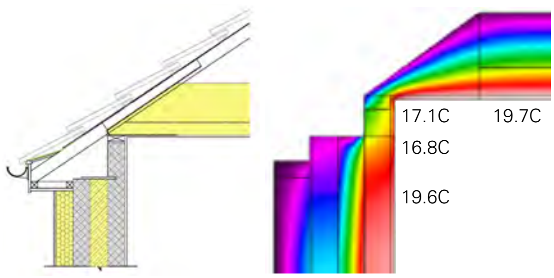
Proposed Option B: 0.08 W/mK



House D - Aerogel, 50mm PIR, Mineral Fibre Insulation

This option called for the removal of four rows of tiles, battens and roofing membrane to access the rafters and fit 50mm PIR insulation between, held down with battens to create a minimum 25mm ventilation gap and to push against the mineral fibre loft insulation, which covered the wall plate and filled the gap above the soffit. An additional layer of 10mm aerogel was wrapped tightly over the rafters and across the PIR to maintain the ventilation gap whilst increasing the thermal performance.

Hypothetical Option C: 0.48 W/mK



This detail was not executed on site but is included to demonstrate the impact of adding loft and external wall insulation, without addressing the lack of insulation above the wall plate.

Eaves Detail Analysis

Both Options A and B show an increase in the internal temperature of 1.5°C and 2.1°C respectively, due to the increased wall and eaves insulation. Table 6.3 shows the psi values for each detail as well as the resultant average heat saving gained from the thermal bridge measures [3] when compared to both the pre-retrofit and SAP 2012 default psi values. Option A does not quite meet the default psi value, whereas Option B is considered thermally bridge free. Both Options reduce heat loss from the eaves junction as expected, compared to hypothetical Option C where no additional PIR is installed. The psi value of Option C increased by 0.1 W/mK after the improvement works meaning it loses more heat than both the default and the pre-retrofit detail. It is clear this location could become problematic if not properly addressed when loft and wall insulation is increased.

Table 6.3: Eaves Detail Analysis

Eaves Detail	Description	Default Psi Value (W/mK)	Psi Value (W/mK)	Average heat saving compared to Pre-Retrofit (W/K)	Average heat saving compared to Default (W/K)
Pre-retrofit	Cavity wall insulation / 300mm mineral wool to roof void	0.12	0.38	-	-
Option A - Houses A, B, C & E	130mm EWI / Cavity wall insulation / 300mm mineral wool to roof void / 25mm PIR board between rafters	0.12	0.13	3.57	-0.14
Option B - House D	210mm EWI / Cavity wall insulation / 300mm mineral wool to roof void / 50mm PIR board between rafters and 10mm aeorgel sheet on top	0.12	0.08	3.96	0.53
Option C - Hypothetical	130mm EWI / Cavity wall insulation / 300mm mineral wool to roof void / no additional eaves insulation.	0.12	0.48	-5.71	-20.54

In terms of cost, the difference between Options A & B is approximately £2,822, but only about £14 if the aerogel is omitted. In conclusion, 50mm thick PIR board fitted between rafters from above, without aerogel, would cost approximately £384, but would improve the heat loss at this junction by more than 3.6 W/K.

3. This accounts for the total length of the thermal bridge within the building.

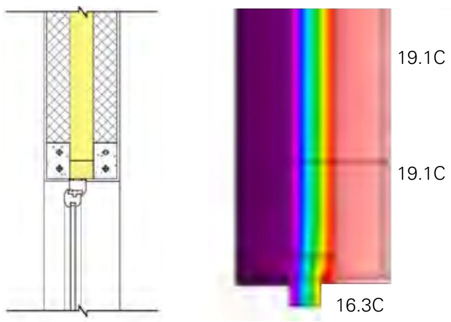
6.4.2 Retrofit Detailing - Lintels

New Energy A rated double glazed windows and GRP doors were installed to all houses, and existing concrete windowsills were either over-clad or replaced entirely with expanded polystyrene insulated Passive Sills.

Fig. 6.5 shows the three different details applied at lintels, with the position of the window adjusted within depth of the wall, pushing it incrementally outwards towards the external insulation layer.

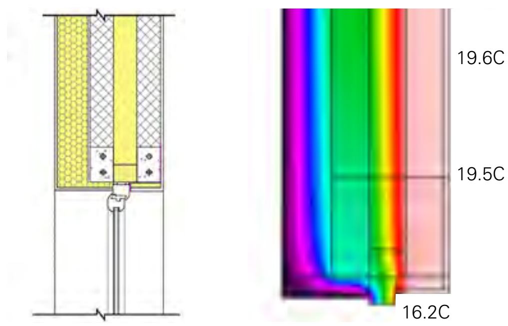
Fig. 6.5: Lintel Details and Corresponding Thermal Models

Pre-retrofit Lintel Detail: 0.04 W/mK



The pre-retrofit construction consisted of cavity wall insulation with the window in the traditional location.

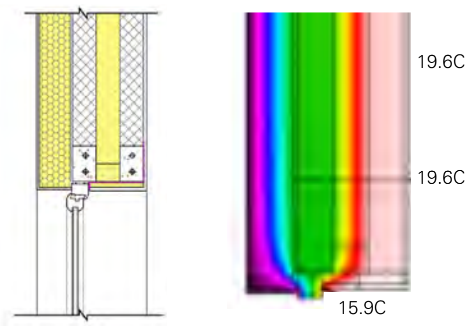
Proposed Option A: 0.00 W/mK



Houses A, C & E - 130mm EWI - Standard window position

This option retains the window in the traditional location with 25mm EPS insulation returned into the external reveal, and 25mm PIR insulation fixed to the underside of the lintel.

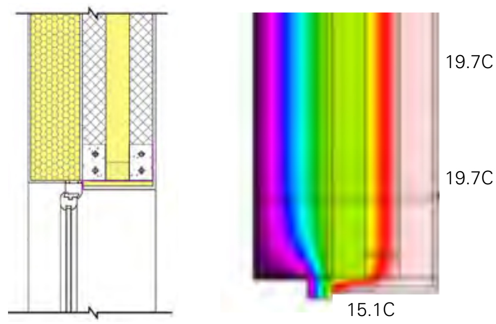
Proposed Option B: -0.01 W/mK



House B - 130mm EWI - Window flush with outer blockwork leaf

In this option, the window is moved outwards flush with the face of the outer leaf with 25mm PIR insulation fixed to the underside of the lintels.

Proposed Option C: 0.0.1 W/mK



House D - 210mm EWI - Window positioned in insulation layer

Here the window sits fully within the insulation layer, with 25mm PIR insulation fixed to the underside of the lintels.

Lintels Detail Analysis

All three options show an increase in the temperature of the internal wall by 0.4°C - 0.6°C, but a decrease in temperature between 0.1°C - 1.2°C at the junction with the window frame. This demonstrates that the position of the window has a slight positive impact on the surface temperature of the wall. The negative effect on the temperature at the junction with the window frame is close to mould-producing conditions. This could be improved in future schemes by ensuring the EWI actually overlaps the window frame. It could be argued that the cost of fixing the window within the insulation layer makes this option less appealing. Table 6.4 shows the psi values for each detail as well as the resultant heat savings from the retrofit details when compared to both the Pre-Retrofit and SAP 2012 default psi values. Each detail is considered to be thermal bridge free and the psi values are all well below the default level. Option B offers the greatest heat saving compared to the pre-retrofit heat saving, and considering its ease of buildability, this is arguably the most effective detail.

Table 6.4: Lintel Detail Analysis

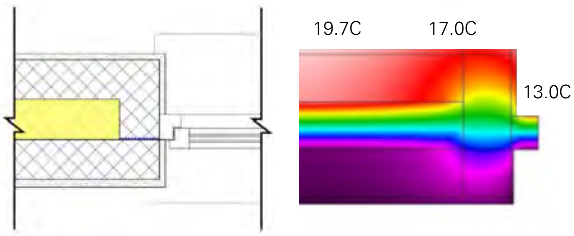
Lintel Detail	Description	Default Psi Value (W/mK)	Psi Value (W/mK)	Average heat saving compared to Pre-Retrofit (W/K)	Average heat saving compared to Default (W/K)
Pre-retrofit	Standard window position	1.00	0.04	-	-
Option A - Houses A, C & E	Standard window position with 130mm EWI	1.00	0.00	0.48	11.89
Option B - House B	Window flush with external masonry leaf with 130mm EWI	1.00	-0.01	0.62	12.58
Option C - House D	Window in insulation layer with 210mm EWI	1.00	0.01	0.34	11.16

6.4.3 Retrofit Detailing - Jambs

Similar to the lintels the jamb details show how the window position was altered within the depth of the wall, pushing it incrementally outwards towards the external insulation layer.

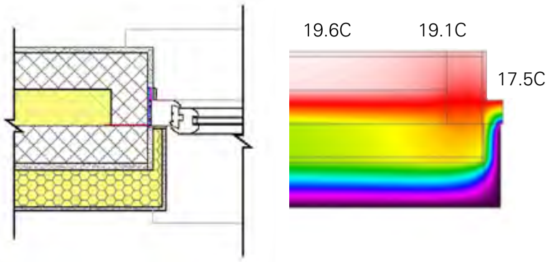
Fig. 6.6: Jamb Details and Corresponding Thermal Models

Pre-retrofit Jamb Detail: 0.47 W/mK



The pre-retrofit construction consists of cavity wall insulation with the window in the traditional location.

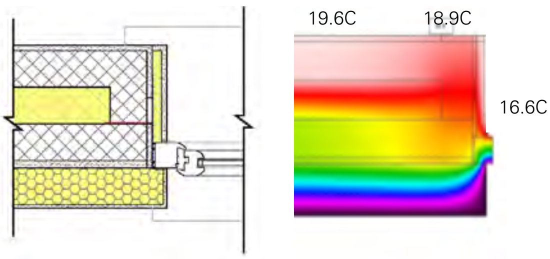
Proposed Option A: 0.08 W/mK



Houses A, C & E - 130mm EWI - Standard window position / reveal Insulation

This option retains the window in the traditional location with 25mm EPS insulation returned into the external reveal.

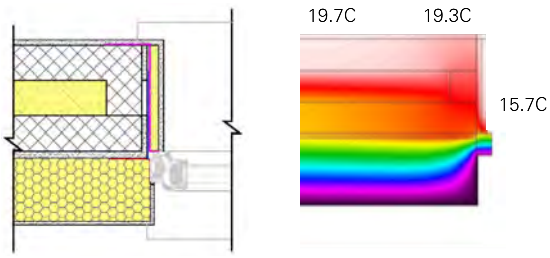
Proposed Option B: 0.04 W/mK



House B - 130mm EWI - Window flush with outer blockwork leaf / EWI overlapping frame

In this option, the window is moved outwards flush with the face of the outer leaf, with 25mm PIR insulation fixed to the internal reveal.

Proposed Option C: 0.01 W/mK



House D - 210mm EWI - Window positioned in EWI layer / EWI abuts frame

Here the window sits fully within the insulation layer, with 25mm PIR insulation fixed to the internal reveal.

Jamb Details Analysis

Options A, B & C indicate an overall improvement on the pre-retrofit scenario due to the application of EWI. All show an increase in internal surface temperature of the wall between 1.9°C - 2.3°C, and an increase at the junction with the window frame of 4.5°C, 3.6°C & 2.7°C respectively. The temperature at the window frame of Option C is concerning as it is closest to mould producing conditions. As with the lintel detail, a greater overlap of EWI across the window frame would improve the internal temperature.

In terms of heat loss through the junction, all details offer an improvement on the default psi value and the pre-retrofit scenario, and all options are considered thermal bridge free. Generally, the results for each option are very close, but improve incrementally as the window moves outwards, which suggests that placing the window in the insulation layer is the optimal thermal solution.

Table 6.5: Jamb Detail Analysis

Jamb Detail	Description	Default Psi Value (W/mK)	Psi Value (W/mK)	Average heat saving compared to Pre-Retrofit (W/K)	Average heat saving compared to Default (W/K)
Pre-retrofit	Standard window position	0.10	0.47	-	-
Option A - Houses A, C & E	Standard window position with 130mm EWI	0.10	0.08	9.65	0.49
Option B - House B	Window flush with external masonry leaf with 130mm EWI	0.10	0.04	11.03	1.54
Option C - House D	Window in insulation layer with 210mm EWI	0.10	0.01	11.79	2.31

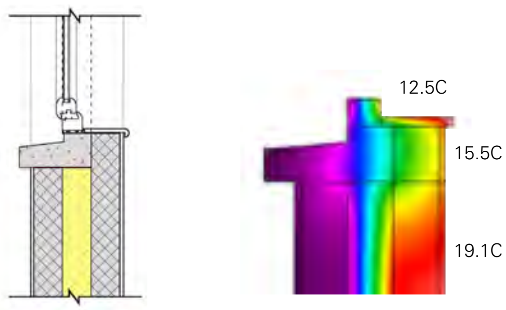
6.4.4 Retrofit Detailing - Sills

The original specification called for aluminium external sills however, the Contractor recommended insulated Passive Sills, which can be faster to install and greatly improve heat loss at this junction. These are available as either an over-sill or a full-sized replacement sill. The sill details below indicate the type utilised in each property.

Four options were trialled to test the location of the window and the type of insulated sill: over-sill or full replacement sill (see Fig. 6.7). The model of the pre-retrofit construction shows dangerously low internal temperatures that could result in condensation and mould growth.

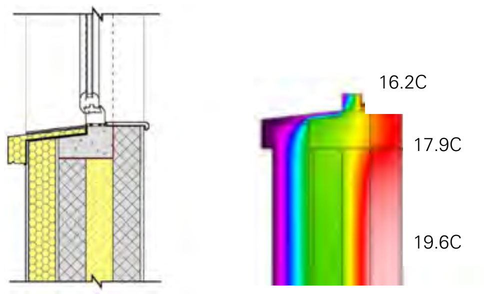
Fig. 6.7: Sill Details and Corresponding Thermal Models

Pre-retrofit Detail: 0.64 W/mK



The pre-retrofit construction consists of cavity wall insulation and concrete sill bridging the cavity with the window in the traditional location.

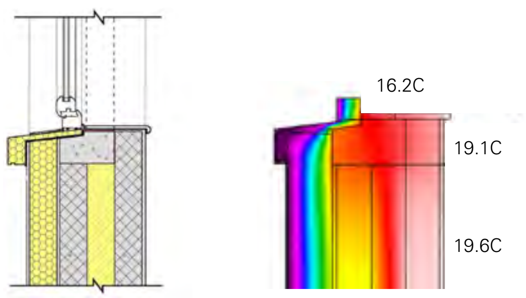
Proposed Option A: 0.28 W/mK



Houses A & E - 130mm EWI - Standard window position / EPS over-sill

The concrete sill has been cut back, the EWI brought up to the top and an insulated over-sill fitted.

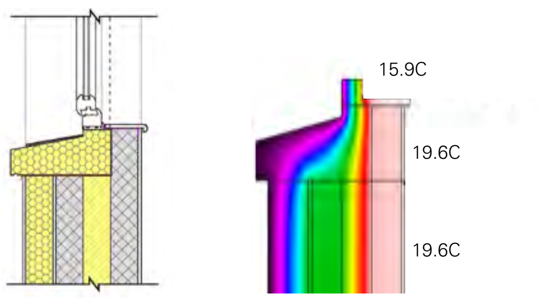
Proposed Option B: 0.11 W/mK



House B - 130mm EWI - Window moved flush with outer blockwork leaf / EPS over-sill

The concrete sill has been cut back, the EWI brought up to the top and an insulated over-sill fitted. The window is fitted on top of the insulated over-sill.

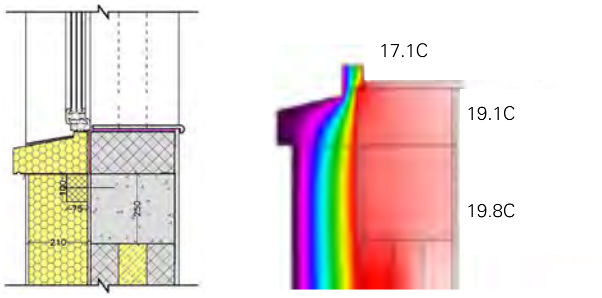
Proposed Option C: 0.02 W/mK



House C - 130mm EWI - Standard window position / EPS full sized sill

The concrete sill has been replaced with a full size insulated Passive Sill, the EWI brought up to the underside of the sill and the window fitted on top in line with the cavity.

Proposed Option D: 0.07 W/mK



House D - 210mm EWI - Window positioned in EWI layer / EPS full sized sill

The concrete sill has been replaced with a full size insulated Passive Sill, the EWI brought up to the underside of the sill and the window fitted on top of the sill in line with the EWI. Substantial reinforcement in the form of a poured concrete lintel was specified by the structural engineer to counteract the weight of the projected window.

Sill Details Analysis

In terms of heat loss at the junction, Options A, B & C increasingly improve on the pre-retrofit detail due to the application of EWI and the insulated sills. Options C & D are better than the default, which is essentially thermal bridge free, and Option C surpasses the SAP approved psi value of 0.04 W/mK. Options A & B do not meet the default, however Option B offers the second greatest total heat saving when compared to the pre-retrofit scenario. All show an increase in internal surface temperature of the wall between 2.4°C - 4.1°C, and an increase at the junction with the window frame of 3.4°C - 4.6°C. Option C offers the greatest increase in wall temperature, but also the lowest increase in temperature at the frame, modelled to be 15.9°C, which is uncomfortably close to mould producing conditions. To improve the surface temperature at the sill/frame junction all details would perhaps benefit from a section of insulation installed below the internal sill and overlapping the window frame.

Table 6.6: Sill Detail Analysis

Sill Detail	Description	Default Psi Value (W/mK)	Psi Value (W/mK)	Average heat saving compared to Pre-Retrofit (W/K)	Average heat saving compared to Default (W/K)
Pre-retrofit	Standard window position	0.08	0.64	-	-
Option A - Houses A & E	Standard window position with Passive EPS Oversill	0.08	0.28	3.85	-2.34
Option B - House B	Window flush with external masonry leaf with Passive EPS Oversill	0.08	0.11	5.54	-0.31
Option C - House C	Standard window position with full Passive EPS Sill	0.08	0.02	5.82	0.56
Option D - House D	Window in insulation layer with full Passive EPS Sill	0.08	0.07	5.35	0.09

Comparison of window installation details

When designing window installations as part of a retrofit scheme, the impact of where the window sits within the depth of the wall should be considered in terms of all three locations: lintel, jamb and sill. Applying these different solutions to the window installations within this pilot offered an opportunity to assess the thermal improvement against the cost, disruption and buildability. The table below expresses the assessment in simple terms, to allow a quick understanding of the merits of each solution.

Table 6.7: Comparison of Window Details in Terms of Heat Savings, Cost, Disruption and Buildability

Location	Option	Heat Saving ★=+5	Cost £=-5	Disruption ☹=-5	Buildability ☺=+5	Score
Lintel						
Standard	A: House A, C & E	★★★	££	☹	☺☺☺	15
Flush	B: House B	★★★	££	☹☹	☺☺☺	10
Projected	C: House D	★★★	££££	☹☹	☺☺	-5
Jamb						
Standard	A: House A, C & E	★★	££	☹	☺☺☺	10
Flush	B: House B	★★★	££	☹☹	☺☺☺	10
Projected	C: House D	★★★★	£££	☹☹	☺☺	5
Sill						
Standard/Oversill	A: House A & E	★	££	☹	☺☺☺	5
Flush/Oversill	B: House B	★★	££	☹☹	☺☺☺	5
Standard/ Full Sill	C: House C	★★★★	£££	☹☹	☺☺	5
Projected/Full Sill	D: House D	★★★	££££	☹☹☹	☺	-15

Window Location	Results	Total	Total exc. Disruption
Standard/Oversill	15+10+5	30	45
Standard/Full Sill	15+10+5	30	50
Flush	10+10+5	25	55
Projected	-5+5-15	-15	20

In terms of heat savings, there may be some benefit in projecting the windows into the insulation layer, but this solution was the most expensive and disruptive to install. Provided there is sufficient coverage of the window frame with insulation, the flush window position can be very effective and is a viable compromise in terms of cost, performance and buildability. It offers good energy performance with some minor disruption internally. The cost and buildability are comparable with those of the standard position because with each option there is either more work to the reveals internally with plasterboard patching, or to those externally with reveal external wall insulation.

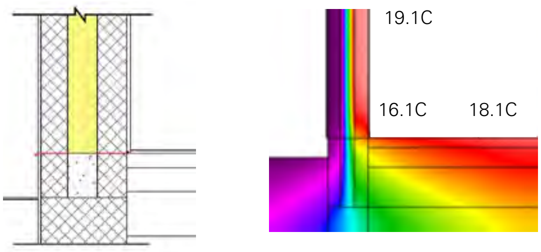
The table indicates the overall performance of the standard location scores the highest, however this results in a lower energy performance, which is arguably more important than disruption. There would be disruption internally with all options, but not to the extent that would require decanting. If disruption is discounted from the analysis as per the results table, the flush position emerges as the more appealing option, resulting in a better energy performance for a similar cost.

6.4.5 Retrofit Detailing - Ground Floor Detail

The original ground floor was built without insulation, so when cavity wall insulation was installed, either at the time of construction, or at a later date this would have exacerbated the heat loss from the perimeter of the houses. The proposals included fixing water resistant insulation below ground level to reduce the thermal bridge. Originally, this was to be protected with bituminous paint however the contractor recommended an aluminium plinth be fitted instead, to speed up installation and to give an attractive finish. The pre-retrofit detail shows a typical cavity wall with an assumption that the cavity below floor level is filled with debris, as is common for this age and type of construction. The two options executed on site are described below with 90mm and 170mm thick XPS insulation fixed below floor level for a depth of 400mm.

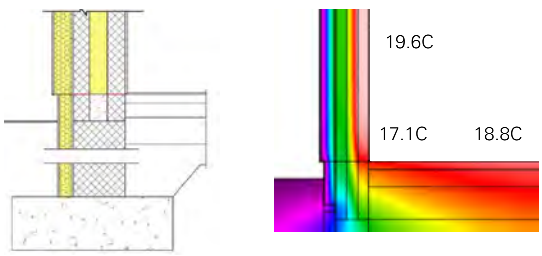
Fig. 6.8: Ground Floor Details and Corresponding Thermal Models

Pre-retrofit Ground Floor Detail: 0.23 W/mK



Typical cavity wall and uninsulated floor.

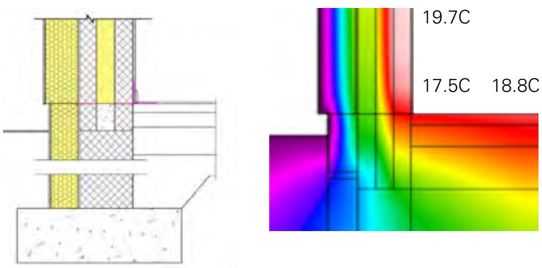
Proposed Option A: 0.13 W/mK



Houses A, B, C & E:

130mm EWI and 90mm thick x 400mm deep expanded polystyrene insulation fixed below DPC.

Proposed Option B: 0.12 W/mK



House D:

210mm EWI and 170mm thick x 400mm deep expanded polystyrene insulation fixed below DPC

Ground Floor Details Analysis:

The internal surface temperature at the floor/wall junctions of Options A & B increase in both options by 1.0°C and 1.4°C respectively, compared with the pre-retrofit detail.

Both options reduce the heat loss from this junction compared to the pre-retrofit scenario, and comfortably surpass the default SAP psi value. This could be improved further by introducing floor insulation, although this measure is often discounted due to cost and disruption. The results from this analysis indicate that insulating the floor is not essential as long as wall insulation is taken down far enough to reduce the impact of the thermal bridge.

Table 6.8: Ground Detail Analysis

Ground/Wall Detail	Description	Default Psi Value (W/mK)	Psi Value (W/mK)	Average heat saving compared to Pre-Retrofit (W/K)	Average heat saving compared to Default (W/K)
Pre-retrofit	No ground floor insulation with pumped cavity	0.32	0.23	-	-
Option A - Houses A, B, C & E	Ground Floor Details with 130mm EWI	0.32	0.13	1.86	3.53
Option B - House D	Ground Floor Details with 210mm EWI	0.32	0.12	1.80	3.28

6.4.6 Conclusion

Thermal bridge modelling tells a lot about the impact of retrofit designs on the property, and highlights where details can be improved to avoid unintended consequences. Analysis can become cumbersome when fractional differences are recorded, however when considered in conjunction with cost, disruption and buildability this information can assist decision-making. Perhaps the most important result to come from the above analysis is the difference between modelled junctions and the SAP 2012 default values. The average additional heat savings from all thermal bridges in all houses compared with the pre-retrofit values is 21.24 W/K, whereas over the default it is 20.19 W/K. The default psi values provided in SAP are not representative of the psi values of the designed details, which often performed better. There is value in modelling each detail to confirm the actual heat loss from that junction and inputting this into the SAP calculation, so that the full improvement is accounted for. This may not result in a higher SAP score, but it will contribute to reducing.

7
Cost/ benefit analysis

7.0 Cost/Benefit Analysis

The impact of retrofit measures in terms of cost and benefit can be calculated in multiple ways of varying complexity. Ideally, over the lifetime of a measure, the cost of installation will be less than the total fuel cost savings, meaning the homeowner benefits from both the reduced bills and increased comfort, health and well-being. The simplest method to analyse this is to calculate the number of years it takes to pay back the capital cost of the measure by dividing it by the annual fuel savings. However, when considering the impact on occupants and Landlords this has little meaning, as the occupant does not pay for the work and the Landlord does not save on fuel bills. Section 6.0 has already investigated the environmental improvements that benefit the occupants, such as comfortable levels of temperature and humidity. In addition to this, a comparison of fuel costs quantifies the financial benefit of the retrofit to the occupant and, importantly, how this could alleviate fuel poverty.

There are other benefits worth investigating and weighing up when developing a retrofit strategy that help decide which measures to implement. For instance, Landlords may wish to promote the energy efficiency of their properties to encourage new occupants, and in some cases to attract higher rent. In order to assess which measures are the most effective they might look at cost per SAP point improvement, or the carbon cost effectiveness (CCE) of a measure, which represents the actual cost of each tonne of carbon saved by the retrofit. It is also worthwhile considering the cost of on-going maintenance, how retrofit can protect the fabric of the building and even prolong its lifespan.

This section analyses the financial benefit to the occupants of the Newry pilot scheme by calculating the difference between the actual fuel cost savings and the estimated savings from SAP, often referred to as the performance gap. It also looks at the carbon cost effectiveness of the retrofit works to each property and the cost of individual measures to determine their value, as well as analysing the response maintenance expenditure since completion to highlight any reduction resulting from the retrofit.

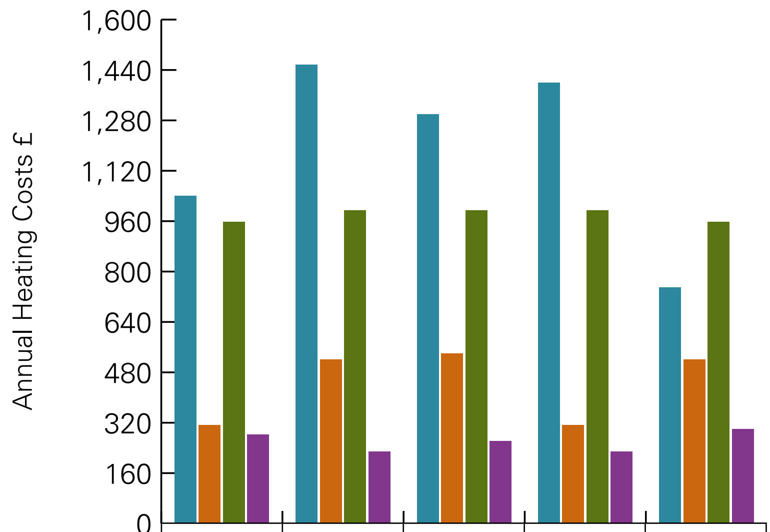
7.1 Fuel Cost Savings and the Performance Gap

The Standard Assessment Procedure (SAP) is a standardised approach to calculating the expected energy costs of a building. It assumes certain criteria depending on the size and occupancy of the dwelling to remove inconsistencies of human behaviour and allow the performance of multiple dwellings to be comparable. Essentially, it removes the variables of how people live in and use their homes, which can often lead to a performance gap between the estimated fuel consumption and real life.

To assess the performance of any retrofit it is useful to gather data from the occupants on their fuel expenditure before and after the work, to make a fair comparison. Figure 7.1 demonstrates the differences between the actual fuel costs before and after the retrofit, compared to the predicted fuel costs taken from SAP. The actual fuel cost data was collated by an Ulster University PhD student at the time, Dr. Anna Czerwinska, who interviewed the occupants on multiple occasions to understand the impact the retrofit has had on their lives[4]. The graph shows the post retrofit SAP figures are lower than the actual spend, which could be for a number of reasons. Perhaps the occupants enjoy a warmer temperature than the default temperatures used in SAP (21°C in the living room and 18°C elsewhere). The occupants may like to open windows more regularly, resulting in greater heat loss, but importantly improving ventilation. Perhaps the retrofit measures were not installed as well as they could have been if it was a new build or an off-site construction. This is a common problem with retrofit where the existing structure and site conditions present a more difficult challenge to execute details precisely, leaving opportunities for heat loss or uncontrolled air infiltration. Regardless of the reasons for the performance gap, the results clearly demonstrate a significant reduction in fuel costs compared to pre-retrofit expenditure.

4. Dr. Czerwinska's research on the Newry houses contributed to her published thesis entitled 'Fuel poverty - retrofitting as a policy solution'.

Figure 7. 1 - Annual Energy Cost Comparison



	House A	House B	House C	House D	House E
Pre-Retrofit (Tenant Estimate)	£1,040.00	£1,456.00	£1,300.00	£1,400.00	£750.00
Post-Retrofit (Tenant Estimate)	£312.00	£520.00	£540.00	£312.00	£520.00
Pre-Retrofit (SAP Estimate)	£956.92	£994.21	£994.21	£994.21	£956.92
Post-Retrofit (SAP Estimate)	£281.93	£227.83	£261.01	£228.60	£300.49

7.2 The Cost of Saving Carbon

The primary objective of this pilot scheme was to determine how to retrofit our stock at scale with a solution that represents the best value for money. Table 7.1 compares the cost of the energy improvement works to each dwelling* in terms of the cost per increased SAP point and the cost per tonne of carbon saved over 30 years.

Table 7.1: Cost of Energy Saved

Whole House Energy Cost Analysis	House A	House B	House C	House D	House E
Post Retrofit	78 C	81 B	79 C	87 B	78 C
Works Cost, £	£21,353	£20,770	£17,236	£23,577	£21,081
SAP Point Improvement from Pre Retrofit	36	40	38	46	36
Cost, £/Increased SAP point	£593	£519	£454	£513	£586
Lifetime Cost, £ (capital & maintenance)	£24,353	£26,770	£20,236	£29,877	£24,081
Lifetime Carbon Savings, tonnes CO_2	149	174	160	181	145
Cost per Tonne Saved, £/tonne CO_2	£163.80	£153.60	£126.62	£164.95	£165.91

** The works cost of House E includes installation of a gas boiler, which was grant funded prior to this pilot scheme, but contributes to the overall energy improvement. The cost of the gas installation is included to make a fair comparison.*

The table indicates that House C has the lowest cost per increased SAP point, followed by House D, meaning that House C achieved the best return for the capital spend. House D cost an additional £59/SAP, but gained eight more SAP points than House C, which comfortably improved House D to SAP B. In comparison, House B only gained two additional SAP points over House C, but cost an additional £65/SAP point, indicating that the additional improvements to House D were better value for money.

In relation to the cost of saving carbon, Houses B and D save the most amount of carbon across the lifespan of 30 years, with House D being the second most expensive option. The carbon savings of Houses B & D cost more than that of House C, which could be due to the introduction of renewable energy systems to both these houses. Renewable energy systems reduce fuel costs, but also require maintenance, which is reflected in the Lifetime Costs. Houses A and E cost a similar amount to House D, but save 32-36 tonnes CO2 less. This could be attributed to the fact they are both end-terraced properties that have an additional exposed wall and subsequently required a greater area of external wall insulation to be installed.

These calculations consider the cost of saving energy and carbon from the landlord's perspective, where there is no saving made from reduced fuel bills. If the same calculations were repeated taking lifetime fuel savings into account, the results would look quite different. This could reduce the average cost per tonne of CO_2 saved to as low as £10. Quantifying carbon savings in this way is referred to as Carbon Cost Effectiveness, which can be a complex calculation, but an important one if we are to consider the benefits as a whole.

Another approach to determining value for money is to compare measures within one property to decipher which will give the best return. This approach is underpinned by the premise that retrofit should be considered as a whole house solution in order to arrive at the most appropriate package and sequence of measures. The law of diminishing returns applies to retrofit, and measures should be carefully programmed to take account of this. For example, the fuel reduction afforded by a more efficient gas boiler will be greater if it is installed before EWI than if it is installed afterwards. Equally, the impact on the heating demand of the house from installing EWI after installing a new boiler may result in the boiler being over-sized. Retrofit strategies should take account of the sequencing of multiple measures to decipher the order in which they have the most impact, and to ensure the accumulative energy savings are accurately predicted[5].

7.3 Response Maintenance Costs

A benefit of retrofit measures often referred to but difficult to demonstrate is the potential reduction in maintenance costs after the retrofit.

As buildings age they can become more costly to maintain to modern acceptable standards. The effects of poor heating, uncontrolled ventilation and high air permeability can exacerbate degradation of the building fabric over time, leading to increased maintenance callouts and repairs. Retrofitting to a high standard of thermal performance by reducing thermal bridges, increasing airtightness and providing adequate ventilation, can mitigate the damaging effects of humidity and low temperatures and improve the lifespan of the building.

At the time this report was written, two years of post-retrofit repair history was gathered to give an insight into the effects of the retrofit on maintenance costs. Fig. 7.2 displays the repair history across eight years, starting from August 2012 to July 2020, including the year of construction, which occurred from February 2018 to July 2018. The tables show All Trades jobs separate from heating jobs and the cost for these per property.

Typical complaints in the lead up to the scheme included heating repairs, roof repairs, leaks and electrical faults.

5. PAS 2035:2019 and the Level 5 Diploma in Retrofit Coordination and Risk Management qualification both reinforce the notion of designing a whole house retrofit, which can either be carried out all at once or in stages over 30 years.

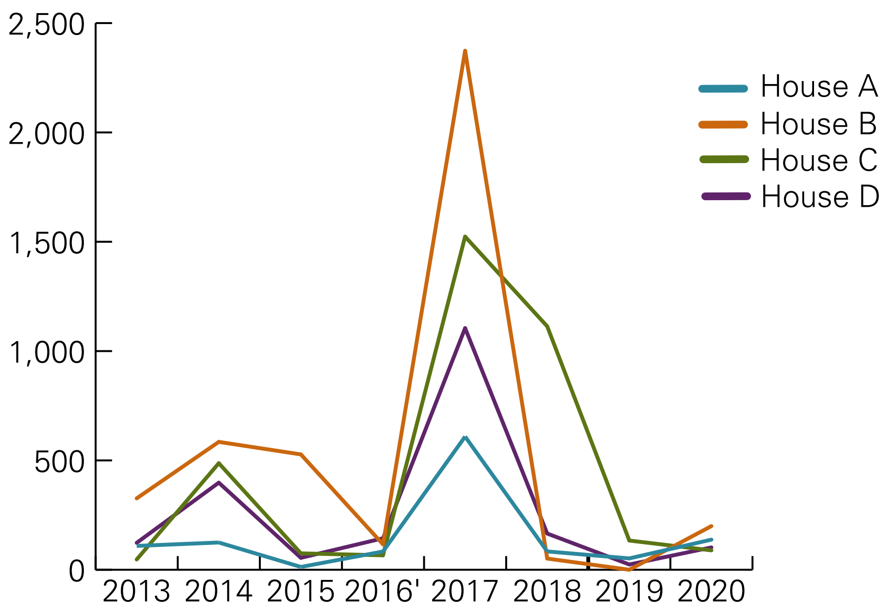
In terms of All Trades, the year prior to construction was the most expensive, reflecting the condition of the properties. This could be attributed to the decision to remove these properties from planned maintenance schemes such as new kitchens and external cyclical maintenance, given the knowledge they would be receiving multi-element improvements as part of the retrofit scheme. Excluding the year of construction and all heating costs, the average cost of repairs pre-retrofit was £326, and £27 post retrofit, a 91.5% decrease in maintenance costs.

In terms of heating, in the year prior to the construction period there was an increase in the number of jobs as the oil fired boilers were in urgent need of replacement. Since then there has been a 45.5% reduction in the cost of repairs.

Overall, there has been 79.25% reduction in maintenance costs amounting to approximately £536 per property.

The figures so far support the notion that retrofit can result in a reduction of maintenance, although arguably this could be said for all maintenance works of significant expenditure. Many more years' data will need to be collected from this scheme and other similar schemes before any solid conclusions can be drawn, particularly regarding the range of any extended lifespan.

Fig. 7.2: Pre and Post Retrofit Response Maintenance Costs



8 Lessons learned

8.0 Lessons learned

This scheme is the Housing Executive's most ambitious retrofit project to date, delivered using in-house expertise and collaboration with industry leaders. The protracted duration of the scheme from inception to completion is reflective of the time taken to consider the best approach and to advance the in-house teams' knowledge of energy efficient design. This brought complexities in terms of the accelerated development of new innovative products over the years of the project, in addition to the continuously evolving trends in low-energy construction.

There is no doubt the experience gained from this scheme has educated and enlightened the Housing Executive in retrofit works. Inevitably, there are issues that emerge from such schemes, and Table 8.1 is a list of lessons learned that have been brought to light, and the recommendations to be applied to future retrofit projects.

Table 8.1: Lessons Learned

ISSUE	LESSON LEARNED	RECOMMENDATION
STRATEGY		
Complex research strategy, testing multiple different options.	Comparing a number of new products, solutions and variations of details in one scheme can confuse results and lead to misinterpretation of the impact of each measure.	When delivering pilot schemes in the future, try to restrict research to a small number of concepts or measures, to avoid the need to overload and complicate one scheme.
Sequence of retrofit measures.	This pilot implemented a number of different measures all at once in a one-off scheme, however this is not practical at scale, and measures will most likely be implemented in phases involving EWI, window and door replacement, boiler replacement and roof replacement. It is important to consider the sequence of these measures, as they are mutually dependent.	Windows and doors are ideally replaced along with EWI installation so their position within the depth of the wall can be adjusted to suit. Fitting extra insulation enables homes to be heated with lower output and lower carbon heating appliances such as heat pumps, or boilers fitted with advanced controls, reducing the need to oversize radiators. If oil boilers or gas meters are installed before EWI is fitted, they should ideally be located away from the external wall to avoid expensive relocation. If roofs require replacement this should happen along with EWI to avoid the need for scaffolding on two separate occasions. Alternatively, if they must be done separately, the roof should be done first and any necessary adjustments made to extend rafters and verges to accommodate the thickness of EWI, or to shade bedroom windows against solar overheating after the installation of EWI.

ISSUE	LESSON LEARNED	RECOMMENDATION
STRATEGY		
Increased in-house resources, skills, knowledge and experience.	The process of delivering this scheme has resulted in an accelerated understanding within the Housing Executive of how to deliver low energy projects successfully, and the impact this has on the future maintenance of an aging portfolio. Understanding how to assess and quantify the performance of a building before and after retrofit is necessary to avoid unintended consequences. This involves calculating u-values, condensation risk analysis, internal surface temperatures and heat loss through thermal bridges, airtightness and adequate moisture control through ventilation.	To enable the Housing Executive to contribute to carbon emissions reductions and address fuel poverty among occupants successfully, it is important that an appropriate number of staff be adequately trained across all Regions in retrofit assessment and design. This would instil confidence in identifying building defects and assessing work carried out by consultants, as well as facilitating more in-house scheme design.
Procurement of a suitably experienced contractor.	Appointing a contractor with previous experience in installing the energy efficiency measures included in this scheme was invaluable as it helped the construction period run smoothly and led to the inclusion of innovative products.	Continue to ensure quality going forward by supporting the developing of industry capacity for EWI and insisting on relevant qualifications in energy efficient construction such as PAS 2035 at tender selection stage.
LOW-ENERGY DESIGN AND ASSESSMENT		
Eaves insulation	Thermal models indicated the benefits of increasing insulation at the eaves above wall plate level. Without this, there is likely to be an increase in complaints relating to mould and condensation at this location after EWI and loft insulation is installed. The option with aerogel wrapped over rafters offered a minor improvement in comparison to the cost of the material, and is therefore not considered cost effective. However, rigid board insulation between the rafters is very effective and affordable.	Introduce additional rigid board insulation between rafters as standard when carrying out schemes such as roof replacements or EWI. This approach is now actively implemented by the Housing Executive in its large-scale insulation schemes.
Window and doors positions	Thermal models indicate that windows are best moved outwards when fitting EWI. This is quite disruptive internally due to the patching required at the heads, reveals and sills. There are also structural implications if the windows are moved into the EWI layer, as they require additional support around the frame, adding to the cost. Moving the windows out flush with the outer face of the wall gives an improved thermal performance than if they were left in the same position, causes less disruption and is less expensive than moving the windows into the insulation layer.	Where possible, position windows and doors flush with outer face of the wall. Fix a thin strip of insulation around the heads, reveals and sills internally to improve surface temperature at these locations.
Plinth insulation	The interface between the external wall and floor needs to be protected from excessive heat loss that could cause moisture related issues or discomfort, particularly where there is no floor insulation.	Ensure wall insulation is taken down below ground floor level by a minimum of 400mm from the top of any floor insulation (or where floor insulation would typically occur).
SAP Assessment and Thermal Modelling	Section 6.4 demonstrates the differences between actual modelled thermal bridge psi values against the default psi values applied in SAP assessments. Whilst using actual modelled values may not lead to increased SAP ratings, it will contribute to increased carbon savings and a reduction in primary energy use.	It is recommended that actual thermal bridge psi values be used in SAP assessments to take advantage of improvements that would otherwise be disregarded if the default values were to be used. This also applies to airtightness tests.

ISSUE	LESSON LEARNED	RECOMMENDATION
PRODUCTS AND MATERIALS		
Prototype systems	Using innovative prototypes in a small-scale pilot is relatively low risk and helps manufacturers refine their products for use in the wider market. However, the nature of a prototype is such that the product is in development and may not initially work as intended. The prototype may need to transition through different iterations and the occupants may find this tiresome.	Where prototypes are to be used, ensure the occupant of the house is well informed and in agreement with the proposals. It is equally important that an exit strategy be agreed to address the situation where the product is not performing and needs to be removed and/or replaced with an alternative.
Renewable energy	Installing renewable energy in the form of solar PV and solar hot water to two properties helped to increase the SAP ratings and reduce carbon emissions. However, it has been difficult to ascertain the actual usage of the renewable energy systems and confirm an actual reduction in fossil fuel consumption, and consequently a reduction in energy costs.	To analyse renewable energy and fuel consumption effectively to determine the benefits, an accurate method of recording this information should be considered at design stage and installed as part of the system.
Aerogel insulation	Aerogel is an insulation material with a very low thermal conductivity that is useful in areas where there is limited depth such as around window sills and over rafters as applied in this scheme. However, aerogel in the form of blankets or rolls is dusty, friable and unpleasant to work with and can cause irritation.	Where aerogel is specified in future, it should be handled with care using PPE as specified by the manufacturer.
Aluminium plinth	An aluminium plinth fixed to extruded polystyrene insulation below DPC level was trialled as a more robust alternative to bituminous paint. The contractor found this to be quicker to install in some ways, but costly and wasteful when the plinth was not quite cut to fit accurately.	As the expected speed of installation was not realised on site and complications led to more cost, this option will not be taken forward in future schemes.
AIRTIGHTNESS		
Implications of reduced air permeability	Applying EWI has the effect of reducing air permeability and great improvements can sometimes be achieved with very little additional interventions. However it is difficult to achieve an improvement of more than approximately 7-10m^3/ ($h.m^2$) without implementing intrusive measures. Equally, if air permeability is reduced to 3 m^3/ ($h.m^2$) or less this will impact on the ventilation of the property and it is essential that a whole house ventilation system be installed.	As it is disruptive and costly to implement air permeability measures in occupied properties it is important that this is addressed opportunistically during planned or response maintenance or at change of tenancy. For instance taping around openings is achievable whilst replacing windows and doors.

ISSUE	LESSON LEARNED	RECOMMENDATION
POST RETROFIT CARE		
Maintenance of innovative technology	A number of products and systems were installed that deviate from the standard specification at the time. This mainly included the two alternative demand controlled ventilation systems. Relevant staff, contractors and occupants should be educated in the requirements to ensure unfamiliar products are maintained	During design stage and before installation, ensure a maintenance regime is considered and agreed, particularly where this relies on the involvement of other departments within the organisation or would result in a compensation event within current maintenance contracts.
Maintenance of EWI system	EWI is an unfamiliar material to the majority of people. It is important that occupants and maintenance staff are educated to understand the damage that can be caused by fixing to the EWI, including creating thermal bridges and compromising the watertight seal of the render.	In future retrofit schemes a handover package should be presented to occupants that includes information on the EWI systems installed, how to avoid causing damage to EWI, the importance of reporting damage and the consequences of drilling through or fixing to EWI, such as water ingress and cold spots that could lead to mould.
Impact of retrofit on occupant's lifestyle and heating routines.	Before retrofit, occupants would have managed their heating in line with affordability, often compromising comfort as a result. The retrofit should reduce the heating demand and increase comfort for more hours in the day, as this pilot has demonstrated. In addition, the dwelling's airtightness may have improved and the ventilation system upgraded to provide more controlled airflow.	As part of the handover package, the occupants must be advised to adjust their heating routines to avoid over or under heating, and to expect that the heat will not need to come on as much as it did previously. Educate occupants on the importance of maintaining good ventilation, including the need for both a supply of fresh air in all habitable rooms and extracted stale air from wet rooms. Also, that poor ventilation and under heating could encourage mould growth even in an insulated property. Advise on changing habits such as drying clothes indoors or using unvented tumble dryers.

ISSUE	LESSON LEARNED	RECOMMENDATION
DEFECTS		
Defective roof flashing	As the roofs were not replaced in the Newry scheme, some old flashing around tile vents remained and in one property, the flashing failed and allowed water to enter the roof and eventually the wall structure. Luckily, the water emerged around a window alerting the occupant to a defect, which was identified and repaired. However, if this had been left undetected water in the structure could have caused a lot of damage and severely affected the integrity of the EWI.	Ensure roof flashings around tile vents, chimneys and the like are checked and repaired when necessary, prior to installing EWI.
Loose rainwater down pipe	The houses in this pilot scheme are situated on a hill and subsequently exposed to high wind speeds. This led to a small number of down pipes detaching from the wall.	Ensure items fixed to the EWI are secured with appropriate fixings for the weight of the item and the location.
Mould on 1st floor ceiling.	Reports were received from two properties of mould appearing on a bathroom and a bedroom ceiling. Both these rooms are situated on the south elevation exposed to prevailing winds. The exact cause of the issue is uncertain however, it is likely to be a combination of a number of issues. For example, the eaves on the south elevation could be subject to wind-washing, where cold air blows through the mineral fibre at this location creating a cold area on the ceiling. Also, both houses have intermittent extract fans in the bathroom and the kitchen and did not receive a continuous ventilation system. Finally, the bathroom was subject to leaking, unrelated to the works, that would have increased the levels of moisture in that area.	Consider the use of a wind-tight membrane at eaves level, particularly in highly exposed areas, to reduce wind-washing. Educate occupants in the importance of operating the ventilation system during, and for some time after, moisture producing activities such as showering and cooking; as well as letting fresh air in by opening windows regularly and keeping trickle vents open. Ensure prompt repair of any leaks.

9 Conclusion

9.0 Conclusion

The Housing Executive manages approximately 86,000 houses across the province, the majority of which were built prior to 1990 using a broad range of construction types including traditional solid walls, cavities and system-built structures. The current average SAP score across the portfolio is 63 SAP D, and in response to the Government's commitment to reduce carbon emissions, there has been a surge in efforts to increase this to SAP C by 2030. This presents a huge challenge financially, and in terms of scheduling and procurement processes, and navigating the inevitable complexities of existing occupied properties. Delivering a high standard of retrofit is even more challenging when there is already a shortage of skills and labour in the construction industry, and limited experience in the realms of retrofit in comparison to the rest of the UK. On a more positive note, Northern Ireland is in a good position to learn from the well-documented failures of retrofit previously experienced in other countries, and to embrace emerging standards for retrofit such as PAS 2035.

The Newry pilot scheme began as the Housing Executive's first experience of deep retrofit, and even though the improvements did not go as far as originally intended, the final approach was a more proportionate solution, and the scheme has proven to be an excellent mechanism to inform future retrofit.

The proven success of the EWI installation, and the fact that it is compatible with a range of heating systems including electric heat pumps, reducing peak winter heating demands and the potential peak load on the grid, makes this a practical and affordable solution for more widespread retrofit.

It is unrealistic to upgrade all existing dwellings to meet net zero carbon emissions. Taking into account the decarbonisation of electricity, the level of carbon reduction required for existing dwellings is realistically around 60%-80%, unless decarbonised district heating is available to make less insulation necessary. A 60% reduction represents a much more achievable programme of works and reduces financial pressure. Equally, the full package of planned retrofit does not need to be completed all at once. Rather, a plan of works implemented over a number of years to coincide with other planned works, such as kitchen and bathroom replacements or external maintenance, is a much more manageable strategy.

On a practical level, the works carried out in Newry caused significant disruption to the occupants who had to decant for at least a month. This was only achievable due to the low number of dwellings involved, and would be difficult on a larger scale. Retrofit measures need to be implemented in a way that keeps displacement to a minimum but takes advantage of opportunities when they arise. For example, applying airtightness tape when fitting windows, or extending rafters and verges for future EWI during roof replacement schemes[6].

The main objective of this small pilot scheme of five dwellings was to reveal the complications of retrofit, so these could be considered and planned for when replicated at scale. This has been invaluable, as the organisation has recently embarked on a much larger scheme to apply external wall insulation to over two thousand non-traditional dwellings. Perhaps the greatest impact on how the Housing Executive will retrofit in the future is evident in the minute detail of junctions and thermal bridges. Soon after the completion of this scheme, improved details of troublesome junctions such as eaves and around windows were introduced to other projects, with a greater emphasis towards reducing thermal bridges and improving airtightness.

The importance of good ventilation will also play a key role in future retrofit schemes, to reduce complaints and maintenance relating to mould and condensation. Robust ventilation systems are now specified as standard in combination with major insulation upgrades, to mitigate against any adverse effects.

In conclusion, the journey to retrofit has been long and difficult at times and there is still a lot to learn, not only for building owners, but also for designers, manufacturers, installers, end users and policy makers. The experience gained through the Newry pilot scheme and other retrofit projects undertaken in the past ten years has provided a solid base upon which the Housing Executive will build its retrofit strategy and respond to the challenges of the decade ahead.

6. The cost of decarbonisation to society can be limited by co-ordinating housing and energy infrastructure upgrades, for example, insulating more rural homes that will depend on the electricity grid for most heating, or installing district heating pipes along with additional street drainage or cycle lanes.

Appendix

APPENDIX A

GLOSSARY OF TERMS

TERM	MEANING
BEIS	Department for Business, Energy & Industrial Strategy
BRE	Building Research Establishment
BREEAM Domestic Refurbishment	BRE standard for domestic retrofit
CCE	Carbon cost effectiveness
CO2	Carbon Dioxide
EnerPHit	Passive House retrofit standard
EPC	Energy Performance Certificate
EPS	Expanded polystyrene insulation
EWI	External wall insulation
GHG	Greenhouse gas
IAQ	Indoor air quality
MVHR	Mechanical ventilation heat recovery
NIHE	Northern Ireland Housing Executive
RH	Relative humidity
SAP	Standard Assessment Procedure
TSB	Technology Strategy Board, now Innovate UK
XPS	Extruded Polystyrene

APPENDIX B

As Built Works Content Per Property

ITEM	House A	House B	House C	House D	House E
Gas heating	✓	✓	✓	✓	Already installed
300mm loft Insulation	✓	✓	✓	✓	✓
Switchee smart heating controls	✓	✓	✓	✓	✕
NIHE standard GRP external doors x 2	✓	✓	✓	✓	✓
Passive triple glazed windows	✕	✕	✕	✓	✕
NIHE standard double glazed windows	✓	✓	✓	✕	✓
External wall insulation (130mm EPS)	✓	✓	✓	✕	✓
External wall insulation (210mm EPS)	✕	✕	✕	✓	✕
Mineral fibre cavity wall insulation topped up	✓	✓	✓	✓	✓
Eaves insulation upgrade (50mm PIR and aerogel)	✕	✕	✕	✓	✕
Eaves insulation upgrade (25mm PIR)	✓	✓	✓	✕	✓
"Front door brought forward, new porch canopy "	✓	✓	✓	✓	✓
Rear store retained: external wall insulation, ceiling & floor insulation	✕	✓	✕	✕	✕
Windows fitted in EWI layer	✕	✕	✕	✓	✕
Windows in-line with outer blockwork leaf	✕	✓	✕	✕	✕
Windows in-line with cavity	✓	✕	✓	✕	✓
Retained concrete window sills	✓	✓	✕	✕	✓
Full Passive Sill	✕	✕	✓	✓	✕
Passive Over-sill	✓	✓	✕	✕	✓
Rigid foam structural window sill support	✕	✕	✕	✓	✕
Chimney breast removed	N/A	✓	N/A	N/A	✕
Demand controlled MEV system	✕	✕	✕	✓	✕
Think.Air smart ventilation system	✕	✕	✓	✕	✕
Solar hot water panels	✕	✓	✕	✕	✕
PV Panels and solar hot water immersion	✕	✕	✕	✓	✕
Full airtightness strategy	✕	✕	✕	✓	✕
Airtightness to windows & doors only	✕	✕	✓	✕	✕

APPENDIX C

BRE Pre and Post Retrofit Monitoring Report

Monitoring results for NIHE Newry Pilot Scheme

This report provides an overview of the post-refurbishment temperature and humidity conditions of the above properties, to examine whether refurbishment of four of the properties which were monitored pre-refurbishment resulted in changes to internal temperature and humidity conditions that align with occupant satisfaction.

As with the pre-refurbishment monitoring period, data loggers were placed in the kitchens, living rooms and main bedrooms of the properties, recording temperature and humidity at 30-minute intervals. Three of these (A, B and D) recorded data from 00.00 on 23rd October 2018 to 23.30 on 11th March 2019, and two (C and E) from 00.00 on 13th October 2018 to 23.30 of 11th March 2019.

As highlighted in the report of pre-refurbishment monitoring, a temperature range of >18°C and <21°C is considered most favourable for occupant satisfaction, while a temperature of >25°C is considered significantly overheated. For this analysis we have considered a temperature range of 15-25°C as acceptable, to account for the fact that some occupants may naturally prefer slightly warmer or cooler room conditions than others.

Relative humidity (RH) is also important to occupant wellbeing, and should be between 40% and 70%. RH of <40% causes discomfort to occupants through dry air, while RH >70% can lead to surface condensation and mould growth.

Notes on data and analysis

For two of the dwellings (C and E), data loggers were deposited on the 12th October 2018 and collected on 12th March 2019, while the data loggers for the remaining three dwellings were deposited on the 22nd October 2018 and collected on 12th March 2019.

To ensure that the data used for analysis corresponded to the time that the loggers were located within the dwellings (as opposed to in transit or storage elsewhere), any data up to and including the day that the loggers were deposited, as well as data on or after the day that they were collected, were removed from the dataset.

Once these were removed, dwellings C and E had 8 more days of data than the other dwellings, and these extra days were not removed from the analysis.

When analysing the data, three new variables (% of time between 18°C and 21°C, % of time between 15°C and 25°C, and % of time between 40 and 70% RH) were created and applied to both the pre- and post-refurbishment datasets, to allow for easier comparison of performance.

The tables below display the results of the data analysis. After each value, the unit change in that value from pre- to post-refurbishment is reported. As such, if average temperature for a room in the dwelling increased from 20°C to 21.5°C, this would be displayed as "21.5 (+1.5)". The exception is House A, which was not monitored pre-refurbishment.

House A

House A	Living room	Kitchen	Bedroom	Average
% of time >21°C	34.3	49.8	30.0	38.0
% of time >25°C	1.6	1.5	0.8	1.3
% of time <18°C	19.3	3.5	7.3	10.0
% of time <15°C	4.6	0.0	0.0	1.5
% of time 18>21°C	46.4	46.7	62.7	51.9
% of time 15>25°C	93.8	98.5	99.2	97.1
Average temperature (°C)	20.0	21.2	20.4	20.5
% of time >70% RH	0.3	0.3	0.8	0.5
% of time >80% RH	0.0	0.0	0.0	0.0
% of time <40% RH	3.2	7.2	0.0	3.5
% of time 40>70% RH	96.5	92.5	99.2	96.1
Average humidity (%RH)	52.9	49.0	58.5	53.5

The data for House A shows that the living room, kitchen and bedroom had fairly low levels of significant overheating above 25°C, but were regularly above 21°C. Meanwhile, the living room was also underheated below 18°C for a notable proportion of the time, suggesting significant swings in temperature within that room. On average across the three rooms, temperatures fell within the 15-25°C acceptable range for 97.1% of the time. Though there were a few instances of humidity of <40% RH in the living room and most notably in the kitchen, the relative humidity was within the 40-70% RH acceptable range for 96.1% of the time.

NB this property was not included in the pre-refurbishment monitoring, and so a pre-post comparison cannot be made.

House B

House B	Living room	Kitchen	Bedroom	Average
% of time >21°C	27.8 (-2.4)	30.7 (+1.3)	20.6 (+17.6)	26.4 (+5.5)
% of time >25°C	0.1 (-0.6)	1.8 (+1.4)	0.1 (-0.9)	0.7 (0.0)
% of time <18°C	1.1 (-16.3)	0.5 (-9.8)	3.7 (-63.8)	1.8 (-30)
% of time <15°C	0.0 (-0.9)	0.0 (-0.1)	0.1 (-17.5)	0.0 (-6.2)
% of time 18>21°C	71.1 (+18.8)	68.8 (+8.5)	75.7 (+46.2)	71.9 (+24.5)
% of time 15>25°C	99.9 (+1.5)	98.2 (-1.3)	99.9 (+18.5)	99.3 (+6.2)
Average temperature (°C)	20.6 (+0.7)	20.7 (+0.6)	20.1 (+3.1)	20.5 (+1.5)
% of time >70% RH	0.2 (-1.0)	0.2 (-0.5)	0.3 (-2.4)	0.2 (-1.3)
% of time >80% RH	0.0 (-0.4)	0.0 (0)	0.0 (0)	0.0 (-0.1)
% of time <40% RH	0.1 (-20.1)	0.1 (-20.6)	0.0 (-2.7)	0.1 (-14.5)
% of time 40>70% RH	99.7 (+21.0)	99.7 (+21.1)	99.7 (+70.2)	99.7 (+37.4)
Average humidity (% RH)	55.5 (+10)	57.0 (+11.5)	61.0 (+5.3)	57.8 (+8.9)

The data show that there are some very slight changes in the proportion of time that the property is overheated above 25°C, though on the whole this is negligible. The data also shows that the property experiences substantially less underheating in the bedroom which was underheated to below 15°C for much of the time prior to refurbishment. On average across the three rooms, temperatures fell within the acceptable range of 15-25°C for 99.3% of the time, up from 93.1% pre-refurbishment.

The living room and kitchen also exhibited significant improvements in terms of humidity - prior to refurbishment their relative humidity was below an acceptable level of 40-70% for around 20% of the time, whereas following refurbishment this was effectively cancelled out entirely, and the relative humidity of all three rooms fell within optimal levels for 99.7% of the time, up from 62.3% of the time pre-refurbishment.

House C

House C	Living room	Kitchen	Bedroom	Average
% of time >21°C	49.7 (+38.9)	40.6 (+39.5)	34.8 (+34.8)	41.7 (+37.7)
% of time >25°C	4.4 (+4.4)	1.0 (+1.0)	0.0 (0.0)	1.8 (+1.8)
% of time <18°C	0.1 (-67.8)	0.2 (-73.6)	0.0 (-84.2)	0.1 (-75.2)
% of time <15°C	0.0 (-19.1)	0.0 (-13.7)	0.0 (-10.4)	0.0 (-14.4)
% of time 18>21°C	50.2 (+28.8)	59.2 (+34.1)	64.5 (+48.7)	58.0 (+37.2)
% of time 15>25°C	95.6 (+14.7)	99.0 (+12.8)	100.0 (+10.4)	98.2 (+12.6)
Average temperature (°C)	21.6 (+4.4)	21.0 (+4.1)	20.8 (+4.1)	21.1 (+4.2)
% of time >70% RH	0.0 (-2.3)	1.1 (+0.4)	0.0 (-4.3)	0.4 (-2.1)
% of time >80% RH	0.0 (-0.4)	0.1 (-0.2)	0.0 (-0.4)	0.0 (-0.3)
% of time <40% RH	4.4 (+1.4)	0.5 (-6.2)	0.2 (+0.2)	1.7 (-1.5)
% of time 40>70% RH	95.6 (+0.9)	98.4 (+7.1)	99.8 (+4.1)	97.9 (+4.0)
Average humidity (% RH)	48.6 (-4.3)	52.6 (+2.7)	52.0 (-6.7)	51.1 (-2.8)

Data from House C shows almost no overheating above 25°C aside from a small amount in the living room, and no significant underheating. This contrasts with some significant underheating prior to refurbishment, especially in the living room which was underheated for almost one fifth of the time. On average across the three rooms post-refurbishment, temperatures fell within the acceptable range of 15-25°C for 98.2% of the time, up from 85.6% pre-refurbishment.

Humidity also falls within an acceptable range of 40-70% for a large majority of the time.

House D

House D	Living room	Kitchen	Bedroom	Average
% of time >21°C	5.3 (+5.3)	28.3 (+20.6)	16.1 (+16.0)	16.6 (+14.0)
% of time >25°C	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
% of time <18°C	16.4 (-82.5)	0.0 (-33.5)	0.0 (-82.7)	5.5 (-66.2)
% of time <15°C	0.0 (-61.5)	0.0 (-4.0)	0.0 (-25.7)	0.0 (-30.4)
% of time 18>21°C	78.3 (+77.2)	71.7 (+40.6)	83.9 (+66.7)	78.0 (+61.5)
% of time 15>25°C	100 (+61.4)	100 (+31.7)	100 (+25.7)	100 (+39.6)
Average temperature (°C)	19.1 (+4.8)	20.7 (+2.5)	20.4 (+4.2)	20.1 (+3.8)
% of time >70% RH	15.3 (-47.9)	1.3 (-3.1)	0.2 (-48.1)	5.6 (-33.0)
% of time >80% RH	0.3 (-19.6)	0.2 (-1.5)	0.0 (-5.1)	0.2 (-8.7)
% of time <40% RH	0.0 (0.0)	0.0 (-0.1)	0.0 (0.0)	0.0 (0.0)
% of time 40>70% RH	84.7 (+47.9)	98.7 (+30.8)	99.8 (+48.1)	94.4 (+42.3)
Average humidity (% RH)	65.5 (-7.5)	59.5 (+2.7)	61.8 (-7.4)	62.3 (-4.1)

This dwelling exhibits no significant overheating or underheating, and all rooms are within the acceptable range of 15°C to 25°C 100% of the time, up from 60.4% pre-refurbishment. The kitchen and bedroom display good humidity characteristics, though the relative humidity of the living room does rise above 70% for a small portion of the time. The percentage of time that relative humidity fell within the acceptable range of 40-70% rose from an average of 52.1% across the three rooms pre-refurbishment, to 94.4% post-refurbishment.

The data suggests a substantial improvement from pre-refurbishment, when the property was underheated for much of the time and the living room was often above 70% RH, to post-refurbishment. Note however that the pre-refurbishment data for this dwelling was considered to be inaccurate, and therefore the extent of any actual changes in performance is uncertain.

House E

House E	Living room	Kitchen	Bedroom	Average
% of time >21°C	26.3 (+24.9)	15.6 (+15.6)	0.2 (-0.2)	14.0 (+13.4)
% of time >25°C	5.4 (+5.4)	1.3 (+1.3)	0.0 (0.0)	2.2 (+2.2)
% of time <18°C	7.3 (-81.1)	16.4 (-81.7)	63.9 (-22.6)	29.2 (-61.8)
% of time <15°C	0.0 (-24.0)	0.0 (-57.5)	0.3 (-34.5)	0.1 (-38.7)
% of time 18>21°C	66.4 (+56.2)	68.0 (+66.1)	35.9 (+22.8)	56.8 (+48.4)
% of time 15>25°C	94.6 (+18.8)	98.7 (+56.2)	99.8 (+34.6)	97.7 (+36.5)
Average temperature (°C)	20.3 (+4.1)	19.5 (+4.9)	17.5 (+2.0)	19.1 (+3.7)
% of time >70% RH	0.1 (-1.2)	0.8 (-0.2)	1.1 (-15.4)	0.7 (-5.6)
% of time >80% RH	0.0 (0.0)	0.0 (-0.1)	0.0 (-1.3)	0.0 (-0.5)
% of time <40% RH	3.3 (+2.4)	1.3 (+1.3)	0.0 (0.0)	1.5 (+1.2)
% of time 40>70% RH	96.5 (-1.2)	97.9 (-1.1)	98.9 (+15.4)	97.8 (+4.4)
Average humidity (% RH)	54.2 (-0.2)	55.8 (-3.0)	61.7 (+3.5)	57.2 (+0.1)

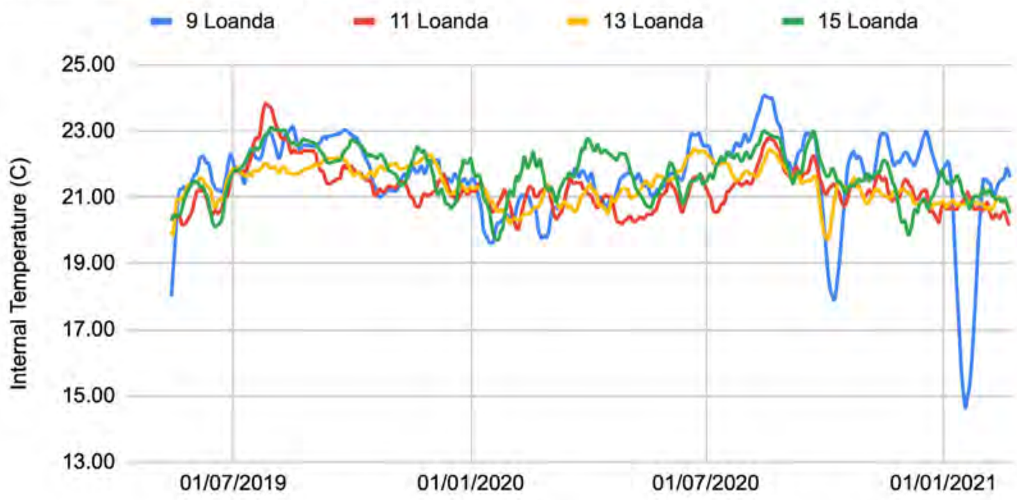
Though this dwelling does not display many instances of significant over- or underheating, there are some significant temperature fluctuations, both spatially and temporally. The living room is heated to between 18°C and 21°C for around two thirds of the time, with around a quarter of the time being above 21°C, and small proportions of time above 25°C and below 18°C. The kitchen is adequately heated for almost all of the time studied, but varies slightly from the living room in that it is heated above 21°C for less time, and below 18°C for more time. The bedroom also is not significantly over or underheated, but is mostly heated to below 18°C, with the remainder between 18 and 21°C, and virtually no time above 21°C. The data shows great improvement over the dwelling pre-refurbishment, which had average temperature ranging from 14.6°C in the kitchen to 16.2 in the living room, and which was significantly underheated much of the time. On average across the three rooms, temperatures fell within the acceptable range of 15-21°C for 97.7% of the time, up from 61.2% pre-refurbishment.

Humidity very rarely falls outside of the acceptable range of 40-70%, which was largely the case prior to refurbishment, with the only notable improvement being in the bedroom, which was above 70% RH for 16.5% of the time prior to refurbishment and then 1.1% of the time after refurbishment.

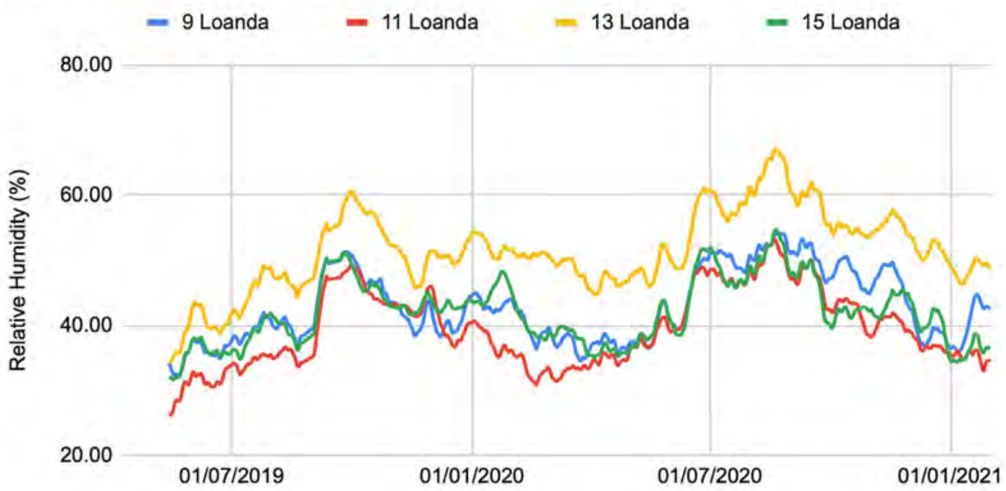
APPENDIX D

Switchee Continuous Monitoring Data

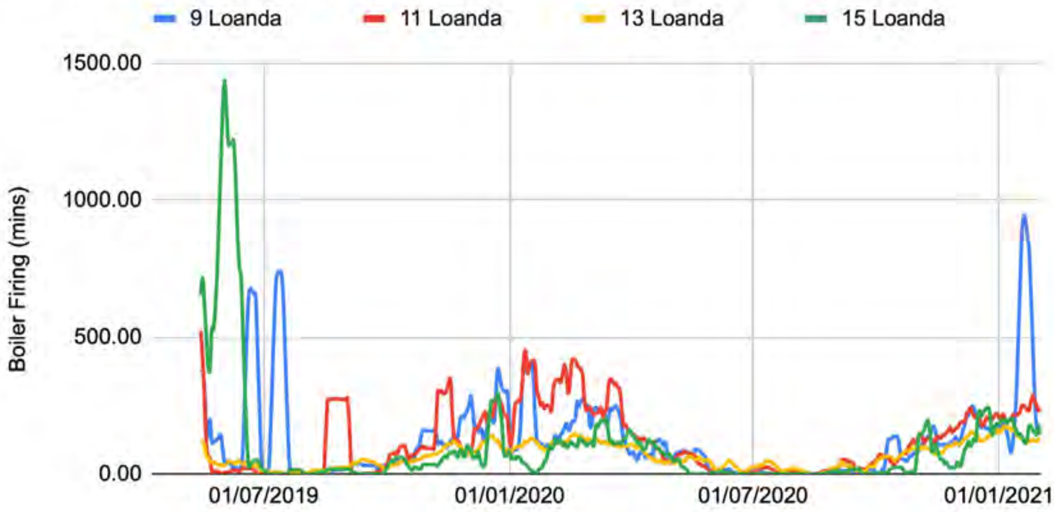
Internal Temperature (C)



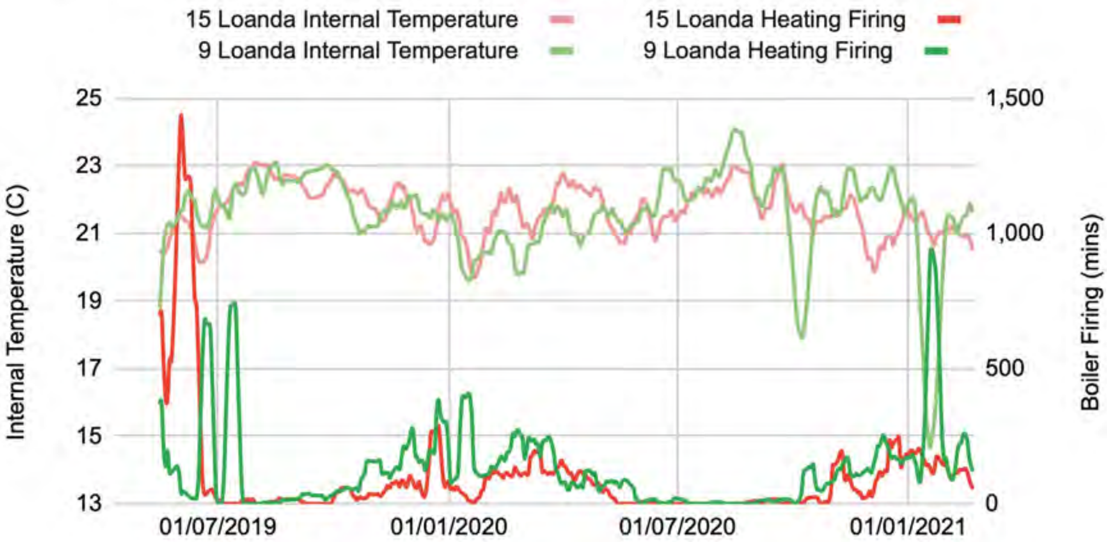
Relative Humidity (%)



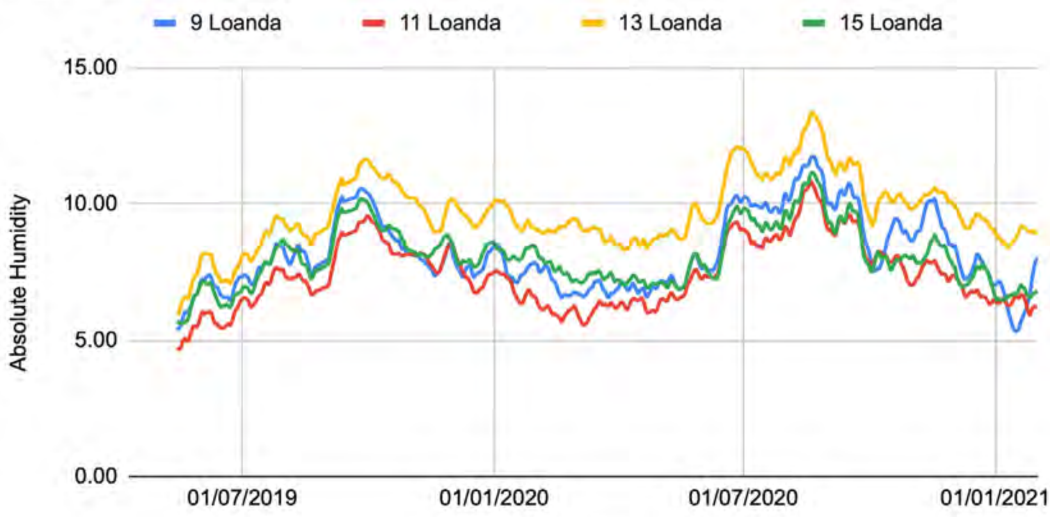
Heating Firing Time (mins)



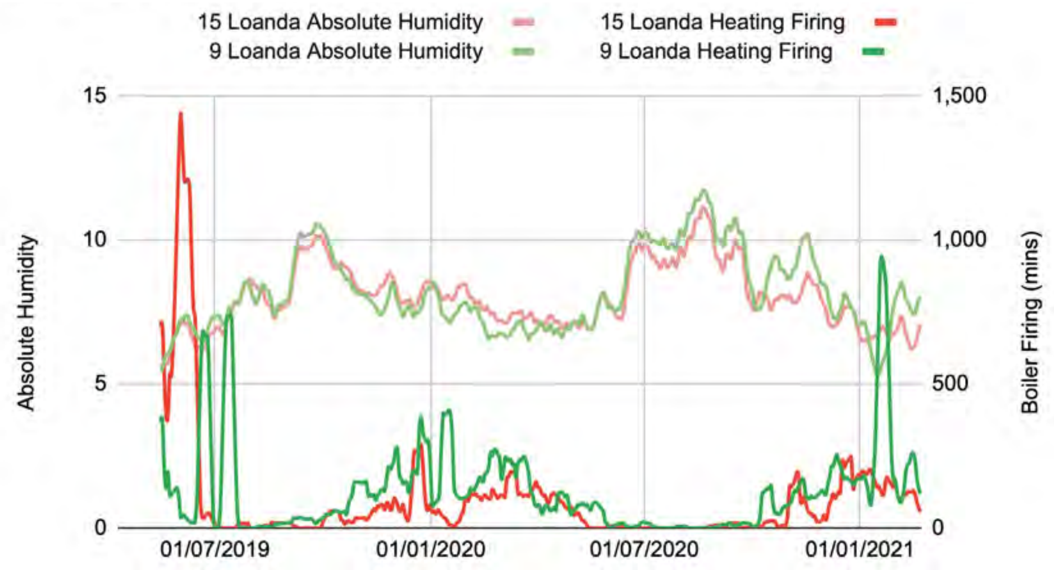
Internal Temperature and Boiler Firing



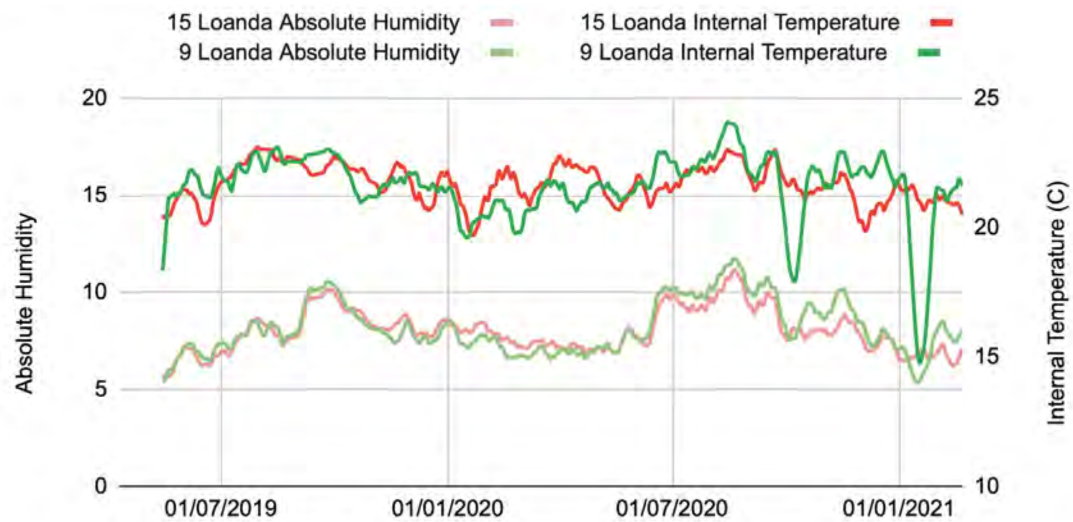
Absolute Humidity



Absolute Humidity & Boiler Firing



Absolute Humidity and Internal Temperature



APPENDIX E

Pre and Post retrofit Response Maintenance Costs

Property	Issued Task Orders from 01/08/19-31/07/20					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	3	2	5	£50.54	£87.20	£137.74
House B	2	6	8	£48.16	£151.54	£199.70
House C	0	2	2	£0.00	£88.74	£88.74
House D	0	4	4	£0.00	£102.20	£102.20
		Average per property	**4.75**	**£24.68**	**£107.42**	**£132.10**

Property	Issued Task Orders from 01/08/18-31/07/19					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	7	3	10	£0.70	£51.19	£51.89
House B	1	0	1	£0.00	£0.00	£0.00
House C	3	2	5	£98.65	£35.00	£133.65
House D	1	1	2	£24.08	£0.00	£24.08
		Average per property	**4.5**	**£30.86**	**£21.55**	**£52.41**

Property	Issued Task Orders from 01/08/17-31/07/18					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	5	3	8	£83.82	£0.00	£83.82
House B	0	1	1	£0.00	£51.19	£51.19
House C	2	1	3	£1,113.19	£0.00	£1,113.19
House D	4	1	5	£165.59	£0.00	£165.59
		Average per property	**4.25**	**£340.65**	**£12.80**	**£353.45**

Property	Issued Task Orders from 01/08/16-31/07/17					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	3	2	5	£577.05	£32.00	£609.05
House B	6	6	12	£1,684.22	£689.24	£2,373.46
House C	7	7	14	£972.38	£551.12	£1,523.50
House D	10	0	10	£1,105.03	£0.00	£1,105.03
		Average per property	**10.25**	**£1,084.67**	**£318.09**	**£1,402.76**

Property	Issued Task Orders from 01/08/15-31/07/16					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	1	2	3	£51.53	£32.00	£83.53
House B	7	1	8	£84.18	£32.00	£116.18
House C	1	1	2	£34.07	£32.00	£66.07
House D	6	2	8	£111.94	£32.00	£143.94
		Average per property	**5.25**	**£70.43**	**£32.00**	**£102.43**

Property	Issued Task Orders from 01/08/14-31/07/15					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	1	2	3	£12.78	£0.00	£12.78
House B	5	4	9	£326.97	£200.50	£527.47
House C	2	2	4	£74.95	£0.00	£74.95
House D	1	1	2	£22.50	£32.08	£54.58
		Average per property	**4.5**	**£109.30**	**£58.15**	**£167.45**

Property	Issued Task Orders from 01/08/13-31/07/14					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	2	3	5	£92.65	£32.00	£124.65
House B	4	4	8	£552.71	£32.00	£584.71
House C	2	5	7	£55.25	£432.08	£487.33
House D	7	1	8	£366.32	£32.00	£398.32
		Average per property	**7**	**£266.73**	**£132.02**	**£398.75**

Property	Issued Task Orders from 01/08/12-31/07/13					
	No. of All Trades	No.of heating jobs	Total No. of jobs	All Trades cost	Heating cost	Total cost
House A	2	2	4	£45.00	£64.00	£109.00
House B	6	1	7	£294.47	£32.00	£326.47
House C	0	4	4	£0.00	£47.00	£47.00
House D	2	2	4	£59.05	£64.00	£123.05
		Average per property	**4.75**	**£99.63**	**£51.75**	**£151.38**

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