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University of Salford MANCHESTER

DEEP Report 5.02
Salford Energy House

Heating Systems Testing

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Executive Summary

The primary objective of the Energy House DEEP heating system tests was to investigate the unintended consequences of performing fabric retrofit without any modification to a dwelling's gas central heating (GCH) system. The research was designed to measure the impact of post-retrofit oversizing and test low-cost strategies to mitigate it. A secondary objective was to identify the point during the piecemeal retrofit process when it becomes viable to replace GCH with an air source heat pump (ASHP). The heating system tests also provided the opportunity to assess the impact of fabric retrofit on occupant thermal comfort.

A whole house approach to retrofit must include consideration of space heating provision. Post-retrofit oversizing resulting from fabric retrofit can reduce the efficiency of GCH systems that use traditional Class I (on/off) boiler controls. This can result in retrofits failing to deliver the anticipated savings in space heating energy use. The extent to which efficiency is reduced is directly related to the size of the dwelling heat load reduction. Any measure or set of measures (for example solid wall insulation and room-in-roof improvements) that result in large heat load reductions are likely to have a significant impact on GCH efficiency and should trigger some evaluation of mitigation measures or an adjustment in energy saving estimates.

GCH systems that use Class V modulating boiler controls are less susceptible to post-retrofit oversizing. Class V controls could provide a low-cost measure for mitigating post-retrofit oversizing. They also have the potential to optimise existing heating systems that are incorrectly sized, so their adoption should be considered as part of any insulation improvement package. However, Class V controls require a boiler to be capable of modulation, so they may not be suitable for older boilers.

An alternative and complementary low-cost post-retrofit oversizing mitigation measure to Class V controls is to modify the boiler flow temperature setpoint to provide better agreement between the heat output of the existing radiators and the heat load of the dwelling. It is a strategy that can be adopted for boilers that are incapable of modulating output and can also be used to improve the performance of incorrectly sized heating systems without significant detriment to their responsiveness and ability to provide space heating in cold weather.

Many solid wall dwellings will require their external walls to be insulated to make the transition from GCH to ASHP viable. However, ASHPs that are incorrectly installed could result in increased energy bills. ASHPs should provide clear diagnostic feedback to installers and householders about installation issues. ASHPs require the appropriate heating curve (weather compensation) to be selected to achieve good control of space heating and optimal efficiencies. Selecting the correct heating curve is difficult due to lack of industry knowledge and tools, leaving installers and consumers reliant on trial and error. User-friendly tools are required to assist with heating curve selection.

The performance of a dwelling's heating system is linked to its fabric performance. Ideally, boiler flow setpoint modification, heating system sizing, and ASHP heating curve selection should be based upon the measured fabric performance, however this is not yet feasible. Current practice is to use two different methodologies to calculate the fabric heat loss of an existing dwelling and size its heating system. Improving the accuracy and alignment of these methodologies would allow heating systems to be optimised for the dwelling's fabric heat loss.

1 Introduction

This report provides findings from the heating systems tests that took place at the University of Salford Energy House test facility during the Department for Energy Security and Net Zero (DESNZ) Demonstration of Energy Efficiency Potential (DEEP) Retrofit Project. Although DEEP was primarily a fabric retrofit project, the controlled test conditions provided the opportunity to investigate the interaction between fabric and heating system performance and occupant thermal comfort.

Heating system tests were performed at each stage of a whole house fabric retrofit of the Energy House[1]. The aims of the heating system tests were to:

1. **Assess the impact of fabric retrofit on GCH system performance.** GCH system components (e.g. boiler and radiators) are sized to meet the calculated heat load of a dwelling. Fabric thermal retrofits could result in an existing GCH system being oversized for the residual heat load. Post-retrofit GCH system oversizing could reduce heating system efficiency undermining improvements in fabric efficiency. The Energy House's GCH remained unmodified throughout the piecemeal fabric retrofit process. Measurements of GCH system performance were undertaken at each stage of the retrofit to assess the impact of post-retrofit oversizing.
2. **Investigate boiler control strategies to mitigate post-retrofit oversizing**. Installing a new GCH system to remedy post-retrofit oversizing may not prove cost-effective in the short to medium-term. The impact of low-cost modifications to boiler controls were assessed. This included use of modulating boiler controls and modifying boiler flow temperature to align the existing radiator output with the post-retrofit heat load.
3. **Identify when it is viable to replace a GCH system with an ASHP system.** ASHP tests were conducted to identify the stage during a piecemeal retrofit process that an ASHP can replace GCH without adversely impacting a householder's energy bills or thermal comfort.
4. **Test ASHP heating strategies.** ASHPs require different heating patterns and flow temperatures to GCH. The use of different heating patterns and curves was tested to assess their impact on space heating provision and system efficiency.
5. **Measure the impact of fabric retrofit on occupant thermal comfort.** Thermal comfort metrics were measured at each stage of the retrofit to assess whether improvements in fabric performance provides an additional thermal comfort benefit above that associated with reduced the cost of space heating.

As DEEP was primarily a fabric retrofit project, prioritisation was given to the fabric testing requirements of the project which placed constraints on the number of heating system tests that could be performed. The testing did not consider domestic hot water (DHW) production.

It must be noted that findings from this work should be regarded as a case study and further work may be required to validate findings.

[1] Full details of the DEEP Energy House fabric thermal performance tests can be found in DEEP Report 5.01.

2 Methodology

2.1 Test subject

2.1.1 The Energy House

Testing was performed at the Salford Energy House test facility. It contains the Energy House (Figure 1), a replica Victorian solid wall end-terrace house constructed within an environmental chamber capable of replicating external air temperatures between -12 °C and +30 °C. It was built using reclaimed materials and traditional construction methods of the time and can be retrofitted to most fabric thermal performance standards[2]. The Energy House shares a party wall with a similar building, referred to as the conditioning void. Environmental conditions in the chamber and conditioning void can be controlled and repeated across multiple test periods. This makes it possible to measure the impact of changes to the Energy House's building fabric and space heating provision with greater confidence and speed than houses in the field[3].

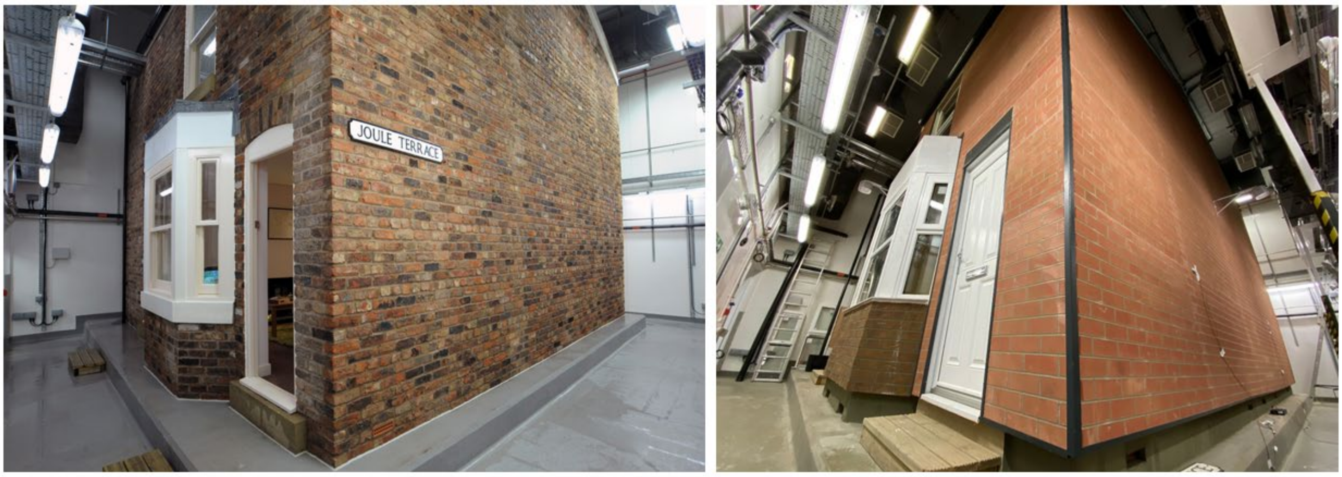

Figure 1: The Salford Energy House pre-retrofit (left) and post-DEEP retrofit (right)

2.1.2 Energy House central heating system

The Energy House has a conventional hydronic central heating system with radiators in each room. The system can be served by either a domestic gas condensing combination boiler or an ASHP by switching valve positions. An Intergas Xclusive 24 kW combination boiler was used in the GCH tests. It is capable of modulating central heating output between 18.7 and 3.6 kW. Nibe F2040 monobloc ASHP 6kW with a Nibe VVM 320 indoor module were used for the ASHP tests. Thermostatic controllers (refer to Section 2.2.1.2 for details) on the internal wall of the living room at mid-storey height (1.15 m) regulated the living room temperature. The boiler controllers and living room radiator provided boiler interlock. Honeywell Home HR92UK digital radiator controllers regulated space heating input to other zones. The ASHP external temperature sensor was located on the rear elevation of the Energy House. Diagrams

[2] Construction details and floor plans are provided in Appendix A and Appendix B, respectively.
[3] The Energy House is frequently modified for test purposes. Therefore, baseline measurements of fabric and heating system performance are undertaken at the commencement of each project.

showing the arrangement of the Energy House's hydronic space heating services are provided in Figure 2 and Figure 3.

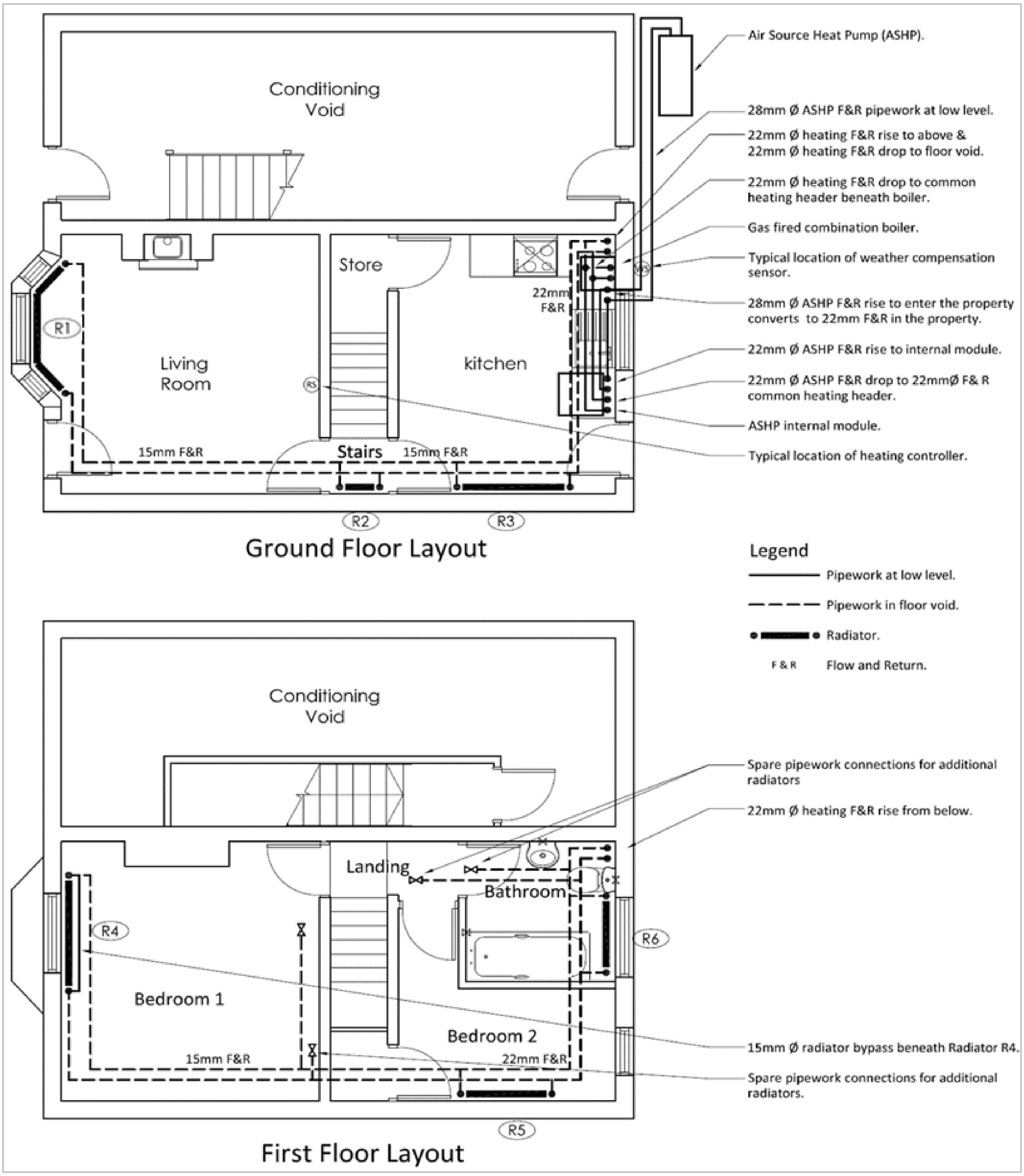

Figure 2: Layout of the Energy House's hydronic heating services

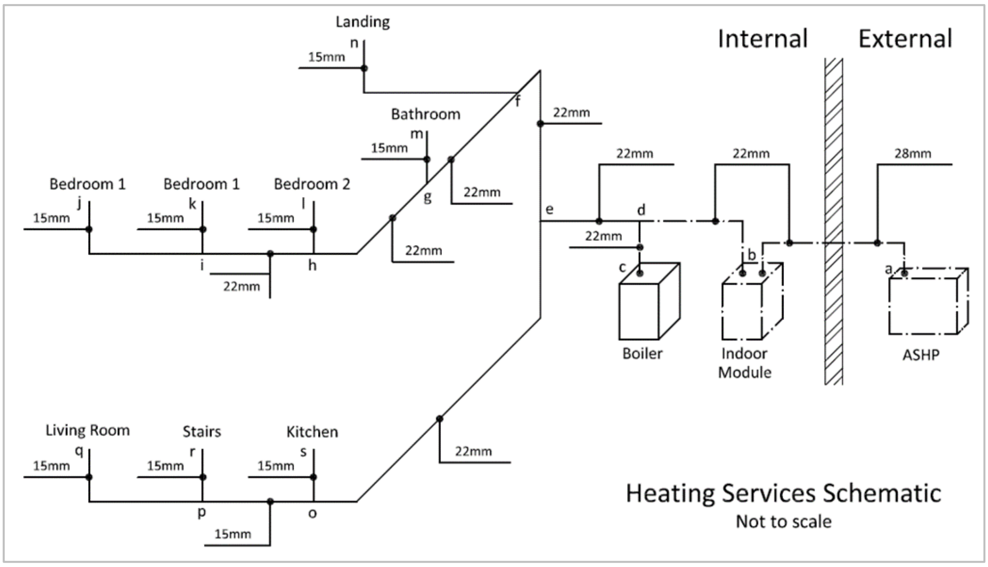

Figure 3: Schematic of the Energy House's hydronic heating services

2.1.3 Energy House DEEP fabric retrofit

The space heating system tests were accommodated within a staged full fabric retrofit of the Energy House. The test programme was designed to compare the following approaches to the full fabric retrofit of solid wall dwellings:

1. **Piecemeal approach**. A piecemeal approach retrofit only considers reducing plane elemental heat losses. The piecemeal retrofit process is often cumulative and involves retrofitting individual elements in isolation. Retrofits typically occur sporadically and are not designed as part of a coordinated programme of works.

2. **Whole house approach (WHA).** The "whole house approach" is a way of thinking about retrofit in manner that is holistic and risk based[4]. It seeks improve building fabric energy efficiency while minimising the risks posed to the health of occupants and the structure of a building. The whole house approach is incorporated within the PAS 2035:2019[5] standard[6].

The test programme involved a staged fabric retrofit of the Energy House simulating a piecemeal retrofit approach (stages 1-5) to the whole house. The sequencing of the piecemeal retrofit was based on performing fabric retrofits in ascending order of financial cost. The Energy House's thermal elements were then adapted to be representative of a retrofit that had been performed following whole house approach retrofit principles, namely the interfaces between elements (Stage 6). Steady-state fabric thermal performance measurements and heating system tests were performed at each stage of the DEEP retrofit. Figure 4 shows the configuration of the Energy House fabric and measured in-situ U-values of thermal elements at each stage of the DEEP retrofit. The test stage numbers are used as shorthand in this report to refer to the fabric configuration throughout the DEEP retrofit.

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[4] STBA (2016), What is the Whole House Approach to Retrofit, in, Sustainable Traditional Buildings Alliance (available from: https://stbauk.org/whole-house-approach/)

[5] BSI (2019), PAS 2035/2030:2019 Retrofitting dwellings for improved energy efficiency - specification and guidance, British Standards Institution, London

[6] The DEEP retrofit test programme was designed prior to the introduction of PAS 2035:2019. Therefore, the whole house approach retrofit was not implemented to this specification.

<table>
<tr><th>Test stage\Retrofit</th><th>Roof</th><th>Openings</th><th>Ground floor</th><th>External walls</th><th>Whole house approach measures</th></tr>
<tr><td>Stage 1 - baseline</td><td>Cold roof - 100 mm mineral wool (0.29 W/m^{2}K)</td><td rowspan="2">'E' rated uPVC double glazing and doors (2.42 W/m^{2}K)</td><td rowspan="3">Suspended timber - uninsulated (0.69 W/m^{2}K)</td><td rowspan="4">225 mm brick with 12.5 mm wet plaster (1.65 W/m^{2}K)</td><td rowspan="5">Junctions untreated</td></tr>
<tr><td>Stage 2 - roof</td><td rowspan="5">Additional 170 mm mineral wool. Total 270 mm mineral wool (0.16 W/m^{2}K)</td></tr>
<tr><td>Stage 3a - openings, roof</td><td rowspan="4">'A' rated uPVC double glazing and GRP doors (1.16 W/m^{2}K)</td></tr>
<tr><td>Stage 4 - ground floor, roof, openings</td><td rowspan="3">150 mm mineral wool between joists + vapour barrier (0.24 W/m^{2}K)</td></tr>
<tr><td>Stage 5 - EWI, roof, openings, ground floor [piecemeal approach full retrofit]</td><td rowspan="2">102 mm mineral wool EWI (0.34 W/m^{2}K)</td></tr>
<tr><td>Stage 6 - whole house approach full retrofit</td><td>EWI below DPC
Bay retrofit
Extended eaves
Openings into EWI</td></tr>
</table>

Figure 4: Configuration of Energy House fabric & in-situ U-values at DEEP test stage

2.1.4 Energy House fabric performance

The Energy House heat transfer coefficient (HTC) measured at each stage of the DEEP retrofit is provided in Figure 5.

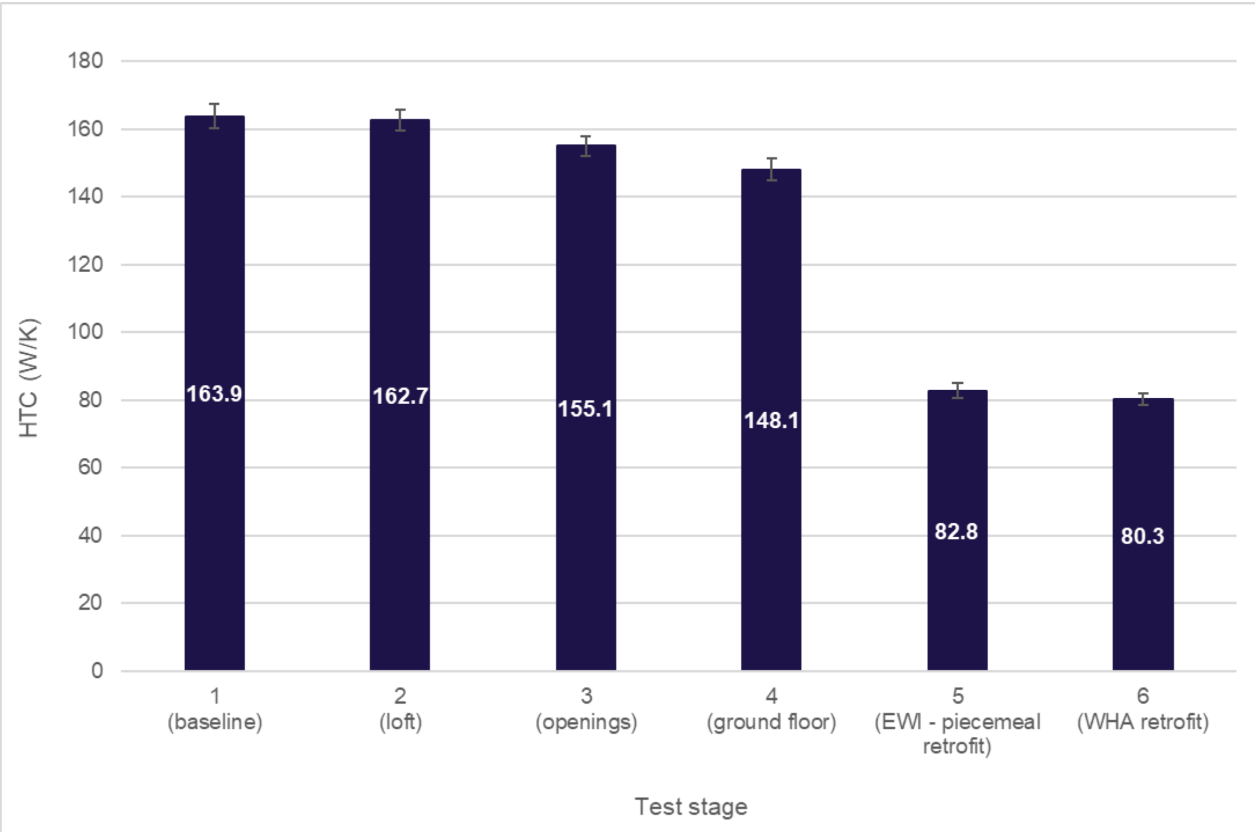


Figure 5: Measured Energy House HTC at each stage of the DEEP retrofit

Retrofits to the roof, openings, and ground floor in Stages 2-4 resulted in modest HTC reductions. The application of external wall insulation (EWI) at Stage 5 reduced the HTC by 44% from Stage 4 and by 50% from the Stage 1 baseline. The high impact of the external wall retrofit and relatively modest reductions in HTC from other retrofits was partially due to the Energy House being an end-terrace. External walls are 47% of its external heat loss area, openings 10%, and the ground floor and roof 21% each. The roof and ground floor also had relatively low baseline U-values in comparison to the external walls.

The whole house approach retrofit measures in Stage 6 had no significant impact on the HTC. At Stage 6, the HTC of the Energy House was 51% lower than the Stage 1 baseline HTC. However, the whole house approach retrofit eliminated almost all the surface condensation and mould risks at junctions that were not addressed by the piecemeal retrofit.

2.2 Heating system tests

2.2.1 Gas central heating system tests

2.2.1.1 Post-retrofit oversizing

The primary objective of the DEEP heating system tests was to assess the impact of post-retrofit oversizing on an existing GCH system. The configuration of the Stage 1 baseline GCH system was designed to be representative of a system installed and commissioned correctly. The rationale being that there is a dearth of evidence detailing ‘typical’ UK GCH system characteristics such as radiator sizing accuracy, balancing, and boiler commissioning.

The heat load and radiator sizing calculation for the Energy House GCH system in its baseline fabric configuration was performed by an independent building services engineer using the 2017 version of the CIBSE Domestic Heating Design Guide (DHDG)[7] based on a flow temperature of 70 °C and a return temperature of 50 °C (60 °C mean water temperature). The 2017 version was used to reflect existing GCH installations. The U-values and air change rates assumed by the DHDG were used to calculate the heat load as measured fabric performance is rarely used in heat load calculations[8], thus representing standard practice. The external design temperature of -3 °C is mid-range for external climates in UK heat load calculations. The output from the heat load and radiator sizing CIBSE DHDG (category A[9]) calculation is provided in Table 1.

Table 1: CIBSE DHDG Energy House heat load and radiator sizing calculation for the baseline (Stage 1) fabric configuration

Zone	Design temp (°C)	Air change rate (ACH)	Heat loss (W)	Installed capacity (W)
External	-3	-	-	-
Living room	21	1.5	2,086	2,086

[7] CIBSE (2017), HVDH Domestic heating design guide, The Chartered Institution of Building Services Engineers
[8] CIBSE DHDG and measured U-values and ventilation rates are compared in Section 3.3.
[9] CIBSE DHDG air change rates for older existing buildings (pre-2000).

Zone	Design temp (°C)	Air change rate (ACH)	Heat loss (W)	Installed capacity (W)
Kitchen	18	2	1,577	1,757
Stairs	18	1.5[10]	278	287
Bedroom 1	18	1	1,294	1,316
Bathroom	22	1.5[11]	703	827
Bedroom 2	18	1	788	815
Total	-	-	**6,726**	**7,088**

Radiators with outputs that closely matched the Stage 1 baseline heat load for each room were installed. The difference between the calculated heat load and installed heat output of the radiators across the entire Energy House was +5%. The radiator lockshield valves were statically balanced to achieve a ΔT of 20 °C across each radiator and the system.

An independent heating consultant programmed the boiler parameters to simulate the behaviour of a 'typical' UK combination boiler commissioned correctly. The boiler's maximum flow temperature was set to 70 °C and its maximum heating output was range rated to 7.5 kW to provide closer agreement with the 6.7 kW calculated Stage 1 heat load of the Energy House. DHW pre-heat was disabled. The GCH system remained unmodified throughout each stage of the fabric retrofit process.

2.2.1.2 Modulating controls

Two types of boiler controller were tested at each stage to assess whether controls capable of modulating boiler output can mitigate the impact of post-retrofit oversizing. The boiler controllers tested are from the following Boiler Plus energy-related products (ErP) classifications:

- **Class I - On/off Room Thermostat**: A room thermostat that controls the on/off operation of a heater. Performance parameters, including switching differential and room temperature control accuracy are determined by the thermostat's mechanical construction.
- **Class V - Modulating room thermostat, for use with modulating heaters**: An electronic room thermostat that varies the flow temperature of the water leaving the heater dependent upon measured room temperature deviation from room thermostat set point. Control is achieved by modulating the output of the heater.

[10] Reduced from CIBSE DHDG recommendation of 2 ACH as no windows on stairs or landing.
[11] Reduced from CIBSE DHDG recommendation of 3 ACH as no extractor fan present in the bathroom.

Class I controls are considered representative of GCH systems with boilers installed prior to the introduction of ErP boiler control classification under the Boiler Plus legislation in 2018. Boiler Plus incentivised the uptake of more advanced controllers that are capable of modulating boiler output. A Sangamo Choice RSTAT3 thermostat was selected for Class I testing as it is an extra-low voltage (ELV) controller that allowed researchers to swap between control classes during the test programme.

Class V control was selected to represent modulating controls as they do not require an external temperature sensor or selection of an appropriate heating curve for weather compensation. These requirements increase the complexity and expense of installing and commissioning modulating controls. A Honeywell Home T6R thermostat was selected for the Class V tests[12]. Learning optimisation was disabled to prevent the thermostat commencing heating before scheduled heating periods for comfort purposes and curtailing heating early to save energy. Learning optimisation was also inappropriate due to the fabric performance changing at each test stage and the short duration of each test.

The boiler's minimum output of 3.6 kW was greater than the DHDG heat load calculated for Stages 1-4 of DEEP at the external temperature of 4.5 °C used in the test programme (refer to Section 2.3.1). Therefore, the boiler was expected to modulate its heat output to match the heat load under test conditions until the application of EWI at Stage 5 of the test programme.

2.2.1.3 Post-retrofit boiler flow temperature modification

At Stage 6 of the test programme the 7,088 W output capacity of the baseline radiators at 70 °C design flow temperature was almost three times greater than the DHDG (category C[13]) calculated heat load of 2,442 W and the HTC derived heat load of 2,563 W (refer to Section 3.3). The cost of replacing major central heating system components to mitigate post-retrofit oversizing may not be cost-effective[14]. Therefore, alternative low-cost post-retrofit oversizing mitigation strategies are required.

Boiler flow temperature was adjusted to provide better alignment between the output of the existing radiators with the post-retrofit heat load. To ensure effective boiler interlock, the boiler flow temperature was recalculated to suit the post-retrofit heat load of the living room. This also provides the benefit of ensuring that the living room is adequately heated. The HTC derived heat load could not be used for this purpose as it does not provide the heat load for individual rooms[15]. The Stage 6 DHDG (category C) was selected as it differed from the Stage 6 HTC derived heat load by only 5%. A calculated flow temperature of 50 °C was found to provide the closest alignment with the living room heat load. Table 2 provides details of the DHDG (category C) heat load calculation for Stage 6 and the installed radiator capacity at 70 °C & 50 °C flow temperatures.

[12] Both the Intergas Xclusive boiler and Honeywell Home T6R thermostat utilise the OpenTherm communication protocol.
[13] CISE DHDG air change rates for new (or existing) buildings constructed after 2006 and complying with all current building regulations.
[14] The cost to install radiators in the Energy House to match the Stage 6 heat load is estimated to be ~£1,000.
[15] This is an important consideration for SMETER based heat load calculations.

Table 2: DHDG (category C) heat load calculation for Stage 6 and the installed radiator capacity for GCH at 70 °C and 50 °C flow temperatures

Zone	Design temp. (°C)	Air change rate (ACH)	Heat load (W)	GCH capacity @ 70 °C flow (W)	GCH capacity @ 50 °C flow (W)	ASHP capacity at 45 °C flow (W)
External	-3	-	-	-	-	-
Living room	21	0.5	822	2,086	814	879
Kitchen	18	1.5	660	1,757	811	689
Stairs	18	0.5	84	287	118	89
Bedroom 1	18	0.5	375	1,316	562	385
Bathroom	22	0.5	361	827	309	370
Bedroom 2	18	0.5	140	815	345	140
Total			**2,442**	**7,088**	**2,958**	**2,552**

The 50 °C flow temperature resulted in the living room radiator being undersized by 1% and the entire system being oversized by 21% in comparison to the Stage 6 DHDG (category C) calculation.

The system was rebalanced prior to the 50 °C flow temperature tests to obtain a ΔT of 20 °C across each radiator and across the system. Test programme time constraints prevented installation and testing of radiators suitable for a 70 °C flow temperature with the Stage 6 fabric configuration to compare 50 °C performance against a system with radiators suitable for a 70 °C flow temperature.

2.2.2 Air source heat pump tests

2.2.2.1 Piecemeal retrofit ASHP installation point

The main aim of the ASHP tests was to identify the stage during the process of a piecemeal retrofit that an ASHP can replace GCH without adversely impacting a householder's energy bills or thermal comfort.

The priority given in the DEEP heating system testing to the GCH post-retrofit oversizing meant that the baseline GCH radiators remained in place until Stage 6. Therefore, it was not practicable to test ASHP performance with correctly sized radiators at each stage of the piecemeal retrofit process. ASHP testing with appropriately sized radiators took place at Stage 6 and with the Stage 3 fabric configuration replicated later in the test programme. Stage 3 was selected as it is the point in the piecemeal retrofit process where the cheapest and least disruptive retrofits (loft and openings) have been performed. ASHP testing took place at Stage 4 with the GCH Stage 1 baseline radiators, however the emitters were undersized for the heat load[16].

An independent building services engineer performed heat load and radiator sizing calculations for each ASHP test stage using the CIBSE DHDG. The design flow and return temperatures at -3 °C external temperature was informed by fabric performance and practical considerations relating to the space available to accommodate low temperature radiators. Table 3 provides the DHDG calculated heat load and radiator capacity at each DEEP ASHP test stage.

Table 3: ASHP sizing and design temperatures at each DEEP ASHP test stage

Test stage	DHDH ventilation category	DHDG heat load (W)	Installed emitter capacity (W)	Emitter capacity deviation from heat load	Flow/return design temp. @ -3 °C T_e (°C)
3	A	6,197	5,970	-4%	55/50
4	A	5,762	4,604	-20%	55/50
6	C	2,442	2,552	+5%	45/40

ASHPs require four times higher flow rates than GCH systems due to the lower ΔT of 5 °C. The higher flow rates mean that ASHP pipework for new installations is typically 28 mm in diameter. The ASHP retrofit testing was conducted using the existing 22 mm pipework as the work in the DEEP project was intended to simulate ASHP installations that use existing GCH pipework. The ASHP was programmed using the manufacturer's recommended parameters. Charging of the DHW cylinder was disabled. The radiator lockshield valves were statically balanced to achieve a ΔT of 5 °C across each radiator and the system.

2.2.2.2 ASHP control strategy

ASHPs typically use weather compensation controls. An external temperature sensor enables the ASHP flow temperature to be modified according to external conditions. Flow temperature decreases as external temperature increases and vice versa. It allows heat input to vary according to the heat load. The ASHP system design flow and return temperatures are those required for a -3 °C external air temperature. The flow temperature either side of the design temperature is dictated by a heating curve selected in the ASHP internal unit settings. Heating curves used in the tests were based on the DHDG calculated and HTC derived heat loads were tested. This enabled the impact of heating curve selection on ASHP performance to be assessed.

ASHPs typically operate with a 3-5 °C setback temperature setpoint between heating periods. A SAP based heating pattern with a 3 °C setback between heating periods (SAP SB) was tested at each stage. A SAP only heating pattern (SAP) was also tested in Stages 3 and 6 to

[16] Emitters were undersized for Stage 4 ASHP testing due to lower mean water temperature and increased flow rate in comparison to GCH.

assess the impact of setback on energy use and thermal comfort and to provide a direct comparison with GCH tests.

2.3 Test conditions

2.3.1 Internal and external environments

The Energy House was heated using the SAP pattern of 07:00-09:00 and 16:00-23:00. The internal setpoint temperatures were based on SAP/SBEM with a 21 °C setpoint in the living room and 18 °C setpoint in all other zones. Internal doors were closed during the heating system tests.

The conditioning void neighbouring the Energy House was maintained at 20 °C throughout the test programme using electric resistance heaters connected to PID controllers with PT-100 RTD temperature sensors.

Table U1 of SAP10 was used to select external temperatures representative of the UK average during the winter months (December to February). The chamber HVAC system was set to maintain ~4.5 °C throughout the test programme.

2.3.2 Test duration

To minimise thermal mass effects resulting from charging and discharging of the building fabric, each test was a minimum of 72 hours in duration. The initial 48-hour period allowed the Energy House to reach a state of dynamic equilibrium[17]. The final 24-hour period for each test was the reporting period. Time constraints meant that Class V controller performance was measured in the 24-hour period immediately following each 72-hour Class I test.

2.4 Measurement and analysis

2.4.1 Energy House monitoring equipment

The findings provided in this report are based on measurements obtained using the equipment listed in Table 4. Measurements were recorded at one-minute intervals by the Energy House's monitoring system.

Table 4: Measurement equipment used in the Energy House DEEP heating system tests

Measurement	Equipment	Uncertainty
Gas consumption[18]	Siargo MF32GD10 digital gas flow meter	± 1.5%

[17] Previous tests at the Energy House have shown that 24-hour periods following the initial 48-hour stabilisation period produce repeatable results thereafter.
[18] Gas energy consumption based on volumetric gas consumption measurement. Energy consumption (kWh) = volume (m^3) * calorific value (MJ/m^3) * pressure and temperature correction factor (1.02264) * 3.6 (converts Watts to kWh). Calorific values for each test period obtained from the National Grid.

Measurement	Equipment	Uncertainty
Electricity consumption	Siemens 7KT PAC1200 digital power meter	± 1%
Boiler & ASHP energy and power output	Sharkey 775 heat meter	± 1 %
Boiler & ASHP flow rate	Sharkey 775 ultrasonic flow meter	± 1 %
Boiler & ASHP flow and return temperature	PT-100 RTD	± 0.3 °C
Mid-room and chamber air temperature	IC temperature sensor	± 0.2 °C
Radiator surface temperatures	PT-100 RTDs	± 0.3 °C
Element surface temperatures	Type-T thermocouples (calibrated to ± 0.1 °C)	± 0.1 °C
Relative humidity	Campbell Scientific HygroVUE10	± 1.5%
Black globe temperature	Type-T thermocouple in 40 mm diameter globe	± 0.1 °C
Air velocity	Kimo SVO omnidirectional hot-wire probe	± 0.05 m/s

2.4.2 Efficiency measurements

Boiler efficiency was calculated using the following equation:

$$Boiler\ efficiency\ = \frac{boiler\ output\ [kWh]}{gas\ consumption\ [kWh]}$$

GCH system efficiency was calculated using the following equation[19]:

$$System\ efficiency\ = \frac{boiler\ output\ [kWh]}{gas\ consumption\ [kWh] +\ boiler\ electricity\ consumption\ [kWh]}$$

ASHP coefficient of performance (COP) was calculated using the following equation[20]:

$$ASHP\ COP\ = \frac{ASHP\ output\ [kWh]}{ASHP\ electricity\ consumption\ [kWh]}$$

[19] Boiler electricity consumption includes boiler operation and pump.
[20] ASHP electricity consumption includes the external and internal units.

2.4.3 Thermal comfort metrics

Occupant thermal comfort was assessed in the centre of each room during the 24-hour reporting period of each heating system test. The primary focus of the thermal comfort analysis was the living room, due to this being the main habitable zone. It is also the location of the thermostat that determines space heating input. The following metrics were used:

- **The Predicted Percentage Dissatisfied (PPD)**. Is the percentage of occupants who are predicted to be *dissatisfied* with their thermal comfort in a given indoor environment. A lower score predicts a more comfortable environment.
- **Operative temperature** considers both the air temperature and radiative temperature and is more indicative of how an occupant would feel in the environment.
- **Comfort benefit** has been defined for the purposes of this project as the difference between the operative and air temperatures. The purpose of this metric is to assess if an occupant would feel more comfortable in a lower air temperature due to changes to either the building fabric or the heating system.

Please refer to Appendix E for more details of the thermal comfort metrics used in this report.

3 Results

3.1 Gas central heating tests

A malfunction in the chamber HVAC system during the Stage 5 GCH tests compromised the energy and system efficiency measurements. However, the Stage 5 HTC was only 1.8 W/K (2%) lower than Stage 6, so fabric performance at both stages was comparable. These tests have been omitted from the reporting. The boiler heat meter malfunctioned during the Stage 3 GCH Class V test, so efficiencies and boiler output for this test are not reported.

3.1.1 GCH system performance

3.1.1.1 GCH system efficiency

Figure 6 shows GCH system efficiency at each stage of the DEEP retrofit using the Class I and Class V controllers at 70 °C maximum flow temperature.

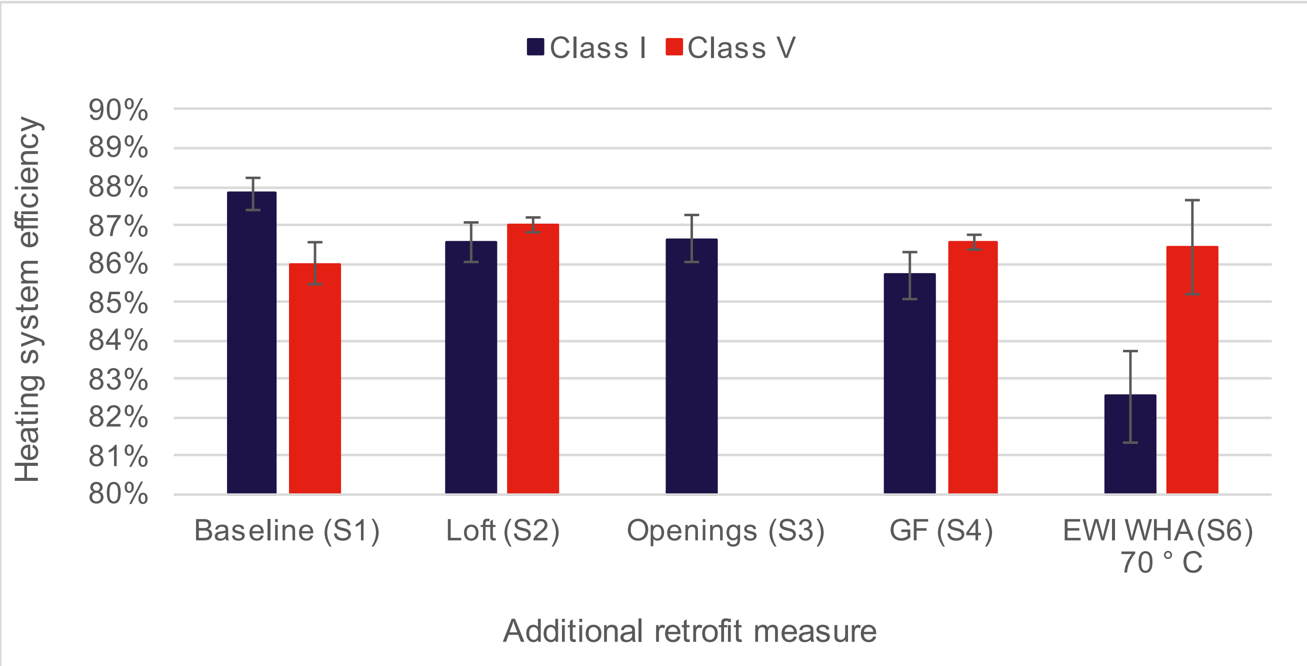


Figure 6: GCH system efficiency at each stage of the DEEP retrofit using Class I and Class V control at 70 °C maximum flow temperature

Heating system efficiency using the Class I controller decreased throughout the DEEP piecemeal retrofit process, from 88% at the baseline stage to 83% at the final retrofit stage. The highest efficiency at the baseline stage indicates that the system was sized correctly. EWI resulted in the single greatest reduction in efficiency of three percentage points. This measure also corresponded with the greatest reduction in HTC[21]. Heating system efficiency using the Class V controller across the piecemeal retrofit process remained consistent at 86-87%. The

[21] Although the Stage 5 Class I test was compromised by a chamber HVAC malfunction. The heating system efficiency measurement of 84% is considered robust. This provides additional evidence of the Class I heating system efficiency reduction following the EWI retrofit.

relationship between HTC and GCH system efficiency using Class I and Class V control is shown in Figure 7.

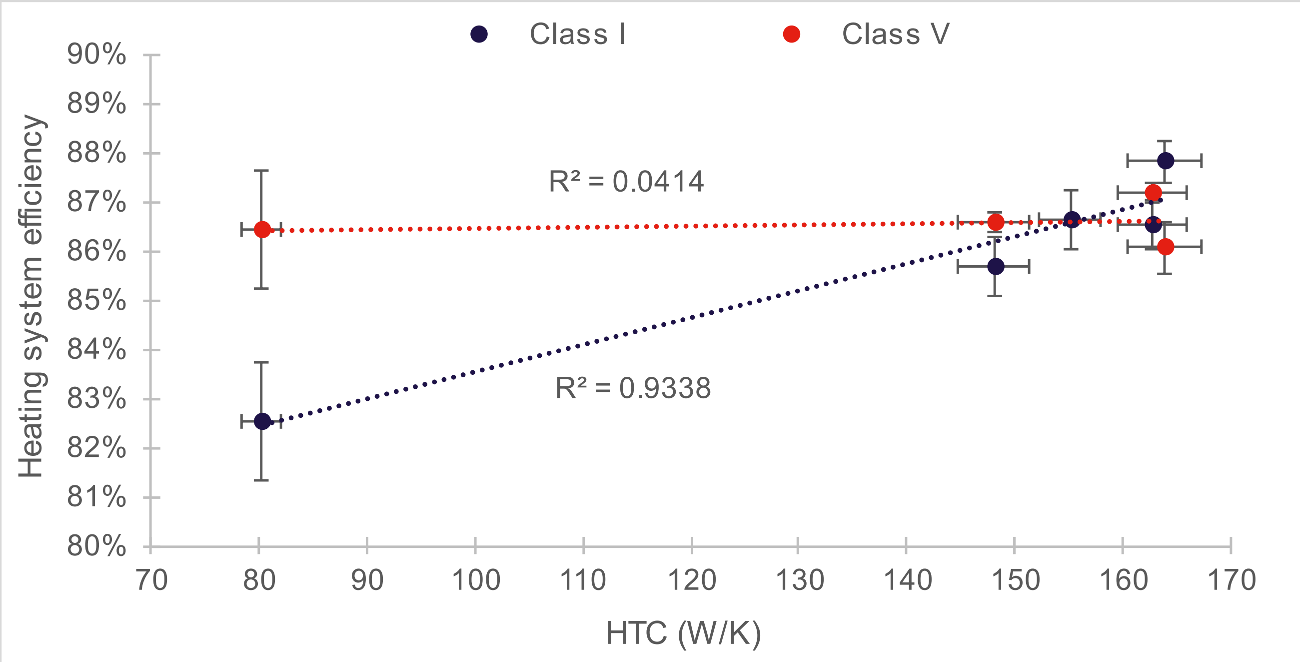


Figure 7: HTC vs. GCH system efficiency using Class I and Class V control

These findings suggest that fabric retrofit has an impact on heating system efficiency for boilers using Class I control. Therefore, post-retrofit oversizing could counteract some of the impact of fabric retrofit measures. Class V boiler controls have the potential to mitigate the impact of post-retrofit oversizing. The relatively low cost of purchasing and installing a Class V controller means that replacing a Class I with a Class V controller may prove cost-effective in the short-term[22]. However, it must be noted that boilers must be capable of modulation, so this strategy may not be an option for dwellings with older, non-modulating, boilers.

[22] An electrician may be required to replace a Class I controller with a Class V controller.

3.1.1.3 Boiler behaviour

Figure 8 shows boiler output during the seven-hour evening heating period at Stage 1 of the DEEP retrofit using Class I and Class V control.

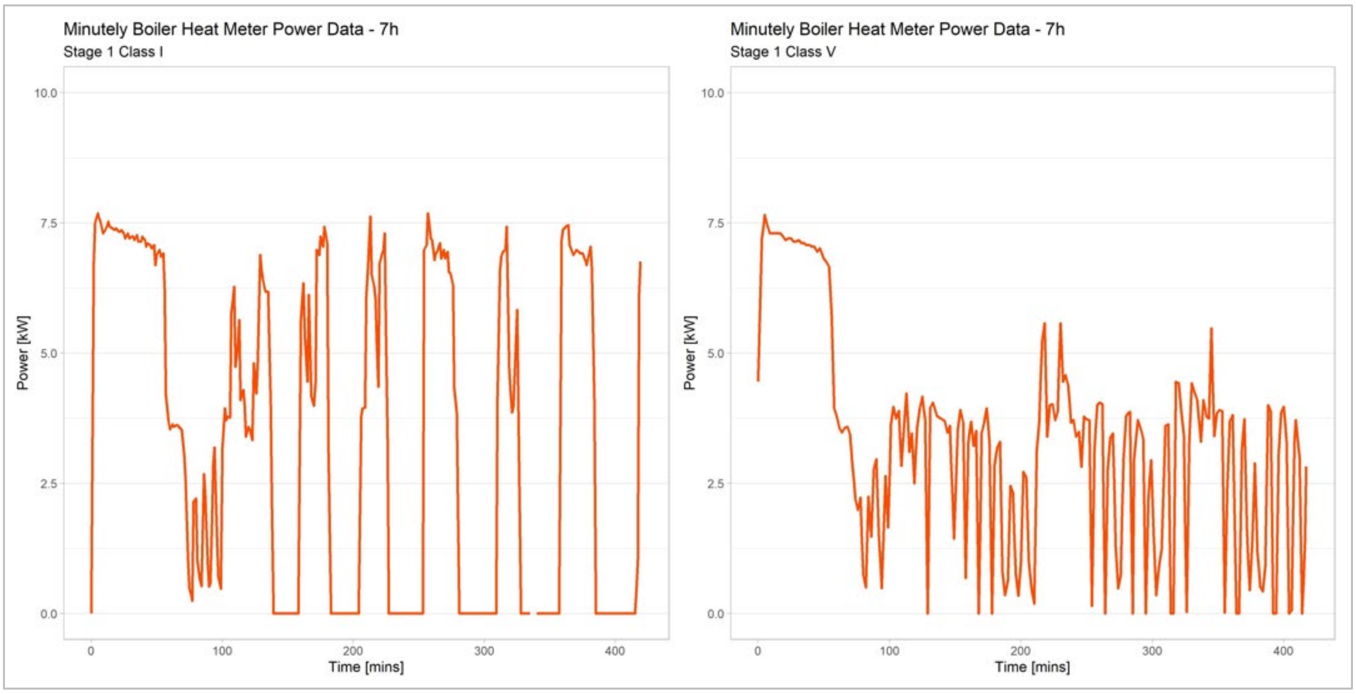


Figure 8: Boiler output during the seven-hour evening heating period at Stage 1 of the DEEP retrofit using Class I (left) and Class V (right) control

Boiler output using both Class I and Class V controllers during the Stage 1 baseline tests demonstrated almost identical behaviour at the start of the evening heating period, with boiler output at the limit of its 7.5 kW range rating. Following the initial firing period, both controllers exhibited on/off behaviour. Class I boiler operation was dictated by the hysteresis of the controller resulting in regular cycling at the 7.5 kW range rated output. Class V control resulted in some periods of continual modulated output, but also periods in low load control mode which resulted in rapid on/off behaviour at its minimum modulation output of 3.6 kW.

The Class V behaviour shows that during 'typical' winter conditions with poor fabric performance, the heat load of the Energy House was too low for the boiler to run constantly at reduced output. The Stage 1 DHDG calculated heat load of 4.5 kW at 4.5 °C external temperature (test conditions) was above the minimum boiler heat output of 3.6 kW, so the boiler was expected to run constantly at reduced output throughout the test. The behaviour observed was attributed to discrepancies between the fabric performance assumptions used in the DHDG heat load calculation and measured fabric performance (refer to Section 3.3). On/off behaviour reduces the potential efficiency gains that can be provided by modulating controls. Although the boiler has a relatively high modulation ratio, its maximum output is sized to meet DHW requirements. This means that many boilers capable of modulation will exhibit on/off behaviour for much of the heating season.

Figure 9 shows boiler flow and return temperatures during the seven-hour evening heating period at Stage 1 of the DEEP retrofit using Class I and Class V control.

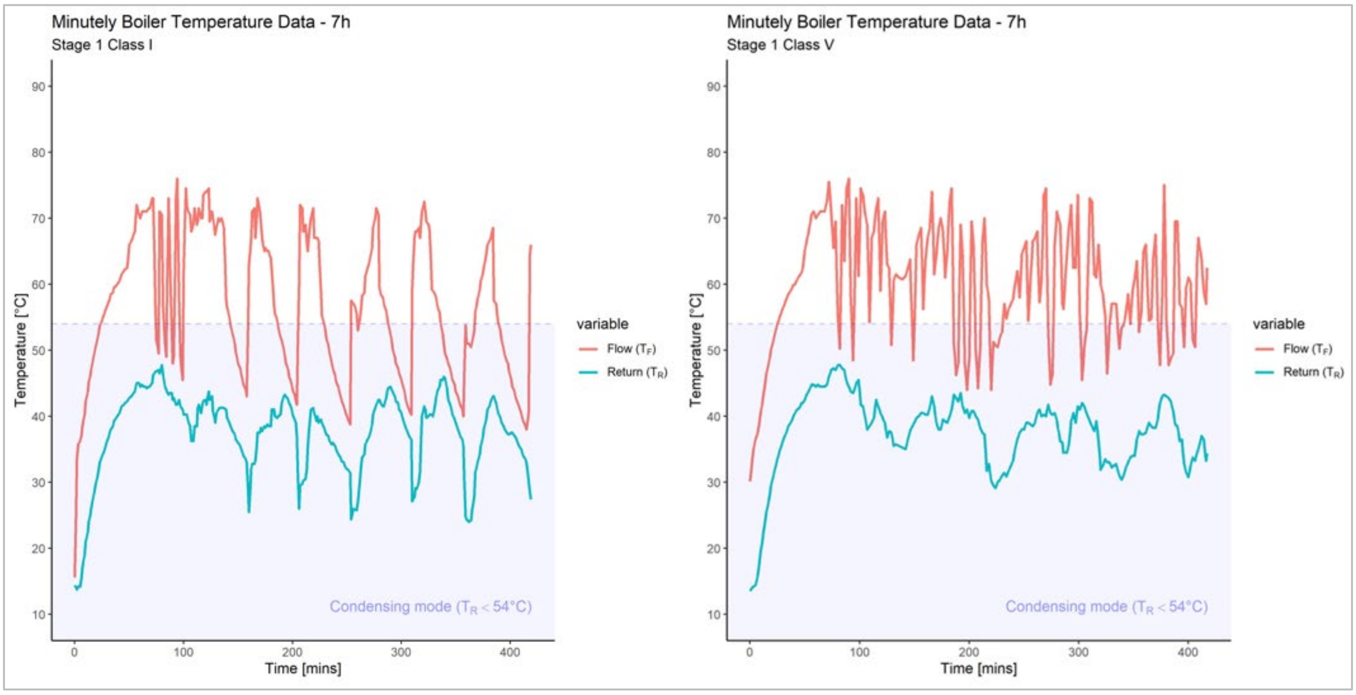


Figure 9: Boiler flow and return temperatures during the seven-hour evening heating period at Stage 1 of the DEEP retrofit using Class I (left) and Class V (right) control

Although Class V control resulted in modulated boiler output for most of the Stage 1 evening heating period, the flow temperature often reached 70 °C and return temperatures during periods of boiler firing periods were similar for each controller. This could explain why the Class I and Class V efficiencies were within measurement uncertainty at Stage 1.

Figure 10 shows boiler output during the seven-hour evening heating period at Stage 6 of the DEEP retrofit using Class I and Class V control.

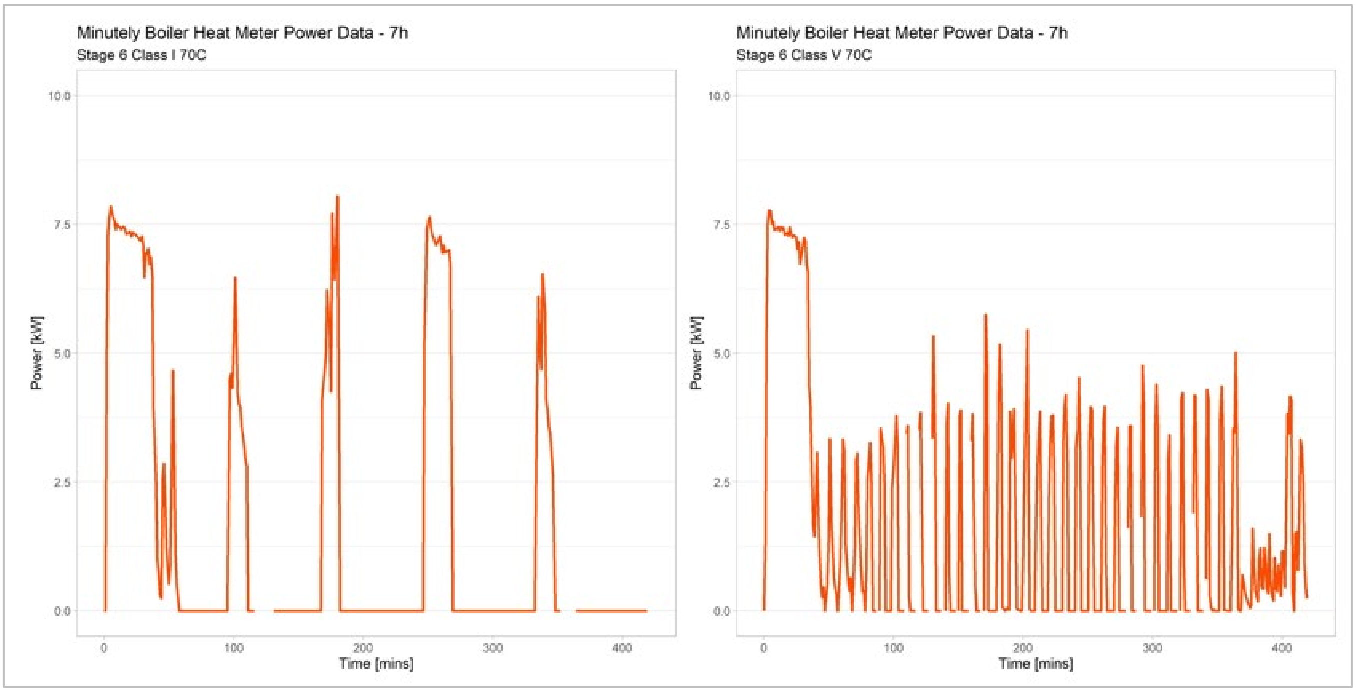


Figure 10: Boiler output during the seven-hour evening heating period at Stage 6 of the DEEP retrofit using the Class I (left) and Class V (right) controllers

Initial boiler output using both Class I and Class V controllers at Stage 6 showed the same characteristics at the start of the evening heating period as Stage 1 (Figure 8) with boiler output at the 7.5 kW range rated output. The initial firing period was shorter than Stage 1 as the internal setpoint temperature was reached sooner due to the reduced heat load. The reduced heat load meant that the boiler cycled less frequently than during Stage 1 using Class I control. However, Class V control demonstrated more rapid on/off behaviour than during Stage 1 as it was continually in low load control mode.

Figure 11 shows boiler flow and return temperatures during the seven-hour evening heating period at Stage 6 of the DEEP retrofit using Class I and Class V control.

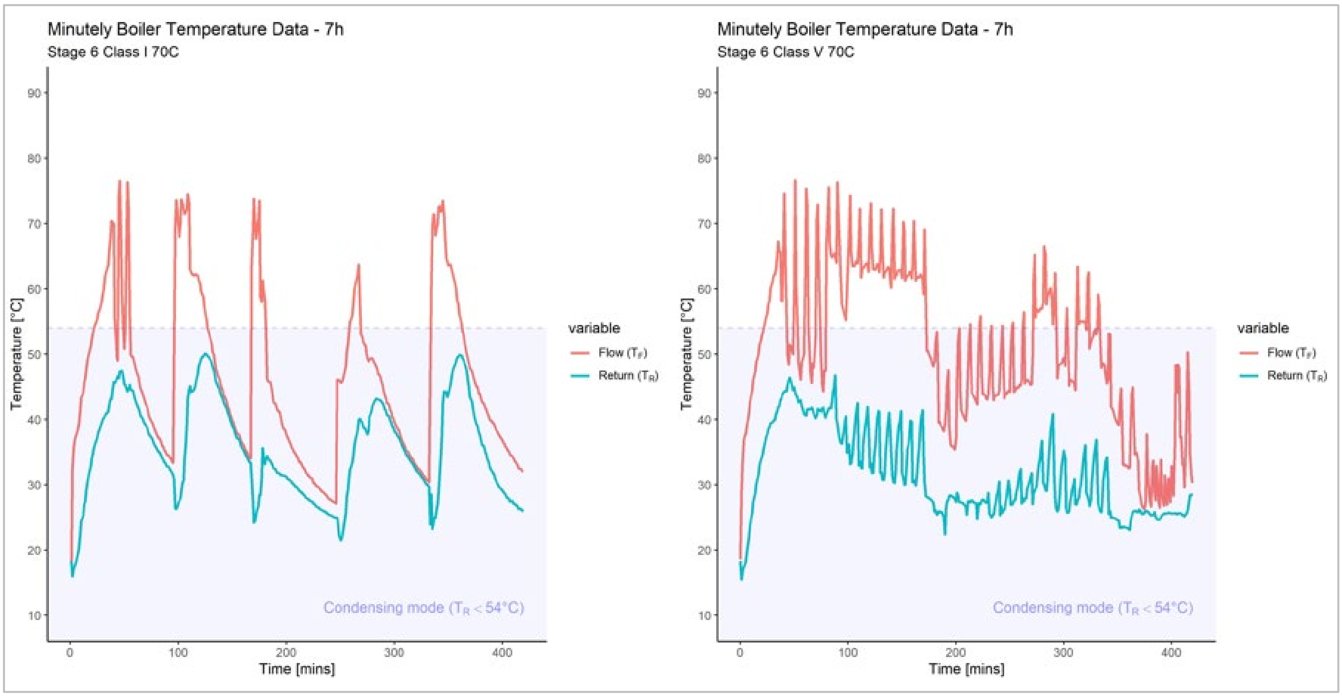


Figure 11: Boiler flow and return temperatures during the seven-hour evening heating period at Stage 6 of the DEEP retrofit using Class I (left) and Class V (right) control

Boiler flow and return temperatures using both Class I and Class V controllers at Stage 6 of the piecemeal retrofit process showed similar behaviour at the start of the evening heating period. However, the return temperature during periods of boiler operation was generally lower throughout the remainder of the heating period using Class V controls. Around three hours into the evening heating period the Class V flow temperature during boiler operation was generally below 54 °C, meaning that both flow and return temperatures were within the condensing zone. This resulted in flue gases condensing across the entirety of the heat exchanger, thereby increasing boiler efficiency. This could explain why the Class V control appeared to be unaffected by post-retrofit oversizing.

3.1.2 Post-retrofit boiler flow temperature modification

3.1.2.1 Heating system efficiency

Figure 12 shows GCH system efficiency at each stage of the DEEP retrofit using Class I and Class V control and the impact of modifying boiler flow temperature at Stage 6.

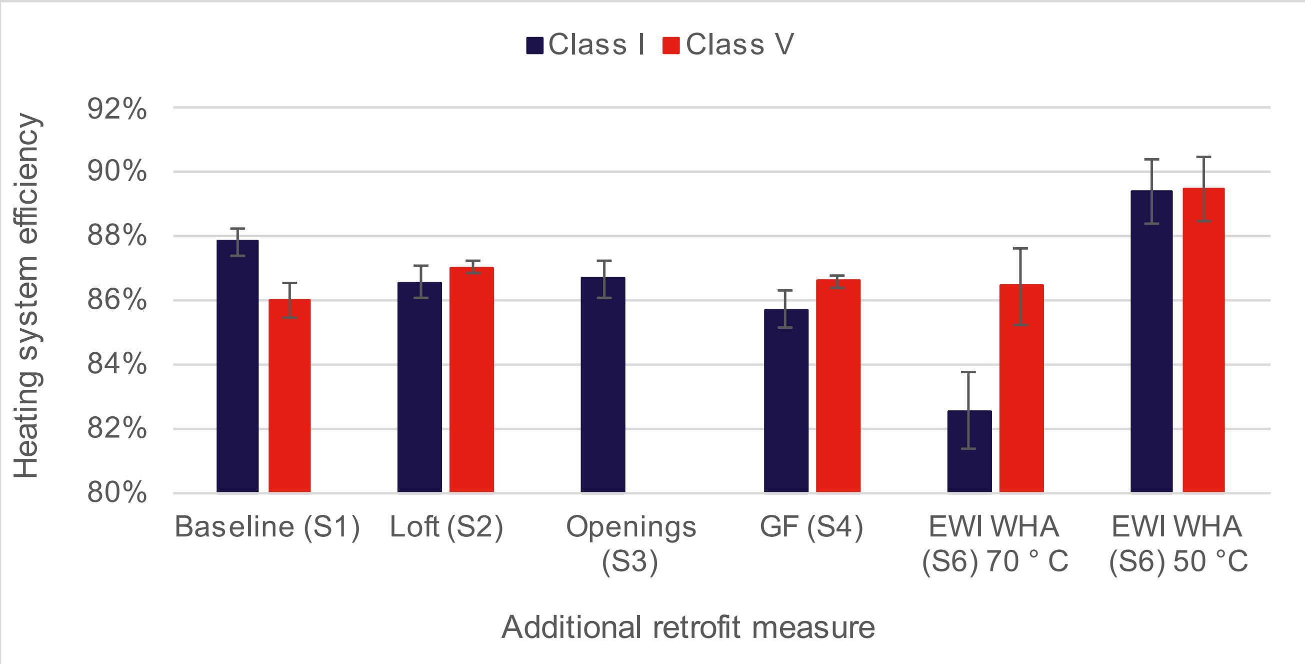


Figure 12: GCH system efficiency at each stage of the retrofit process using the Class I and Class V controllers at 70 °C and at 70 °C and 50 °C maximum flow temperature at Stage 6

Modifying boiler flow temperature to enable the output from the existing radiators to align more closely with the Stage 6 heat load resulted in six and three percentage point increases in heating system efficiency for Class I and Class V controls, respectively. The 89% efficiency obtained for both control classes was greater than their Stage 1 baseline values.

This strategy differs from guidance issued by the UK Government to reduce boiler flow temperature[23] as the revised flow temperature is an informed modification of boiler flow temperature that is intended to match the heat load of a dwelling. Whereas UK Government guidance is based on a flow temperature setpoint of 60 °C for all dwellings. It is recommended that when following this strategy, the interlock thermostat should be in the living room or moved to that location if possible.

3.1.2.2 Boiler behaviour

Figure 13 shows boiler output using Class I control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C and 50 °C flow temperature setpoints.

[23] https://helpforhouseholds.campaign.gov.uk/energy-saving-advice/

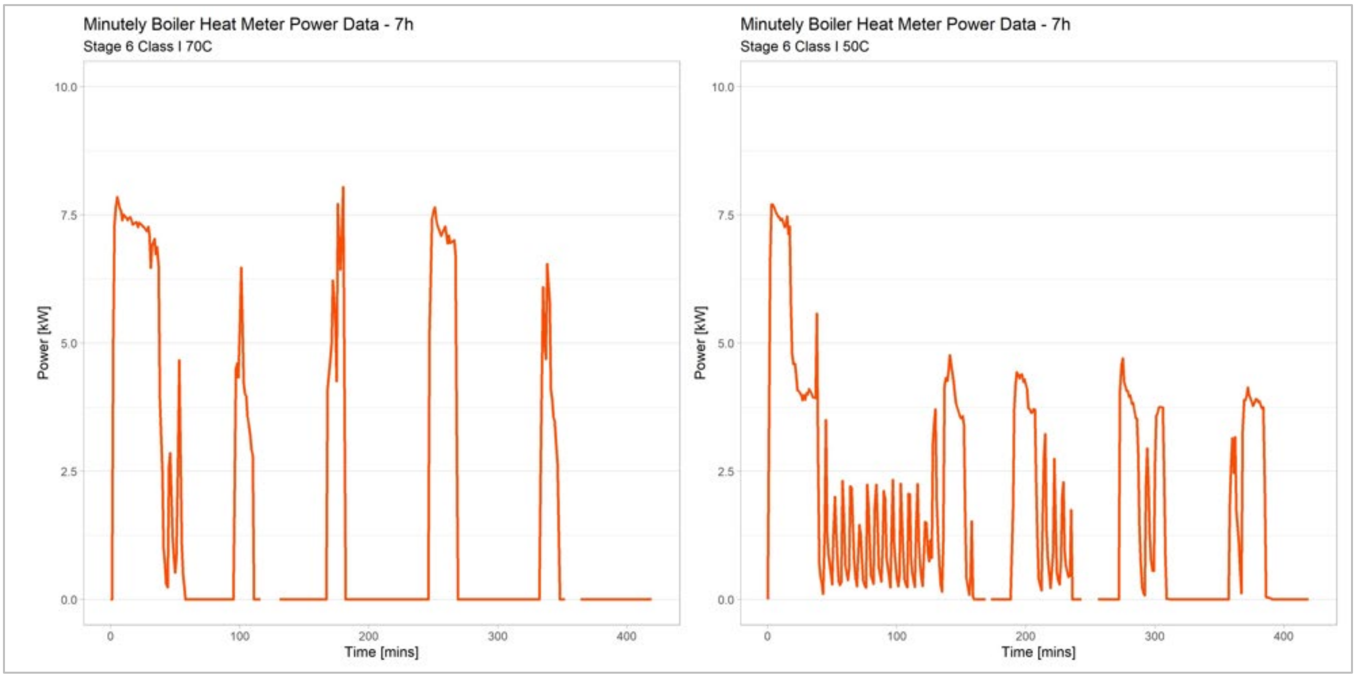


Figure 13: Boiler output using Class I control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C (left) and 50 °C (right) flow setpoints

Figure 14 shows boiler flow and return temperatures using Class I control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C and 50 °C flow setpoints.

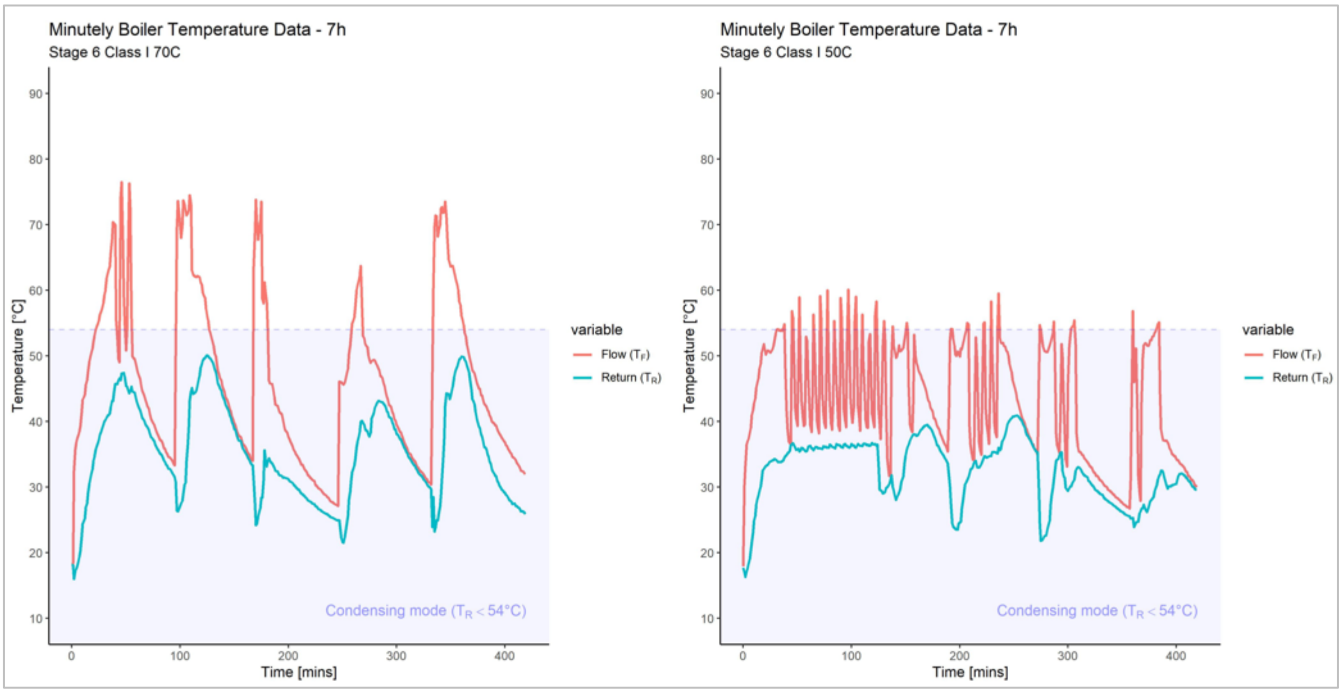


Figure 14: Boiler flow and return temperatures using Class I control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C (left) and 50 °C (right) flow setpoints

Modifying the boiler flow temperature with the Class I boiler controller reduced boiler peak output throughout the majority of the seven-hour evening heating period. Flow and return temperatures were reduced which resulted in increased condensing and heat recovery from of flue gasses and an increase in boiler efficiency.

Figure 15 shows boiler output using Class V control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C and 50 °C maximum flow temperature setpoints.

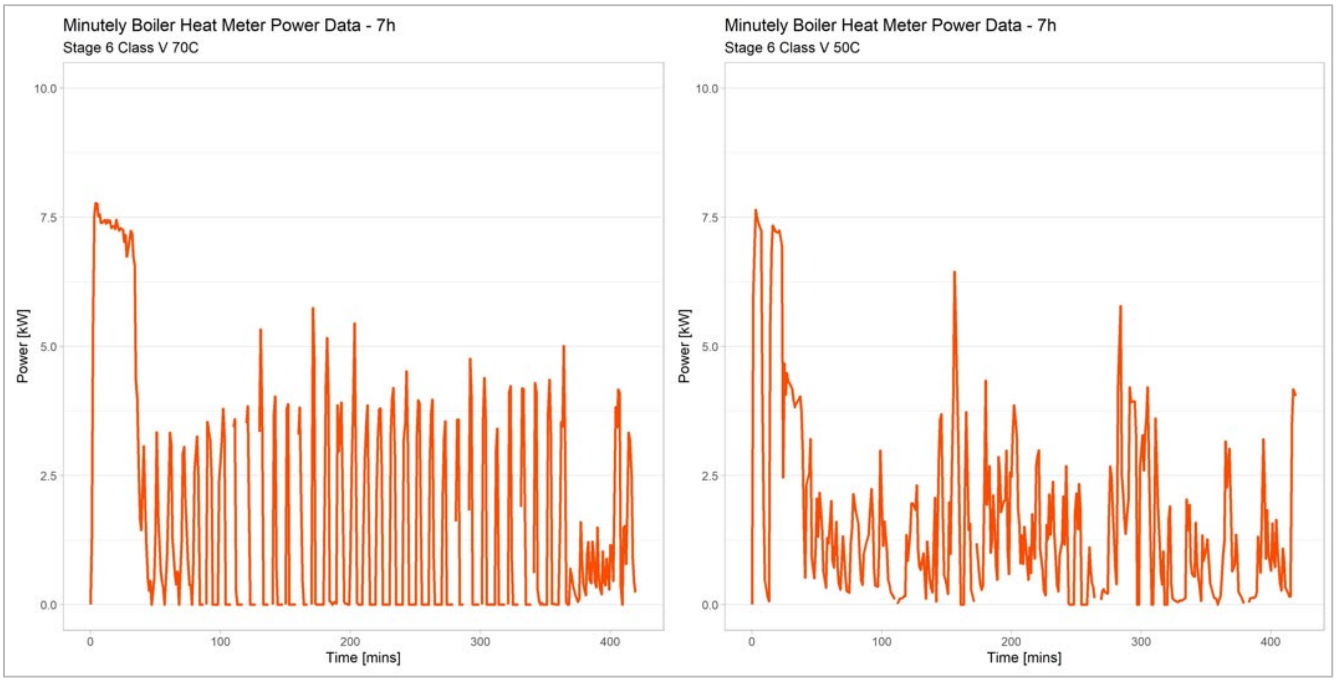


Figure 15: Boiler output using Class V control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C (left) and 50 °C (right) maximum flow setpoints

Figure 16 shows boiler flow and return temperatures using Class V control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C and 50 °C maximum flow temperature setpoints.

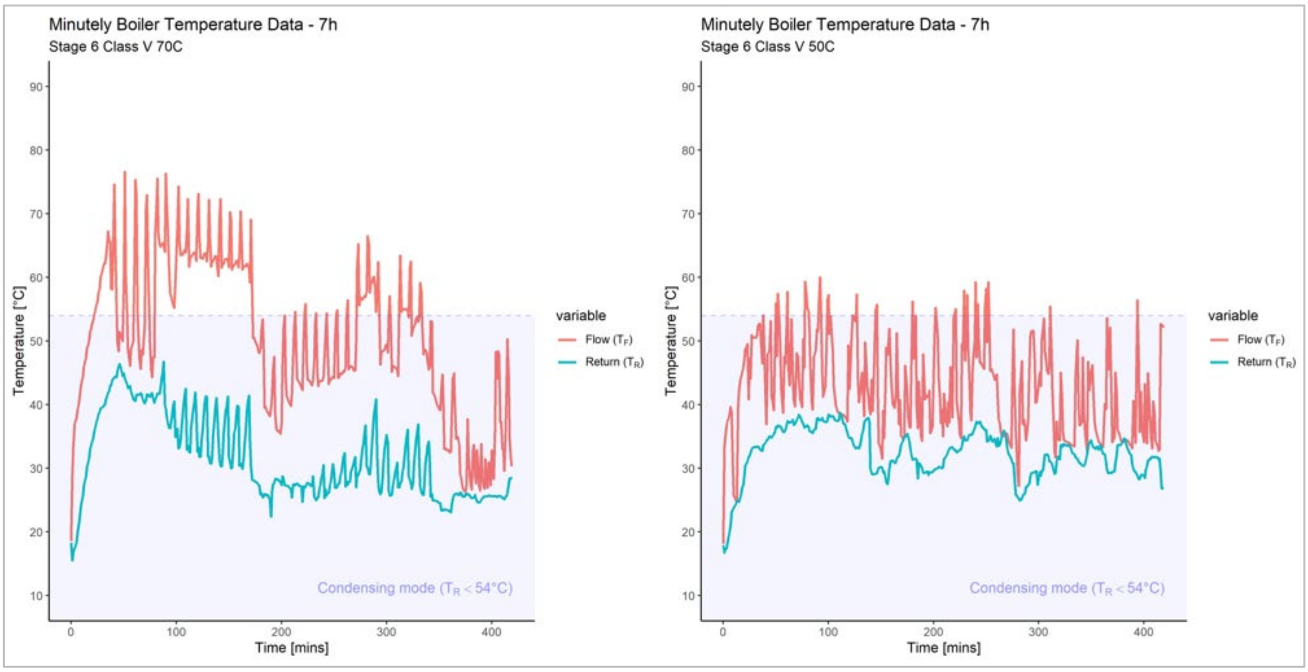


Figure 16: Boiler flow and return temperatures using Class I control during the seven-hour evening heating period at Stage 6 of the DEEP retrofit with 70 °C (left) and 50 °C (right) maximum flow setpoints

Modifying the maximum boiler flow temperature with the Class V boiler controller had a less dramatic impact on boiler behaviour than for the Class I controller. It brought the flow temperature during firing periods within the condensing zone for almost the entirety of the seven-hour evening heating period, resulting in greater condensing capacity and increased boiler efficiency.

3.1.4 Energy use

3.1.4.1 Space heating energy use

Table 5 provides the DEEP GCH boiler and heating system measurements for each test.

Table 5: DEEP GCH testing boiler and heating system measurements

Test stage	Control class	Flow setpoint (°C)	Gas use (kWh)	Boiler electric (kWh)	Boiler output (kWh)	Boiler eff. (%)	Heating system eff. (%)	Boiler on time (mins)
1	I	70	37.0	0.09	32.6	88	88	355
1	V	70	37.8	0.10	32.6	86	86	457
2	I	70	35.5	0.09	30.8	87	87	291
2	V	70	36.0	0.10	31.5	87	87	458
3	I	70	33.0	0.09	28.7	87	87	316
3	V	70	34.4	0.09	-	-	-	-
4	I	70	31.5	0.09	27.1	86	86	330
4	V	70	31.3	0.09	27.1	87	87	384
6	I	70	19.2	0.05	15.9	83	83	178
6	V	70	20.4	0.06	17.7	87	86	255
6	I	50	18.3	0.07	16.4	90	89	334
6	V	50	17.9	0.08	16.0	90	89	372

Space heating gas use is dictated by the internal to external temperature difference (ΔT) as well as heating system efficiency (the ΔT measured in each test can be found in Table 6). The different controllers resulted in differing boiler output and therefore internal temperatures, so caution needs to be applied when comparing their gas use.

Figure 17 shows gas energy use at each stage of the piecemeal retrofit using Class I and Class V control and the impact of the flow temperature setpoint modification at Stage 6.

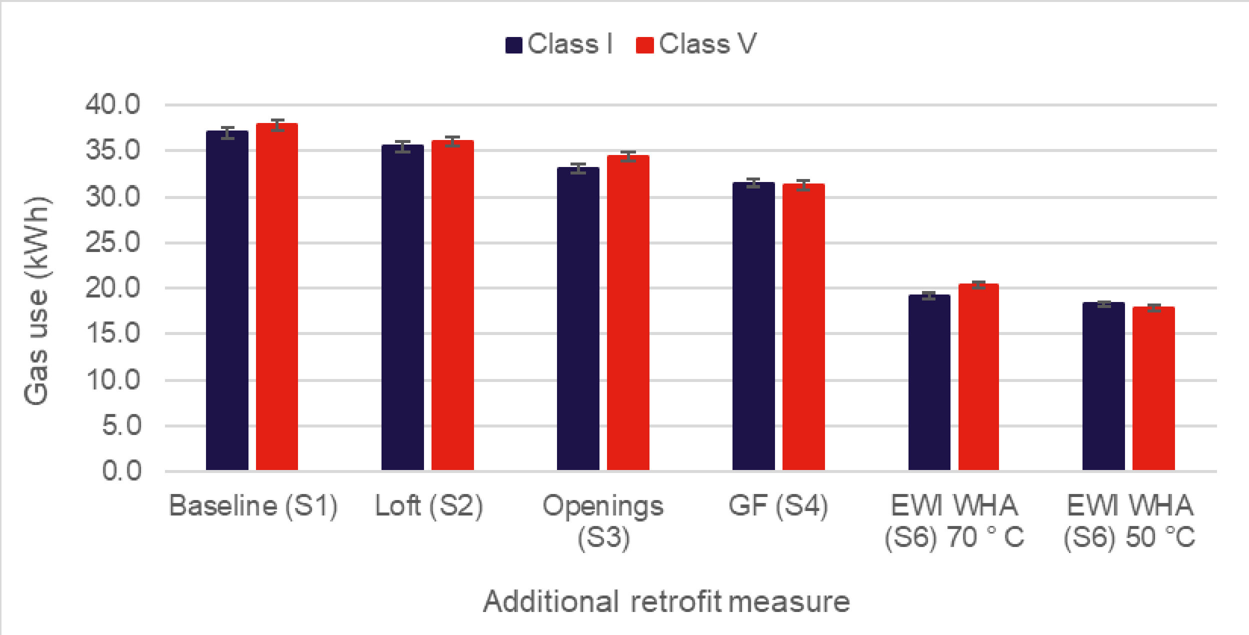


Figure 17: Gas energy use at each stage of the piecemeal retrofit using Class I and Class V control and the impact of the flow temperature setpoint modification at Stage 6

Figure 18 shows boiler output at each stage of the piecemeal retrofit using Class I and Class V control and the impact of flow temperature setpoint modification at Stage 6.

Figure 18: Boiler output at each stage of the piecemeal retrofit using Class I and Class V control and the impact of flow temperature setpoint modification at Stage 6

Class I and Class V gas use and boiler output decreased following each fabric retrofit. The EWI retrofit reduced gas use between Stages 4 and 6 by 39% (12.2 kWh) and 35% (10.9 kWh) for Class I and Class 5 controls respectively. Stage 6 gas use using Class I and Class V controls with a 70 °C flow temperature setpoint was reduced from Stage 1 baselines by 48% (17.8 kWh) and 46% (17.4 kWh), respectively. The flow temperature setpoint modification at Stage 6 reduced Class I and Class V gas use by 5% (0.9 kWh) and 12% (2.5 kWh) respectively. The combined impact of the whole house approach fabric retrofit with flow temperature modification was to reduce baseline gas use by 50% (18.7 kWh) using Class I control and by 51% (19.9 kWh) using Class V control.

Class V gas use was generally greater than Class I. At Stage 1, this can be attributed to greater Class I heating system efficiency as boiler outputs and internal conditions were similar. At Stages 2-4, heating system efficiencies for both control classes were comparable and differences in gas use were related to differences in boiler output and higher internal temperatures (refer to Table 6). At Stage 4 where efficiency, boiler output, and internal conditions were similar, the gas use for each controller was effectively the same. At Stage 6 with a 70 °C flow setpoint, Class V gas use was 6% (1.2 kWh) greater than Class I. However, Class V boiler space heating output was 11% (1.8 kWh) greater than Class I. Higher gas use using Class V control at this stage is therefore attributed to higher internal temperatures and greater thermal comfort (refer to Section 3.1.4). The greater Class V efficiency at this stage means that it is likely gas use would have been less than Class I if internal conditions were similar. Test programme time constraints meant that it was not possible to match average internal temperatures for each control class at each test stage.

The Stage 6 boiler flow temperature modification using Class I control resulted in a 5% reduction in gas use and delivered a 3% increase in boiler output. For Class V control, gas use was reduced by 12% with a 9% reduction in boiler output. The difference in gas use and boiler output between control classes following flow temperature modification was 2.6% and 2.4%, respectively. The similar behaviour is also observed in the heating system efficiency of 89% for both control classes. The flow temperature modification at Stage 6 increased boiler running times and pump electrical use from the 70 °C flow setting. The ~20 Wh additional energy is insignificant in comparison to the reductions in gas use and reduced heating system efficiency by approximately a quarter of a percentage point.

3.1.4.2 Space heating energy reduction vs. HTC reduction

Figure 19 compares measured reductions in HTC and gas use during the DEEP retrofit process.

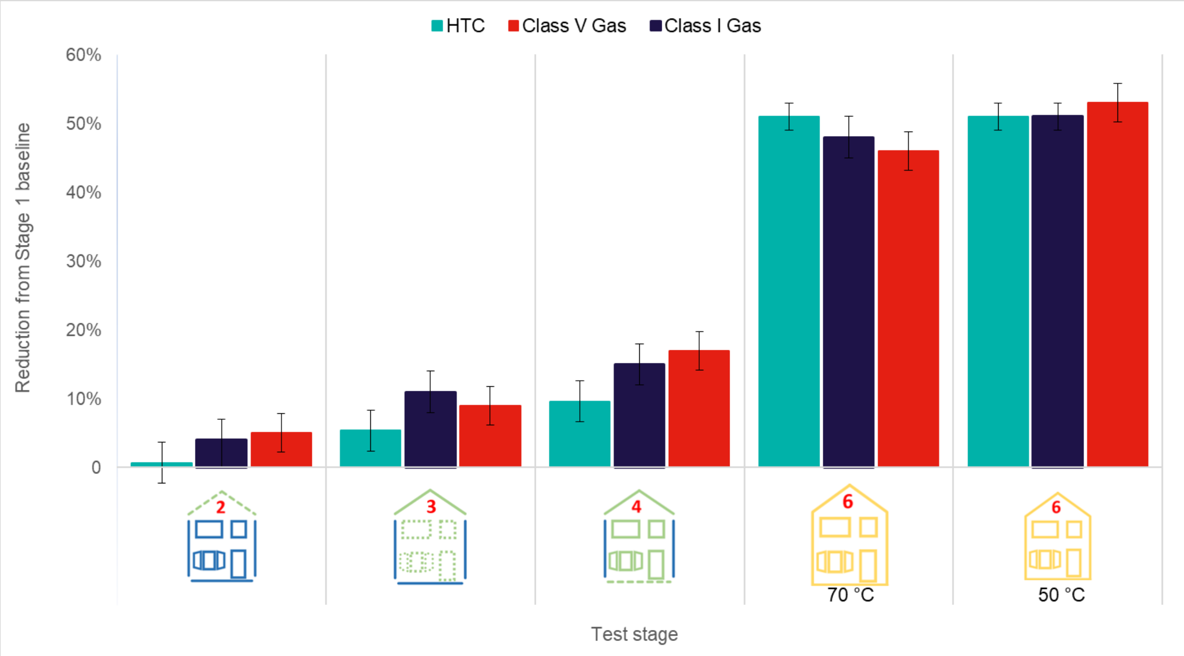


Figure 19: Reductions in HTC and gas use during the DEEP retrofit process

Reductions in gas use from baseline at each stage were greater than the measured reductions in HTC from baseline until the application of EWI at Stage 5[24]. The initial Stage 6 Class I and Class V gas use reductions from baseline of 48% and 46 %, respectively were below the 51 % HTC reduction. This highlights the impact that post-retrofit oversizing could have on counteracting improvements in fabric efficiency.

The flow temperature modification resulted in Class I and Class V gas use reductions from baseline of 51% and 53% respectively. This brought gas use reductions in line with the HTC reduction. This finding demonstrates the potential for boiler flow temperature modifications to provide an effective low-cost post-retrofit oversizing mitigation strategy.

Although the percentage changes in gas use uncertainty are associated with reasonably high uncertainty, boiler output measurements suggest lower boiler efficiency resulted in gas reductions failing to match HTC reductions in the 70 °C Stage 6 test. Figure 20 shows that reductions in boiler output from baseline were consistent with reductions in gas use following the boiler flow temperature modification.

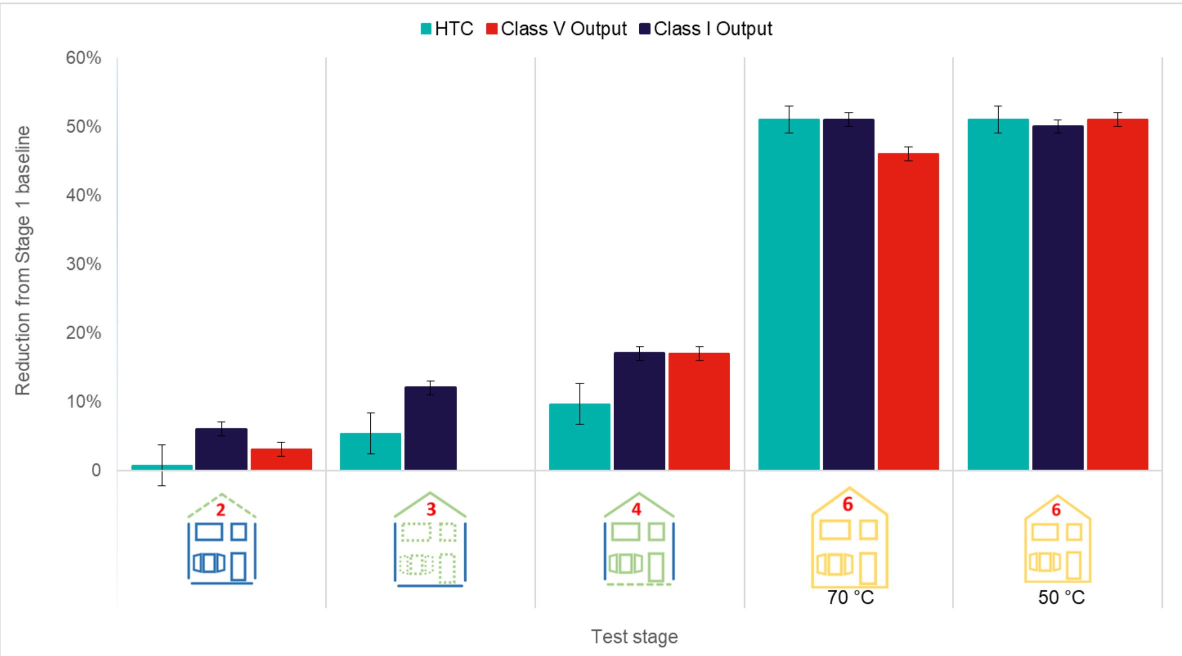


Figure 20: Reductions in HTC and boiler output during the DEEP retrofit process

[24] The Stage 5 test results are not presented due to a chamber HVAC malfunction. The whole house approach measures at Stage 6 did not result in a measurable change in the HTC of the Energy House from Stage 5.

3.1.6 Internal conditions

3.1.6.1 24-hour internal temperature

Table 6 provides summary statistics of the 24-hour volume weighted average internal temperature (T_i) and ΔT in each DEEP GCH test.

Table 6: 24h volume weighted average internal temperature and ΔT for each GCH test

Test stage	Control class	Flow setpoint (°C)	Mean T_i (°C)	Minimum Ti (°C)	Maximum T_i (°C)	24h mean external temp (°C)	24h mean ΔT (°C)
1	I	70	16.3	14.4	18.6	4.7	11.6
1	V	70	16.3	14.4	18.4	4.7	11.6
2	I	70	16.2	14.4	18.4	4.7	11.5
2	V	70	16.4	14.3	17.9	4.6	11.8
3	I	70	16.1	14.4	18.0	4.9	11.3
3	V	70	16.3	14.4	17.9	4.9	11.4
4	I	70	16.5	14.7	18.7	4.8	11.7
4	V	70	16.5	14.6	18.3	4.9	11.6
6	I	70	18.5	17.5	20.2	4.7	13.8
6	V	70	18.7	17.5	21.9	4.7	14.0
6	I	50	18.3	17.3	19.5	4.7	13.7
6	V	50	18.5	17.5	21.6	4.6	13.9

Figure 21 shows the 24-hour mean volume-weighted average internal temperature (T_i) in each DEEP GCH test.

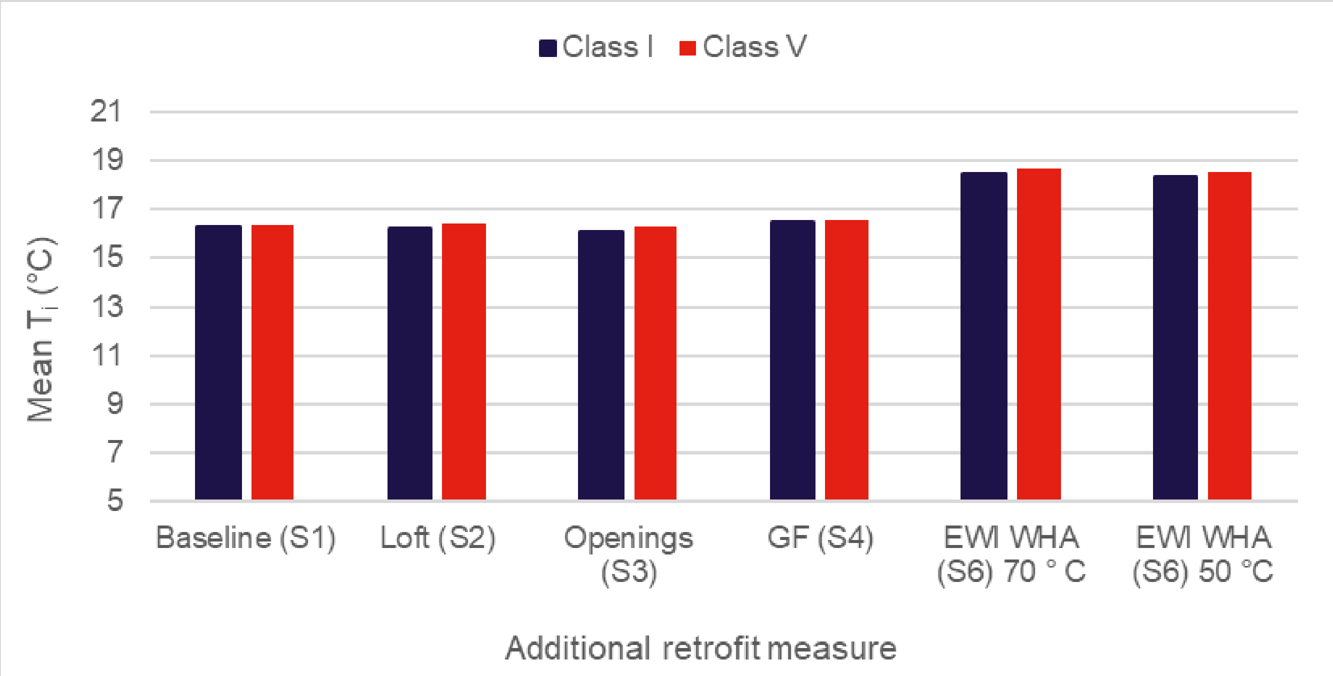


Figure 21: 24-hour mean volume weighted average internal temperature (T_i) in each DEEP GCH test

24-hour average internal temperatures were similar in Stages 1-4, at around 16.3 °C and 16.4 °C for Class I and Class V control, respectively. Following the application of EWI, average temperatures rose by ~2 °C. The reduction in fabric heat loss meant that the minimum average internal temperatures during Stage 6 were ~17.5 °C, so heating periods commenced from a ~3 °C higher temperature than in Stages 1-4. The boiler flow temperature setpoint modification to 50 °C in Stage 6 caused a 0.2 °C reduction in average internal temperature for both Class I and Class V control.

The minimum average internal temperatures during Stage 6 tests are within the range of setback temperature setpoints of 3-5 °C below heating period setpoint used by ASHPs. The relatively minor impact of modifying the boiler flow temperature setpoint in Stage 6 and minimum internal temperatures suggest that the Stage 6 fabric configuration was suitable for a low temperature ASHP to be installed.

Figure 22 – Figure 25 provide 24-hour air temperature measurements and box plots of living room air temperature in each of the DEEP GCH tests. As well as being important for occupant comfort, living room temperature behaviour provides an indication of boiler operation due to it being the location of the boiler controller.

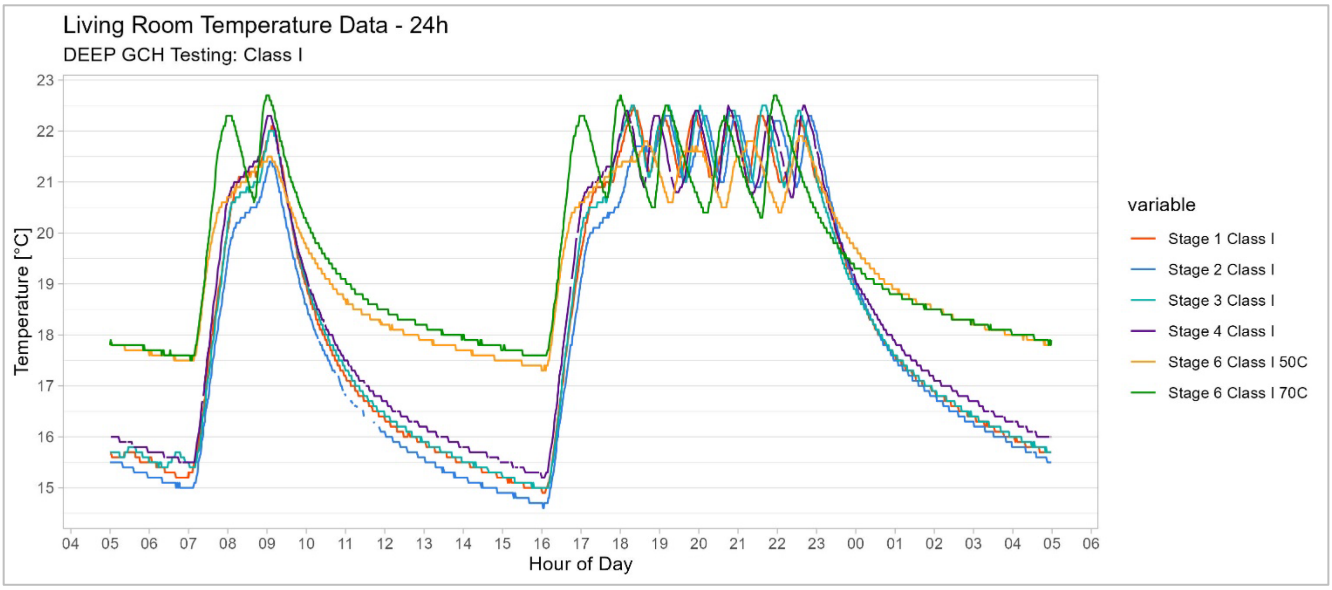


Figure 22: 24-hour living room air temperature measurements during each Class I test

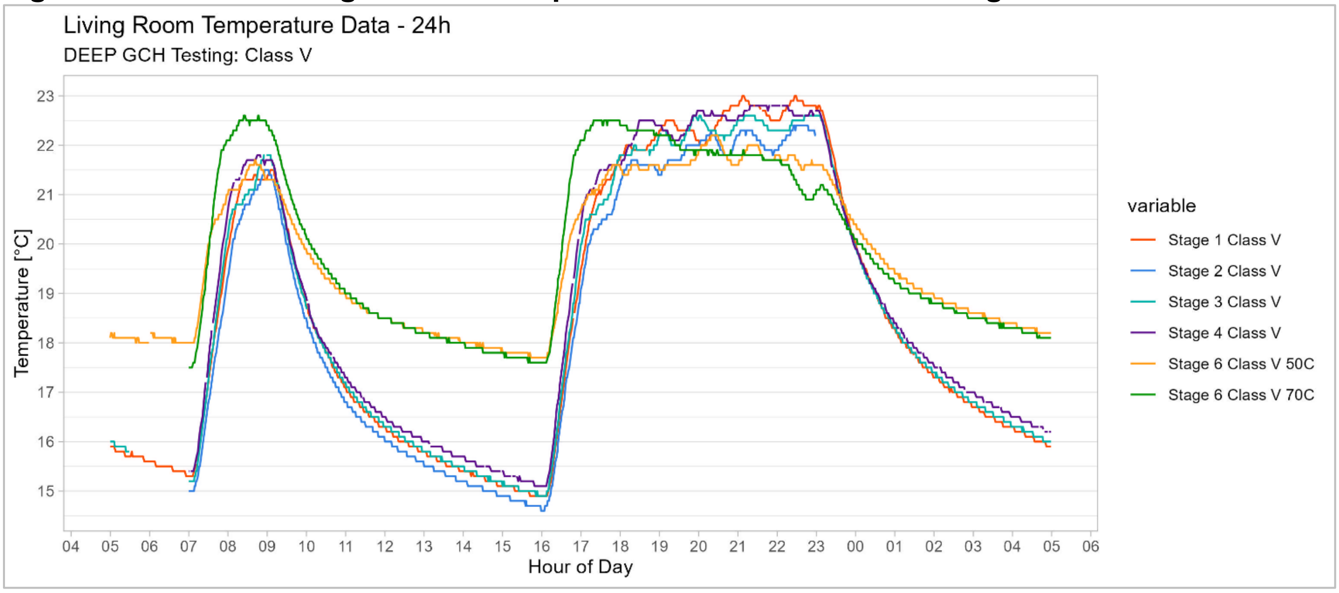


Figure 23: 24-hour living room air temperature measurements during each Class V test

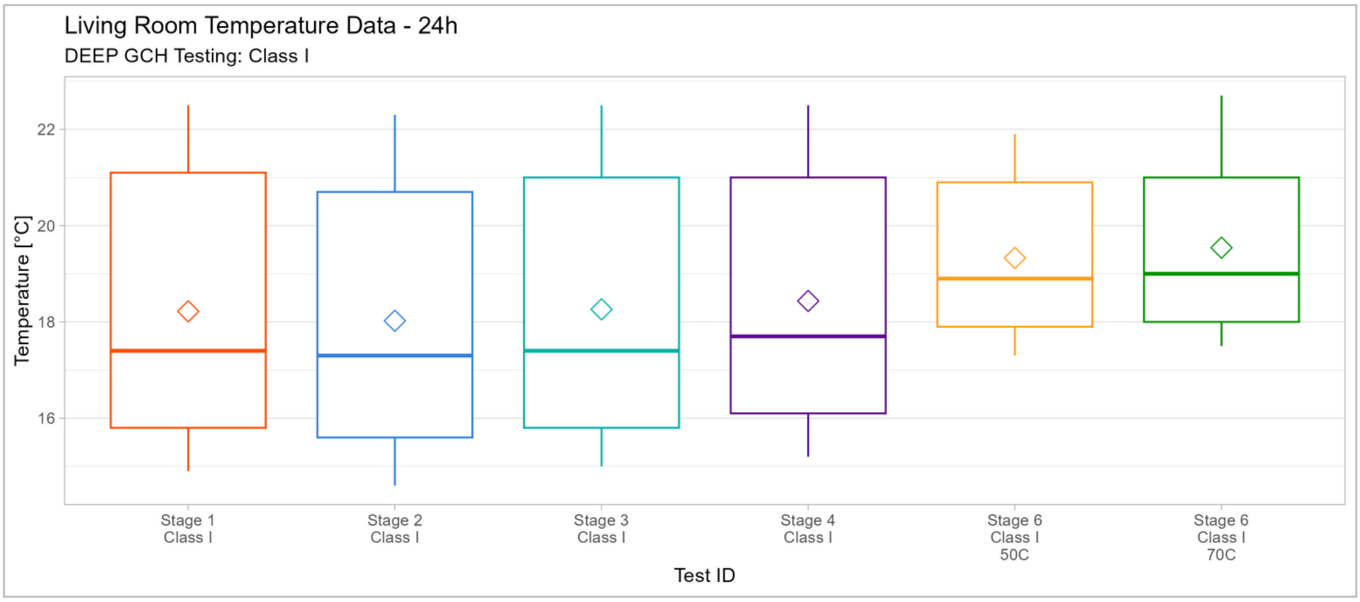


Figure 24: Box plot of living room air temperature during the 24-hour period of each Class I test

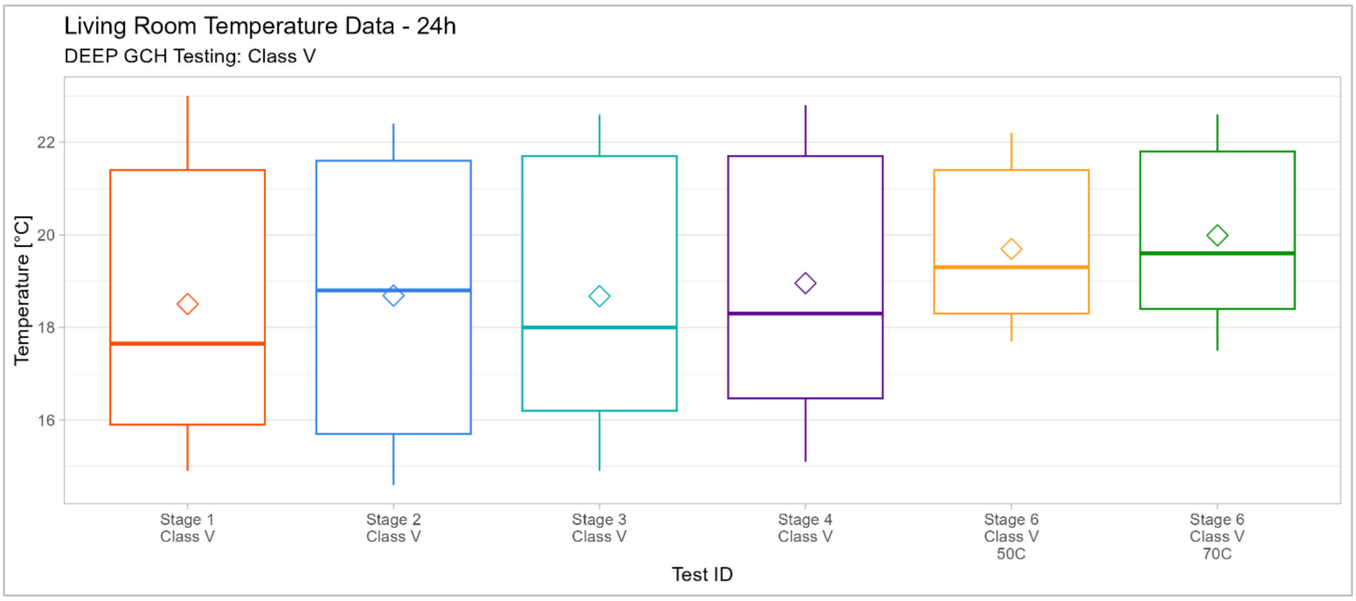


Figure 25: Box plot of living room temperature during the 24-hour period of each Class V test

The impact of the EWI retrofit is evident in the reduced time to setpoint and slower air temperature decay rate between heating periods in Stage 6. The elevated temperature at commencement of Stage 6 heating periods with 70 °C flow setpoint resulted in these tests being the only ones in which setpoint was achieved and maintained throughout most of the two-hour morning heating period.

The impact of the Class V controller modulating boiler output is evident in the relatively stable internal temperature during the seven-hour evening heating periods in comparison to notable hysteresis resulting from Class I control.

3.1.6.2 Seven-hour evening heating period

Table 7 provides the living room and bedroom 1 median air temperatures during the seven-hour evening heating period in each DEEP GCH test. The median temperature provides a useful indicator of the temperature at which the room was maintained during most of the heating period as it is less influenced by the starting temperature and warm-up time.

Table 7: Living room and bedroom 1 median air temperatures during the seven-hour evening heating period in each DEEP GCH test

Test stage	Control class	Flow setpoint (°C)	LR median T_i (°C)	Bed1 median Ti (°C)
1 – baseline	I	70	21.5	16.5
1 – baseline	V	70	22.3	16.4
2 – roof	I	70	21.3	16.0
2 – roof	V	70	21.7	15.9
3 – openings	I	70	21.6	15.5
3 – openings	V	70	22.2	15.0
4 – GF	I	70	21.3	16.0
4 – GF	V	70	22.5	15.7
6 – WHA	I	70	21.3	18.1
6 – WHA	V	70	21.9	17.8
6 – WHA	I	50	21.2	18.0
6 – WHA	V	50	21.6	18.2

The median living room air temperature during the seven-hour evening heating period was reasonably consistent throughout the piecemeal retrofit process. For the Class I tests the air temperature was in reasonable agreement with the 21 °C setpoint. The median air temperature using Class V control was around 22 °C. However, the median temperature in bedroom 1 was below the 18 °C setpoint using both control classes until the installation of EWI after Stage 4. This could partially be explained by boiler operation being dictated by the controller situated in the living room. Zoned heating controls could compensate for underheating in other zones.

Figure 26 – Figure 29 provide temperature profiles and box plots of living room air temperature during the seven-hour evening period in each of the DEEP GCH tests.

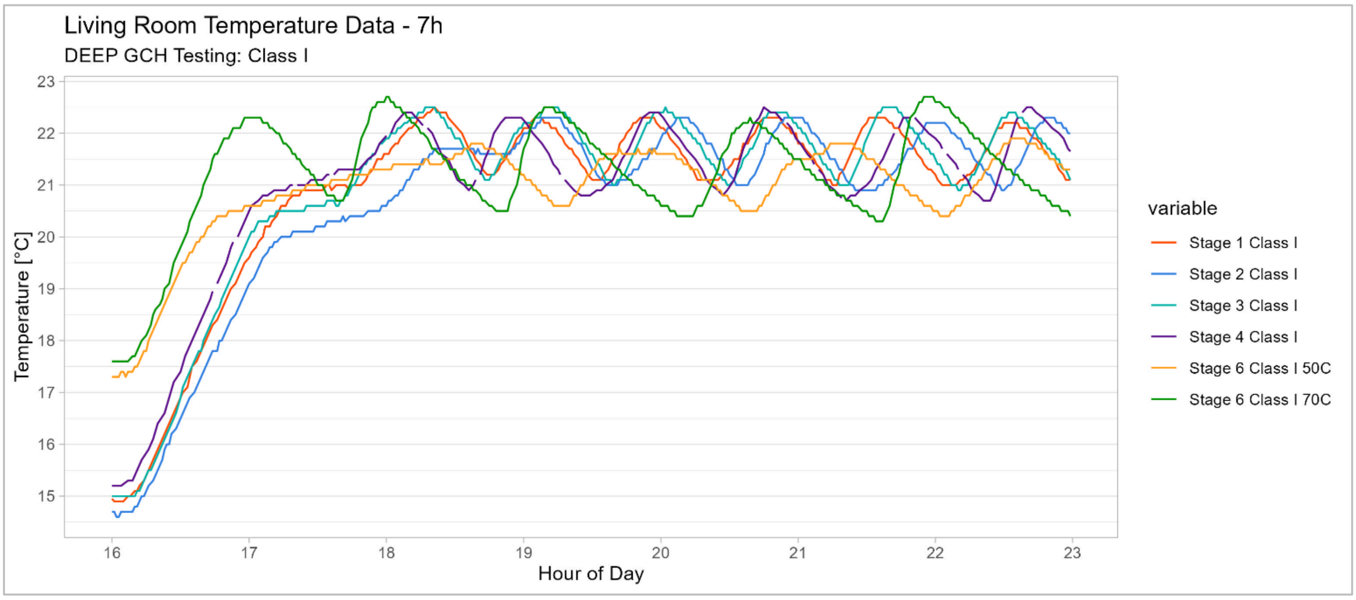


Figure 26: Seven-hour living room air temperature measurements during each Class I test

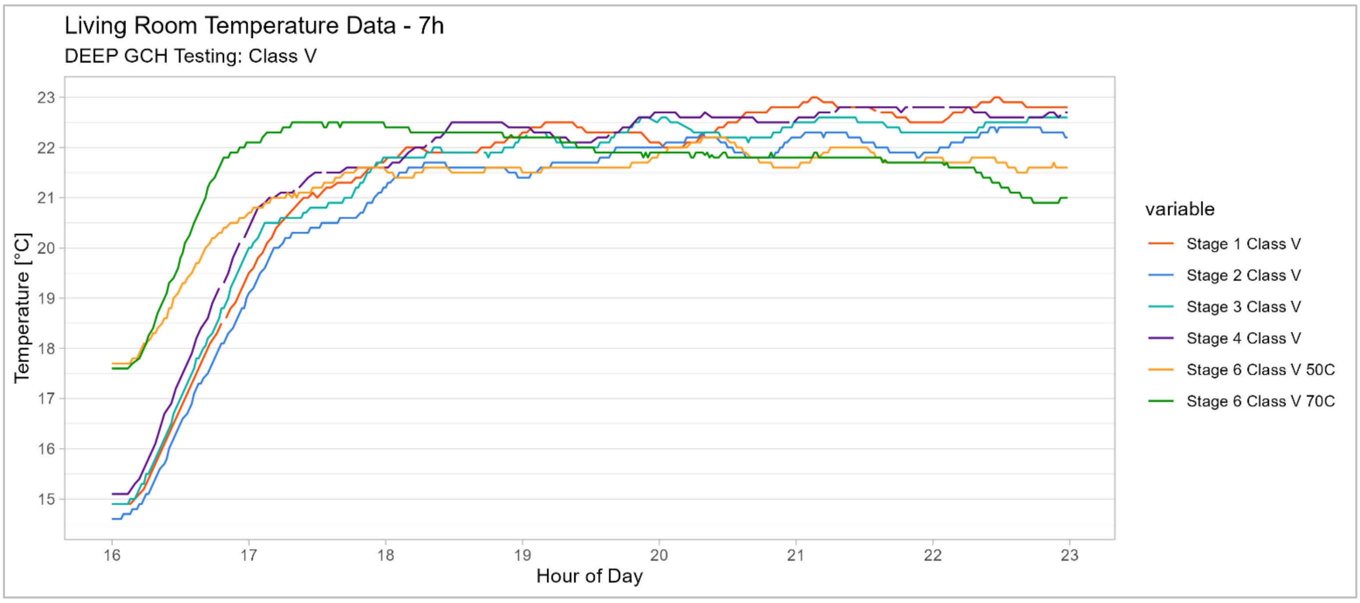


Figure 27: Seven-hour living room air temperature measurements during each Class V test

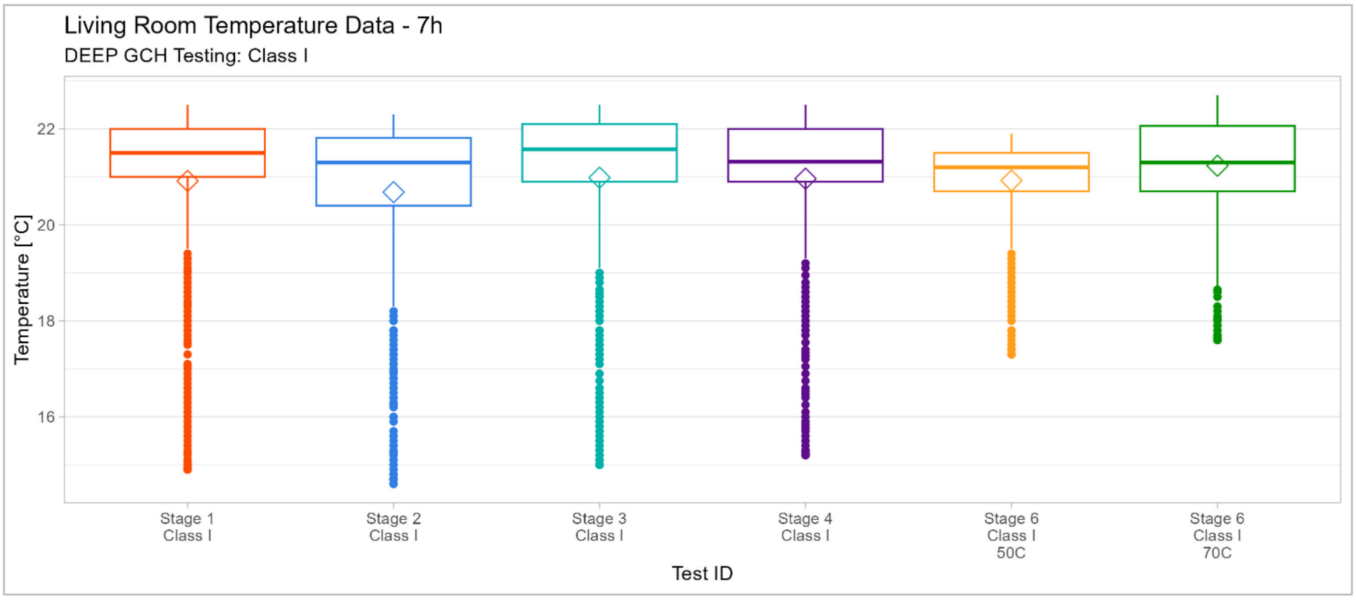


Figure 28: Box plot of living room air temperature during the seven-hour period of each Class I test

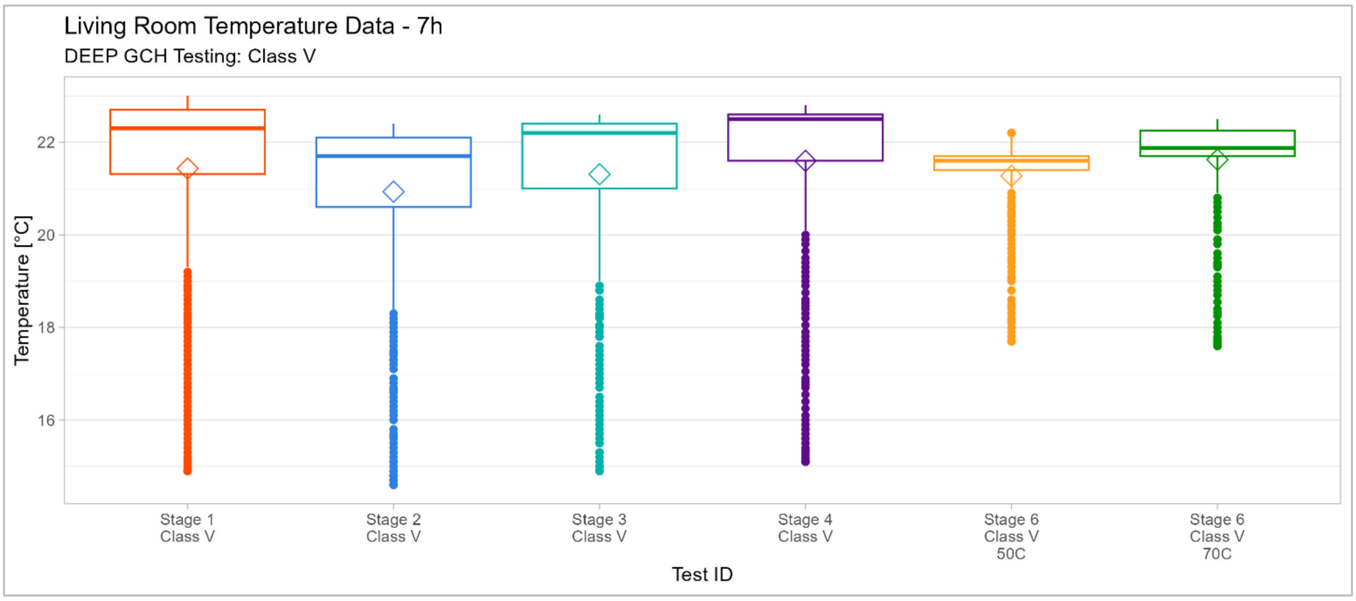


Figure 29: Box plot of living room air temperature during the seven-hour period of each Class V test

For Class I control with a 70 °C flow setpoint, hysteresis at Stage 6 (±1.1 °C) was almost double that of Stage 1 (±0.6 °C). The increase in hysteresis is due to post-retrofit oversizing of the living room radiator. Reducing the flow temperature to 50 °C more closely aligned radiator output with the heat load of the living room and reduced hysteresis to the ±0.6 °C Stage 1 value and resulted in a more consistent temperature. The flow temperature modification at Stage 6 resulted in a reduction in median living room temperature during the evening heating period of 0.1 °C and 0.3 °C for Class I and Class V, respectively against the Stage 6 70 °C tests.

3.1.6.3 GCH thermal comfort

Table 8 shows the metrics relating to occupant thermal comfort throughout the 7-hour evening heating period for each GCH test.

Table 8: GCH evening heating period thermal comfort statistics

Test stage	Control class	Flow setpoint (°C)	Median T_i (°C)	Median T_{op} (°C)	Comfort benefit (°C)	Time to < 50 PPD (mins)	Time to < 25 PPD (mins)
1	I	70	21.5	21.4	-0.1	45	72
1	V	70	22.3	22.4	0.1	48	76
2	I	70	21.3	21.4	0.1	53	119
2	V	70	21.7	21.9	0.2	53	103
3	I	70	21.6	21.6	0.0	47	94
3	V	70	22.2	22.3	0.1	45	84
4	I	70	21.3	21.3	-0.1	41	62
4	V	70	22.5	22.4	-0.1	41	62
6	I	70	21.3	21.1	-0.2	19	36
6	V	70	21.9	21.8	-0.1	19	36
6	I	50	21.2	21.1	-0.1	22	78
6	V	50	21.6	21.5	-0.1	23	62

The median comfort benefit during the seven-hour evening heating period was similar throughout the piecemeal retrofit process. This suggests that the heating system of a dwelling has a more dominant role over occupant thermal comfort than the dwelling's fabric performance during heating periods. Although a switch from positive to negative comfort benefit at Stage 4 is observed, this is well within the uncertainty of the measurement.

It was anticipated that the increased internal surface temperatures resulting from the fabric retrofit would have had a substantial impact on the radiative heating component and increase the operative temperature and comfort benefit. Although GCH are primarily convective in nature, heat transfer also has a radiative component. The 50 °C flow setpoint tests resulted in a mean water temperature of 40 °C, meaning the radiator was 20 °C cooler than during the 70 °C flow setpoint tests. This would be expected to reduce comfort benefit. However, neither of these interventions changed the comfort benefit at the centre of the room where the measurements were taken. Given that a 20 °C change in radiator surface temperature appeared to have no impact on comfort benefit, and that changes in fabric surface temperature resulting from their retrofit were lower than 20 °C, it is likely that any change in comfort benefit resulting from fabric retrofit was too small to measure. Further work should perform thermal comfort measurements at more locations to assess spatial distribution of pre- and post-retrofit thermal comfort.

The graphs in Figure 30 – Figure 32 have the PPD on the Y-axis (which has been reversed). A more favourable, lower PPD score is presented as further up the Y-axis than a less favourable, higher PPD score. In essence, a PPD score of 50 calculates that half of the theoretical occupants would be satisfied with the conditions in the space. A PPD score of 25 calculates that 75% of theoretical occupants would be satisfied with the conditions in the space. It must be noted that thermal comfort calculations are not applicable to all humans as the model contains multiple assumptions, so should be treated with caution. Please refer to section 2.4.3 for details of the thermal comfort calculation method.

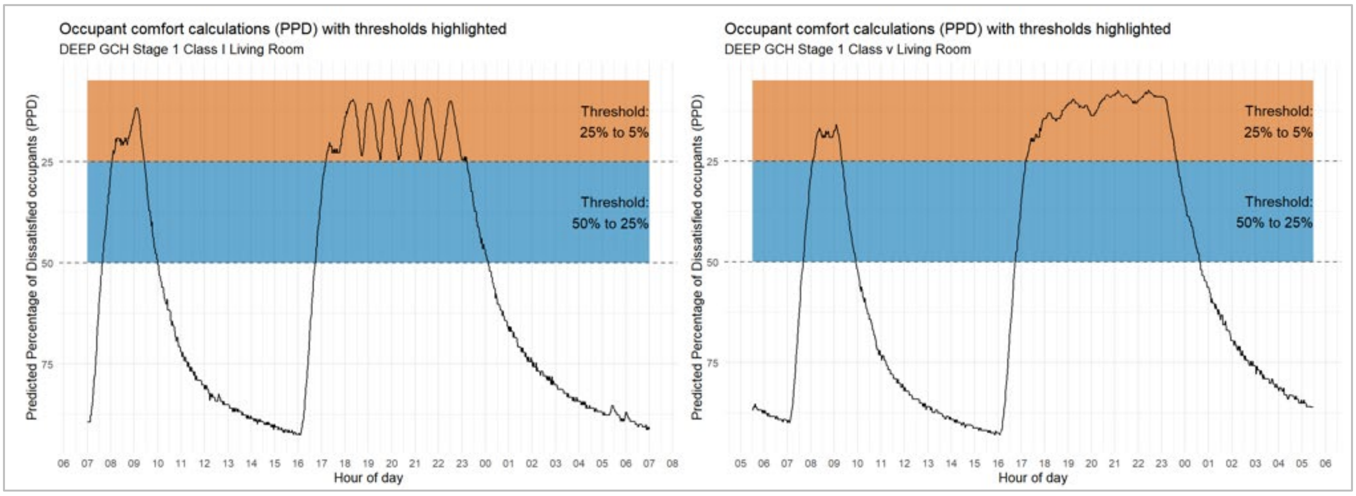


Figure 30: 24h time series of the PPD within the living room during Stage 1 of the DEEP retrofit using Class I (left) and Class V (right) control

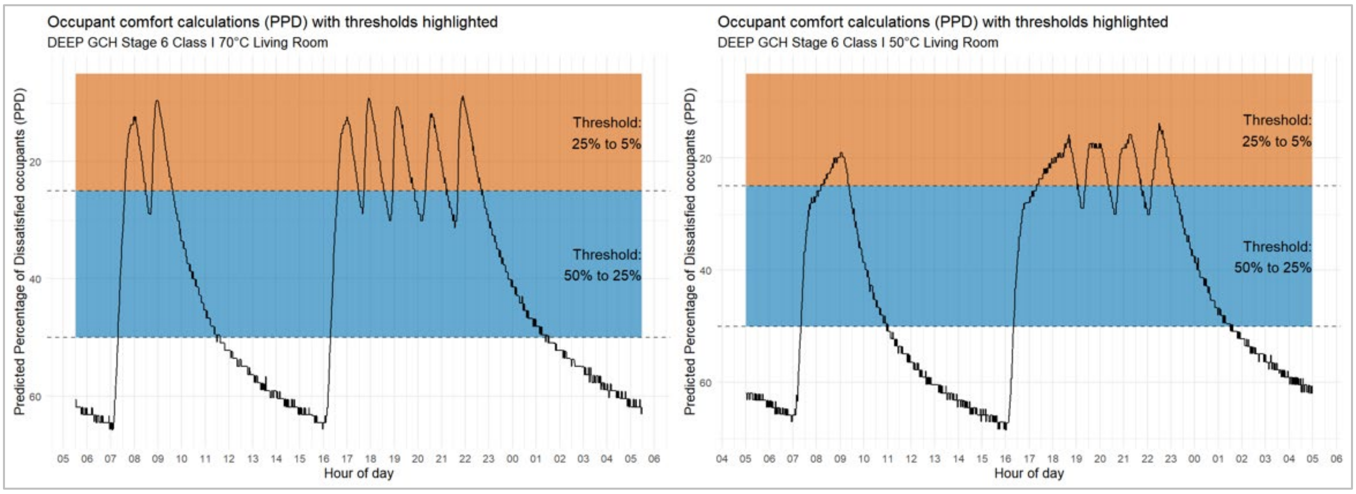


Figure 31: 24h time series of the PPD within the living room during Stage 6 of the DEEP retrofit using Class I control at 70 °C (left) and 50 °C (right) flow setpoints

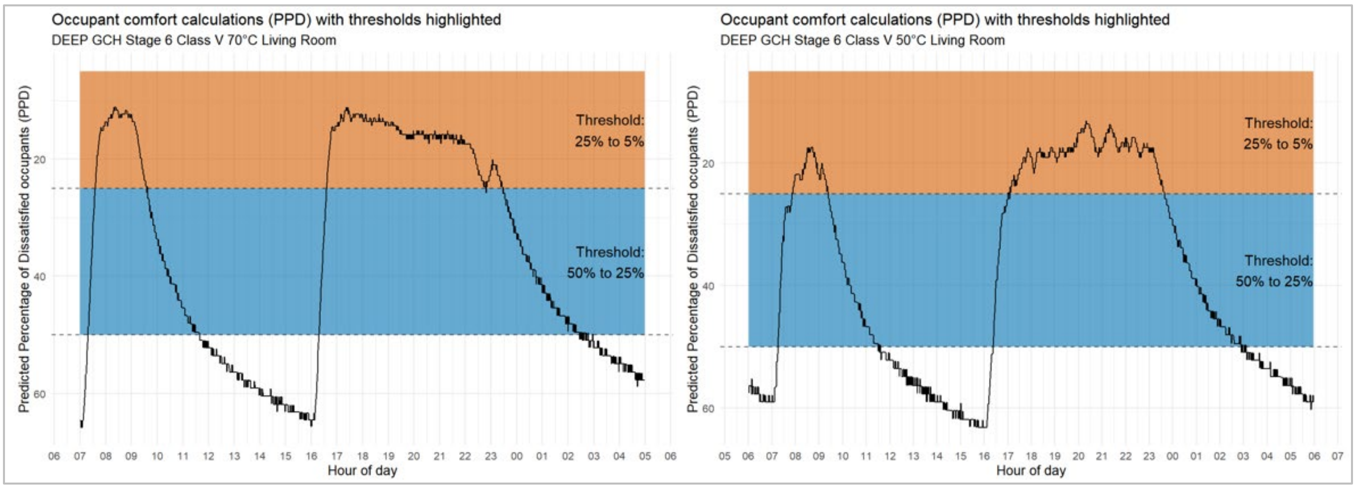


Figure 32: 24h time series of the PPD within the living room during Stage 6 of the DEEP retrofit using Class V control at 70 °C (left) and 50 °C (right) maximum flow setpoints

Figure 33 – Figure 36 illustrate the proportion of time spent within each PPD threshold during the morning and evening heating periods at each stage of the DEEP retrofit GCH tests using Class I and Class V control.

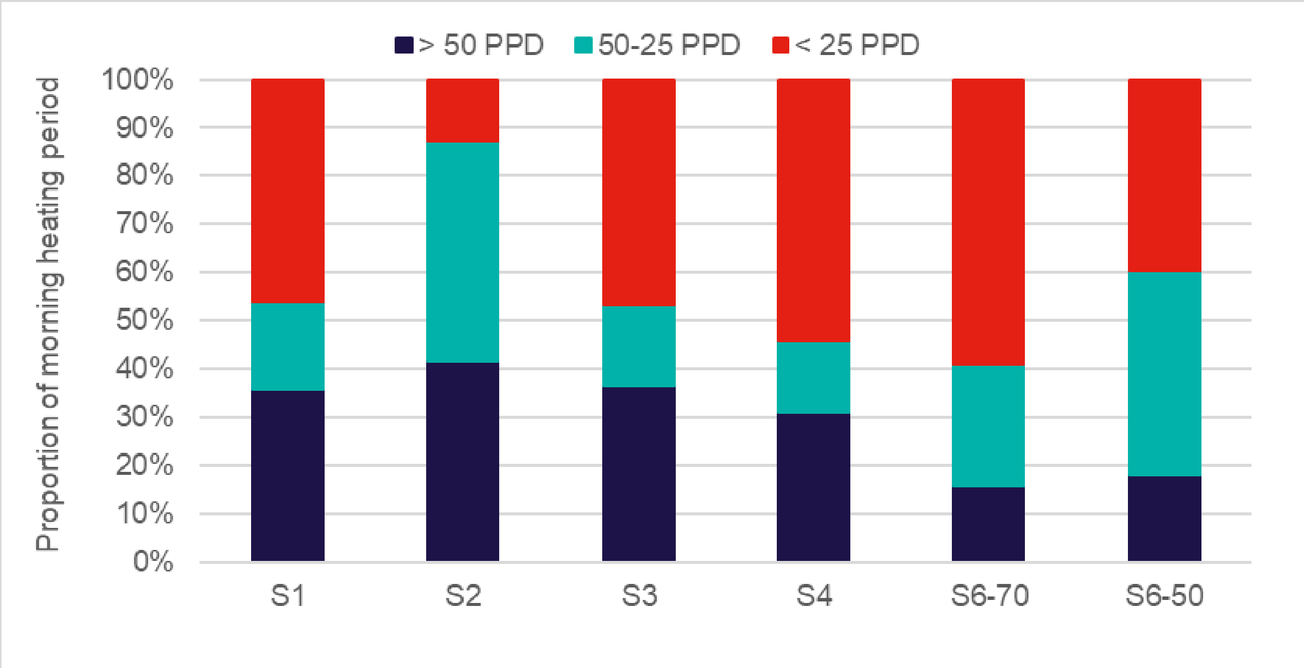


Figure 33: Duration in each PPD threshold in the living room during the two-hour morning heating period in the DEEP GCH Class I control tests

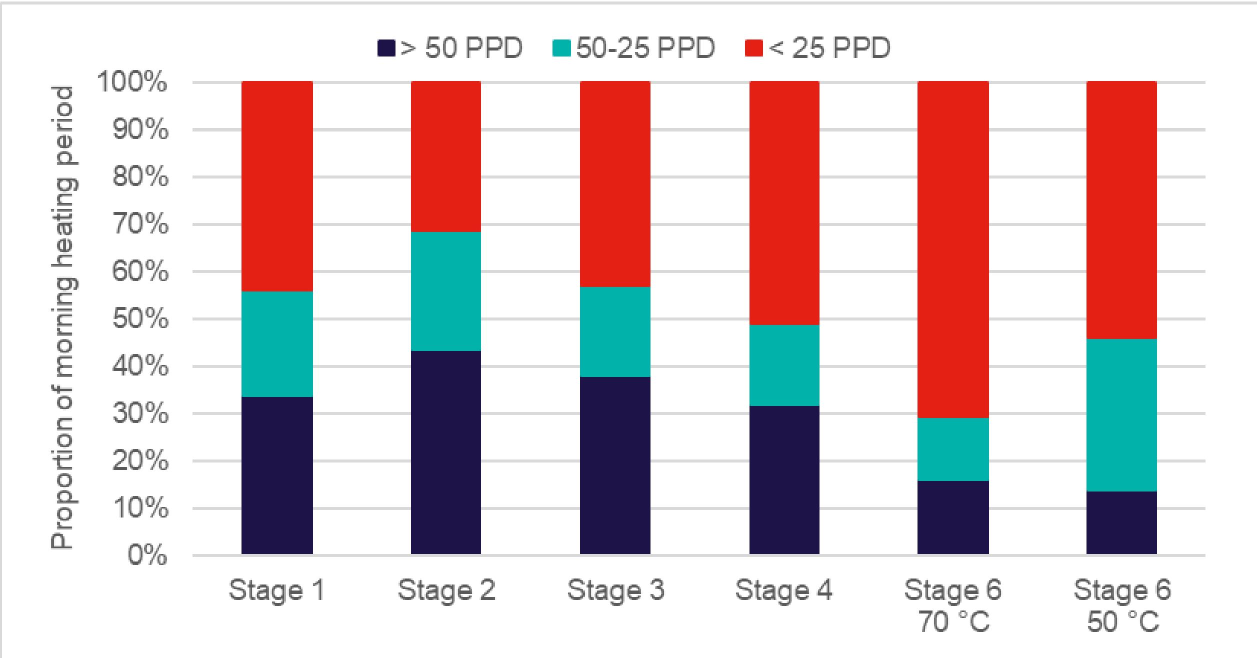


Figure 34: Duration in each PPD threshold in the living room during the two-hour morning heating period in the DEEP GCH Class V control tests

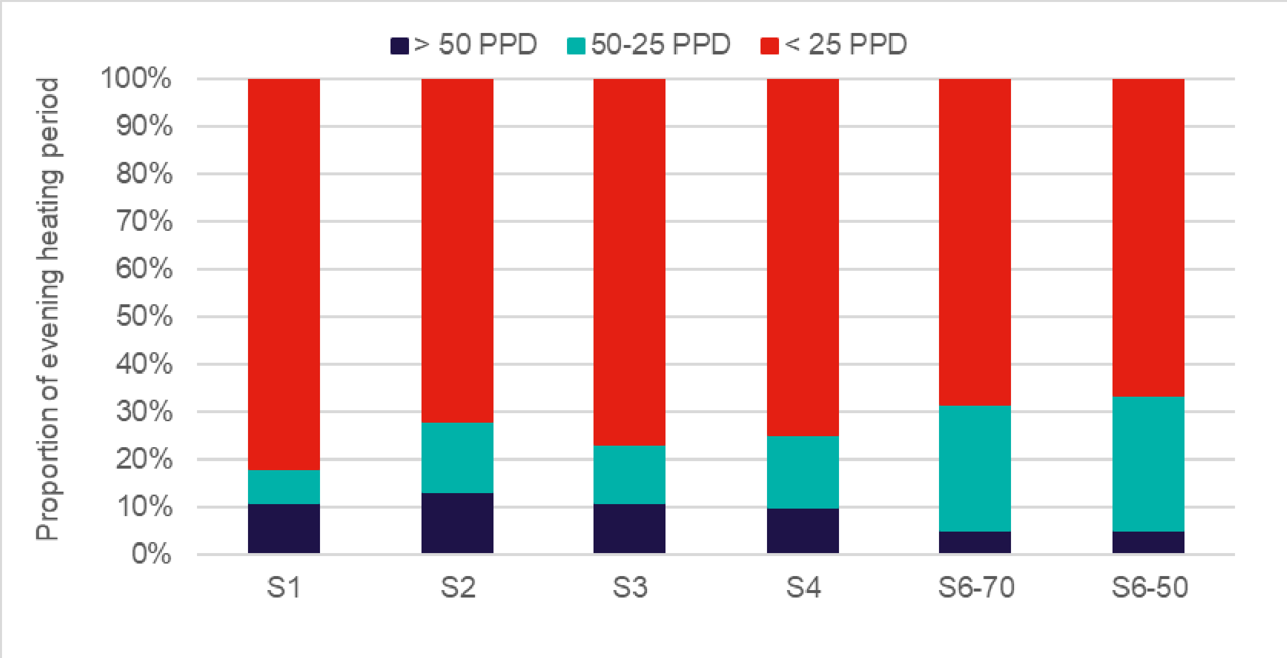


Figure 35: Duration in each PPD threshold in the living room during the seven-hour evening heating period in the DEEP GCH Class I control tests

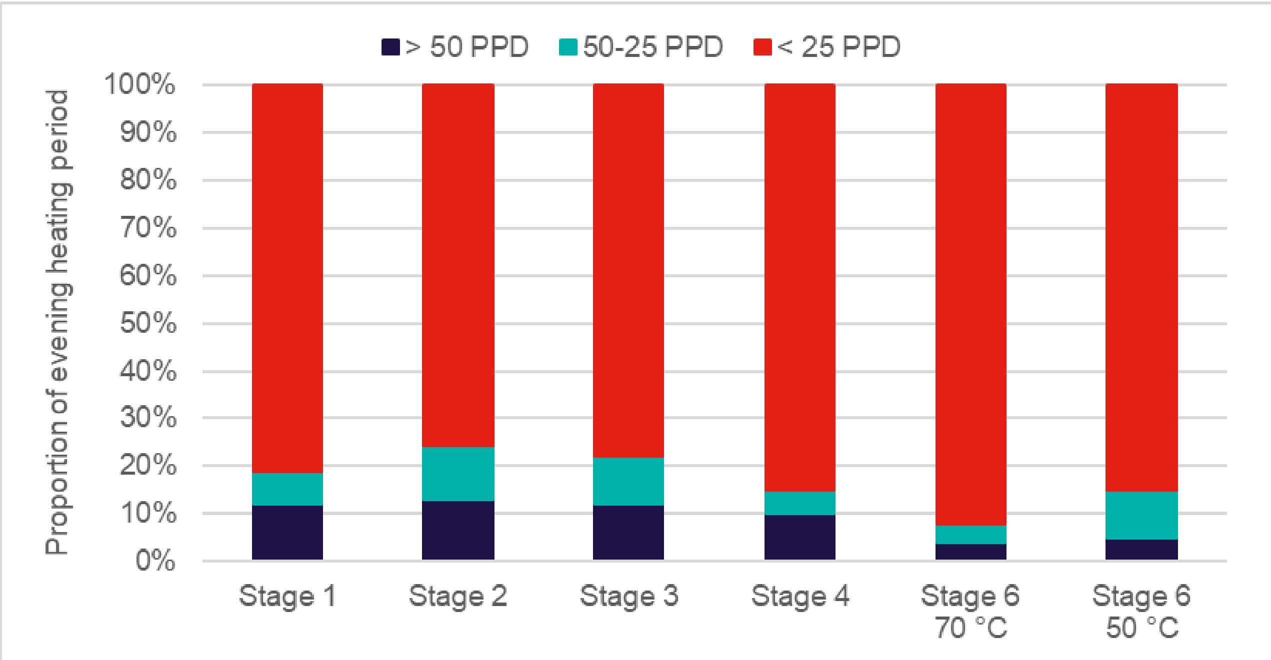


Figure 36: Duration in each PPD threshold in the living room during the seven-hour evening heating period in the DEEP GCH Class V control tests

The proportion of time spent in the lowest comfort threshold decreased following the application of each retrofit measure applied to the thermal elements of the living room[25]. Thermal comfort for both control classes was reasonably similar between Stages 1-4. The EWI retrofit resulted in faster heat-up times and reduced the proportion of time with >50 PPD

[25] The loft retrofit at Stage 2 did not change the fabric thermal performance characteristics of the living room.

during the Stage 6 morning and evening heating periods using both control classes. Class V control during Stage 6 resulted in the greatest proportion of time spent with <25 PPD in all the DEEP GCH tests.

Despite EWI resulting in warmer internal conditions outside of the heating periods, the proportion of the evening heating period with <25 PPD was lower in Stage 6 than in Stages 1-4 using Class I control at 70 °C flow setpoint. This is due to the increased hysteresis caused by oversizing. PPD at the lowest point within the hysteresis was 30 PPD at Stage 6 compared with ~25 PPD in Stages 1-4. Reducing the flow setpoint to 50°C resulted in a 38-minute increase to reaching <25 PPD compared with the Stage 6 Class I 70 °C flow test. The longer initial heat-up time was most detrimental to thermal comfort during the morning heating period with the proportion of time with >25 PPD increasing by ~45%. As the evening heating period is five hours longer, increased initial heat-up time had less impact on the proportion of time with >25 PPD.

The stable conditions provided by Class V control meant that comfort metrics improved at Stage 6 from Stages 1-4 using both 70 °C and 50 °C flow setpoints. The modification to flow temperature resulted in a 26-minute increase to reaching <25 PPD compared with the Stage 6 Class V 70 °C flow test.

The thermal comfort measurements suggest that Class V control provides more comfortable internal conditions than Class I control due to more stable temperature control. Thermal comfort using Class V control was least impacted by the boiler flow temperature modification. This suggests that Class V controls should be installed, if possible, when modifying boiler flow temperature to address post-retrofit oversizing.

3.3 ASHP tests

3.3.1 ASHP installation issues

Figure 37 shows the ASHP COP measured during Stages 3, 4, and 6 using the SAP heating pattern with a 3 °C setback setpoint (18 °C) between heating periods (SAP SB).

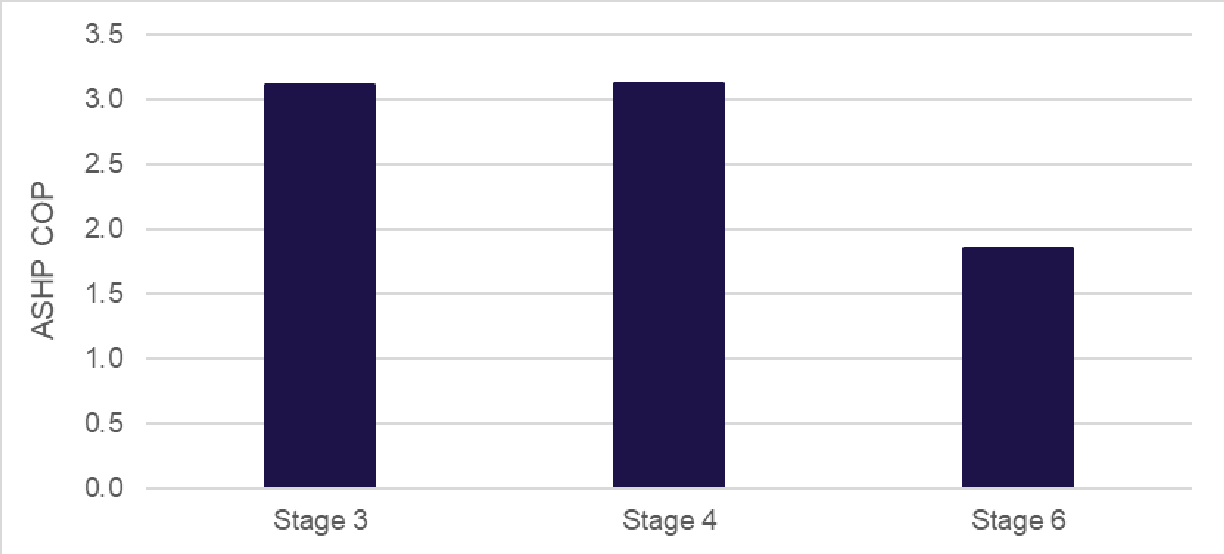


Figure 37: ASHP COP measured during Stages 3, 4, and 6 using the SAP heating pattern with 3 °C setback between heating periods

During Stages 3 and 4, the ASHP achieved a COP of 3.1 using a 55 °C design flow temperature. At Stage 6 the improved fabric performance allowed the design flow temperature to be reduced to 45 °C. At the lower flow temperature, the COP of the ASHP was expected to increase. However, the COP measured in Stage 6 using the same heating pattern as before was 1.9. The highest COP measured during the ASHP tests in Stage 6 was 2.4, when a Class I controller was used in a SAP-only pattern with a fixed 45 °C flow temperature. This scenario should have resulted in the lowest COP of all Stage 6 tests due to the higher flow temperature and omission of a setback.

The reason for the poor performance was only identified after the Stage 6 tests had been completed. The ASHP connections to the external unit were disconnected after the Stage 4 test to allow the pipework to be extended for the application of EWI. At this point the heating engineer accidentally swapped the flow and return connections to the external unit for the Stage 6 tests. The heat meters did not highlight this error as they automatically compensated for the reversed configuration by switching flow and return values. The ASHP did not provide any clear warnings that the connections were incorrect. The issue with the ASHP flow and return connections was identified when the external unit was disconnected to allow the EWI to be removed.

The ASHP installation issue means that it is not possible draw conclusions from ASHP performance at Stage 6 of the DEEP retrofit. However, it does provide a valuable lesson regarding the impact that incorrectly installing an ASHP can have on their performance, the need for installers to be adequately trained, and ASHPs to provide clear diagnostic feedback of incorrect installation.

3.3.2 ASHP control strategy

Figure 38 shows grid energy consumption and gas heating and space heating output from the ASHP and gas boiler during the DEEP Stage 3 tests.

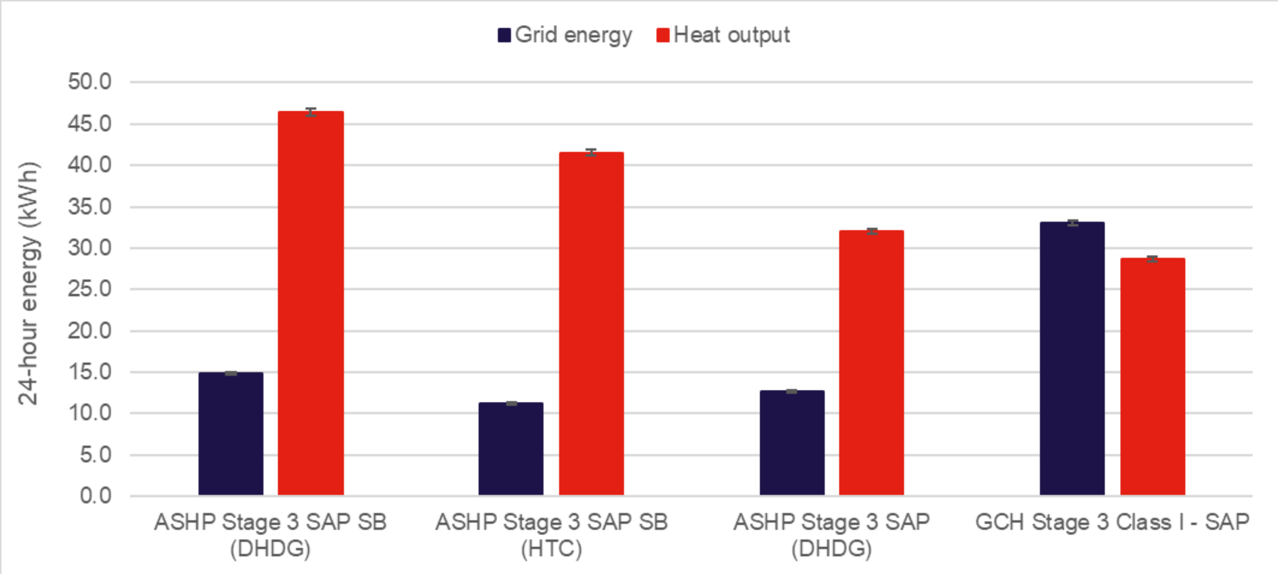


Figure 38: DEEP Stage 3 24-hour grid ASHP and GCH energy consumption and heat output

At Stage 3 of the DEEP retrofit, space heating output from the ASHP was between 1.1-1.6 times greater than boiler output in each ASHP control scenario tested. However, superior ASHP efficiency/COP meant that ASHP grid energy use was between 2.2-2.9 times lower than GCH. Figure 39 shows the COP measured in each Stage 3 ASHP test.

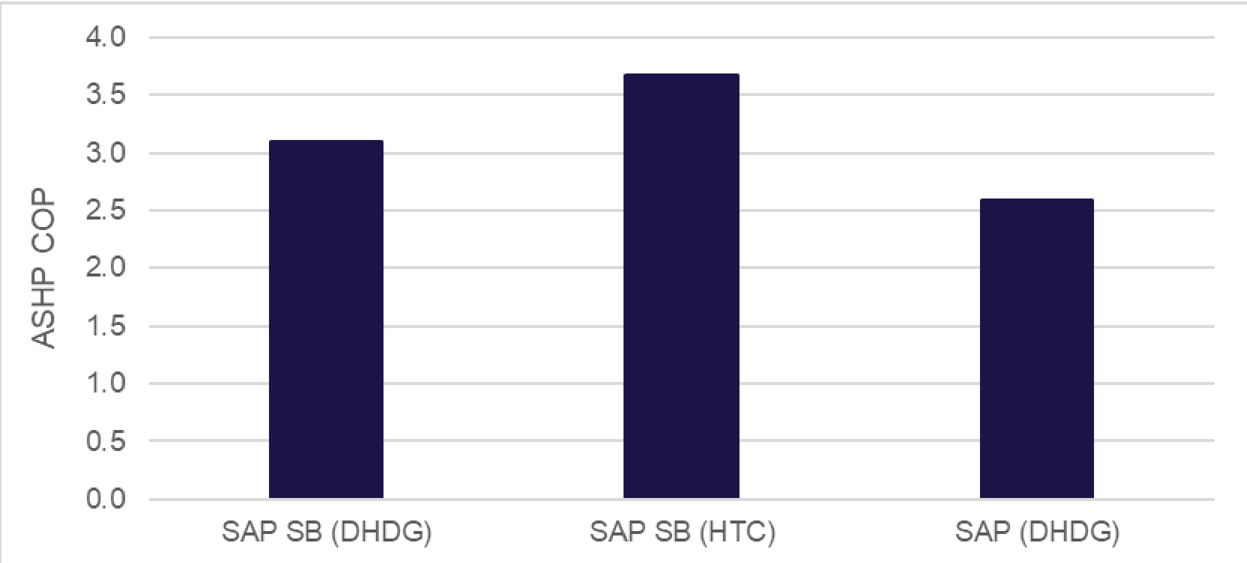


Figure 39: Stage 3 ASHP COPs using differing heating strategies

The SAP with setback heating profile yielded better COP than the SAP only profile, when using the same weather compensation curve (DHDG). The COP was then further improved for the SAP with setback heating profile by using a weather compensation curve calibrated to the measured heat transfer coefficient (HTC) of the dwelling. However, the HTC heating curve test maintained the living room at 19.3 °C during the evening heating period and 18.8 °C during setback periods (refer to Figure 40). This is due to the initial HTC-based heating curve not including the additional 15% heat input used in heat load calculations for intermittent heating. The DHDG heating curve maintained 21.4 °C during the evening heating period, but provided poor setback control at 20.5 °C. The findings suggest that the correct heating curve was between the DHDG and HTC heating curve. This suggests that if the correct heating curve had been selected, the COP would have been ~ 3.4 (based on mean of SB tests).

Introduction of a setback between heating periods relatively close to the setpoint temperature provides a better COP and internal conditions than intermittent heating patterns (e.g. SAP), so is therefore recommended. Special consideration needs to be paid to selection of the correct heating curve as they are critical to achieving internal temperature control and efficient ASHP operation. The research team was unable to find any definitive guidance to assist with the heating curve selection.

3.3.3 Piecemeal retrofit ASHP installation point

The incorrect ASHP installation at Stage 6 meant that it was not possible to measure whether a correctly installed ASHP would have resulted in space heating energy costs equal to or lower than GCH at the full retrofit stage. So, an estimation was made of the potential ASHP energy use at Stage 6 based on Stage 6 ASHP space heating output and COPs measured at Stage 3,

Figure 40 shows the heating patterns during Stages 3 and 6 using each heating curve.

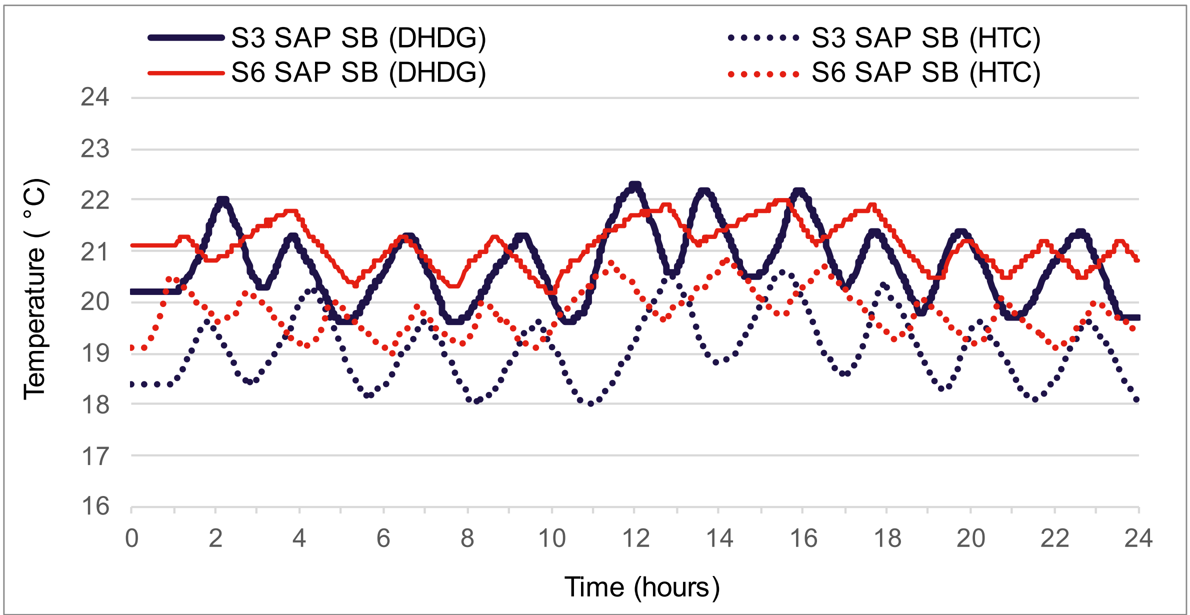


Figure 40: Living room temperature with SAP SB heating profile using DHDG and HTC heating curves in Stages 3 and 6

Heating patterns at each test stage were similar for each heating curve. This shows that the ASHP at Stage 6 was able to provide similar space heating despite being installed incorrectly.

Figure 41 shows the relationship between GCH and ASHP heat output vs ΔT during Stages 3 and 6.

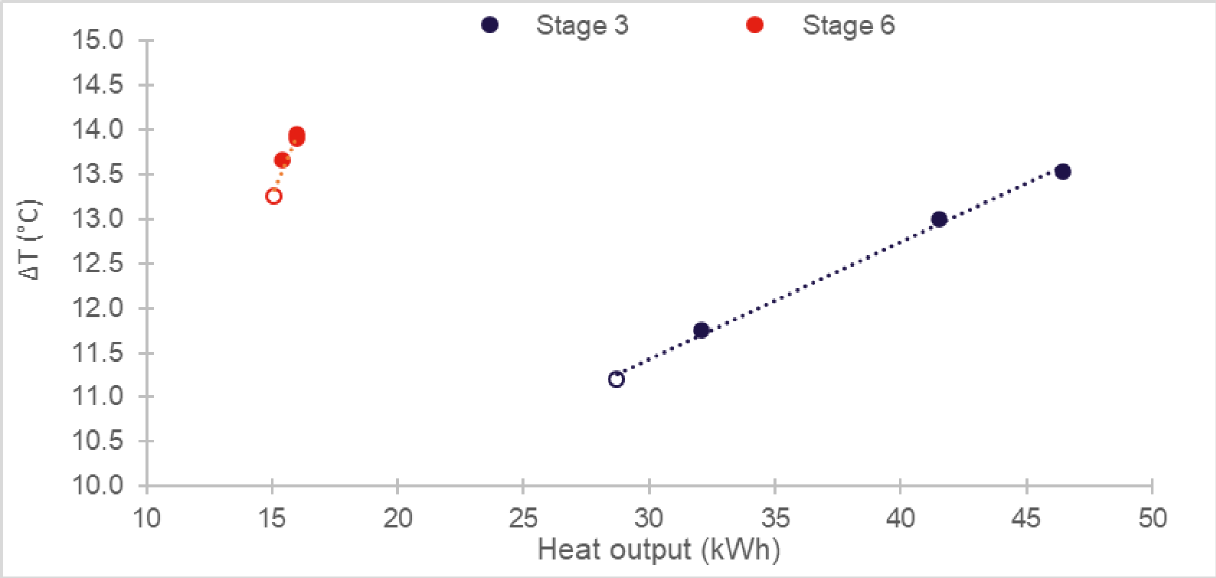


Figure 41: ΔT vs 24-hour ASHP and GCH space heating output in Stages 3 and 6 (GCH data points have no fill)

Heat output vs ΔT for both systems were in good agreement during each test stage. Given that the ASHP provided reasonable control of space heating at Stage 6 it can be assumed that heat output from a correctly installed ASHP would have been the same.

An estimate of the Stage 6 ASHP energy consumption without installer issues was made by dividing the ASHP space heating output measured in the Stage 6 tests by the measured COPs for the equivalent tests in Stage 3. It must be noted that the lower flow temperatures in Stage 6 would be expected to result in higher COPs than Stage 3, so actual costs are likely to be lower.

As the correct heating curve was estimated to be between the DGDG and HTC curves, price comparison between GCH and ASHP is based on the average cost of the two SAP setback tests (SAP SB). Figure 42 compares Stage 3 and Stage 6 GCH and ASHP 24-hour energy cost in February 2021 and March 2023.

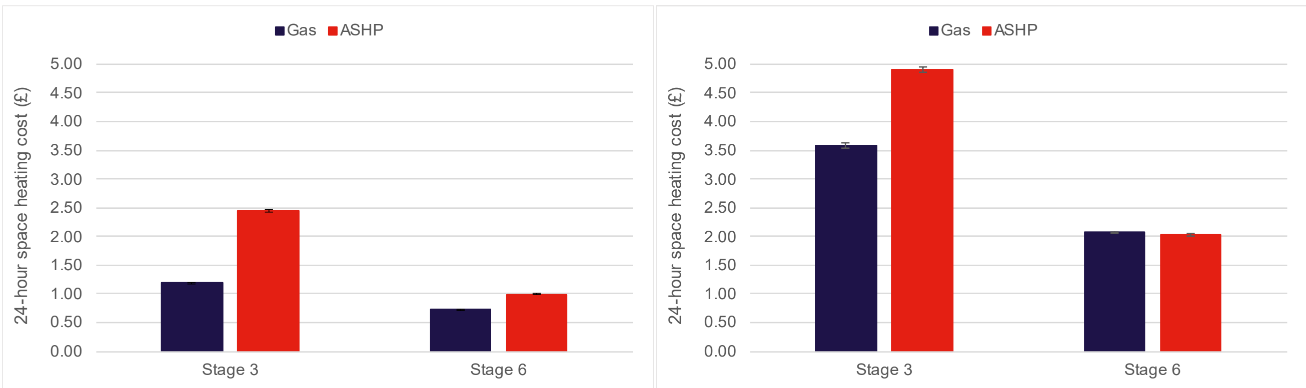


Figure 42: Stage 3 and Stage 6 GCH and ASHP 24-hour energy cost in February 2021 (left) and March 2023 (right)

At Stage 3, 24-hour ASHP energy cost was 2.1 times the cost of GCH at February 2021 energy prices and 1.4 times the cost of GCH at March 2023 prices. This suggests that the electricity-to-gas price ratio must narrow significantly to make ASHP installation viable in solid wall end-terrace/semi-detached dwellings with only their loft and openings retrofitted. It should be noted that although the ASHP daily running cost was more expensive that GCH in Stage 3, it provided warmer internal conditions throughout the 24-hour period. The 24-hour volume weighted average internal temperature (T_i) for ASHP was 18.3 °C compared to 16.1 °C for GCH. At Stage 6, the internal conditions were similar to each other, with ASHP and GCH measuring 18.7 °C and 18.5 °C, respectively. The reason for this is due to the increased thermal performance of the fabric, meaning the internal temperature did not drop as far outside of heating periods, reducing the effect of the setback heating profile.

At Stage 6, 24-hour ASHP energy cost was 1.4 times the cost of GCH at February 2021 energy prices and the same cost of GCH at March 2023 prices. The narrowing of the electricity-to-gas price ratio since the beginning of DEEP has resulted in correctly installed ASHPs becoming a viable alternative to GCH for fully retrofitted solid wall end-terrace/semi-detached dwellings. However, the running costs for the incorrectly installed ASHP would have been ~50% greater than GCH.

3.5 Heat load calculations

The heat load at each stage of the test programme was calculated using DHDG assumed U-values for untreated elements and AD L1b U-values for retrofitted elements. Calculations assumed air change rates for pre-2000 dwellings (category A). Figure 43 compares the calculated reductions in heat load with the measured reductions in HTC and gas use from the Stage 1 baseline.

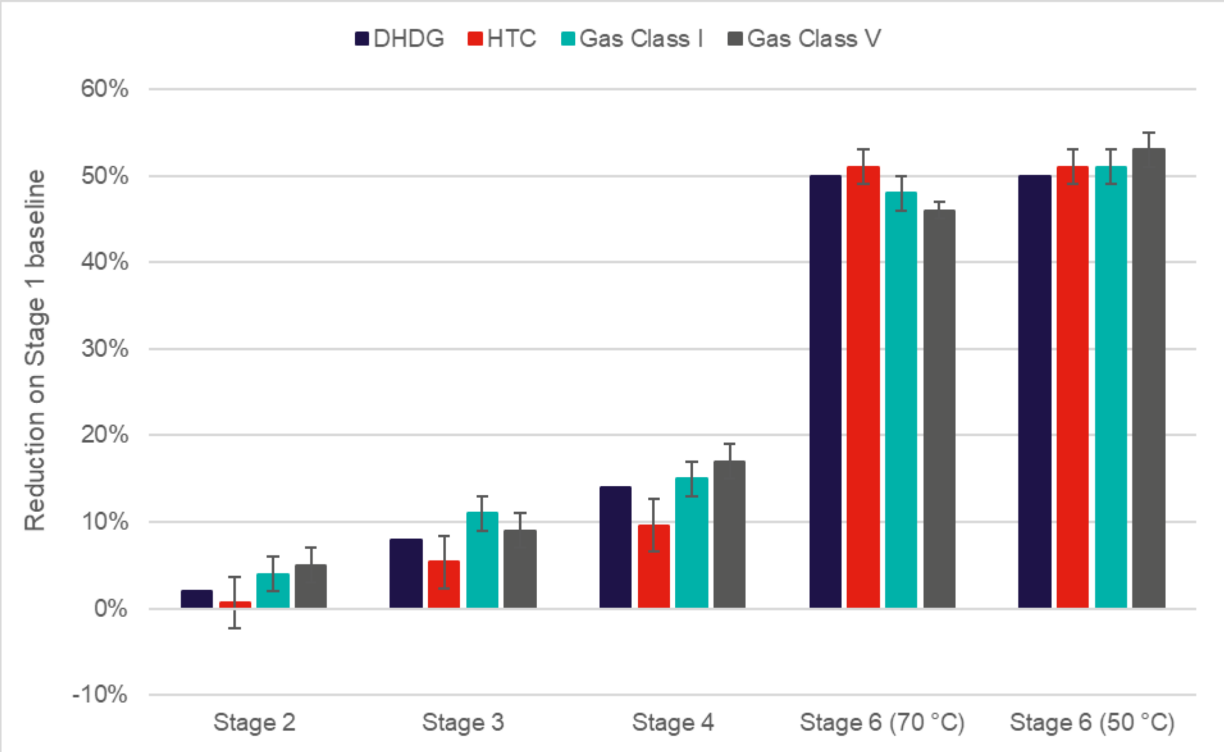


Figure 43: Calculated DHDG reductions and measured reductions in HTC and gas use from the Stage 1 baseline each

DHDG calculated heat load reductions were found to be a reasonable predictor of and gas use reductions at each stage of the DEEP retrofit process. The agreement between the calculated DHDG heat load reduction and measured HTC and gas use reductions was in closest agreement at Stage 6 of the retrofit following the boiler flow temperature modification.

The DHDG heat load calculations assume air changes rates for the following categories of building:

- Category A: Air change rates for older existing buildings (Pre-2000).
- Category B: Air change rates for modern buildings (2000 or later) with double glazing and regulatory minimum insulation.
- Category C: New (or existing) buildings constructed after 2006 and complying with all current Building Regulations.

The ventilation categories provide little guidance as to the appropriate category for pre-2000 buildings at various stages of a piecemeal retrofit. Category A could be assumed to apply for Stages 1-3, Category B for Stage 4, and Category C for Stages 5 and 6. Clearer guidance would assist with sizing heating systems for existing buildings. This could include aligning ventilation categories with air permeability measurements (e.g. blower door test results).

Table 9 compares the HTC derived heat load[26] and DHDG calculated heat load for each ventilation category.

Table 9: HTC derived and DHDG calculated heat load for each ventilation category

Test stage	HTC derived heat load (W)	DHDG category A heat load (W)	DHDG category B heat load (W)	DHDG category C heat load (W)	DHDG Cat A difference from HTC heat load	DHDG Cat B difference from HTC heat load	DHDG Cat C difference from HTC heat load
1	4,686 (±94)	6,726	6,376	5,955	+31%	+27%	+22%
2	4,655 (±93)	6,613	6,263	5,843	+30%	+26%	+21%
3	4,462 (±89)	6,197	5,847	5,427	+28%	+24%	+18%
4	4,285 (±86)	5,762	5,413	4,994	+26%	+21%	+15%
5	2,627 (±79)	3,354	2,863	2,442	+23%	+9%	-6%
6	2,563 (±51)	3,354	2,863	2,442	+25%	+12%	-4%

The DHDG calculated heat loads are greater than the HTC derived heat loads in all categories at each test stage, except for category C after the introduction of EWI. DHDG category C heat loads were closest to the HTC derived heat loads. This can be explained by the sheltered test environment of the Energy House reducing ventilation heat loss[27]. The close agreement between the Stage 6 HTC and category C heat load was the reason for selecting it as the basis for the boiler flow temperature modification. The category A Stage 6 heat load is 17% greater than the category C heat load.

The discrepancy between DHDG calculated and HTC derived heat loads reduced throughout the test programme. This can be explained by the replacement of DHDG assumed U-values with AD L1b post-retrofit target U-values at each stage. The retrofit target U-values were in reasonable agreement with measured U-values. Figure 44 compares measured U-values with those assumed by the DHDG and calculated according to BRE 443.

[26] HTC derived heat load includes DHDG assumptions of additional 15% to account for intermittent heating and consideration of party wall heat transfer with neighbouring dwelling heated at 10 °C (SAP assumes zero ΔT).
[27] This finding suggests that category C air change rates should be used for heat load calculations of the Energy House.

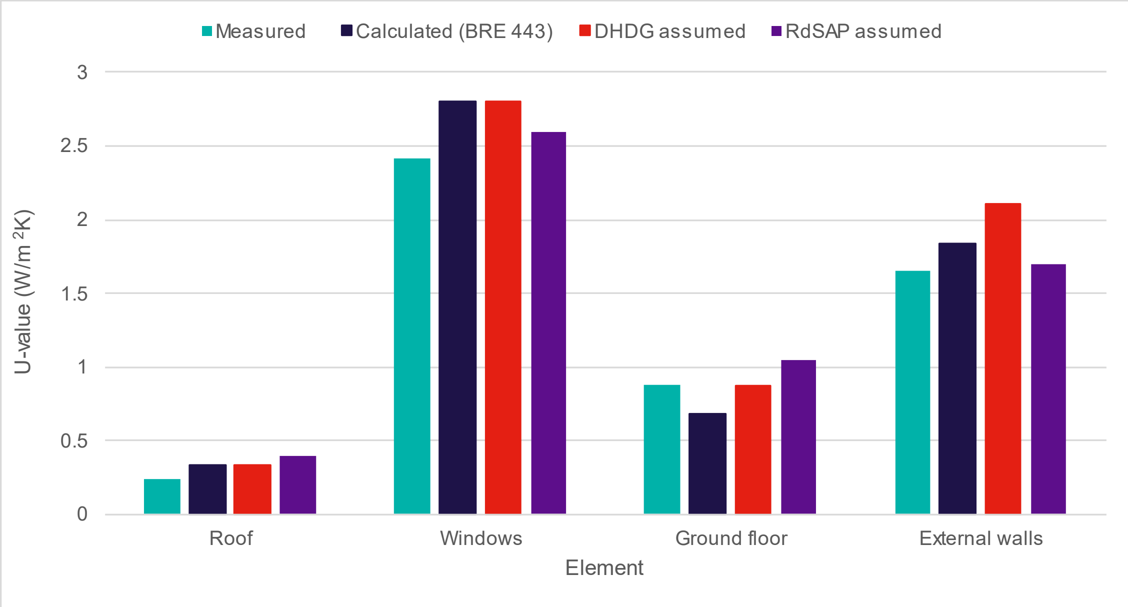


Figure 44: BRE 443 calculated and DHDG assumed U-values compared with measured U-values

DHDG and BRE 443 calculated U-values are not consistent. The DHDG assumed U-value for external walls (2.11 W/m^{2}K) is comparable to pre-2017 RdSAP value of 2.10 W/m^{2}K, but lower than the current assumption of 1.70 W/m^{2}K. Table 10 compares the DHDG heat load with heat loads based on BRE 443 calculated values and measured values of fabric thermal performance.

Table 10: Heat load at each test stage based on measured and assumed values

Test stage	HTC derived heat load (W)	DHDG category A heat load (W)	BRE 443 U-values & DHDG ACH heat load (W)	Measured U-values & DHDG ACH heat load (W)	Measured U-values & ACH heat load (W)
1 – baseline	4,686 (±94)	6,726	6,357	5,780	4,457
2 – roof	4,655 (±93)	6,613	6,244	5,683	4,358
3 – openings	4,462 (±89)	6,197	5,882	5,307	3,981
4 – GF	4,285 (±86)	5,762	5,566	4,968	3,644
5 – EWI	2,627 (±79)	3,213	3,395	3,122	1,798
6 – WHA	2,563 (±51)	3,213	3,395	3,122	1,798

Substituting BRE 443 calculated U-values for DHDG U-values in the DHDG heat load calculation reduced the discrepancy between calculated and HTC derived heat loads until Stage 5. In the final two test stages, the DHDG U-value calculated heat loads were more closely aligned with the HTC derived heat loads. From Stage 5, the DHDG and BRE 443 U-values for all external elements were very similar except for the openings. The BRE 443 U-values for openings were substantially higher than the DHDG U-values, which resulted in discrepancy between the heat load calculations. Inputting measured U-values in the DHDG heat load calculation improved the alignment with HTC derived heat loads at each stage.

The introduction of measured air change rates with measured U-values in the DHDG calculation further reduced the discrepancy with HTC derived heat load until Stage 5. In Stages 5 and 6 the calculated heat load was 30% below the HTC derived heat load. It is thought that some of the discrepancy could be explained by the DHDG heat load calculation not accounting for the substantial increase in thermal bridging heat loss (+15 W/K) resulting from the application of EWI at Stage 5.

The findings suggest that accuracy of heat load calculations could be improved with more accurate inputs, preferably using measured values if available. Heat load calculations should also account for the change in thermal bridging heat loss that can result from a fabric retrofit.

4 Conclusions and recommendations

Fabric retrofit can have unintended consequences for the efficiency of a GCH system that can result in a retrofit failing to deliver the anticipated savings in space heating energy use. Post-retrofit oversizing resulting from a full fabric retrofit was found to reduce the efficiency of a GCH system using Class I (on/off) controls by 5%. The application of EWI resulted in the single greatest reduction in HTC and GCH system efficiency. Solid wall insulation is likely to have the greatest impact on GCH efficiency of any retrofit measure for end-terrace solid wall dwellings. It is also likely to be the costliest retrofit measure, so consideration of its impact on an existing GCH system and mitigation measures must be made when specifying this measure.

GCH systems that use Class V modulating boiler controls are less susceptible to post-retrofit oversizing. Boilers that are capable of modulation should be fitted with Class V controls. They provide a low-cost post-retrofit oversizing mitigation measure. They also have the potential to optimise existing oversized systems and provide superior thermal comfort to Class I controls. The potential for Class IV controls to provide similar benefits for boilers that are not capable of modulation should be investigated. However, the rapid on/off behaviour that may occur when fitted to oversized systems could increase wear and tear on a boiler and shorten its lifespan. Boiler control classes that use weather compensation are not recommended due to the issues highlighted with heating curve selection in the ASHP tests and the expense and complexity associated with fitting an external temperature sensor.

The modification to boiler flow temperature to mitigate post-retrofit oversizing resulted in heating system efficiency improvements of 5% and 1% for Class I and Class V controls respectively. This effectively restored any GCH system efficiencies lost to post-retrofit oversizing and enabled the full benefit of fabric insulation measures to be realised. Boiler flow temperature modification to match the heat load of a dwelling could therefore provide a low-cost mitigation post-retrofit oversizing measure. Where possible it should be combined with the introduction of Class V controls. It is a different strategy to the general energy saving advice given to householders to reduce boiler flow temperature which does not consider the heat load of a dwelling and could result in significantly increased heat-up times or insufficient heat input during cold weather[28]. The flow temperature modification strategy is an informed modification of boiler flow temperature that is intended to satisfy the heat load of a dwelling, thereby minimising its impact on occupant thermal comfort. This strategy also has the potential to optimise the performance of existing GCH systems.

The ASHP tests found that ASHP running costs were only comparable with GCH after the application of EWI based on October 2022-March 2023 energy prices. The electricity-to-gas price ratio at the commencement of the Energy House DEEP tests in February 2021 would have made ASHP installation financially unviable. This shows that ASHP viability is dependent on energy prices and fabric performance. It is likely that end-terrace or semi-detached solid wall dwellings will require solid wall insulation to make ASHP installation financially viable in the short-medium term. Further work should be undertaken to assess whether mid-terrace solid wall dwellings with a low proportion of external wall area may not require solid wall

[28] https://www.nesta.org.uk/report/salford-energy-house-boiler-flow-temperature-testing-initial-report-october-2022/

insulation to make ASHP installation viable if all other elements have a good level of thermal performance.

The ASHP installation error by a highly experienced heating engineer at the full retrofit test stage may be symptomatic of a wider ASHP installer skills gap. The fault was not initially detected because no clear warning was provided by the ASHP, and adequate space heating was provided. The faulty installation resulted in a lower COP that meant running costs were estimated to be at least 50% greater than would have been expected from a correctly installed ASHP. It is conceivable that such an error might only be identified in the real world after a householder receives their energy bill. The findings highlight the importance of ensuring ASHP installers are correctly trained. ASHP units need to provide clear diagnostic feedback relating to installation errors.

The tests highlighted the importance of selecting the correct ASHP heating curve (weather compensation). An incorrect heating curve can impact ASHP efficiency and/or result in poor internal temperature control. There is a lack of clear and practical guidance available to installers and householders on how to select the most appropriate heating curve. ASHP controls will ultimately become more sophisticated and able to select the appropriate curve based on identification of fabric parameters. However, there is a need for clear tools that can assist installers with heating curve selection during commissioning and enable householders to make appropriate adjustments if required.

The dominant effect on occupant thermal comfort throughout the retrofit process was the time taken until comfort was achieved. Improving thermal performance of the building fabric reduces the rate of temperature decay between heating periods. This results in a greater initial temperature at the start of the heating period, and less time required to raise the room temperature back to a comfortable level.

Knowledge of fabric performance parameters was found to be important for GCH and ASHP sizing, boiler flow temperature modification, and ASHP heating curve selection. Ideally, parameters used in these calculations should be based on measured fabric performance, though this is not currently practicable. The fabric performance of existing dwellings is usually based on assumed values of thermal performance. However, differing assumptions are used in the methodologies used for specifying a dwelling’s retrofit fabric performance and sizing its heating system. This results in a mismatch between how fabric retrofits and heating systems are specified. Closer alignment of these methodologies would allow heating systems to be optimised for the dwelling’s fabric heat loss.

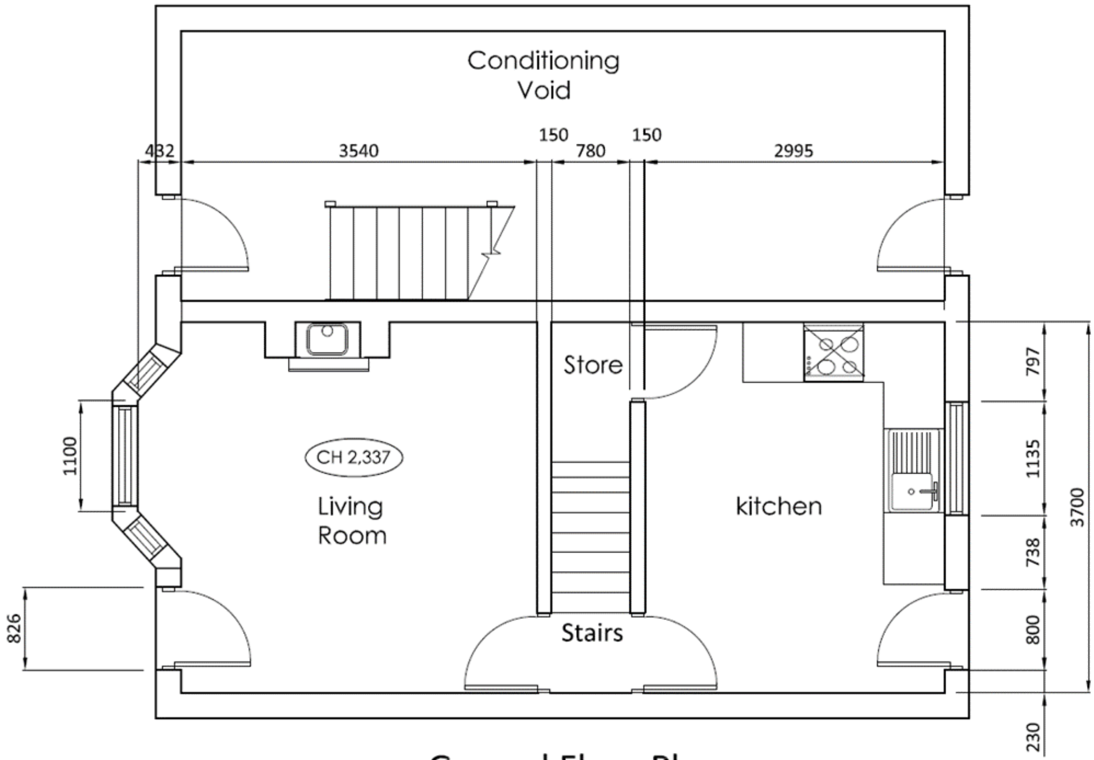
The DEEP heating systems tests highlighted the important link between fabric performance and both GCH and ASHP performance. Ultimately, a successful whole house approach retrofit strategy must include consideration of space heating provision.

Appendix A – Energy House construction

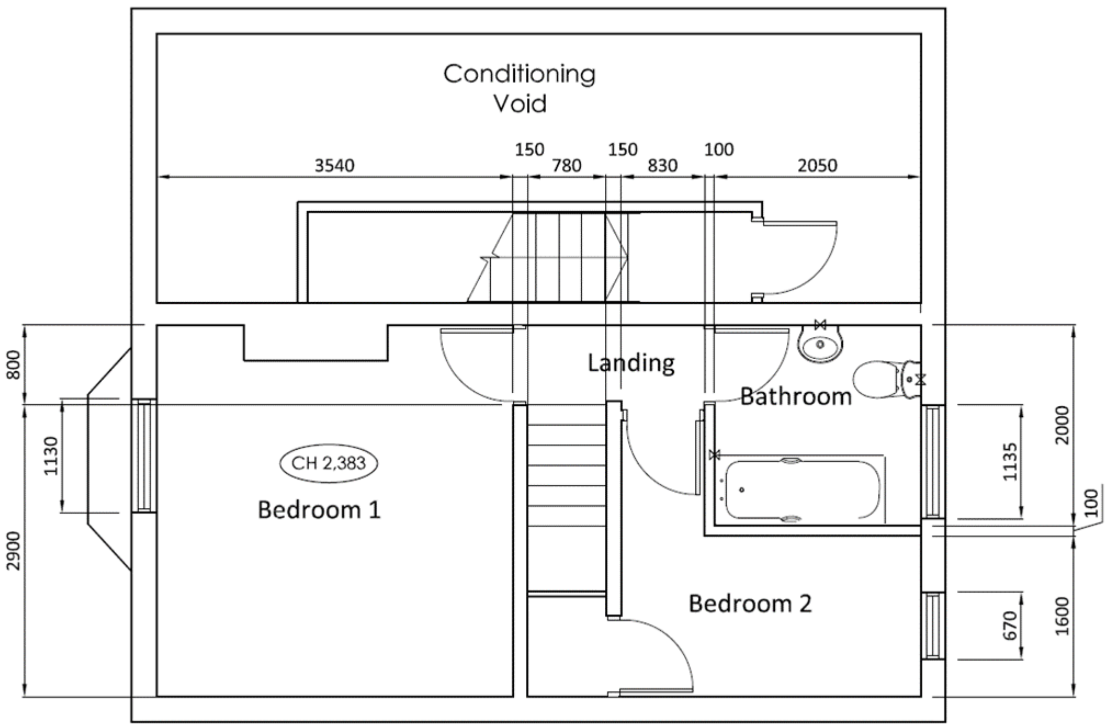
Table A1: Energy House construction at the baseline test stage (Stage 1)

Thermal element	Construction
External walls	Solid wall – 222.5 mm brick arranged in English bond (5 courses) with 9 mm lime mortar and 10.5 mm British Gypsum Thistle hardwall plaster with a 2 mm Thistle Multi-Finish final coat. The ground and intermediate floor joists are built-in to the gable wall.
Roof	Purlin and rafter cold roof structure with 100 mm mineral wool insulation (λ 0.044 W/mK) at ceiling level between 100x50 mm ceiling joists. Ceiling joists run parallel to the gable wall at 400 mm centres above lath (6 mm) and plaster (17 mm) ceiling
Ground floor	Suspended timber ground floor above a ventilated underfloor void (20 mm depth). 150x22 mm floorboards fixed to 200x50 mm floor joists at 400 mm centres. Floor joists run between the gable and party wall with joists ends built into masonry walls.
Windows	‘E’ rated double glazing units in uninsulated uPVC frames.
Doors	Front – ‘E’ rated uPVC Rear – ‘E’ rated half glazed uPVC.
Party wall	Solid wall – as external walls but with plaster finish on both sides.

Appendix B – Energy House floor plans



Ground Floor Plan



First Floor Plan

Appendix C – Thermal comfort metrics

Radiative temperature is a measure of the radiative heat in a given environment. This can be influenced by the temperature of objects such as heat emitters and surfaces.

$$\bar{T_r} = \left[(T_{BG} + 273)^4 + \frac{1.1 \cdot 10^8 \cdot v_{ar}^{0.6}}{\varepsilon \cdot D^{0.4}} (T_{BG} - T_a) \right]^{\frac{1}{4}} - 273$$

Where:

$\bar{T_r}$ = radiative temperature (°C)

T_{BG} = black globe temperature (°C)

T_a = air temperature (°C)

D = diameter of black globe sensor (mm)

v_{ar} = air velocity (m/s)

Operative temperature considers both the air temperature and radiative temperature and is a more indicative of how an occupant would feel in the environment.

$$T_{op} = \frac{\left(\bar{T_r} + \left(T_a \times \sqrt{10 v_{ar}} \right) \right)}{1 + \sqrt{10 v_{ar}}}$$

Where:

T_{op} = Operative temperature (°C)

Comfort benefit has been defined in this project as the difference between the operative and air temperatures. The purpose of this metric is to assess if an occupant would feel more comfortable in a lower air temperature due to changes to either the building fabric or changes to the heating system.

$$Benefit = T_{op} - T_{air}$$

The thermal comfort of the living room was calculated using the predicted percentage of dissatisfied (PPD) index prescribed by the comfort standards ASHRAE 55[29] and ISO 7730[30].

To calculate this, the predicted mean vote (PMV) must first be calculated. This metric is based on the heat balance of the human body and predicts the mean value in which a large group of persons would vote for on the seven-point thermal sensation scale (Table C1).

[29] ANSI/ASHRAE Standard (2020) 55 Thermal Environmental Conditions for Human Occupancy
[30] BS EN ISO 7730:2005 Ergonomics of the thermal environment. Calculation of the PMV and PPD indices, and local thermal comfort criteria

Table C1: Seven-point PMV thermal comfort scale

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	1	2	3

$$PMV = \left[0.303 \cdot e^{(-0.036 \cdot M)} + 0.028\right] \cdot \left\{ \begin{matrix} (M-W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot [(M-W) - 58.15] \\ -1.7 \cdot 10^{-5} \cdot M \cdot (5867 - P_a) - 0.0014 \cdot M \cdot (34 - T_a) \\ -3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(T_{cl} + 273)^4 - (\overline{T_r} - 273)^4] - f_{cl} \cdot h_c \cdot (T_{cl} - T_a) \end{matrix} \right\}$$

Where:

$$P_a = RH \cdot 10 \cdot e^{\left(16.6536 - \frac{4030.183}{T_a + 235}\right)}$$

$$T_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(T_{cl} + 273)^4 - (\overline{T_r} + 273)^4] + f_{cl} \cdot h_c \cdot (T_{cl} - T_a)\}$$

$$h_c = \begin{cases} 2.38 \cdot |T_{cl} - T_a|^{0.25} & for \quad 2.38 \cdot |T_{cl} - T_a|^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & for \quad 2.38 \cdot |T_{cl} - T_a|^{0.25} < 12.1\sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & for \quad I_{cl} \leq 0.078 \ \mathrm{m}^2 \cdot \mathrm{K/W} \\ 1.05 + 0.645 I_{cl} & for \quad I_{cl} > 0.078 \ \mathrm{m}^2 \cdot \mathrm{K/W} \end{cases}$$

The PPD gives the estimated percentage of people who would be dissatisfied by the current thermal conditions; a lower PPD indicates a higher proportion of people are comfortable.

$$PPD = 100 - 95 \cdot e^{(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)}$$

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