Bellway "The Future Home" Baseline Performance Report

Quality Assurance

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1. Introduction

This report provides the initial results from a larger piece of research on Future Homes. This research consists of a study of two Future Homes demonstrators, measured under controlled conditions at the Energy House 2.0 research facility at the University of Salford.

This first report will present the findings of the fabric performance of Bellway's plot called "The Future Home" (TFH) This will be followed by other reports focussing on space heating, domestic hot water, overheating, thermal comfort, and smart systems.

2. Executive Summary

The Future Home (TFH) constructed by Bellway is a prototype home, consisting of innovative fabric design, multiple heating, hot water and ventilation systems, and advanced controls. Although the home visually reflects an existing Bellway archetype, it is fundamentally different in terms of construction, heating systems and control. The research covered in this report was to study the performance of the fabric of TFH.

The intention was to evaluate the performance of TFH and identify any issues where the fabric performance did not reflect the design intent, often designated as a performance gap. This is the difference between the design (often established through the Standard Assessment Procedure model) and the measured performance. This measured performance is undertaken using a number of different methods, which are identified in Section 8.0.

Previous research has found significant issues with the performance gap in new build homes in the UK. A study by Leeds Beckett University (LBU) established fabric performance gaps of 5% - 140% in a sample of 30 new build homes [1]. The performance gap can be caused by many different issues, including poor construction, substitutions of materials, incorrect assumptions within the models, and homes not being used as predicted.

This report only focuses on the fabric component of the performance gap. The following factors were measured; U-values, airtightness, and whole house heat loss. Our main findings are highlighted below:

The overall fabric heat loss of TFH was 7.7% worse than the design model[a] predicted. If we extrapolate this performance gap by amending the SAP model, the Dwelling Fabric Energy

[a] Steady state model, with similar inputs to SAP, however, it does not account for seasonal changes in the mechanical and passive ventilation of the dwelling.

Efficiency (DFEE) will increase by 3.54 kWh/m^2/yr. The majority of this difference was due to the airtightness not meeting the design value (2.5 m^{3}h^{-1}m^{-2}), with a measured result of 4 m^{3}h^{-1}m^{-2}. This equates to a 1.5 m^{3}h^{-1}m^{-2} difference, which is 61% worse than the design figure. Thermal imaging and visual inspections point to this being caused by the addition of many extra sockets, and service penetrations (more than would be found in a non-research building) coupled with detailing at the 1st floor to external wall junction where continuity of insulation was not achieved.

The roof of TFH was found to be underperforming by around 56%, this appears to be mostly down to poorly laid and disturbed insulation. Additionally, the addition of a large decking area in the loft, (around 50% of the ceiling area) would have made this difficult to check before completion.

The external walls of TFH performed well with the non-rendered wall performing in line with the design prediction and the rendered wall performing exactly to the designed values. This is probably driven by the continuous layer of PIR insulation to the inside face of the home, which has minimised many issues around thermal bridging.

The ground floor U-values of TFH are difficult to measure. This is not only an issue with this project. Previous research indicates that there are no spot measurements that can be taken that reflect the actual design U-value of a suspended floor [2], as such, the measured values presented are the "point thermal transmittance" (PTT). When the uncertainty of the PTT is considered then the floor was found to be performing broadly in line with the design values. A learning for industry is that there is no standardised method for measuring the thermal performance of suspended floors, as such, when in-situ performance measurement is considered, then this is very difficult to achieve.

The windows and doors of TFH performed well, but there was a lack of modelling data from the manufacturer for these units, so only basic measurements were taken at the centre pane of the windows which performed in line with their specification. The front door also had a lack of available data from the manufacturer as to how its U-value had been calculated, therefore a simple weighted average calculation was used, which indicated that the door was overperforming by around 29%.

Overall, TFH had a performance gap of 7.7%. Whilst this is significant, the measurements and supporting analysis have led to identification of the influencing factors, and this has led to identified rectification strategies. This is to be expected in a home that is a prototype, built to explore new fabric types, and multiple HVAC systems.

Figure 1 shows how the percentage performance gap of TFH compares to that of other newbuild properties from the Leeds Beckett University (LBU) coheating database [1], which is the largest published dataset of coheating tests conducted on new build properties. TFH performance gap of 7.7% is below that of 28 of the new build dwellings tested by LBU prior to 2015. It should be noted that the measurement of eHome2 was conducted under controlled conditions, whereas the LBU work was conducted in the field. Due to greater control of variables in Energy House 2.0, there is less uncertainty in the measurements, meaning smaller differences in performance can be identified as measurable compared to field trails.

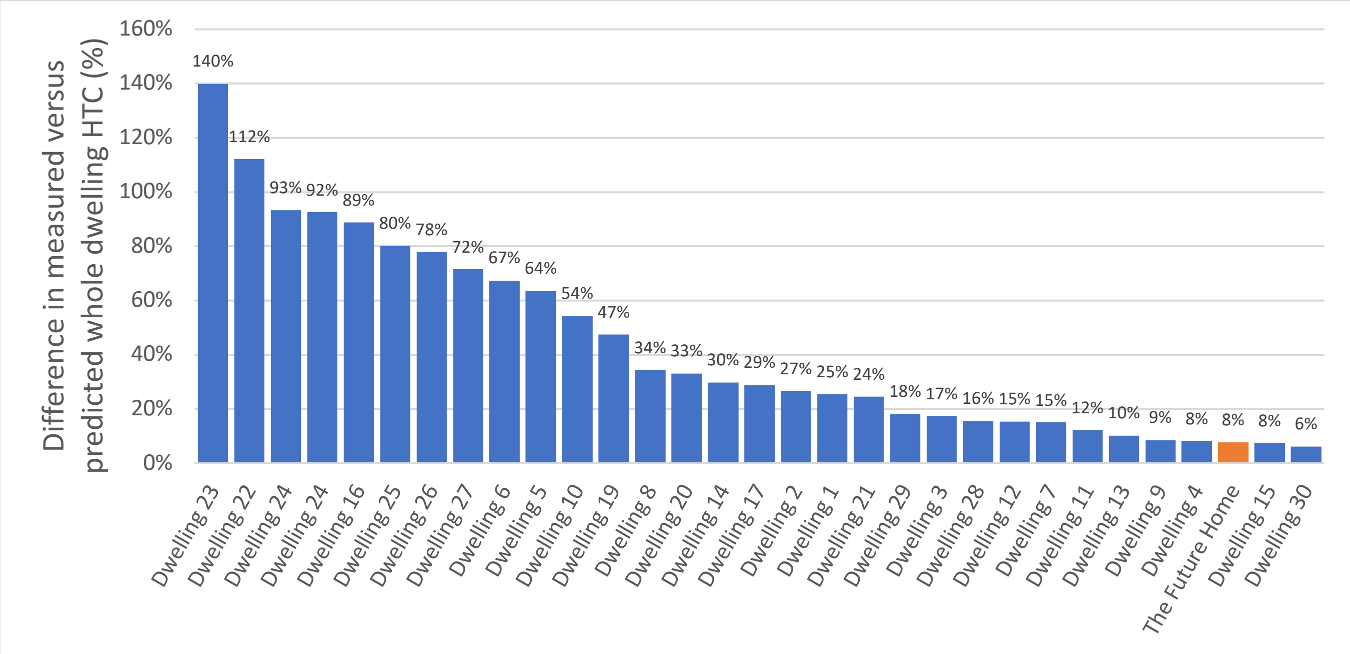


Figure 1. Difference in measured HTC of the predicted steady state HTC of the Leeds Beckett University coheating database (newbuild homes) (as a percentage), including TFH performance gap.

Key learnings of the Energy House 2.0 partners have taken from these findings is that as we move to very highly efficient homes to deliver our zero-carbon agenda, it is critical that details and products are applied correctly as minor variances can have localised impacts.

A future report by Energy House Labs on heating and modelling will identify what effect this performance gap means in terms of the impact on heating system performance in a more realistic scenario. It will give a view on whether this gap is material, and the extent of its impact. Following these next periods of modelling and measurement, a further building pathology exercise will be undertaken by the Energy House Labs team to pinpoint the issues that are driving the gaps. Following this TFH will have rectification work to address the identified issues. This will mean the performance gap can be reduced, and then the TFH will be remeasured. This will provide useful supporting information to the industry.

3. Nomenclature

Table 1.Nomenclature

Symbol	Description
A_{sw}	Solar aperture m^2
ASHP	Air Source Heat Pump
DWS	Domestic water source
HTC	Heat Transfer Coefficient (W/K)
H_{tr}	Heat Transfer Coefficient (W/K)
H_v	Ventilation Heat Transfer Coefficient (W/K)
MEV	Mechanical Extract Ventilation
MVHR	Mechanical Ventilation with Heat Recovery
n	Ventilation rate
psi	linear thermal heat transmittance
Q	Power input (W)
q	Heat flow rate (W/m^2)
q_{sw}	Solar irradiance (W/m^2)
U	U-value (thermal transmittance) (W/m^2K)
ΔT	Internal to external temperature difference (K)
λ	Thermal conductivity (W/mK)

4. Background

4.1. The Future Homes Standard

In 2019, the UK Government committed to introducing a new standard for energy performance in homes, called the Future Homes Standard (FHS). This is set to be introduced in 2025, although the final date has yet to be confirmed. This standard will require new homes to have low carbon heating and with high levels of fabric efficiency and be "future-proofed" to allow them to fully transition to net zero. The fabric elements of these changes will be delivered through amendments to Approved Document Part L (ADL).

To provide a staged approach to the rollout of the FHS an update to ADL was implemented in June 2022, requiring a reduction in the carbon emissions of new homes by 31% when compared to the 2013 standard. This was supplemented by changes in other Approved Documents to allow for changes in ventilation (Part F) and overheating (Part O).

The FHS will extend improvements, with government expectations that the average new build home will generate 75% less carbon emissions than those built under the 2013 regulations. These homes are defined as "*zero carbon ready*", with the approach considering the projected decarbonisation of the energy supply.

Whilst much remains unknown about the FHS, as it has yet to seek approvals through consultations and the legislative process, some "*features*" of a home built to these regulations are defined in the current government consultation for the Future Homes Standard.

Table 2. Anticipated features of a FHS home [3]

Item	Draft Future Homes Standard Specification
Floor U-value	0.11 (W/m^2K)
External wall U-value	0.15 (W/m^2K)
Roof U-value	0.11 (W/m^2K)
Window U-value	0.8 (W/m^2K)
Door U-value	1.0 (W/m^2K)
Air permeability	5.0 ($m^3/(h/m^2)$)
Heating appliance	Low-carbon heating (e.g. Heat pump)
Heat Emitter type	Low temperature heating
Ventilation System type	Natural (with extract fans)
PV	None
Wastewater heat recovery	No
Y value (W/m^2K)	0.05

Following the initial consultation on the FHS, the Future Homes Hub was created. This is a collection of industry experts, civil servants, and academics, coming together to help identify solutions and provide advice as to how the FHS can be delivered. The Future Homes Hub has also presented evidence on hypothetical homes that could meet a version of the FHS [4]. These have been developed as "Contender Specifications". These are presented below, alongside the reference values of a 2021 standard home [4] and a home built to the consultation version of the FHS [3].

TFH is built to most closely reflect the Contender Specification 2 (CS2). However, it does have many differences, in terms of energy storage, PV and the use of multiple heating systems for the purposes of comparison. However, in terms of fabric performance, this is the closest Contender Specification.

The full specification of TFH will be discussed in greater detail later in this report.

Table 3. Contender Specifications, The nearest to TFH is highlighted in red [4]

Future Homes Hub specifications with TFH added.									
	Ref 2021 (ADL1a) [5]	Ref 2025	CS1	CS2	CS2a	CS3	CS4	CS5	TFH Design
Wall U-value W/m²K	0.18	0.15	0.19	0.19	As per CS2	0.15	0.13	0.10 / 0.13	0.18/0.15
Roof U-value W/m²K	0.11	0.11	0.11	0.11	As per CS2	0.11	0.1	0.1	0.09
Floor U-value W/m²K	0.13	0.11	0.15	0.15	As per CS2	0.11	0.1	0.08	0.11
Glazing type	Double	Triple	Double	Double	As per CS2	Double	Triple	Triple	Double/ Triple
Thermal bridging W/m²K	Psi values - Set A	y-value = 0.05	Psi values - Set A	Psi values - Set A	As per CS2	Psi values - Set B	Psi values - Set B	Psi values - Set B	y-value =0.05
Air permeability m³/(h.m²) @ 50 Pa	5.0	5	5	4.5 - 5.0	As per CS2	3	1	0.5	2.5
Ventilation	dMEV	Natural ventilation with extract fans	dMEV	dMEV	As per CS2	MVHR	MVHR	MVHR integral with EAHP	dMEV/ MVHR
Heating	Gas boiler	ASHP	ASHP	ASHP	IR	ASHP	ASHP	None	ASHP/IR
DHW / WWHR	Gas boiler	ASHP	ASHP	ASHP & WWHR	Immersion + smart cylinder	ASHP & WWHR	ASHP & WWHR	DHW cyl EAHP & MVHR & WWHR	ASHP & WWHR
PV philosophy	To achieve 2021 Part L Pass	None	None, unless req. for min. 75% redn	40% GF area, max 3.68 kWp	Maximise roof area for PV	40% roof area max 3.68 kWp			Simulated
Battery	No	No	No	No	6.5kWh hybrid	No	No	No	6.5 kWh

5. Energy House Labs

5.2. Introduction

Energy House Labs is a research group based at the University of Salford in the UK. It consists of 4 research laboratories, focussed on research on energy use in buildings. These facilities are supported by a team of academics and technical staff who work across the fields of building physics, smart energy systems, data analytics and renewable systems. The have globally unique research capability in assessing buildings under controlled conditions in Energy House 2.0 and the Salford Energy House.

6. Energy House 2.0 Description

6.1. Introduction

Energy House 2.0 is a globally unique building performance test facility. The building was constructed to allow for full-scale testing of structures under a controlled range of climatic conditions. The facility consists of two large chambers which can accommodate four family homes: two homes in each chamber. The chambers each contain a soil filled pit, 1200 mm deep which is isolated by insulation from the ground beneath and surrounding the pit. The walls and ceilings of the chamber are insulated, providing isolation from the external climate, with high levels of airtightness.

Both chambers are independently conditioned by a large heating, ventilation, and air conditioning (HVAC) system. In addition, there are weather rigs, which provide additional climatic effects. These control the climate in the chambers as follows:

- Temperature: (-20 °C to 40 °C)
- Relative Humidity (20% to 90%)
- Wind
- Rain
- Solar Radiation (up to 1200 W/m^2)
- Snow

Temperature and relative humidity can be held at constant steady state or varied in seasonal or daily patterns. The facility is illustrated below in Figure 2, 3 and 4.

Figure 2. Energy House 2.0 external

Figure 3. Construction of soil pits, present in each chamber to a depth of 120mm

Figure 4. HVAC systems providing close climatic control to chambers

7. The Future Home Description

7.1. Introduction

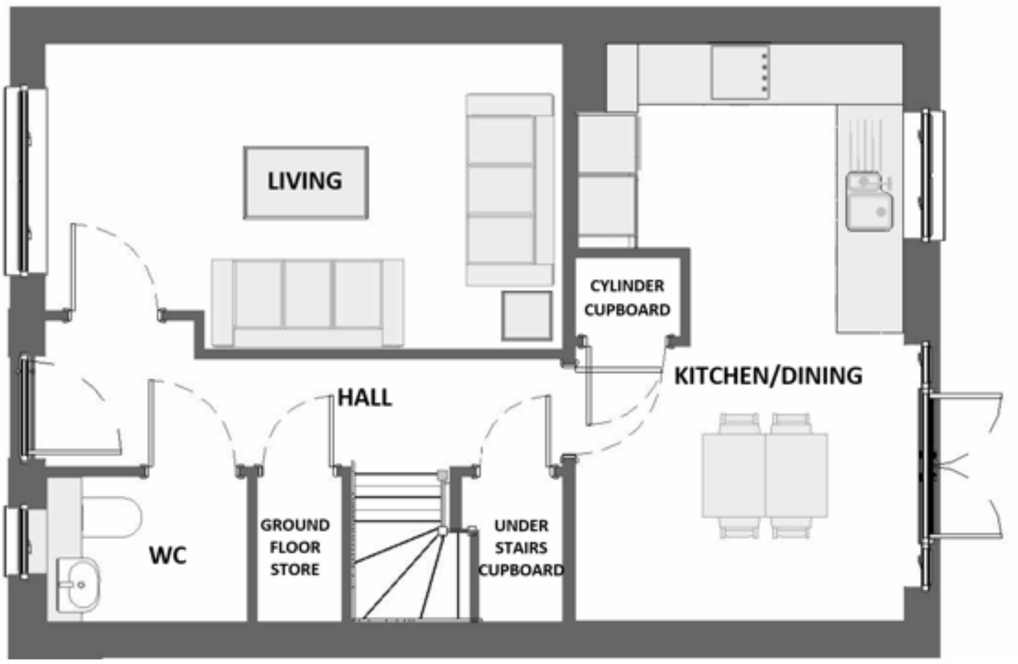
The aim of TFH was to deliver the first Bellway home that represented the challenges of the upcoming FHS. This would present a home that not only reflected the draft FHS, in terms of the fabric and services specifications, but also to extend the research past these standards. This was done by developing a home that has fabric options that can be interchanged and updated, alongside multiple heating, hot water, and renewables systems that can easily be "switched". This gives the research team opportunities for ground-breaking research in novel areas, both for fabric and services. The building is illustrated below in Figure 5 and Figure 6.

Figure 5.Front elevation of TFH.

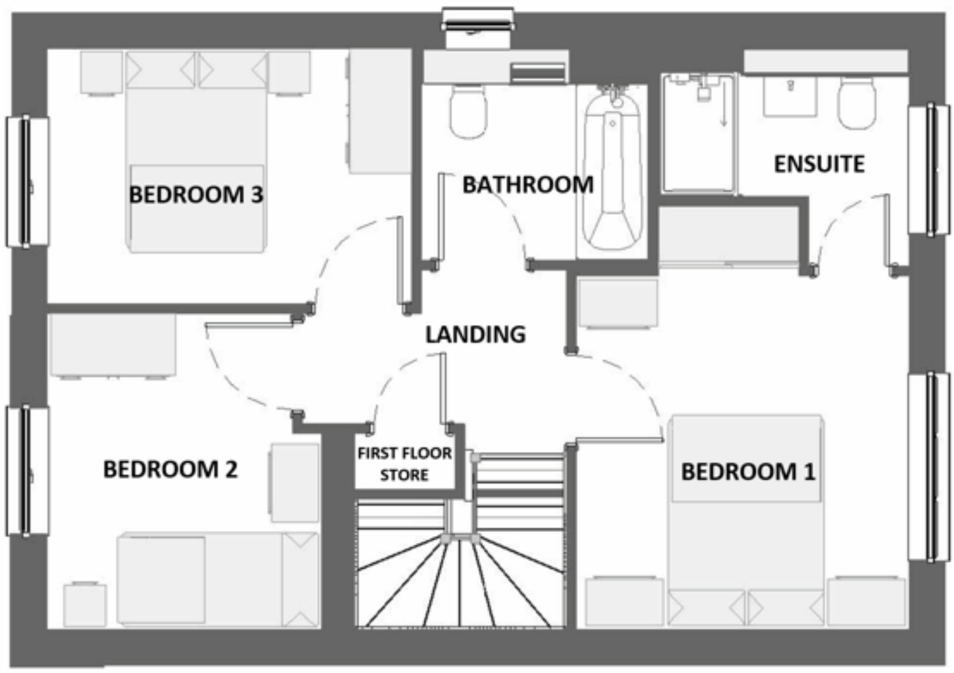
Figure 6. Rear Elevation of TFH

7.2. Architectural layout

The TFH is designed by Bellway and is a reproduction, although with minor changes, to the "Coppersmith" housing type that is currently being sold by Bellway. Figure 7 and Figure 8 below provide the design layouts and elevations of TFH.



(a)Ground Floor



(b) First Floor

Figure 7. Design layouts of TFH.

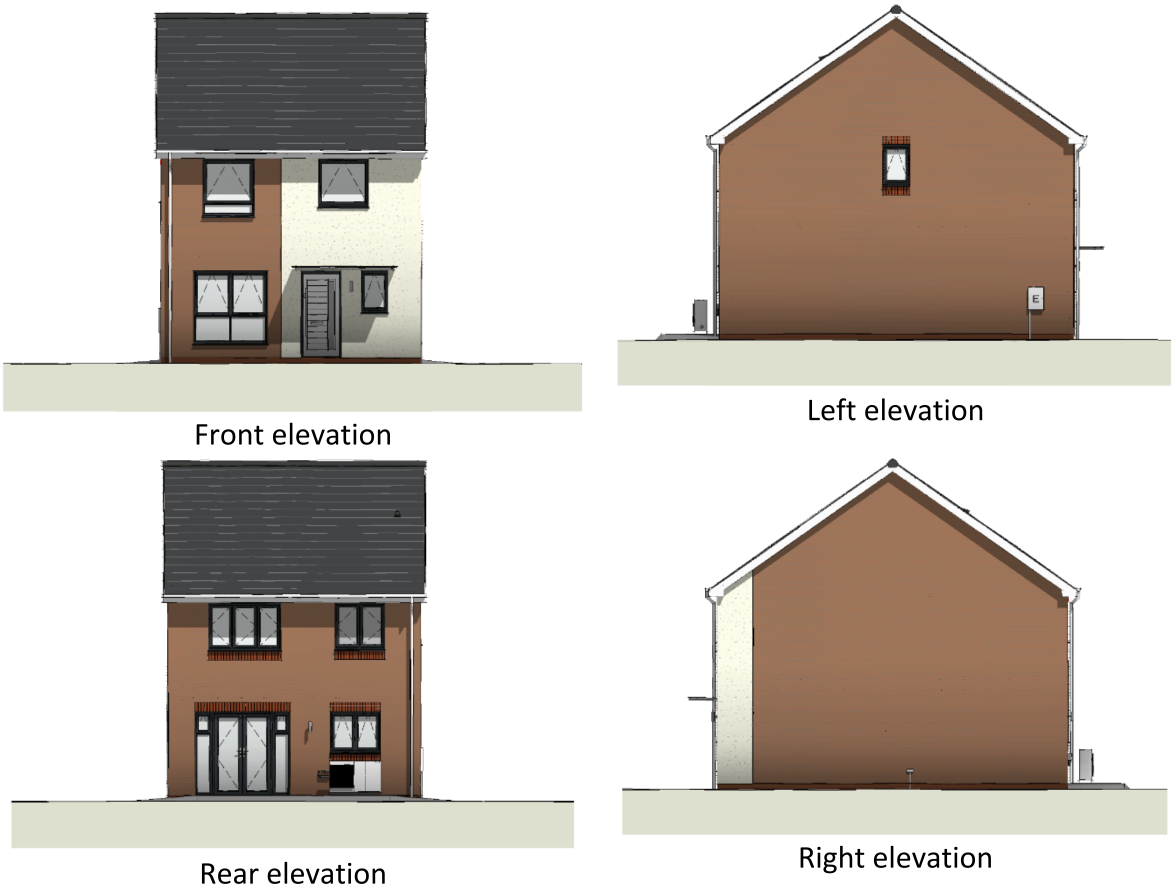


Figure 8. Elevations of TFH.

7.3. Fabric

7.3.1. Sub floor and foundation

TFH is built within an environmental chamber containing a pit of earth that is surrounded by insulation. This acts to reduce heat transfer from/to the ground beneath and surrounding the pit. The pit is filled with locally sourced graded soil which is compacted and closely matches both the structural and thermal nature of UK soil. The soil is 6N graded fill.

The TFH has a 600x225 mm concrete strip foundation, this was formed of GEN 3 concrete mix.

7.3.1.1. Floors

The floors in TFH are suspended concrete to the ground floors and timber to the first floor.

7.3.1.1.1. Ground floor

This ground floor is formed using an insulated precast slab system (NUSPAN375). This is a concrete slab system with EPS based insulation. The floor has a design U-value of 0.11 W/m^2K. This can be seen in Figure 9 and Figure 10 below.

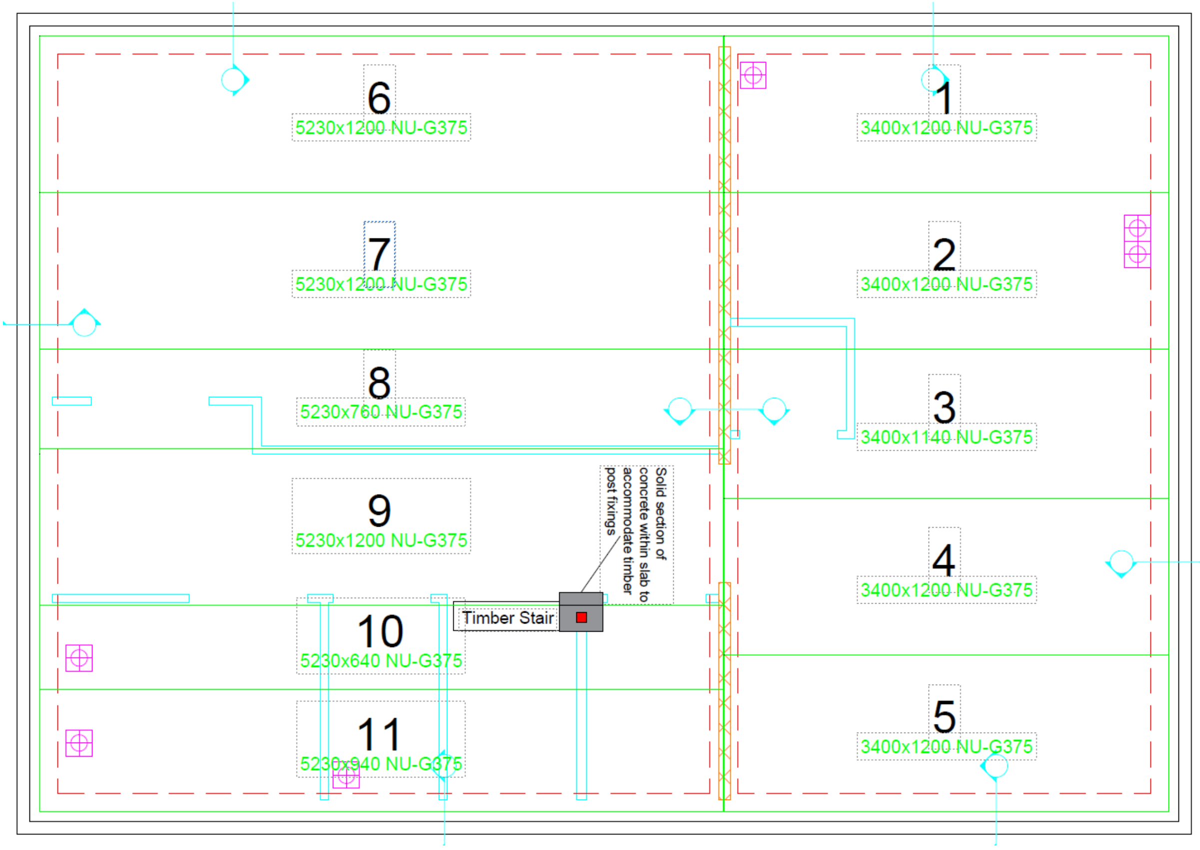


Figure 9. Ground floor slab layout

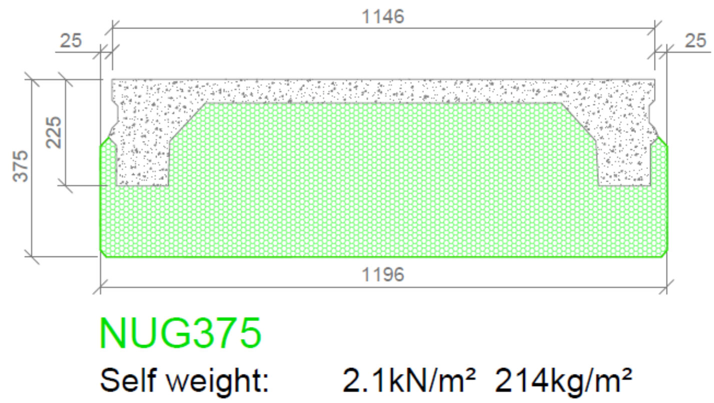


Figure 10. Ground floor slab section

7.3.1.1.2. First floor

This comprises 22 mm Caberdek chipboard floors with tongue and groove joints, these are glued and sealed with tape. These sit on 300 mm I-Joists at 60 mm centres and the perimeter is insulated with mineral fibre (λ value of 0.035 W/mK).

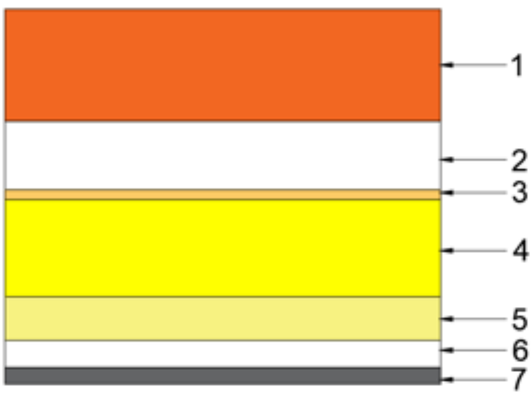
7.3.2. External walls

The walls of TFH are constructed using an open panel timber framed system, with three differing wall build ups, to allow for rendering and services zones. The breakdown of these individual wall types are as follows:

- Main walls - bricks finish. This is the dominant wall of the house with 107.3 m^2. This has two subtypes of wall, to allow for service zones, which were necessary to allow for the heating pipework to be installed.
  - Main brick wall with **25mm** service void (87.3 m^2 of wall)
  - Main brick wall with **38mm** service void (19.97m^2 of wall)
- Main wall – rendered finish with **25mm** service void (13.77m^2 of wall)

The main wall (brick finish), according to the design provided to the UoS, appears to be ventilated to a low level, as described in BSEN ISO 6946 [6]. This is due to the fact that there is a vent, equivalent to an open joint, every 1.2 m of wall length in the external walls. This occurs at both the bottom and top of the walls, resulting in an opening of at least 10 mm x 7 mm every 1.2 m. This results in opening areas of approximately 580 mm^2 per metre of length, in the horizontal direction, as such this cavity is partially ventilated. Each wall type is detailed in Table 4, Table 5 and Table 6.

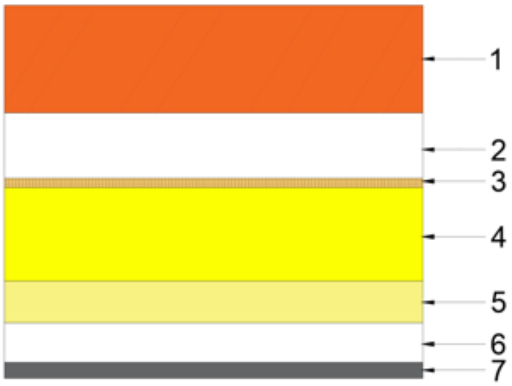
Table 4. Main walls - brick finish (1)

External Wall (25mm service zone) Overall thickness 343.5mm
 1. 102.5 mm facing brickwork 2. 63 mm ventilated cavity 3. 9 mm OSB board 4. 89 mm timber frame with 0.035 W/mK mineral fibre insulation 5. 40 mm PIR insulation board 0.022 W/mK 6. 25 mm service void (25 x 38 mm battens) 7. 15 mm gypsum plasterboard
Design U-value: 0.18 W/m²K[b]

[b] Refer to Annex A (point 6)

Table 5. Main Walls - brick finish (2)

External Wall (38 mm service zone)- Overall thickness - 356.5 mm

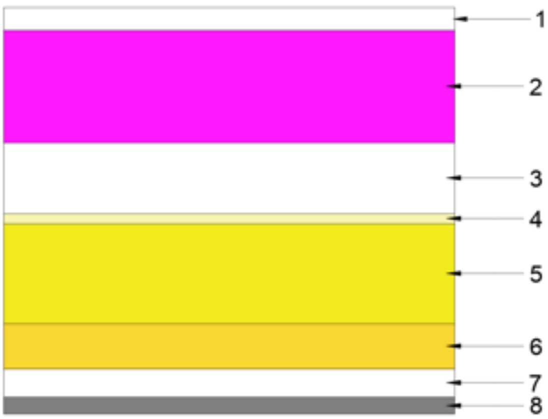


1. 102.5 mm facing brickwork
2. 63 mm ventilated cavity
3. 9 mm OSB board
4. 89 mm timber frame with 0.035 W/mK mineral fibre insulation
5. 40 mm PIR insulation board 0.022 W/mK
6. 38 mm service void (38 x 63 mm battens)
7. 15 mm gypsum plasterboard

Design U-value: 0.18 W/m²K[c]

Table 6. Main walls – rendered (3)

Rendered External Wall (25 mm service zone) - Overall thickness 361 mm



1. 20 mm Render
2. 100 mm Blockwork
3. 63 mm ventilated cavity
4. 9 mm OSB board
5. 89 mm timber frame with 0.035 W/mK mineral fibre insulation
6. 40 mm PIR insulation board 0.022 W/mK
7. 25 mm service void (25 x 38 mm battens)
8. 15 mm gypsum plasterboard

Design U-value: 0.17 W/m²K[d]

7.3.3. Walls below Damp-Proof Course (DPC)

External walls with cavities extend below DPC and are filled with insulation The DPC is approximately 150 mm above ground level. Telescopic vents are provided with expanded polystyrene board around 70 mm (λ 0.038 W/mK). There are seven uPVC periscope vents located to the perimeter of the property each with a free area of approx. 6000 mm^2.

[c] Refer to Annex A (point 6)
[d] Refer to Annex A (point 7)

7.3.4. Below ground walls

The walls to the underside of the DPC are formed as follows; 140 mm aerated concrete blocks up to underside of NU-span insulated concrete plank. A 72 mm cavity is filled with expanded polystyrene board (λ 0.038 W/mK).

7.3.5. Windows

The windows in TFH are made from PVCu with the following U-values: the centre pane U-value is 1.07 W/m^2K and the typical whole window U-value is 1.3 W/m^2K[e]. Included as part of the window package are the patio doors to the rear of the dwelling, these have a U-value of 1.4 W/m^2K[f].

Note:

(University of Salford (UoS) were not provided a full breakdown of each window U-value)*.*
We relied on the values provided to us in the SAP calculation, these values are generic and are for a building not specific to TFH.

7.3.6. Doors

TFH has only one external door, which is to the front elevation with a U-value = 1.0 W/m^2K[g]. The door is PVC with a steel reinforced frame and the frame is also PVC. The door has a vision panel, the U-value of this glazing panel was not provided. Patio doors (Section 7.3.5) provide access via the rear elevation.

7.3.7. Roof

The roof to TFH is pitched with interlocking concrete tiles with underfelt. The roof is ventilated with over fascia vents and a vented ridge tile system. The free ventilation space for the roof was not provided but was treated as a well-ventilated cold roof for the purpose of experiments on heat loss.

The first-floor ceiling of TFH is insulated at ceiling joist level with 500 mm of mineral wool insulation, laid between joists in layers. This is laid onto the 12.5 mm plasterboard. The loft hatch has 50 mm of PIR insulation. The U-value for the ceiling is 0.087 W/m^2K, with the correction included for the loft hatch this is amended to 0.09 W/m^2K[h].

7.3.8. Linear Thermal Bridging

Detail specific Psi-value calculations were performed to accurately account for heat losses from non-repeating thermal bridges. These were provided to UoS and are contained in

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[e] Refer to Annex A (point 2)
[f] Refer to Annex A (point 4)
[g] Refer to Annex A (point 3)
[h] Refer to Annex A (point 7)

Annex J. The calculated Y value is 0.05 W/m^{2}K. A breakdown of these Psi-values can be found in Annex K.

7.4. Services

This section will act as an introduction to the services provided in TFH and is provided for context only. A full report on the performance of the installed services will follow. The services provided on TFH are not limited to one heating or hot water system. There are four different space heating sources alongside several options for the provision of domestic hot water, which have yet to be agreed.

7.4.1. Air Source Heat Pump (1) (Panasonic -External)

The primary source of space and hot water provision is provided by a mono bloc air to water heat pump system. This is a Panasonic WH-MDC05J3E5 running on R32 refrigerant (difluoromethane). This specification will provide 5 kW of heating with a coefficient of performance (COP) of 5.08 at an outside air temp of 7 °C, with a heating flow temperature of 35 °C (underfloor heating), and a COP of 3.01 at 55 °C (radiator heating). This unit also has a cooling capability, which is not currently used.

7.4.2. Air Source Heat Pump (2) (Worcester Bosch – Loft Mounted)

An additional heat pump system was added to the TFH later in the design process. This consists of a heat pump system that is entirely contained within the roof space of TFH. The setup is a split system. The condenser unit, which would traditionally be located outside of the building, is located in a "Hydrotop" container, which has a heat exchanger that replaces an area of the roof covering. The unit is a Bosch CS3400i AWS 4 OR-S rated at 4 kW. This is connected via refrigerant lines laid in the roof space to the indoor unit, a Bosch AWE 4-10. The system has a quoted COP of 4.68 at 7 °C external whilst providing 35 °C to an underfloor heating circuit. This system can provide heating and hot water to TFH.

7.4.3. Heat Emitting Systems – Radiators

A combination of single and double panel compact radiators has been installed as shown in Table 7.

Table 7. Stelrad Radiator Specification
(Compact series, sized at 45 °C flow -3 °C design temperature)

Installed Radiators				
Location	Height(mm)	Length(mm)	Type	Quantity
Living	600	700	K2	1
Kitchen/Dining	700	900	K2	1
Kitchen/Dining	700	500	K2	1
WC	700	600	K1	1
Hall	600	700	K1	1
Bedroom 1	450	700	K2	1
Ensuite	600	500	K2	1
Bedroom 2	450	600	K2	1
Bedroom 3	450	600	K2	1
Landing	600	400	K1	1
Bathroom	700	800	K1	1

7.4.4. Heat Emitting Systems – Underfloor Heating

The underfloor heating (UFH) system is installed at the ground floor areas only, and excludes the ground floor storage area, understairs cupboard, cylinder cupboard and the first-floor store. Six loops are provided through a manifold system located in the understairs cupboard. This feeds a network of 17 mm PVC pipes, laid onto a Gyvlon TERMIO+ screed. The design value of the floor surface is between 23 °C and 28.5 °C, with a temperature drop of 5 °C between feed and return. This system can be fed individually by either of the air source heat pumps present in the property.

7.4.5. Infrared Heating System – Wondrwall – Ceiling Mounted

The Wondrwall system consists of ceiling mounted far infrared panels. In heating mode these have a surface temperature of between 90 °C and 105 °C. These are connected to remotely addressed relays that are mounted in the ceiling voids. The emitters are controlled by an app and have local temperature sensors contained in the light switches of each room. The size and output power of each heater can be found in Table 8. It should be noted that the system is not present in the WC, Bathroom and Ensuite.

Table 8. Size and power rating of Wondrwall heaters

Room	Size (mm)	Power (W)
Kitchen/Dining	1205 x 905	800
Living	1205 x 905	800
Hall	1005 x 605	450
Bedroom 1	1205 x 905	800
Bedroom 2	1205 x 905	800
Bedroom 3	1205 x 905	800

7.4.6. Infrared Heating System – Ambion – Wall Mounted

The Ambion system is wall mounted infrared system with carbon elements. The product contains a control system that allows for pulsing of heating and accurate control. The panels are rated as far infrared with a wavelength of 4-9 µm. The panels are controlled through a central panel, with a local temperature sensor at the bottom of the heater. The panel details are shown in Table 9.

Table 9. Size and power rating of Ambion heaters

Room	Size (mm)	Power (W)
Kitchen/Dining Heater 1	1105 x 640	820
Kitchen/Dining Heater 2	555 x 645	430
Living Heater 1	1105 x 640	820
Living Heater 2	555 x 645	430
Hall	1105 x 640	820
Bedroom 1	1105 x 640	820
Bedroom 2	605 x 1145	820
Bedroom 3	605 x 1145	820
Ensuite	555 x 645	430
WC	555 x 645	430
Bathroom	555 x 645	430

7.4.7. Wet central heating system heating controls (Radiators and underfloor heating)

The underfloor (UFH) and Radiator systems are controlled by a Honeywell Evohome system, this consists of a central controller which is in the Living room, which in turn controls TRV heads on the radiators, (Honeywell HR924UK). The UFH manifold zone heads are controlled by a separate controller (Honeywell HCC80R). Local temperature sensing for the radiator systems is located at the TRV head, whereas the UFH system has wall mounted room sensors (Honeywell Y87RF2024 and DT92E1000). The system can be linked to an app.

7.4.8. Wastewater heat recovery

TFH has two wastewater heat recovery (WWHR) systems. The ensuite shower tray has a built-in heat exchanger, a Mira HeatCapture Integrated Tray, this has a quoted efficiency of between 34% and 40%. The Bathroom shower has a Mira HeatCapture Vertical pipe system, this has a quoted efficiency of between 58% and 64%.

7.4.9. Domestic Hot Water (DHW) Systems

The default DHW system currently at TFH is a UK Cylinders –189 Litre Indirect unvented heat pump cylinder with an external expansion tank and a 3 kW immersion heater (WWA2000HP). During the tests this will be changed for other systems.

7.4.10. Ventilation Systems

For experimental purposes, two ventilation systems are present in TFH, these systems will be run independently depending on the test required. One system is a whole house system, and the second is an extract system in the moisture generating areas of TFH. These are detailed below.

7.4.10.1. Decentralised Mechanical Extract ventilation (dMEV) System

The dMEV system is provided by Titon TP640 units located in the kitchen, downstairs WC, bathroom and Ensuite. This is a ducted system. They have been designed and commissioned as shown in Table 10. This is a continually running system, with the opportunity for a manual boost.

Table 10. dMEV design flow rates

Room	Continuous Flow Design Rate l/s	Continuous Flow Measured Rate l/s
Kitchen/Dining	13	13
WC	8	6
Ensuite	8	8
Bathroom	8	8

7.4.10.2. Mechanical Ventilation with Heat Recovery (MVHR) system

The home is also served by a whole house ventilation system, a Titon HRV1.6Q Plus unit. The system is designed and commissioned as shown in Table 11 (measurements taken by commissioning engineers).

Table 11. MVHR design flow rates

Room	Continuous Flow Design Rate l/s	Continuous Flow Measured Rate l/s	Boost Flow Design Rate l/s	Boost Flow Measured Rate l/s
Kitchen/Dining	11.5	7.2	13	13.7
Living	9.4	10.5	10.6	11
WC	5.3	5.6	6	6.1
Ensuite	7.1	7.1	8	8.6
Bathroom	7.1	7.2	8	8.2
Bedroom 1	7.5	8	8.5	8.6
Bedroom 2	7.2	7.3	8.1	8.3
Bedroom 3	6.9	8.3	7.8	8.9

7.4.11. Renewables

TFH has a battery installation and a solar PV inverter, however no PV panels are installed. This is due to the chamber having no solar input. Solar radiative thermal gain is simulated, but not in the frequency spectrum suitable for PV panels. A DC signal is fed to the inverter to replicate PV input commensurate with the required daily pattern as defined by the experimental design.

The battery installation comprises a Growatt SPH3000 inverter, a Growatt GBU6532 battery system provides 6.5 kWh of energy storage.

7.5. Outline of future interventions

TFH will undergo a series of future interventions during the lifetime of the project. Those that involve the fabric are as follows:

7.5.1. Cavity fill

The 63 mm cavity to the external wall, that is currently unfilled, will be retrospectively filled with blown insulation (Knauf Supafil CarbonPlus 0.034 W/mK). It is calculated that this will improve the U-value from 0.18 W/m^{2}K to 0.15 W/m^{2}K.

7.5.2. Triple Glazing

The existing double-glazed windows (Minimum U-value of 1.3 W/m²K) are to be replaced with UPVC triple glazed with Low-E glass soft coating to achieve a minimum U-value of 0.8 W/m²K.

External doors (French doors and patio doors) (minimum U-value currently 1.4 W/m²K) to be upgraded to a new door with a U-value of glazed doors to achieve a minimum U-value of 1.0 W/m²K.

8. Building Fabric Research

8.1. Building performance evaluation methods

This section presents the methods used to measure the thermal performance of fabric of TFH. The main test found here are industry recognised standard tests with published methodologies and standards. More innovative test methods were also used, to allow for these methods to be compared to the recognised standard methods.

8.1.1. Steady state thermal performance measurements

A unique strength of the Energy House 2.0 facility is the ability to recreate not only realistic weather patterns but also to create and maintain steady chamber temperatures. This was used to carry out this series of tests as it allows for steady state conditions to be reached. This means measurements can be taken with less disturbance from outside factors, such as occupants, solar radiation etc, and for results with lower levels of uncertainty to be produced.

All the tests and measurements of the TFH were carried out within the environment of the Energy House 2.0. Table 12 illustrates the average temperatures in the UK according to SAP [7], which were used to provide a representative external temperature of the United Kingdom during the winter months (December to March). The chamber's HVAC system was set to maintain 5 °C during the test days.

Table 12. U1 of SAP10 [8]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UK average (°C)	4.3	4.9	6.5	8.9	11.7	14.6	16.6	16.4	14.1	10.6	7.1	4.2

The steady state test of the fabric performance was divided into two stages, the first was the coheating test to obtain the heat transfer coefficient (HTC), the second stage was a test to obtain the U-value of the elements of the envelope. This allows for U-values to be measured without the high airflow rate often associated with coheating, which uses circulation fans. During both tests, TFH was maintained at 21 °C throughout the steady state measurement period using electric resistance heaters connected to PID controllers with PT-100 RTD temperature sensors.

8.1.2. Building heat transfer coefficient (HTC) measurement

The HTC is defined in ISO 13789:2017 [9] as "*the sum of transmission and ventilation heat transfer coefficients of a building, where the transmission heat transfer coefficient represents heat flow rate due to thermal transmission through the fabric of a building, divided by the difference between the environment temperatures on either side of the construction and the ventilation heat transfer coefficient represents heat flow rate due to air entering a conditioned space either by infiltration or ventilation, divided by the temperature difference between the internal air and the supply (external) air temperature*".

The HTC is the rate of heat loss (fabric and ventilation) in Watts (W) from the entire thermal envelope of a building per Kelvin (K) of temperature differential between the internal and external environments and is expressed in W/K. This metric represents the heating power required to maintain a 1 K temperature difference over the building envelope.

HTC measurements were used to quantify the change in whole house heat loss. The HTC captures the aggregate change in plane elements, thermal bridging, and unintentional ventilation (air infiltration and leakage) heat losses from the house.

The 2013 version of the Leeds Beckett (formerly Metropolitan) University Whole House Heat Loss Test Method [10] was adapted for HTC measurements in TFH. The main differences from the Leeds Beckett approach being the test duration and analysis of test data.

A coheating test typically assumes the steady state whole house energy balance. In a typical coheating test whole house energy balance is expressed as follows [11].

$$\boldsymbol{Q + A_{sw}.\, q_{sw} = (H_{tr} + H_v).\, \Delta T} \qquad \text{Eq. 1}$$

Where:
Q = Power input (W)
A_{sw} = Solar aperture (m^2)
q_{sw} = Solar irradiance (W/m^2)
H_{tr} = Transmission heat transfer coefficient (W/K)
H_v = Ventilation heat transfer coefficient (W/K)
ΔT = Internal to external temperature difference (K)

In the Energy House 2.0 test facility, the terms A_{sw} and q_{sw} can be removed from the whole house energy balance, as solar systems were not used in this test and no natural sunlight enters the chamber. Thus, the equation is rearranged to show how, at steady state, the HTC can be calculated from measurements of Q and ΔT. Equation 2 shows the HTC calculation in TFH test.

$$\boldsymbol{HTC = \frac{Q}{\Delta T}} \qquad \text{Eq. 2}$$

Where:

$HTC = H_{tr} + H_v$ (W/K)

Q = power input (W) [i]

ΔT = average internal air temperature (T_i) minus average chamber air temperature (T_e)

To obtain the HTC, a coheating test was carried out. During the test, to increase the homogeneity of the air temperature inside the house, air circulation fans were used, which remained in the same location and at the minimum speed setting during the test as in Figure 11. This setting allows for the air to be mixed but without significantly altering any surface resistance to the external elements. The fans and heaters were positioned in such a way that they do not directly affect the temperature sensors.

[i] Q is based on total cumulative energy input to the Energy House over 24-hour period. Refer to Annex C for details of the HTC uncertainty calculation.

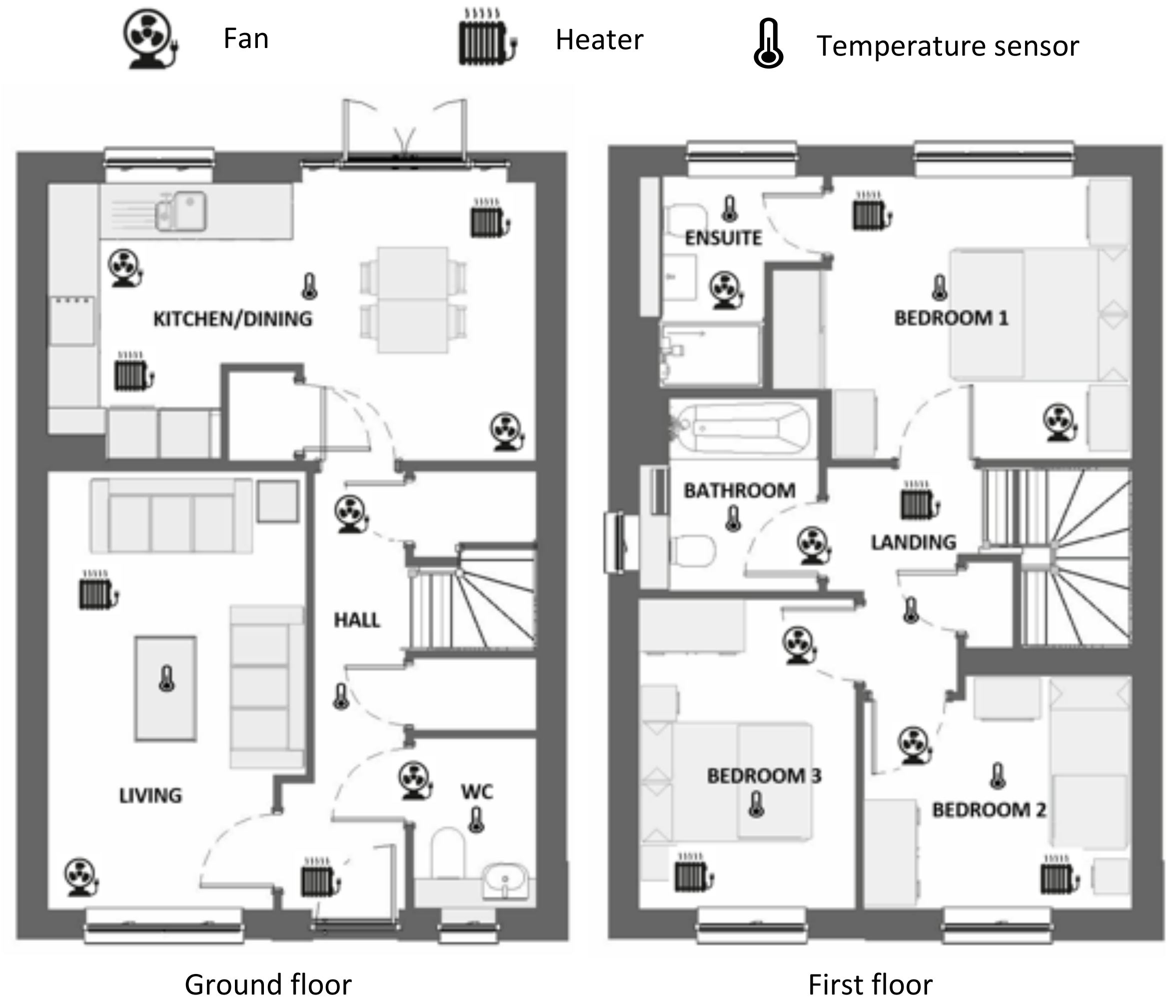


Figure 11. Coheating test heaters and fans locations.

During the coheating test, the temperatures on both sides of the fabric remained at steady state for 8 days. Figure 12 shows the rate of change of the temperature difference (ΔT) during the coheating test, the ΔT remained steady with variations between 0% and -1%.

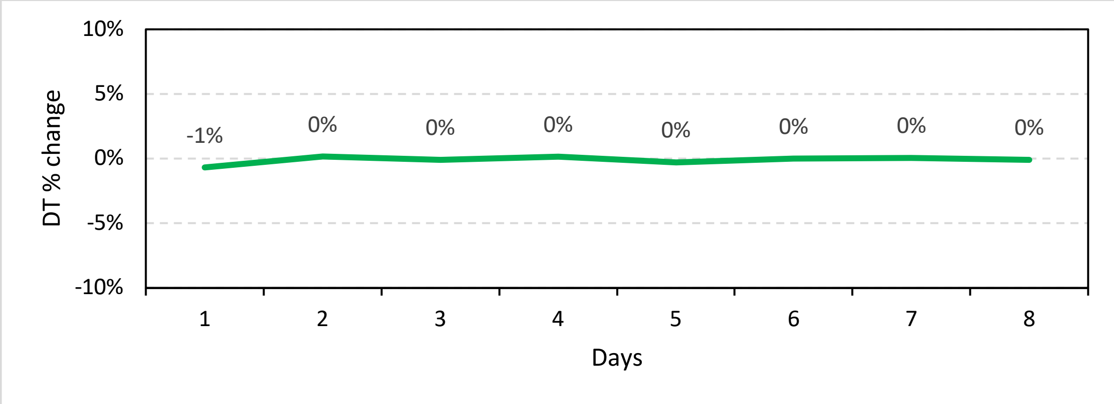


Figure 12. Rate of change of the temperature difference (ΔT) during coheating test.

8.1.3. Alternative HTC measurement methods

The test programme also provided the opportunity to compare commercial rapid HTC test methods against the coheating test. Saint-Gobain QUB [12] and Veritherm [13] can perform dynamic HTC measurements of unoccupied dwellings over one night, as opposed to the coheating test that typically requires a test period of 2-3 weeks in duration.

Both are dynamic methods that involve a stabilisation period of constant internal temperature, followed by a heating period with constant power input, then a free cooling period. They both use assumptions of fabric performance to calculate the power input required for the test. Both also utilise integrated hardware and software to control heat input, monitor power input and environmental conditions, and perform data analysis. The main difference in equipment between the two methods is that Veritherm also uses air circulation fans during the test, but QUB does not.

8.1.4. Ventilation heat transfer coefficient (Hv)

The air infiltration/leakage ventilation rate (n) from which the ventilation heat transfer coefficient was calculated was obtained using two different test methods, the fan pressurisation method, and the Pulse test. For the analysis of TFH we will use data from the fan pressurisation method.

8.1.5. Airtightness testing

8.1.5.1. Fan pressurisation tests

A fan pressurisation test, commonly referred to as a blower door test, was performed to measure the air permeability value at 50 Pa (AP_{50}) and air change rate at 50 Pa (n_{50}). The test was undertaken in accordance with ATTMA Technical Standard L1 [14]. All intentional ventilation openings such as MVHR ducts, trickle vents, the cooker hood and wastewater services were sealed throughout the test programme.

Fan pressurisation test n_{50} values were used to derive n using the $n_{50}/20$ 'rule of thumb' [15]. The derivation includes the correction factor for dwelling shelter factor contained within SAP 2012 [7].

8.1.5.2. Pulse Test

A Pulse test [16] was performed using a portable compressed air-based system to measure the air leakage of a building at a near ambient pressure level of 4 Pa. In the UK, the system is a recognised air pressure testing methodology under both Part L1A building regulations. All intentional ventilation was sealed, as in the fan pressurization test.

8.1.6. In-situ heat flux and U-value measurement

For the U-value test, the chamber was set to 5 °C, the elements were evaluated for periods longer than 72 hours in accordance with ISO 9869 [17]. Unlike the coheating test, during the U-value test, no fans were used, only heaters.

The thermal transmittance of a building element (U-value) is defined in ISO 7345 [18] as the *"Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system"*. To account for thermal storage and release, ISO 9869-1 uses a cumulative moving average of the heat flow rate and ΔT to calculate in-situ U-values. However, steady state conditions at the Energy House 2.0 during TFH test allowed in-situ U-values to be calculated as defined by ISO 9869[17] using equation 3.

$$\boldsymbol{U} = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}(T_{ij} - T_{ej})} \qquad \text{Eq. 3}$$

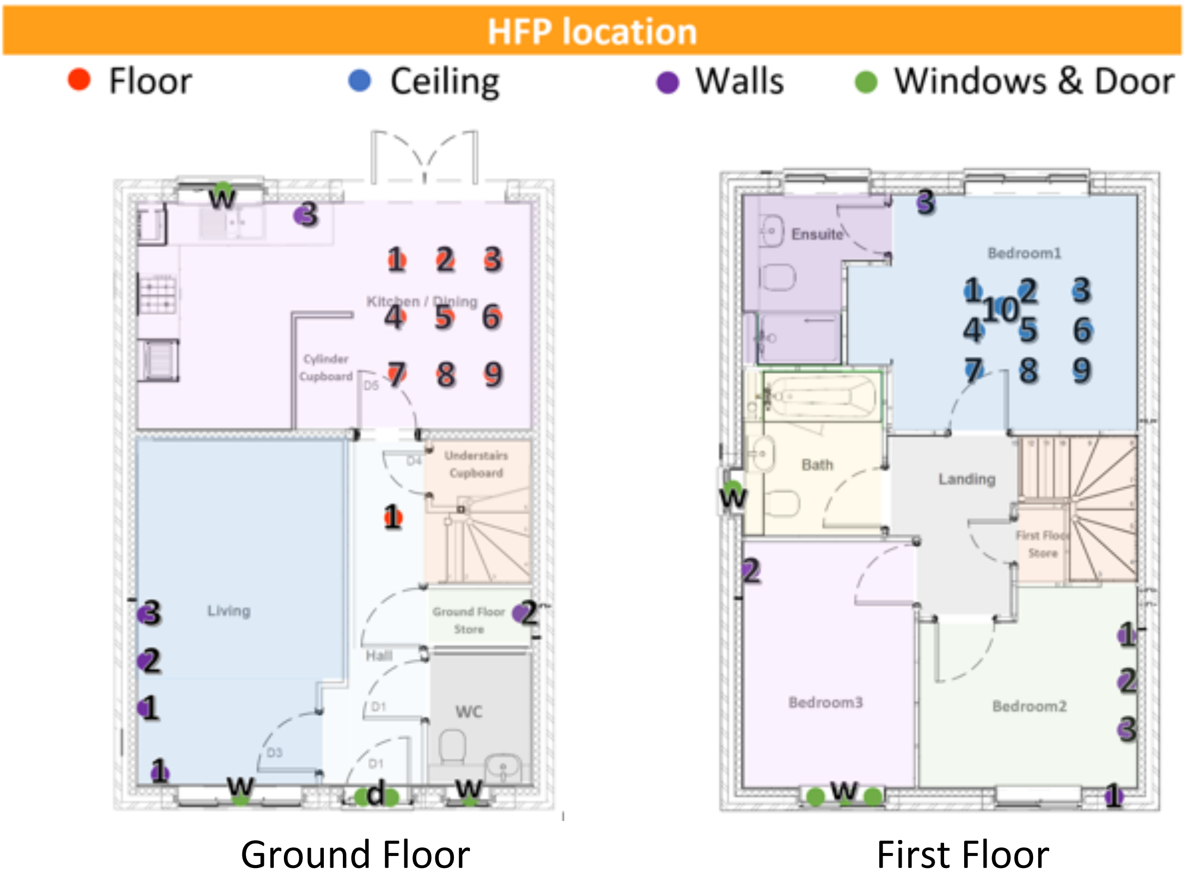
Where:
U = in-situ U-value (W/m^2K)[j]
q = mean heat flow rate (W/m^2)
T_i=indoor temperature (K)
T_e=chamber temperature (K)
j= enumeration of measurements[k]

[j] Refer to Annex D for details of the in-situ U-value uncertainty calculation
[k] Based on 10 min average

Measurements of heat flux density (heat flow rate), from which in-situ U-values were calculated, were taken at 57 locations on the external elements of TFH using heat flux plates (HFPs). Figure 13 shows the HFP location.

Heat flux plates (HFPs) used to measure in-situ U-values were positioned at the mid-point between repeating thermal bridges within an element (such as centre of timber frame panels) and at the location of repeating bridges (such as the studs of the timber frame). Thermography was used to identify these measurement locations to find areas representative of heat loss through bridged and unbridged heat loss paths through an element, which are shown in the Annex G.

HFPs were positioned in 3x3 grids for the ceiling, floor and external walls in locations considered to be representative of the whole element, it was also considered an extra measurement of the heat flux density of the timber frame studs, positioned with the aid of thermography. For the elements that are in the 3x3 grid, for the interior temperature, hygroVUE 10 sensors were used in the centre of the grid and for the individual elements on the floor, walls, windows and doors thermocouples were used.



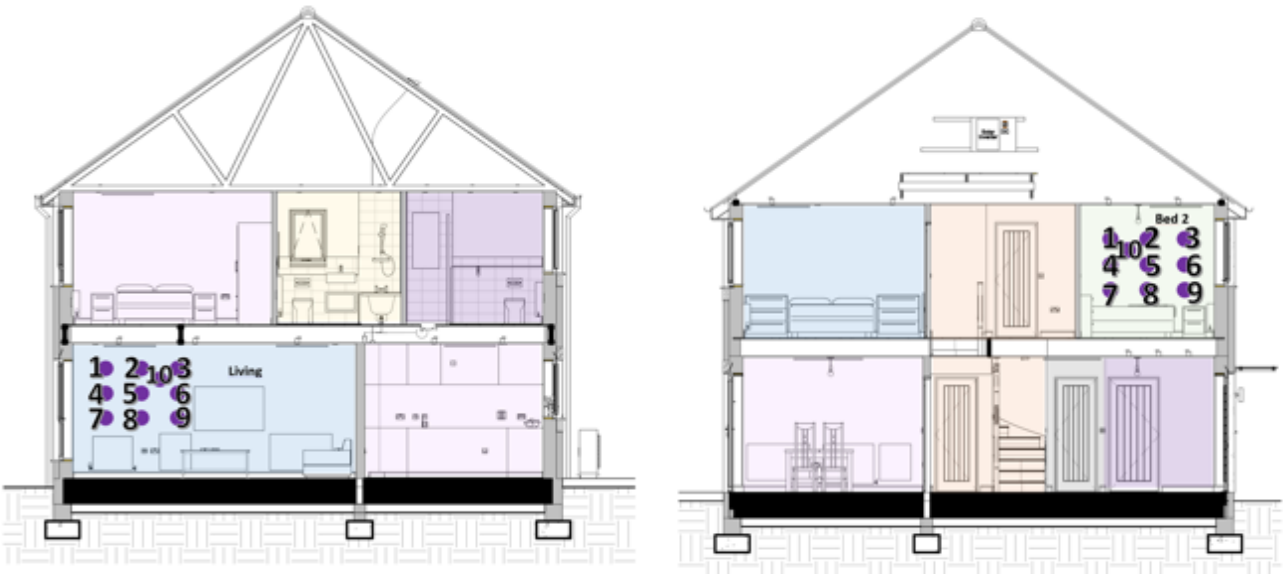
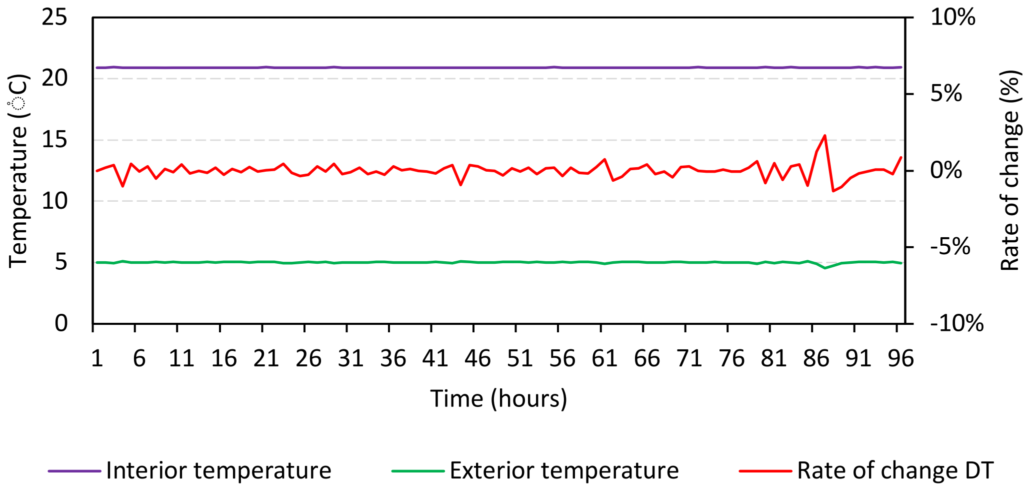


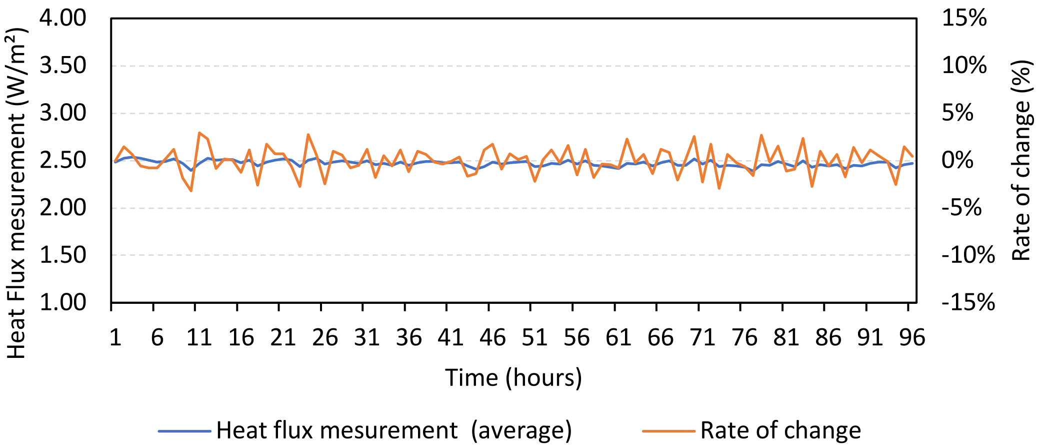
Figure 13. HFP location

The HFPs were fixed to surfaces using adhesive tape and thermal contact paste. The ΔT for each in-situ U-value measurement was calculated using the internal and external air temperature differential measured in the vicinity of each HFP.

Figure 14 (a) shows the indoor temperature, the chamber temperature, and the rate of change of the ΔT (T_i-T_e) for the living room. This illustrates that the indoor temperature does not present significant changes and the chamber temperature has a difference of up to 2.2% (~0.5 °C). Figure 14 (b) shows the rate of change of the average HFP measurement of the grid in the living room during the test. It is observed that steady state was reached for more than 95 hours, the rate of change per hour is less than 3% during the test. It is important to mention that all the measurements (temperature and heat flux) in the other elements had the same behaviour, with rates of change of less than 3% during the test.



(a) Temperature



(b) Heat Flux measurement

Figure 14. Steady state of Bedroom 2 measurements

8.2. Energy House 2.0 monitoring equipment

The findings provided in this report are based on measurements obtained using the equipment listed in Table 13. Measurements were recorded at one-minute intervals by the Energy House 2.0 monitoring system:

Table 13: Measurement equipment used in the Energy House TFH fabric performance tests. Equipment for novel methods pulse, QUB and Veritherm are not included in this table.

Measurement	Equipment	Uncertainty[l]
Electricity consumption	Siemens 7KT PAC1200 digital power meter[19]	±1%
Room air temperatures	hygroVUE 10 (20 to 60 °C) [20]	±0.1 °C
Chamber air temperatures	hygroVUE 10 (–40 to 70 °C) [20]	±0.2 °C
Internal air temperatures	Type-T thermocouple[m]	±0.1 °C
Heat flux density	Hukseflux HFP-01 heat flux plate[21]	±3%
Air permeability	Retrotec 5000 Blower Door System [n]	±2.5%[o]

9. Results

9.1. Measured HTC compared with predicted HTC

The coheating test was carried out for 8 days, the chamber temperature was set at 5 °C. Table 14 shows the average daily power (based on energy consumption), the average temperature difference for each of the test days and the daily and average measured HTC.

Table 14. Results of the HTC

DAY	Power (W)	ΔT (K)	HTC (W/K)[p]
1	1301.7	15.7	82.8 ±2.76
2	1298.0	15.8	82.4 ±2.85
3	1297.2	15.7	82.4 ±2.59
4	1291.9	15.8	82.0 ±2.78
5	1281.6	15.7	81.6 ±2.54
6	1289.3	15.7	82.0 ±2.69
7	1290.8	15.7	82.1 ±2.73
8	1288.5	15.7	82.0 ±2.63
Design HTC			**76.3**
Average HTC (set Te 5°C)			**82.2 ±1.77**

[l] uncertainties were taken from supplier data sheet
[m] Energy house 2.0 in house calibration process
[n] Certificate of calibration: UK_52369, UK_52343
[o] The sheltered test environment allows measurement uncertainty to exclude wind-based errors, the ± 2.5% uncertainty value applies only to test apparatus
[p] Refer to annex C to uncertainty calculation

Figure 15 shows the measurements for the HTC. To maintain an indoor temperature of 21 °C at a chamber temperature of 5 °C, an average daily power input of ~1300 W is needed, that reflects a steady HTC which indicates that to maintain a 1 K temperature difference over the building envelope 82 W of heating power is required.

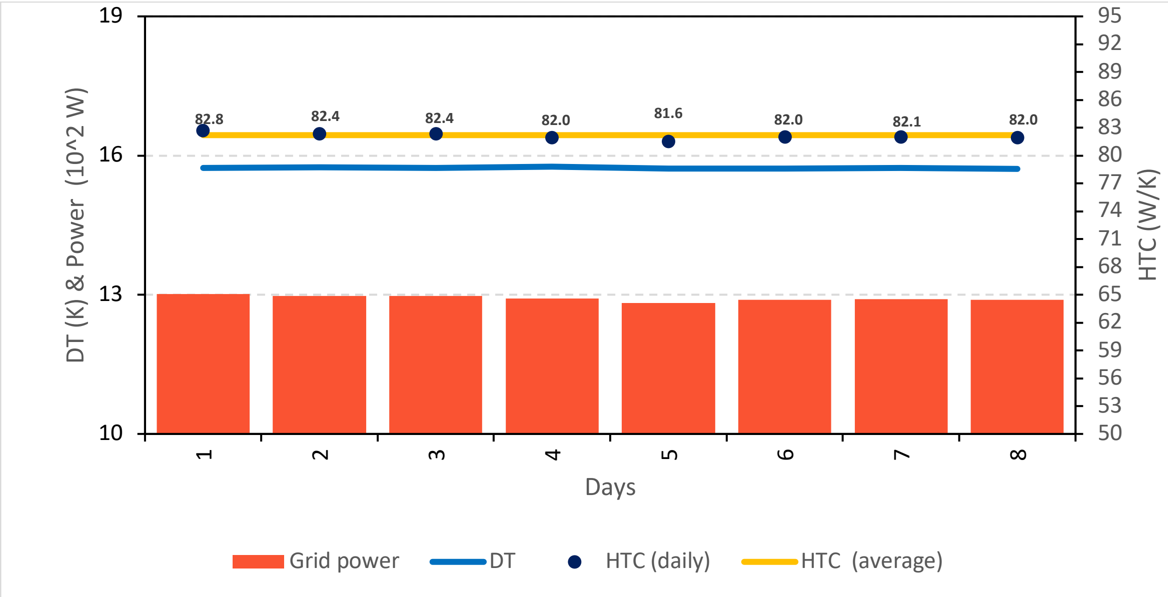


Figure 15. HTC results.

TFH has a design HTC of 76.3 W/K, which was extracted from the design model document (Annex A). This considers the total fabric heat loss and the infiltration heat loss. The final measured HTC using the coheating method was 82.1 (±1.8) W/K thus giving a performance gap of 5.9 W/K or 7.7%. This is higher than the level of uncertainty so suggests a performance gap issues, although minor in extent.

9.2. Alternative in-situ test methods

HTC measurements were performed using the Saint-Gobain QUB [12] and Veritherm test [13] methods. Veritherm and QUB visited TFH to carry out tests independent of the research team. These were carried out under the same environmental conditions as the coheating method, with a set point of 5 °C in the chamber, to allow for direct comparison. The results from the coheating and alternative HTC test methods can be found in Table 15 and Figure 16.

Table 15. HTCs measured using the coheating, QUB, and Veritherm tests

Coheating HTC (W/K)	QUB [q] HTC (W/K)	Veritherm[r] HTC (W/K)	QUB difference from coheating	Veritherm difference from coheating
82.2 ±1.77	76.5±6.1	85.6[s]	-7%	+4%

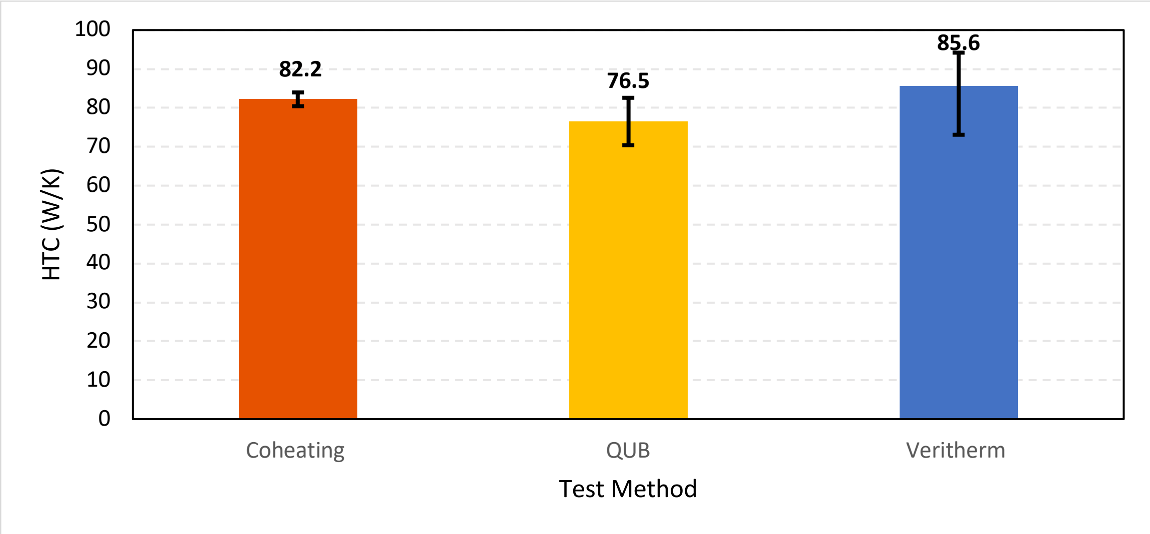


Figure 16: Comparison between HTCs measured using the coheating, QUB, and Veritherm tests

The HTCs measured by the alternative methods were generally in agreement with the coheating test HTCs, when measurement uncertainty is considered. Veritherm uncertainty is up to twice that of the QUB uncertainty. However, the HTC obtained by QUB is 7% lower than the coheating test and Veritherm result is 4% greater than the coheating test.

9.1. Airtightness and ventilation

Table 16 provides the AP_{50} value measured using the blower door and pulse test, the tests were carried out under the same conditions, 5 °C for the chamber temperature and 21 °C for the indoor temperature. All intentional ventilation openings such as MVHR ducts, trickle vents, the cooker hood and wastewater services were sealed throughout the test programme.

[q] Refer to Annex H
[r] Refer to Annex I
[s] Confidence level from 76.5 to 98.1 W/K

Table 16 - AP_{50}, n_{50}, and derived background ventilation rates and ventilation heat losses for TFH

Test	Air permeability [AP_{50}] ($m^3h^{-1}m^{-2}$ @ 50 Pa)	Air change rate [n_{50}] (ACH @ 50 Pa)	Infiltration rate [n] (h^{-1})	Infiltration heat loss (W/K)
Blower Door	4.00±0.04[t]	3.98	0.18	14.3
Pulse	3.25±0.13[u]	3.23	0.15	11.6
Design	**2.5**	**2.5**	**0.11**	**8.9**

Difference between test methods:

The main difference between the methods, is that the blower door fan test measures building air leakage by creating a positive or negative pressure differential across the building fabric of 50 pascals, while Pulse testing measures it at a lower pressure differential of 4 Pa created by a pulse of air delivered over a much shorter period.

The results between the test methods show a difference of 0.75 $m^3/(h/m^2)$ @ 50 Pa for the air permeability and 0.75 ACH for the air change rate. This represents a difference of 17% for the ventilation rate and 19% for the ventilation heat loss between the blower door and the pulse test.

Difference between design and as built.

If the measured ventilation heat loss is compared against the design value, there is a difference of 61% (5.4 W/K) and 30% (2.7 W/K) for the blower door and Pulse test respectively.

9.2. Thermography

An air infiltration investigation was performed on TFH following the depressurisation phase of the blower door test. A pressure differential of -50 Pa was maintained while a thermographic survey was undertaken. Areas of air infiltration are identifiable in the thermograms below as streak patterns and regions of cooler internal surfaces, indicating air movement behind plasterboard. The thermograms from Figure 17 to Figure 20 have the same temperature span, so locations of cooler air infiltration generally signify in a more pronounced and direct air paths.

[t] Refer to annex E
[u] Refer to annex F

All the figures show that the primary air infiltration paths identified were through the ceiling (Figure 17-Figure 20). Air infiltration was observed on the ceiling even without an artificially induced differential pressure.

The ceiling of the landing and stairs (Figure 19) had a significant number of air infiltration routes that increased during the depressurization process. This was significant, mainly affecting the internal partition wall (Figure 20). The thermography concurs with the airtightness tests which indicates a ventilation heat loss larger than the design value. This is mainly attributed to the wall to ceiling junctions and areas around the loft hatch.

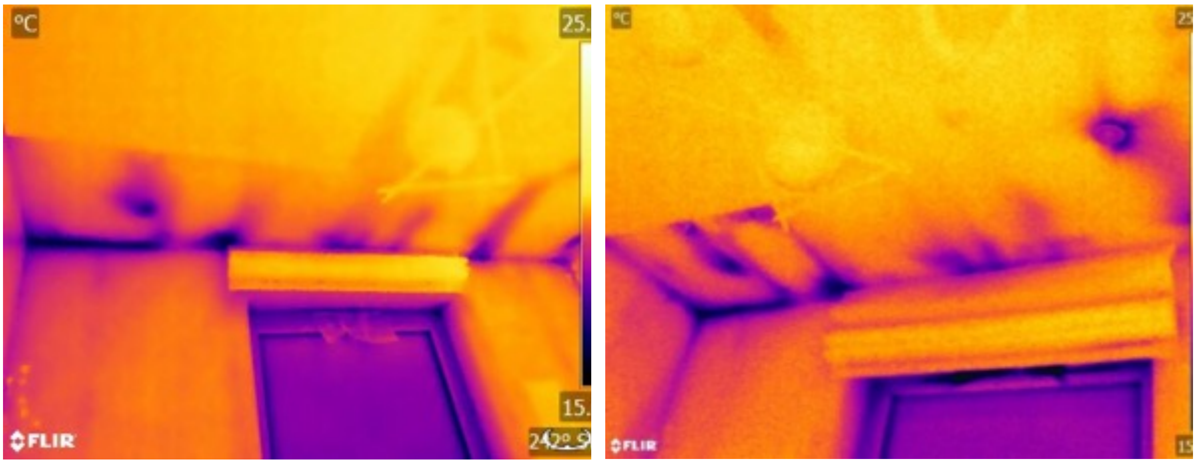


Figure 17. Bedroom 2 under no artificially induced pressure differential (left). During depressurisation (right) air infiltration visible along the ceiling and vents. This effect has been exaggerated by inadequate placement of loft insulation above the ceiling.

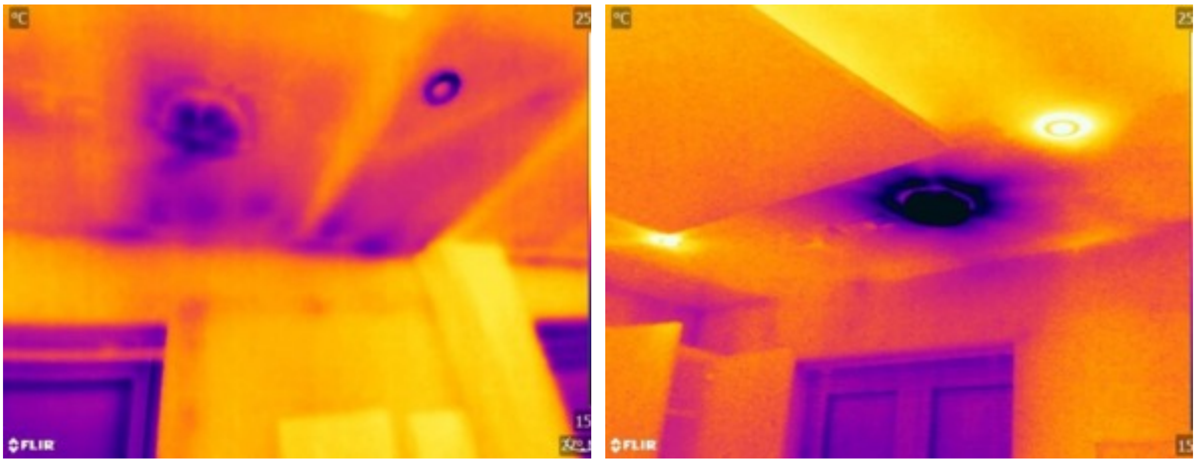


Figure 18. Kitchen under no artificially induced pressure differential (left). During depressurisation (right) air infiltration visible within intermediate floor void and entering the habitable space through the area surrounding the sealed vent.

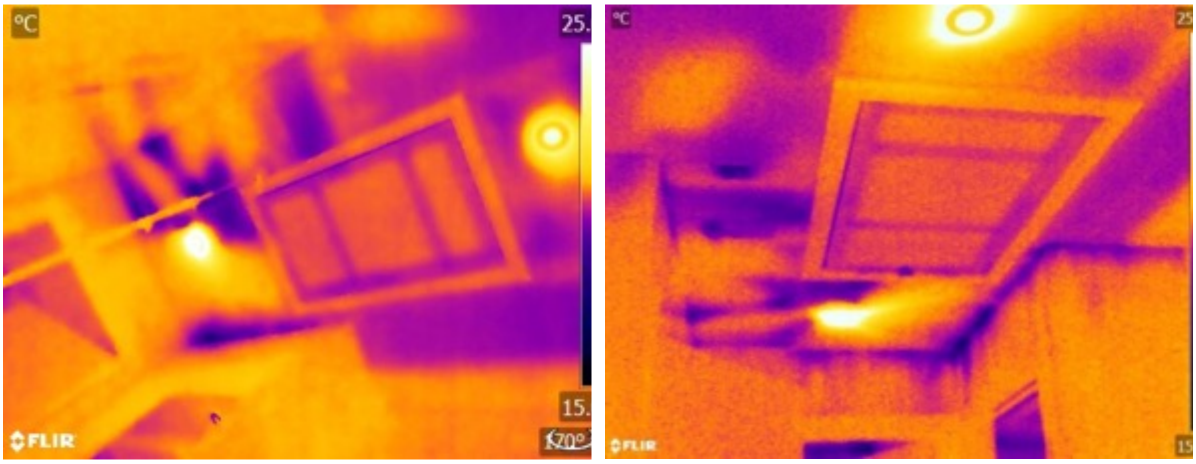


Figure 19. Landing under no artificially induced pressure differential (left). During depressurisation (right) highlighting air leakage pathway between partition walls and loft space.

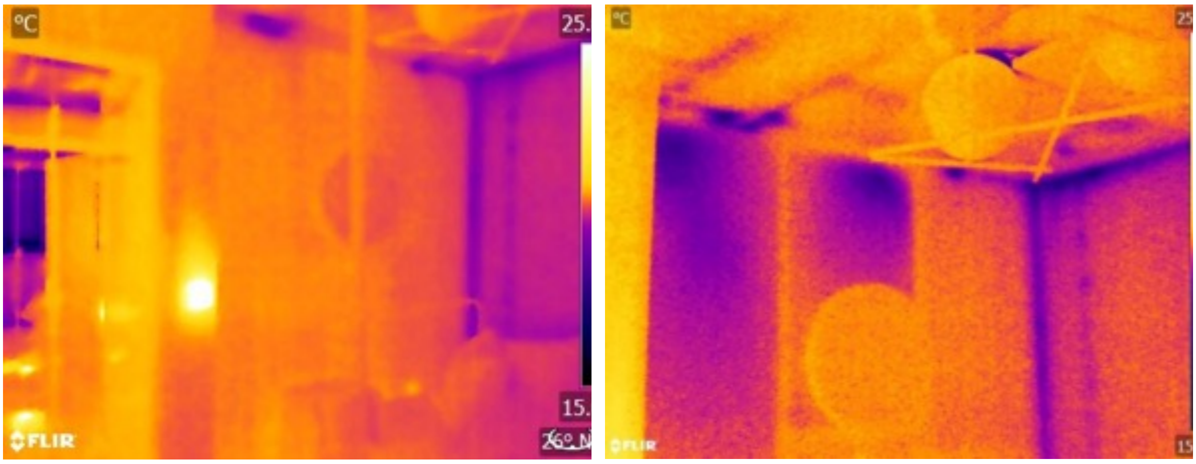


Figure 20. Bedroom 2 under no artificially induced pressure differential (left). During depressurisation (right) air infiltration path visible from the loft space into the internal partition walls.

9.3. In-situ U-value measurement

In-situ U-value measurements were undertaken on selected thermal elements in TFH in accordance with ISO 9869 [17] . Measurements were used to assess whether elements achieved the design level of thermal performance, these were compared with elemental design U-values.

Table 17 summarizes the results of the in-situ U-value measurements and compares them to the design U-value for each measured heating element. The detail of the calculation of the U-values for each of the elements in-situ can be found in the following section.

Table 17. Locations and design U-values

Element	Measurement locations	Design U-value (W/m^{2}K)
Door (front) body &window	2	1.00
Windows	7	1.20
Floor (ground floor)	10	0.11
External Walls (25 mm service zone)	16	0.18
External Walls (38 mm service zone)	9	0.18
External Walls Rendered	1	0.17
External Walls (Timber Stud)	2	
Ceiling	9	0.09
Ceiling (Timber Stud)	1	

Note on U-values measured in chamber conditions:

BS EN ISO 6946:2017 (simplified method) states that the external surface layer of insulation for a wall element, has assumed wind speed of 4 m/s. This allows for wind to be considered when comparing buildings in-situ to designs. However, the chamber environment found at Energy House 2.0 does not impose these wind loads as standard, although they can be if required. However, in a chamber environment, well distributed laminar flow, which is consistent across each façade is difficult to replicate.

The air velocity has been mapped for each square metre of wall of TFH, with an average velocity of 0.25 m/s, with variations ranging from 0 to 1.2 m/s, further details can be found in Annex L. Calculation of U-value with different R_{se}

We have presented the results here as raw and unadjusted results, which do not account for this discrepancy although this is likely to represent a minor difference of around 1% across a typical wall value of TFH.

9.3.1. External Walls

In situ U-value measurements of the external walls were taken at 26 locations between the timber frame members and at two locations on the timber stud. These were distributed as follows: two 3x3 grids placed in the living room (Figure 21) and Bedroom 2 (Figure 22), an extra location was also placed in each grid to measure the timber stud components. The other six sensors were located on the remaining exterior walls to take spot measurements, three on the ground floor and three on the first floor as in Figure 13.

Note on U-value measurement adjacent to corners:
It should be noted that although measurements taken in both the Living room and the bedroom are adjacent to the wall corners, we do not believe that they are affected by any thermal bridging issues; the thermal imaging and the U-value measurements (Figure 21, Figure 22 and Figure 25) confirm this. They are 750 mm and 600 mm from the corner point of living and bedroom 2 wall, respectively.

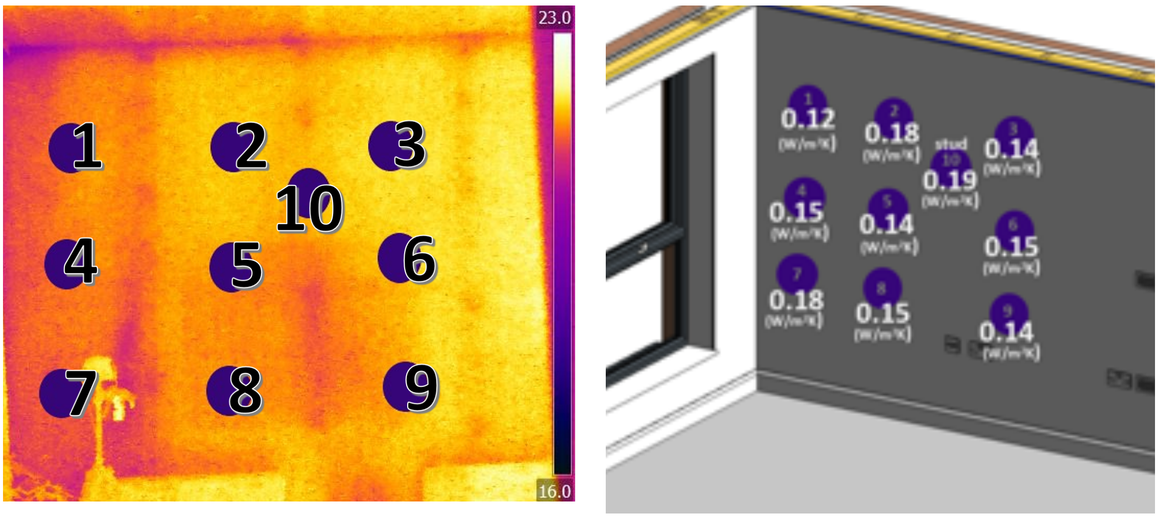


Figure 21. Living room results (U-value)

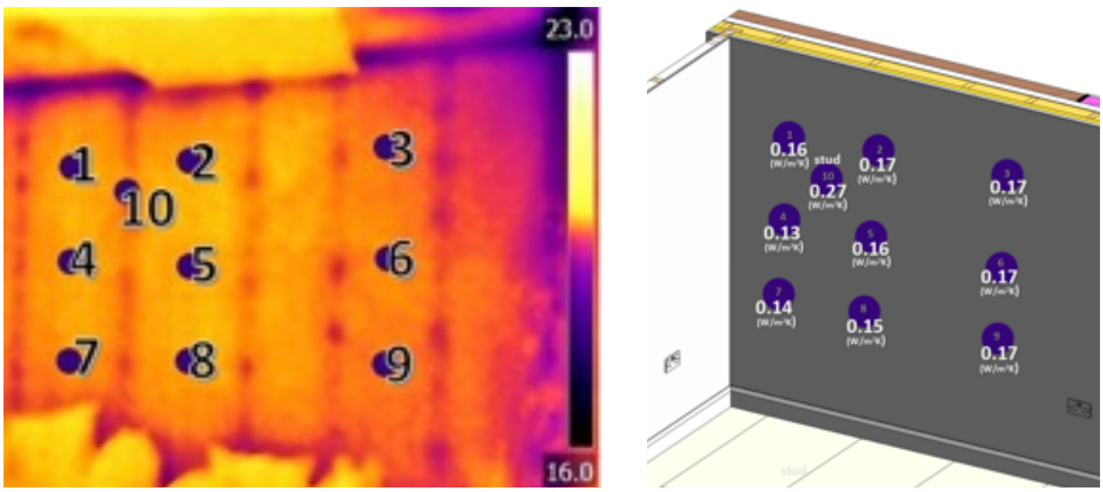


Figure 22. Bedroom 2 (U-value)

Table 18 shows the average U-values for each of the measurements. These values were obtained using a weighted average considering 15% of the values obtained from the timber stud U-value of 0.21 W/m^{2}K as a timber fraction as described in BR443 [23]. The U-value obtained for Wall 1 (located on the first floor as in Figure 13) is measuring the rendered wall. Its value was not considered for the average of the brick walls.

Table 18. In-situ U-values for External Walls

HFP	Ground Floor Measured U-value (W/m^2K)	First Floor Measured U-value (W/m^2K)
1	0.12±0.02[v]	0.16±0.02
2	0.18±0.02[r]	0.17±0.02
3	0.14±0.02[r]	0.17±0.02
4	0.15±0.02[r]	0.13±0.02
5	0.14±0.02[r]	0.16±0.02
6	0.15±0.02[r]	0.17±0.02
7	0.18±0.02[r]	0.14±0.02
8	0.15±0.02[r]	0.15±0.02
9	0.14±0.02[r]	0.17±0.02
Wall 1	0.11±0.03	0.16±0.04[w]
Wall 2	0.17±0.02	0.17±0.02
Wall 3	0.19±0.02	0.16±0.02
10 (Timber Stud)	0.21±0.03	0.27±0.02

	Brick wall (Service zone 25 mm)	Brick wall (Service zone 38 mm)	Rendered wall
Measured U-value Average(W/m^2K)[x]	0.17±0.02	0.17±0.02	0.17±0.05
Design (W/m^2K)	0.18	0.18	0.17
Difference to design (W/m^2K)	-0.01	-0.01	0.0
Difference to design (%)	-6%	-6%	0.0%

There was little difference between the averaged U-values and those provided in the design, a difference of only 0.01 W/m^2K, which is within the range of the measurement uncertainty. As such, this wall would be deemed as performing in line with the design.

9.3.2. Roof

In situ U-value measurements of the roof were taken at 9 locations between the timber frame and at one location on the timber joist component. Figure 23 shows the location and the

[v] Brick Wall- Service Zone 38 mm
[w] Render wall
[x] Using weighted average using 15% of the timber frame stud

results of the HFP and U-values. The average U-values calculated for the ceiling regions are 0.11 W/m^{2}K and 0.30 W/m^{2}K for the ceiling centre panel and the timber joist component, respectively.

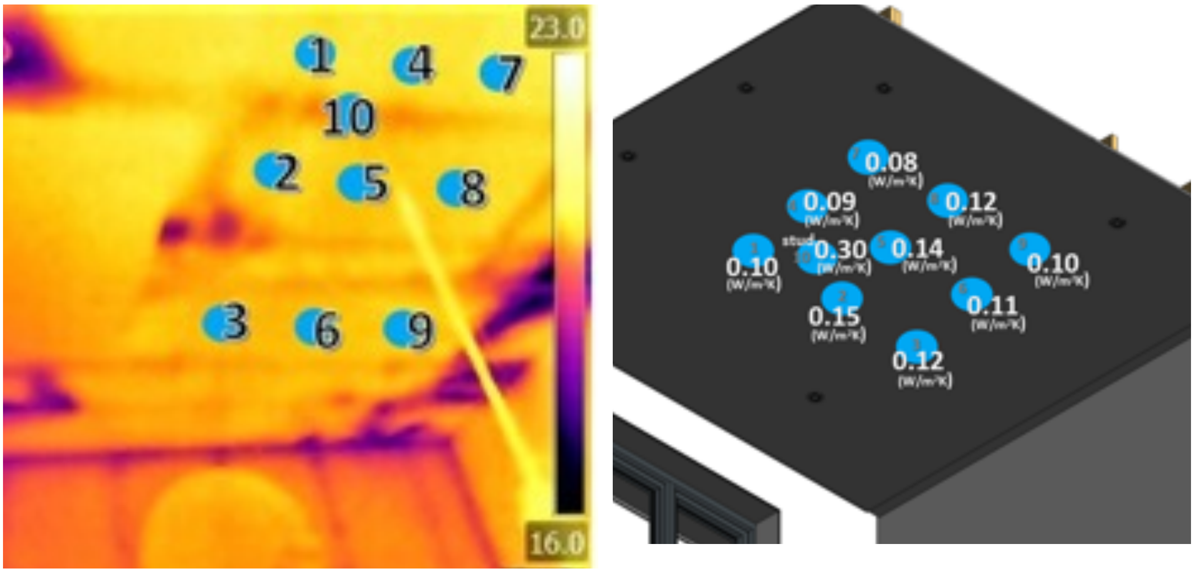


Figure 23. Main bedroom ceiling results (u-value)

Table 19 shows the results of the U-values calculated for each of the measurements. The average U-value of the ceiling (0.14 W/m^{2}K) has a difference of 0.05 W/m^{2}K compared to the design U-value (0.09 W/m^{2}K). A weighted average was used considering a 15% timber fraction with the U-value obtained for the timber joist component.

Table 19. In-situ U-values for Ceiling

HFP	Measured U-value (W/m^{2}K)
1	0.10±0.01
2	0.15±0.02
3	0.12±0.02
4	0.09±0.01
5	0.14±0.02
6	0.11±0.01
7	0.08±0.01
8	0.12±0.02
9	0.10±0.01
10(Timber joist)	0.30±0.04

Measured U-value Average(W/m²K)	0.14± 0.03[y]
Design(W/m²K)	0.09
Difference to design (W/m²K)	0.05
Difference to design (%)	+55.6%

The ceiling is underperforming, and this is outside of the margin of error of the measurement, so it is significant. Several issues were found in the ceiling insulation, such as disturbance, non-homogeneity, and non-uniform thickness across the loft zone. There were also some assumed areas of air infiltration identified by the thermographic images. This is found in section 9.2. Some defects were difficult to identify as around 50% of the loft has decking installed making direct observation difficult at this stage of the research.

9.3.3. Ground Floor

Note on U-value measurement of floors:

There is no standardised methodology for the in-situ measurement of floor U-values. As such, this next section will present the "**point thermal transmittance**" of the floor of TFH.

There is no single point on a floor which will provide an representative match with designed U-value [2]. Floor U-value design calculations consider several different variables which are difficult to capture with in-situ measurements, these include:

- Buffering effect of the ground
- Exposed perimeter of the floor
- Ratio of perimeter to area

Given these facts, the authors feel that whilst these "**point thermal transmittance**" (PTT) are indicative, they should not be directly compared to floor design U-values as this could be misleading.

In situ "point thermal transmittance" measurements of the floor were taken at 10 locations, nine distributed on a 3x3 grid in the Kitchen (Figure 24) and one located in the Hall. The HFPs 1,2,3,6 and 9 are closer to the exterior walls and has a higher value compared to those closest to the centre of the room.

[y] Using weighted average using 15% of the timber frame stud

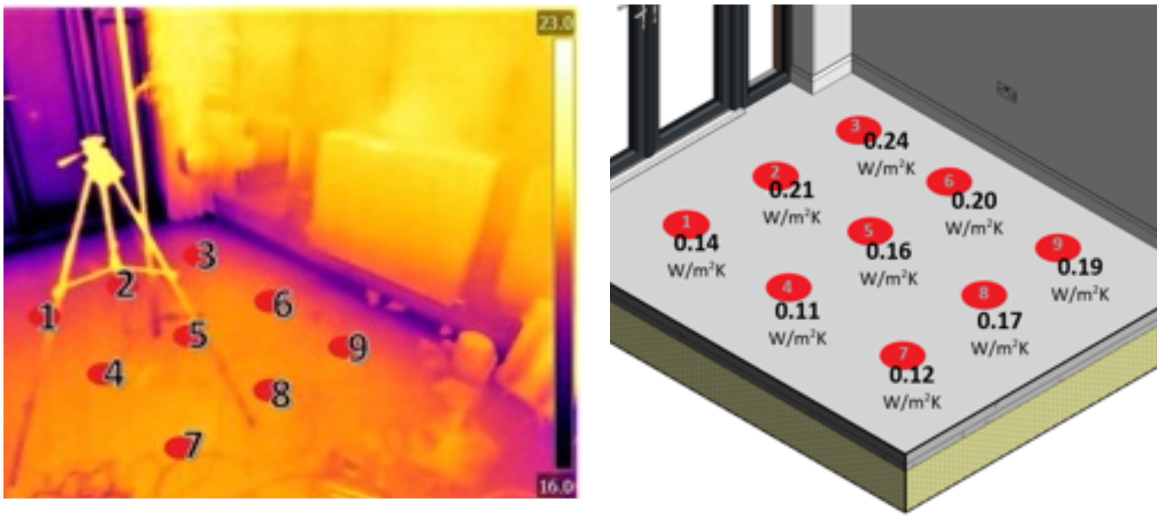


Figure 24. Kitchen Floor Results (U-value)

Table 20. In-situ PTT for the floor

HFP	Measured PTT (W/m^{2}K)
1	0.14±0.02
2	0.21±0.03
3	0.24±0.03
4	0.11±0.02
5	0.16±0.02
6	0.20±0.03
7	0.12±0.02
8	0.17±0.02
9	0.19±0.03
Hall	0.15±0.02
Measured PTT Range (W/m^{2}K)	**0.11-0.24**
Design U-value (W/m^{2}K)	**0.11**

When we consider the range of PTT shown in Table 20, it can be seen the design value falls within the measurement range. This range can be explained by the placement of sensors being affected by thermal bridging, ventilation to the floor and the unique nature and complex geometry of the NuSpan floor, which has varying resistance across its profile. As we have previously stated, there is no collection of PTT points which would align with the design U-value of *any* suspended floor.

It is worth noting that the **Hall PTT** is a singular measurement which may be influenced by a section of the slab which was specifically designed to support the newel post and stair structure.

9.3.4. Windows and Door

UoS were not provided with specific U-value design calculations for the windows or doors of TFH, as such we have used in SAP document (Annex A). BFRC (Annex B) provides the value of the centre pane of the window.

In situ measurements of the centre pane of the windows were taken at seven locations on the windows: Three locations on Bedroom 3 window (Figure 25), another four in the locations shown in the Figure 13, and at two locations on the door (Figure 26), one on the main body and one on the door glazing.

Figure 25. Bedroom 3 window results (centre pane)

The average U-value measured for the centre pane of the windows is 1.09 W/m^{2}K (Table 21) which agrees with the centre pane design value of 1.07[z] W/m^{2}K with a difference of up to 2% between them. If the uncertainty (±0.15 W/m^{2}K) is considered, this is higher than the difference between the design value and the measured value (0.02 W/m^{2}K), so in the case of windows it is considered that the measured U-value agrees with the design U-value.

[z] Refer to annex B

Table 21. In-situ centre pane for the Windows.

HFP	Measured centre pane (W/m^{2}K)
Dining	1.11±0.15
Living	1.19±0.16
WC	1.08±0.15
Bath	1.02±0.14
Bedroom 3 _Centre	1.07±0.14
Measured centre pane Average(W/m^{2}K)	**1.09±0.15**
Design centre pane (W/m^{2}K) [v]	**1.07**
Difference to design (W/m^{2}K)	**0.02**
Difference to design (%)	**+1.9%**

Table 22 shows the data of the U-values of the door elements (body and window) for each of the measurements. These are illustrated in Figure 26. The design U-value is 1 W/m^{2}K[aa], if the average of the measured elements is considered (1.04 W/m^{2}K) then we consider the door to achieving its designed U-value.

Figure 26. Door Results (centre pane)

[aa] Refer to annex B

Table 22. In-situ centre pane for the Door.

HFP	Measured U-value centre pane (W/m^2K)
Body	0.61±0.08
Window	1.48±0.20
Weighted Average	**0.71±0.09**
Design U-value (W/m^2K) [w]	**1.0**
Difference to design Weighted Average(W/m^2K)	**-0.29**
Difference to design Weighted Average (%)	**-29%**

Overall, it is quite difficult to assign a figure to the window and door performance that can be used to directly compare with the design performance. Firstly, we did not have the actual window design figure, which would generally detail the thermal performance of the frame and glazed element separately. We have a BFRC and SAP value, however these are generally for a typically sized windows and not specific to the TFH. If we consider only centre pane values then the data suggests that window as a whole appeared to meet the design U-value.

9.4. Performance gap

This section will focus on the whole house performance gap highlighted in Section 9.4. A minor performance gap was found in TFH, which will be quantified in this section, but a more detailed building pathology report will be prepared. This will use some more in-depth testing methods to identify specific intervention points and will assist Bellway in improving the fabric of the home and reduce the performance gap.

9.4.5. Element breakdown

Table 23 shows the results of the HTC of the fabric calculation, in which three HTC values are compared, the first is the design HTC (76.3 W/K), the second is the HTC obtained using the measured U-values and measured infiltration heat loss (84.3 W/K) and the third HTC obtained in the coheating test (82.2 W/K).

The difference between the second and third HTC is 2.1 W/K. This difference may be due to the uncertainties related to the measured values and potential discrepancies between calculated and as-built thermal bridging heat losses. It is important to mention that in the case of the HTC obtained from the U values, the uncertainties of the windows and doors were not considered, as there was not enough data to obtain the measured U-value of each element (only centre pane was measured). However, both tests broadly agree with the value of the HTC.

Table 23. Performance gap

Element	Area (m^2)	Design U-value (W/m^2K)	Design Heat loss (W/K)	As-built U-value (W/m^2K)	As-built Heat loss (W/K)
Doors (front door)	2.15	1.00	2.15	1.00[bb]	2.15
Windows	12.96	1.20	16.85	1.20[bb]	16.85
Floor	46.41	0.11	5.11	0.14±0.02[cc]	6.50
External Walls (25 mm service zone)	87.88	0.18	15.82	0.17±0.03	14.93
External Walls (38 mm service zone)	19.38	0.18	3.49	0.17±0.03	3.29
External Walls rendered	13.77	0.17	2.34	0.17±0.05	2.34
Ceiling	46.41	0.09	4.18	0.14±0.03	6.50
Patio Doors	4.98	1.30	6.97	1.3[bb]	6.97
Plane element heat loss (W/K)		55.1		57.7	
Thermal bridging heat loss (W/K)		12.3		12.3[dd]	
Total fabric heat loss (W/K)		67.4		70.0	
Ventilation heat loss (W/K)		14.3		14.3	
HTC (design) (W/K)				76.3	
HTC (measured fabric and measured infiltration) (from U-value) (W/K)				84.3	
HTC coheating (W/K)				82.2±1.8	
Difference fabric performance gap (W/K) (U-value vs coheating)				2.1	
Gap				**Absolute (W/K)**	**%**
Design fabric and infiltration performance gap				5.9	7.7%
Fabric performance gap				0.5	1%
Infiltration performance gap				5.4[ee]	61%
Contribution to design and fabric performance gap					
Fabric performance gap contribution				9%	
Infiltration performance gap contribution				91%	

[bb] Design values are considered for windows, front and patio doors, because there is not enough data for the calculation (only centre pane).

[cc] For plane element analysis, it was necessary for a measured in-situ "U-value" to be calculated. For this, the measurements of HFP 4,5,7 and 8 were considered for the average. The average U-value calculated for the floor region is 0.14 W/m^2K. ***This is not a U-value which can be compared to a design figure.***

[dd] Assumed design value used in "As-built" heat loss calculation

[ee] Refer to Table 16 to see results of the blower door test

The HTC obtained in the coheating test 82.2±1.8 W/K shows a design fabric and infiltration performance gap of 5.9 W/K (7.7 %). Figure 27 shows a gap of 0.5 W/K due to fabric performance and 5.4 W/K due to infiltration performance. The fabric performance gap is 1 % which indicates a good performance of the fabric. However, in case of infiltration performance gap performance represents 61% higher than the design infiltration value. Of the 5.9 W/K gap, 9% is due to the fabric and 91 % to infiltration, indicating conductivity over performance is undermined by a lower performance in terms of airtightness.

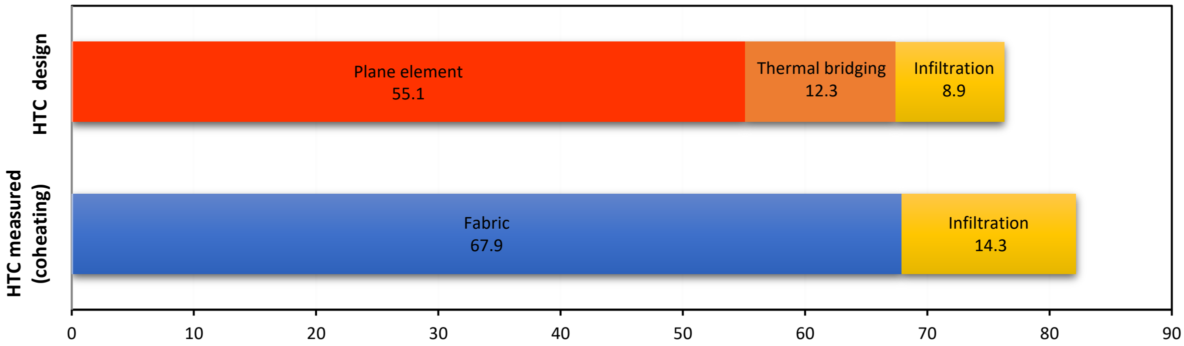


Figure 27. HTC design vs measured.

If the design plane element is compared to the plane elements obtained with the U value measurement, it shows that in the design, the openings represent 43.9% of the heat loss, the walls 39.3%, ceilings 9.3% and the floor 7.6%. However, in the measurements, the openings represent 41.9%, the walls 35.6%, the floor 11.2% and the ceiling 11.2%.

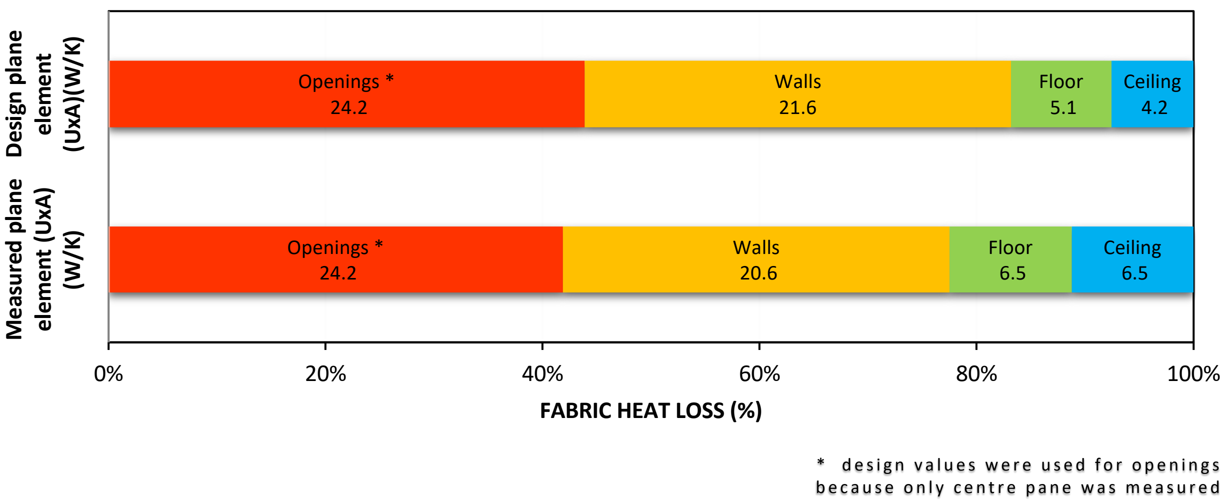


Figure 28. Fabric Heat Loss by components

9.4.6. Different test methods

Figure 29 compares the HTC obtained by the different methods with the design HTC. The performance gap measured by the coheating test is 7.7%, 0.3% by QUB and 12.2% by Veritherm.

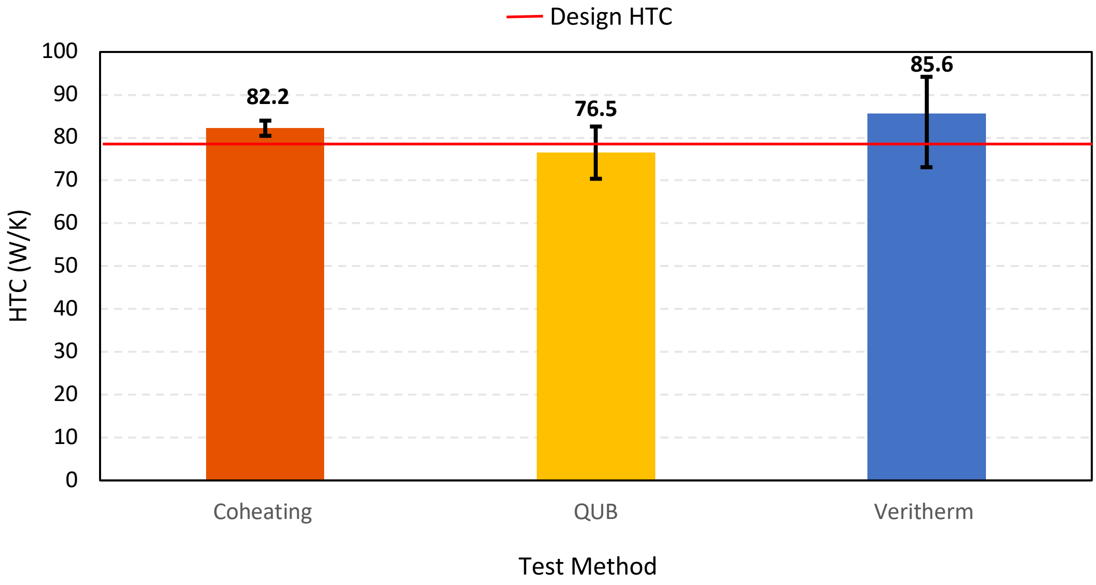


Figure 29. HTC obtained from each test method.

9.4.7. As-built SAP assessment

UoS were provided with the as designed SAP file (xml). This file was manipulated in the following way, to achieve an as-built HTC:

- Inserted the as-built air permeability test result (section 37)
- Manipulated the U-values to give us an as-built plane element fabric heat loss value.

The output files were then generated to produce the results as shown in Table 24. This helps to contextualise the performance gap, utilising the assumptions and normalised process found within SAP.

Table 24. Performance Gap as obtained from the Design and As-Built SAP assessments.

	Design	As Built	Difference
CO_2 (t/yr)	-0.20	-0.19	0.01
Primary Energy Use (kWh/m^2/yr)	-14.0	-13.0	1.00
SAP Rating	108 (A)	107 (A)	1
Dwelling Fabric Energy Efficiency (kWh/m^2/yr)	39.54	43.08	3.54

As shown in Table 24, the performance gap does have an effect on the running cost of TFH, with the house consuming an additional 1 kWh/m^2/yr to run as a result of the underperformance. If we then consider CO_2 emissions, then there is an additional 0.01 tonnes per year.

10. Summary

Overall, the fabric of TFH performed well, with the in-situ measurement of most building elements being in-line with the design performance in terms the heat loss through the fabric by conduction and radiation. This was assumed to be influenced by the installation of a continuous line of PIR insulation that internally envelops TFH. This allows for thermal bridging to be less pronounced than may be seen on a traditional closed panel timber framed system. However, TFH still does have a performance gap of 7.7%, which is outside of our margin of measurement error (±2.2%) and therefore indicative of a measurable gap. This is entirely due to infiltration heat loss, which is 61% higher than the design figure. In terms of energy modelling, the Dwelling Fabric Energy Efficiency (DFEE) has a 3.54 kWh/m^2/yr increase, according to SAP.

Figure 30 shows how the percentage performance gap of TFH compares to that of other newbuild properties from the Leeds Beckett University (LBU) coheating database [1], which is the largest published dataset of coheating tests conducted on new build properties. The TFH performance gap of 7.7% is below that of 28 of the new build dwellings tested by LBU prior to 2015. It should be noted that the measurement of TFH was conducted under controlled conditions, whereas the work carried out by LBU was conducted in the field.

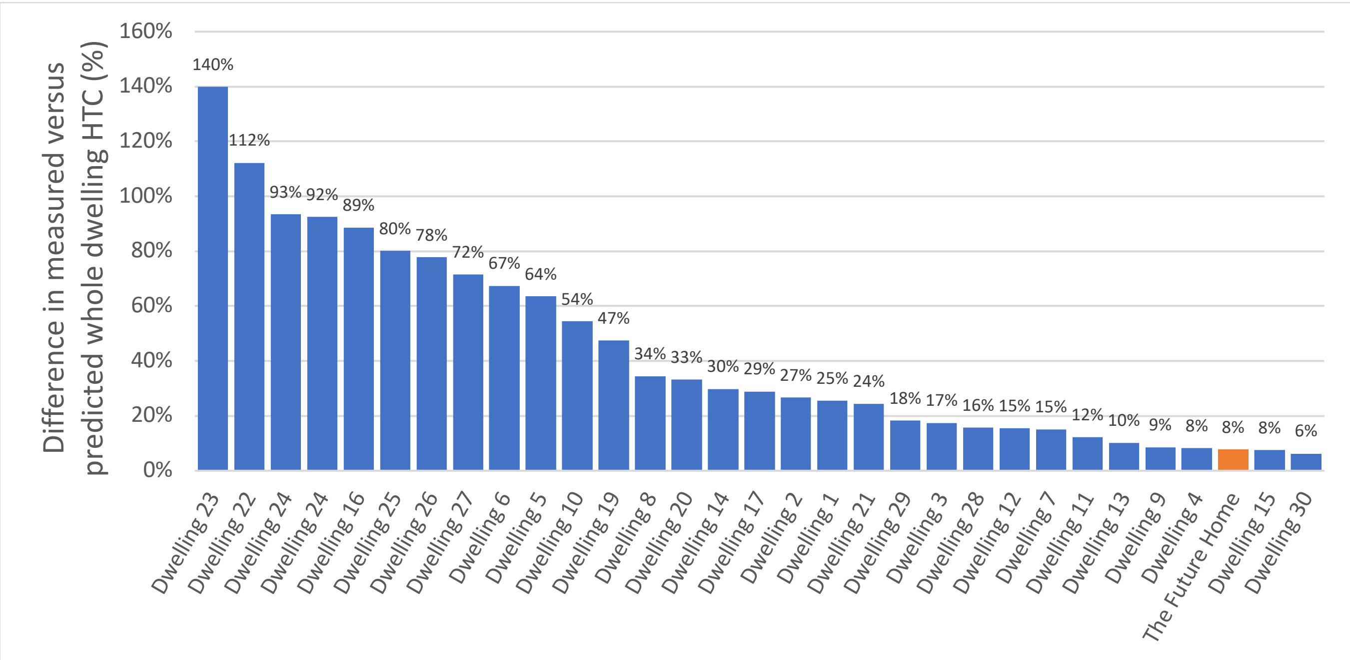


Figure 30. Difference in measured HTC of the predicted steady state HTC of the Leeds Beckett University coheating database (newbuild homes) **(as a percentage)**, including TFH performance gap.

There are some reasons why this infiltration heat loss gap may occur; firstly, TFH is a prototype building. The approaches and techniques in the design and delivery of the building were new to the developer. Secondly, when a building is studied in this amount of detail, many additional penetrations, sockets, and openings in the fabric exist, which may not be present in a house built on a normal construction site, presenting many issues in terms of infiltration.

Further work will involve further investigation of the loft space, particularly focusing on the direct leakage paths and air movement to the internal partition walls, as observed under the depressurization tests, and improper placement of insulation leading to cold bridges, visible in the thermography. A further thermography report will include a more in-depth study of this air leakage, expanding on the issues highlighted in section 9.2.

11. Annex A – SAP (design)

Summary for Input Data

elmhurst energy

Property Reference	BELLWAY AUDITED NOV2	Issued on Date	01/12/2023
Assessment Reference	BELLWAY AUDITED NOV2	Prop Type Ref	Coppersmith EH2.0
Property	BELLWAY, BELLWAY, BELLWAY, BELLWAY, BELLWAY, BELLWAY		

SAP Rating	108 A	DER	-2.28	TER	11.67
Environmental	102 A	% DER < TER			119.54
CO_2 Emissions (t/year)	-0.21	DFEE	39.54	TFEE	41.31
Compliance Check	See BREL	% DFEE < TFEE			4.29
% DPER < TPER	124.09	DPER	-14.68	TPER	60.94

Assessor Details	Dr. Richard Fitton	Assessor ID	AP51-0001
Client	BELLWAY, BELLWAY		

SUMMARY FOR INPUT DATA FOR: New Build (As Designed)

Orientation	South
Property Tenture	ND
Transaction Type	6
Terrain Type	Urban
1.0 Property Type	House, Detached
2.0 Number of Storeys	2
3.0 Date Built	2020
4.0 Sheltered Sides	1
5.0 Sunlight/Shade	Average or unknown
6.0 Thermal Mass Parameter	Precise calculation
7.0 Electricity Tariff	Standard
Smart electricity meter fitted	No
Smart gas meter fitted	No

7.0 Measurements

	Heat Loss Perimeter	Internal Floor Area	Average Storey Height
Ground floor:	27.78 m	46.41 m²	2.39 m
1st Storey:	27.78 m	46.41 m²	2.69 m

8.0 Living Area 14.99 m²

9.0 External Walls

	Description	Type	Construction	U-Value (W/m²K)	Kappa (kJ/m²K)	Gross Area(m²)	Nett Area (m²)	Shelter Res	Shelter	Openings	Area Calculation Type
6	BRICK Clad timber frame	Timber Frame	Timber framed wall (one layer of plasterboard)	0.18	9.00	122.98	107.26	0.00	None	15.72	Calculate Wall Area
7	External Wall 2 Render	Timber Frame	Timber framed wall (one layer of plasterboard)	0.17	9.00	18.14	13.77	0.00	None	4.37	Enter Gross Area

9.2 Internal Walls

Description	Construction	Kappa (kJ/m²K)	Area (m²)
Internal Wall 1	Plasterboard on timber frame	9.00	222.00

10.0 External Roofs

	Description	Type	Construction	U-Value (W/m²K)	Kappa (kJ/m²K)	Gross Area(m²)	Nett Area (m²)	Shelter Code	Shelter Factor	Calculation Type	Openings
8	External Roof 1	External Plane Roof	Plasterboard, insulated at ceiling level	0.09	9.00	46.41	46.41	None	0.00	Calculate Wall Area	0.00

10.2 Internal Ceilings

Description	Storey	Construction	Area (m²)
Internal Ceiling 1	Lowest occupied	Plasterboard ceiling, carpeted chipboard floor	46.41

11.0 Heat Loss Floors

	Description	Type	Storey Index	Construction	U-Value (W/m²K)	Shelter Code	Shelter Factor	Kappa (kJ/m²K)	Area (m²)
5	Heat Loss Floor 1	Ground Floor - Solid	Lowest occupied	Suspended concrete floor, carpeted	0.11	None	0.00	75.00	46.41

11.2 Internal Floors

Description	Storey Index	Construction	Kappa (kJ/m²K)	Area (m²)
Internal Floor 1		Plasterboard ceiling, carpeted chipboard floor	9.00	46.41

12.0 Opening Types

Summary for Input Data

elmhurst energy

	Description	Data Source	Type	Glazing	Glazing Gap	Filling Type	G-value	Frame Type	Frame Factor	U Value (W/m²K)
2	Windows	BFRC, BSI or CERTASS data	Window	Double glazed			0.32			1.20
3	Front Door	Manufacturer	Solid Door							1.00
4	French Doors	Manufacturer	Window	Double glazed			0.71		0.70	1.30

13.0 Openings

Name	Opening Type	Location	Orientation	Area (m²)	Pitch
Front Door	Front Door	External Wall 2 Render	South	2.15	
Front Windows	Windows	BRICK Clad timber frame	South	5.04	
Rear Windows	Windows	BRICK Clad timber frame	North	4.98	
French	French Doors	BRICK Clad timber frame	North	4.98	
Left	Windows	BRICK Clad timber frame	West	0.72	
Front Windows W2	Windows	External Wall 2 Render	South	2.22	

14.0 Conservatory	None	
15.0 Draught Proofing	100	%
16.0 Draught Lobby	No	

17.0 Thermal Bridging — Calculate Bridges

17.1 List of Bridges

Bridge Type	Source Type	Length	Psi	Adjusted	Reference:	Imported
E2 Other lintels (including other steel lintels)	Independently assessed	13.40	0.05	0.05	NRG	No
E3 Sill	Independently assessed	9.99	0.03	0.03	NRG	No
E4 Jamb	Independently assessed	28.35	0.05	0.05	NRG	No
E5 Ground floor (normal)	Independently assessed	27.80	0.19	0.19	NUSPAN	No
E6 Intermediate floor within a dwelling	Independently assessed	27.80	0.06	0.06	NRG	No
E10 Eaves (insulation at ceiling level)	Independently assessed	11.18	0.08	0.08	NRG	No
E12 Gable (insulation at ceiling level)	Independently assessed	16.60	0.04	0.04	NRG	No
E16 Corner (normal)	Independently assessed	20.28	0.04	0.04	NRG	No
E18 Party wall between dwellings	Independently assessed	33.10	0.03	0.03	Internal partitions Ext wall	No

Y-value	0.05	W/m²K

18.0 Pressure Testing	Yes	
1 Designed AP_{50}	2.50	m³/(h.m²) @ 50 Pa
Test Method	Blower Door	

19.0 Mechanical Ventilation

Mechanical Ventilation

Mechanical Ventilation System Present	Yes
Approved Installation	No
Mechanical Ventilation data Type	Database
Type	Mechanical extract ventilation - decentralised
MV Reference Number	500755
Duct Type	Flexible
Wet Rooms	3

19.1 Mechanical extract ventilation - Decentralised

SFP	Fan/Room Type	Count
0.15	In Room Fan Kitchen	1
0.15	In Room Fan Other Wet Room	0
0.00	In Duct Fan Kitchen	0
0.00	In Duct Fan Other Wet Room	0
0.11	Through Wall Fan Kitchen	0
0.14	Through Wall Fan Other Wet Room	3

20.0 Fans, Open Fireplaces, Flues

21.0 Fixed Cooling System — No

22.0 Lighting

No Fixed Lighting — No

Name	Efficacy	Power	Capacity	Count
Pen	90.00	9	810	9
Down	100.00	8	800	19

24.0 Main Heating 1 — Database

12. Annex B – Supporting evidence for U-values

12.1. Ground Floor

Bellway, Energy House

Documentation of the component — 30. March 2023

Thermal transmittance (U-value) according to BS EN ISO 6946 — Page 1/2

Source: **own catalogue - Bellway, Energy House**

Component: **Bellway, Energy House**

INSIDE

OUTSIDE

Assignment: Suspended ground floor

		Manufacturer	Name	Thickness [m], number	Lambda [W/(mK)]	Q	R [m²K/W]
		Rsi					0.1700
☑	1	Nuspan	NUG375+75MM Screed	0.4500	0.058	E	7.6923
		Rse					0.1700
				0.4500			

U = 0.11 W/(m²K) — Explanation see next page

Q .. The physical values of the building materials has been graded by their level of quality. These 5 levels are the following

A .. A: Data is entered and validated by the manufacturer or supplier. Data is continuously tested by 3rd party.

B .. B: Data is entered and validated by the manufacturer or supplier. Data is certified by 3rd party

C .. C: Data is entered and validated by the manufacturer or supplier.

D .. D: Information is entered by BuildDesk without special agreement with the manufacturer, supplier or others.

E .. E: Information is entered by the user of the BuildDesk software without special agreement with the manufacturer, supplier or others.

U = 0.11 W/(m²K) R_T = 8.03 m²K/W

Calculated with BuildDesk 3.4.6

Suspended floor according to BS EN ISO 13370

U_f - thermal transmittance of the floor between internal environment and basement according to BS EN ISO 6946

R_T	Total thermal resistance [m²K/W]	8.032	($R_T = R_{si} + \Sigma(d/\lambda) + R_{se}$)
U_f	Thermal transmittance [W/(m²K)]	0.120	

Further input data:

λ	Thermal conductivity [W/(mK)]	1.50	(Thermal conductivity of the ground)
A	Floor area [m²]	47.40	
P	Exposed perimeter [m]	28.04	
R_g	Thermal resistance [m²K/W]	0.0	(any insulationon on the base of underfloor space)
w	Thickness of basement wall w [m]	0.30	(walls of underfloor space)
U_w	Thermal transmittance [W/(m²K)]	0.50	(walls of underfloor space)
h	Height of floor above ground [m]	0.150	

ε	Ventilation openings [m²/m]	0.0015
v	Average wind speed at 10m height v [m/s]	5.0
f_w	Wind shielding factor [-]	0.05

Intermediate results:

B'	Characteristic dimension [m]	3.381
d_g	Equivalent thickness [m]	0.615
U_g	Thermal transmittance [W/(m²K)]	0.776
U_x	Thermal transmittance [W/(m²K)]	0.205

U = 0.11 W/(m²K) **Thermal Transmittance**

L_S = 5.1 W/K **Steady-state thermal coupling coefficient**

12.2. Roof

Element type: Roof - Pitched roof - insulated ceiling - Calculation Method: BS EN ISO 6946

Bellway Homes_500mm Knauf Insulation Loft Roll 44_0.09

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.100		Rsi
1	12.5	0.190			0.066		Gyproc WallBoard
2	100	0.044	0.130	0.0900	2.273	0.769	Knauf Insulation Loft Roll 44
3	400	0.044			9.091		Knauf Insulation Loft Roll 44 (2/200mm)
4		R-value[1]			0.200		Roof space
					0.040		Rse
	513 mm				11.769		

[1]Roof space - tiled roof, with felt or sarking boards

Total resistance: Upper limit: 11.616 Lower limit: 11.429 Ratio: 1.016 Average: 11.523 m²K/W

U-value (uncorrected) 0.087

U-value corrections

Air gaps in layer 2	ΔU = 0.000	(Level 0)
Loft hatch	ΔU = 0.004	(Insulation thickness = 50 mm)

Total ΔU 0.004 (4.5% of U)

U-value (corrected) 0.091

U-value (rounded) 0.09 W/m²K

12.3. External Walls (25mm service zone)

Calculated by:
Matthew Prowse
Knauf Insulation
PO Box 10
Stafford Road
St Helens
WA10 3NS
Tel: 07739 446 378

U-value calculation by BRE U-value Calculator version 2.04j - Printed on 23 Aug 2023 at 16:45

Element type: Wall - Timber framed - warm frame or hybrid - Calculation Method: BS EN ISO 6946

Bellway Homes_EH2.0 Coppersmith_Exemplar External Wall_0.18 v.4
Thermal Resistance of low-e cavities
taken from info published by others.

Slightly ventilated air layer: calculation is done for unventilated and ventilated

1. Thermal resistance for unventilated air layer:

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.130		Rsi
1	15	0.190			0.079		Knauf Wallboard
2	25	R-value[1]	0.130	0.118	0.670	0.192	Cavity unventilated low-E (0.05)
3	40	0.022			1.818		PIR
4							Vapour control layer
5	89	0.035	0.120	0.150	2.543	0.742	Knauf FrameTherm® Roll 35 / frame
6	9	0.130			0.069		OSB sheathing
7							Protect TF200 Thermo
8	50	R-value[2]			0.710		Cavity unventilated low-E (0.03)
9	102.5	0.770			0.133		Brick outer leaf
					0.040		Rse
	331 mm (total wall thickness)				6.192		

[1]Calculated with specified emissivity of 0.05
[2]Calculated with specified emissivity of 0.03

Total resistance: Upper limit: 5.771 Lower limit: 5.361 Ratio: 1.076 Average: 5.566 m^2K/W

2. Thermal resistance for ventilated air layer:

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.130		Rsi
1	15	0.190			0.079		Knauf Wallboard
2	25	R-value[1]	0.130	0.118	0.670	0.192	Cavity unventilated low-E (0.05)
3	40	0.022			1.818		PIR
4							Vapour control layer
5	89	0.035	0.120	0.150	2.543	0.742	Knauf FrameTherm® Roll 35 / frame
6	9	0.130			0.069		OSB sheathing
7							Protect TF200 Thermo
8	50	R-value					Cavity ventilated low-E (0.03)

9	102.5	0.770		Brick outer leaf
			0.380[2] #	Rse
	331 mm (total wall thickness)		5.689	

[1]Calculated with specified emissivity of 0.05
[2]Calculated with specified emissivity of 0.03
this resistance substitutes for Rse and the resistance of layers 8-9 because of the ventilated air layer (layer 8)

Total resistance: Upper limit: 5.257 Lower limit: 4.858 Ratio: 1.082 Average: 5.057 m²K/W

3. Thermal resistance for slightly ventilated air layer (using the above results):
Ventilation openings: 500 mm² per m length:
Total resistance = 0.001 × [(1500 - 500) × 5.566 + (500 - 500) × 5.057] = 5.566

U-value (uncorrected) 0.180

U-value corrections

Air gaps in layer 5	ΔU = 0.000	(Level 0)
Fixings in layer 8	ΔU = 0.000	(4.40 per m², 6.6 mm² cross-section, λ = 17.0)

Total ΔU 0.000 (0.1% of U)

U-value (corrected) 0.180 (ΔU not added since it is less than 3% of U)
U-value (rounded) 0.18 W/m²K

12.4. External Walls (38mm service zone)

KNAUF INSULATION

Calculated by:
Matthew Prowse
Knauf Insulation
PO Box 10
Stafford Road
St Helens
WA10 3NS
Tel: 07739 446 378

U-value calculation by BRE U-value Calculator version 2.04j - Printed on 23 Aug 2023 at 16:46

Element type: Wall - Timber framed - warm frame or hybrid - Calculation Method: BS EN ISO 6946

Bellway Homes_EH2.0 Coppersmith_Exemplar External Wall_0.18 v.4_(38mm Svc Void)
Thermal Resistance of low-e cavities
taken from info published by others.

Slightly ventilated air layer: calculation is done for unventilated and ventilated

1. Thermal resistance for unventilated air layer:

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.130		Rsi
1	15	0.190			0.079		Knauf Wallboard
2	38	R-value[1]	0.130	0.118	0.670	0.292	Cavity unventilated low-E (0.05)
3	40	0.022			1.818		PIR
4							Vapour control layer
5	89	0.035	0.120	0.150	2.543	0.742	Knauf FrameTherm® Roll 35 / frame
6	9	0.130			0.069		OSB sheathing
7							Protect TF200 Thermo
8	50	R-value[2]			0.710		Cavity unventilated low-E (0.03)
9	102.5	0.770			0.133		Brick outer leaf
					0.040		Rse
	344 mm (total wall thickness)				6.192		

[1]Calculated with specified emissivity of 0.05
[2]Calculated with specified emissivity of 0.03

Total resistance: Upper limit: 5.785 Lower limit: 5.425 Ratio: 1.066 Average: 5.605 m²K/W

2. Thermal resistance for ventilated air layer:

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.130		Rsi
1	15	0.190			0.079		Knauf Wallboard
2	38	R-value[1]	0.130	0.118	0.670	0.292	Cavity unventilated low-E (0.05)
3	40	0.022			1.818		PIR
4							Vapour control layer
5	89	0.035	0.120	0.150	2.543	0.742	Knauf FrameTherm® Roll 35 / frame
6	9	0.130			0.069		OSB sheathing
7							Protect TF200 Thermo
8	50	R-value					Cavity ventilated low-E (0.03)

9	102.5	0.770		Brick outer leaf
			0.380[2] #	Rse
	344 mm (total wall thickness)		5.689	

[1]Calculated with specified emissivity of 0.05
[2]Calculated with specified emissivity of 0.03
this resistance substitutes for Rse and the resistance of layers 8-9 because of the ventilated air layer (layer 8)

Total resistance: Upper limit: 5.271 Lower limit: 4.922 Ratio: 1.071 Average: 5.096 m²K/W

3. Thermal resistance for slightly ventilated air layer (using the above results):
Ventilation openings: 500 mm² per m length:
Total resistance = 0.001 × [(1500 - 500) × 5.605 + (500 - 500) × 5.096] = 5.605

U-value (uncorrected) 0.178

U-value corrections

Air gaps in layer 5	ΔU = 0.000	(Level 0)
Fixings in layer 8	ΔU = 0.000	(4.40 per m², 6.6 mm² cross-section, λ = 17.0)

Total ΔU 0.000 (0.1% of U)

U-value (corrected) 0.178 (ΔU not added since it is less than 3% of U)
U-value (rounded) 0.18 W/m²K

12.5. External Walls – Rendered

Calculated by:
Matthew Prowse
Knauf Insulation
PO Box 10
Stafford Road
St Helens
WA10 3NS
Tel: 07739 446 378

U-value calculation by BRE U-value Calculator version 2.04j - Printed on 23 Aug 2023 at 16:45

Element type: Wall - Timber framed - warm frame or hybrid - Calculation Method: BS EN ISO 6946

Bellway Homes_EH2.0 Coppersmith_Exemplar External Wall_0.17 v.4 (Render Panel)
Thermal Resistance of low-e cavities
taken from info published by others.

Slightly ventilated air layer: calculation is done for unventilated and ventilated

1. Thermal resistance for unventilated air layer:

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.130		Rsi
1	15	0.190			0.079		Knauf Wallboard
2	25	R-value[1]	0.130	0.118	0.670	0.192	Cavity unventilated low-E (0.05)
3	40	0.022			1.818		PIR
4							Vapour control layer
5	89	0.035	0.120	0.150	2.543	0.742	Knauf FrameTherm® Roll 35 / frame
6	9	0.130			0.069		OSB sheathing
7							Protect TF200 Thermo
8	63	R-value[2]			0.710		Cavity unventilated low-E (0.03)
9	100	0.150	0.880	0.0670	0.667	0.114	Standard Aircrete
10	22	1.000			0.022		Weber Monocouche Render*
					0.040		Rse
	363 mm (total wall thickness)				6.748		

[1]Calculated with specified emissivity of 0.05
[2]Calculated with specified emissivity of 0.03

Total resistance: Upper limit: 6.296 Lower limit: 5.753 Ratio: 1.094 Average: 6.024 m²K/W

2. Thermal resistance for ventilated air layer:

Layer	d (mm)	λ layer	λ bridge	Fraction	R layer	R bridge	Description
					0.130		Rsi
1	15	0.190			0.079		Knauf Wallboard
2	25	R-value[1]	0.130	0.118	0.670	0.192	Cavity unventilated low-E (0.05)
3	40	0.022			1.818		PIR
4							Vapour control layer
5	89	0.035	0.120	0.150	2.543	0.742	Knauf FrameTherm® Roll 35 / frame
6	9	0.130			0.069		OSB sheathing
7							Protect TF200 Thermo

8	63	R-value				Cavity ventilated low-E (0.03)
9	100	0.150	0.880	0.0670		Standard Aircrete
10	22	1.000				Weber Monocouche Render*
					0.380[2] #	Rse
	363 mm (total wall thickness)				5.689	

[1]Calculated with specified emissivity of 0.05
[2]Calculated with specified emissivity of 0.03
this resistance substitutes for Rse and the resistance of layers 8-10 because of the ventilated air layer (layer 8)

Total resistance: Upper limit: 5.257 Lower limit: 4.858 Ratio: 1.082 Average: 5.057 m²K/W

3. Thermal resistance for slightly ventilated air layer (using the above results):
Ventilation openings: 500 mm² per m length:
Total resistance = 0.001 × [(1500 - 500) × 6.024 + (500 - 500) × 5.057] = 6.024

U-value (uncorrected) 0.166

U-value corrections

Air gaps in layer 5	ΔU = 0.000	(Level 0)
Fixings in layer 8	ΔU = 0.000	(4.40 per m², 6.6 mm² cross-section, λ = 17.0)

Total ΔU 0.000 (0.0% of U)

U-value (corrected) 0.166 (ΔU not added since it is less than 3% of U)
U-value (rounded) 0.17 W/m²K

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12.6. Windows

Thermal Performance Calculation Summary Sheet

eurocell
All together better

Simulation No. M75-678

Window Profiles Summary

System:	Modus
Type:	Casement
Outerframe:	LSF1021
Sash:	LSF1005
Mullion:	LSF1002/03
Bead:	LSF1301
Reinforcing Spec:	
Outerframe:	None
Sash:	None
Mullion:	EWS801P
Calculation prepared by:	
Print:	Andy Grosse
Signed:	

BFRC
BFRC Certified Simulator 022

Glazing Unit Summary:

Glazing Overview:	28mm Double Glazed	
External Pane:	4mm Saint Gobain Diamant	
Centre Pane:	N/A	
Internal Pane:	4mm Saint Gobain Planitherm One T FG	
Gas Fill Details:	90% Argon 10% Air	
Spacer Bar:	Swisspacer Ultimate/Thermobar	
Glazing u-value:	1.07	W/(m²·K)
Glazing g-value:	0.51	g⊥

SEL Licence Number
N/A

A++, A+, A, B, C, D, E	C
energy index (kWh/m²/year)	-13
thermal transmittance (U window)	1.20
solar factor (g window)	0.32
air leakge (L factor)	0.00

12.7. Front Door

Technical Specification

- PAS24:2016 – meets Part Q & Secured by Design
- Kitemarked under BSi scheme
- CE marked to EN14351.1
- Built under ISO9001 & ISO14001 management systems
- TS007 security cylinder and protection to 3*
- TS008 letterplate
- U-value = 1.0 W/m2K
- Dangerous Substances – none
- HCFC & CFC – free
- GWP Rating – less than 5
- O Zone Depletion – zero
- 914mm door leaf gives clear opening of 850mm

13.Annex C. HTC uncertainty

HTC uncertainty was calculated by considering type A and type B uncertainties.

Type A uncertainty

Type A uncertainty considers statistical variation in the recorded data [24] is calculated as the standard error of the average of each measurement. For HTC measurements 10 minutes averages were used for type A uncertainty.

$$u_A = \frac{\sigma}{\sqrt{n}} \qquad \textit{Eq. C1}$$

Type B uncertainty

Type B uncertainty considers the uncertainty attributed to the accuracy of the measurement device. The accuracy and standard uncertainty of equipment used in the HTC calculation are stated in Table E1.

Table C1: Accuracy and standard uncertainty of equipment used in the HTC calculation

Variable	Device	Accuracy	Probability distribution	Divisor	Standard Uncertainty
Q [W]	Siemens 7KT PAC1200 digital power meter	1% of measurement	-	-	1% of measurement
Ti [°C]	hygroVUE 10/thermocouple	±0.1 °C (20 to 60 °C)/ ±0.1 °C	normal	2	0.05
Te [°C]	hygroVUE 10	±0.2 °C (–40 to 70 °C)	normal	2	0.10

The type B uncertainty of total power input is calculated by taking the average power input (based on cumulative energy data) and multiplying by the stated accuracy (1% of measurement).

The type B uncertainty of both the T_{i_vw} and the average external temperature is calculated using Table E2 and Table E3. The standard uncertainty of each individual temperature sensors is scaled by the same coefficient using the volume of each sensed area to form the weighting. These are then summed following the residual sum of squares (RSS) method.

Table C2: T_{i_vw} type B uncertainty

Zone	Weighting	hygroVUE 10 sensor uncertainty	Scaled uncertainty
Kitchen	0.11	0.05	0.006
Dinning	0.11	0.05	0.006
Living	0.181	0.05	0.009
WC	0.035	0.05	0.002
Hall	0.072	0.05	0.004
Bedroom 1	0.146	0.05	0.007
Bedroom 2	0.095	0.05	0.005
Bedroom 3	0.107	0.05	0.005
Bath	0.055	0.05	0.003
Ensuite	0.049	0.05	0.002
Landing	0.041	0.05	0.002
Quadrature sum (k = 1)			0.017
k = 2			0.034

Table C3: T_e type B uncertainty

Elevation	Weighting	hygroVUE 10 sensor uncertainty	Scaled uncertainty
Front	0.25	0.1	0.025
Left	0.25	0.1	0.025
Right	0.25	0.1	0.025
Rear	0.25	0.1	0.025
Quadrature sum (k = 1)			0.05
k = 2			0.10

Combined Uncertainty

The Type A and Type B uncertainty attributed to each measurement are combined through the RSS method prior to error propagation in the HTC calculation.

$$u_{combined} = \sqrt{u_A^2 + u_B^2} \qquad Eq.\ C2$$

Uncertainty Propagation

The uncertainty propagation of the HTC calculation is given by the following equation:

$$u_{HTC} = \sqrt{\left(\frac{u_Q}{\Delta T}\right)^2 + \left(\frac{Q^2}{\Delta T^4}\right) \cdot \left(u_{T_i}^2 + u_{T_e}^2\right)} \quad \textit{Eq. C3}$$

Expanded Uncertainty

All prior uncertainties have been given as k=1. When stating the uncertainty on plots, the expanded uncertainty (k=1.96) is stated, such that:

$$U = k \cdot u \quad \textit{Eq. C4}$$

Such a coverage factor should result in a 95% confidence interval.

14.Annex D. In-situ U-value uncertainty

ISO 9869 [17] applies an uncertainty value of 14-28% to in-situ U-value measurements. However, this uncertainty is based on measurements undertaken in the field without control of external conditions. The ISO 9869 uncertainty calculation was modified for the controlled environment and to include type A and type B uncertainties.

Type A uncertainty

Type A uncertainty considers statistical variation in the recorded data (GUM), is calculated as the standard error of the average of each measurement. For U-values measurements 10 minutes averages were used for type A uncertainty.

$$u_A = \frac{\sigma}{\sqrt{n}} \qquad \textit{Eq. D1}$$

Type B uncertainty

Type B uncertainties are based on the sources of uncertainty listed in ISO 9869. Table C1 lists the measurement uncertainties provided by ISO 9869 and modifications that were made for TFH based on the apparatus and test environment. It must be noted that many of the assumptions regarding sources of uncertainty contained within ISO 9869 are not accompanied with background information as to how they have been derived.

Table D1: Measurement uncertainties provided by ISO 9869 and modifications made for TFH

ISO 9869 consideration	Notes	% error	Absolute error
Apparatus - Logger	Based on logger accuracy	0.3	
Apparatus - HFP	Hukesflux HFP01 datasheet	3	
Apparatus - hygroVUE 10 temperature sensor	Based on steady state ΔT	0.5	0.3
HFP contact	ISO 9869 - unadjusted	5	
Isotherm modification	ISO 9869 - unadjusted	2	
Variation in temp & heat flow	ISO 9869 ~10%. Removed as steady state measurement reported. Captured in type A uncertainty	0	
Variation in air (T_i) & radiant (T_r) temperature differences	ISO 9869 suggests 5%.	2.5	

type B uncertainty	Quadrature sum	6.7

Combined Uncertainty

The Type A and Type B uncertainty attributed to each measurement are combined through the sum of squares (RSS) method prior to error propagation in the U-value calculation (as described in GUM).

$$u_{combined} = \sqrt{u_A^2 + u_B^2} \qquad Eq.\ D2$$

Uncertainty Propagation

The uncertainty propagation of the U-value calculation is given by the following equation:

$$u_{U-value} = \sqrt{\left(\frac{u_q}{\Delta T}\right)^2 + \left(\frac{q^2}{\Delta T^4}\right) \cdot \left(u_{T_i}^2 + u_{T_e}^2\right)} \qquad Eq.\ D3$$

Expanded Uncertainty

All prior uncertainties have been given as k=1. When stating the uncertainty on plots, the expanded uncertainty (k=1.96) is stated, such that:

$$U = k \cdot u \qquad Eq.\ D4$$

Such a coverage factor should result in a 95% confidence interval.

15.Annex E. Blower door Test

Summary

retrotec FanTestic	version: **5.12.84**	licensed to: **Salford University**
Test date: **2023-03-06**	By: **GH, HD, RF, AS**	
Customer:		
Building Lot Number:		
Building address:	**EH2 Bellway**	

Building and Test Information	
Test file name:	**ATTMA 2023-03-13 1424 eh2 Bellway corrected**
Building volume [m³]:	**234.6**
Envelope Area [m²]:	**233.2**
Floor Area [m²]:	**46.2**
Building Height (from ground to top) [m]:	**0**

Results	
Air flow at 50 Pa, Q_{50} [m³/h]	**933.25**
Air changes, n_{50}	**3.98**
Equivalent leakage area at 50 Pa [cm²]	**189.0**
Permeability at 50 Pa [m³/h/m²]	**4.002**

Building Information

Building Measurements

Building Volume [m^3]: 234.6

Envelope Area (A_T) [m^2]: 233.2

Building Height (from ground to top) [m]: 0

Heating/Ventilation System

HVAC Systems Present:

Pictures

Test Method

Carried out in accordance with the following standards:

- ATTMA TS1 Issue 2 – Measuring Air Permeability of Building Envelopes
- BS EN13829:2001 Thermal Performance of Buildings
- BINDT – Quality Procedures and Explanatory Notes for Air Tightness Testing

The building was tested using the equipment listed in the equipment appendix.

Openings and Temporary Sealing

Deviations from Standard Methods:

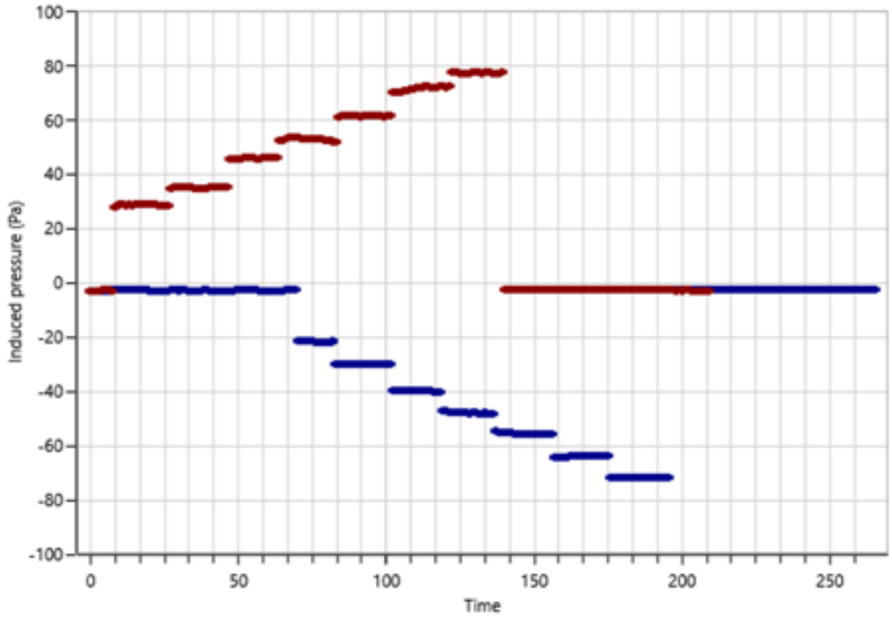
Large Building Setup Notes:

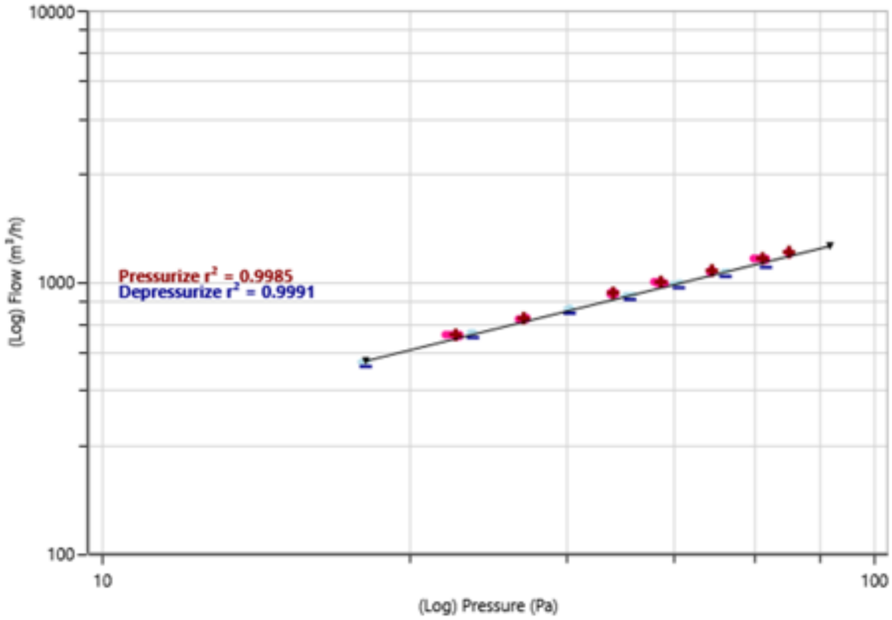
Tester Complaints:

Discussion of Results

Combined Test Data (Average Values)

	Results	Uncertainty
Air flow at 50 Pa, Q_{50} [m^3/h]	933.25	+/-1.1%
Air changes, n_{50}	3.98	+/-1.1%
Equivalent leakage area at 50 Pa [cm^2]	189.0	+/-1.1%
Permeability at 50 Pa [m^3/h/m^2]	4.002	+/-1.0%





Air Leakage Test Data Appendix–

Depressurize Data Set

Test Dataset Date: 2023-03-06

Start time: 11:48:33

Test was carried out under Method B (method A, B or C).

Environmental Conditions		
Wind speed:	0	
Operator Location:	Inside the building	
Initial Bias Pressure:	-2.95 Pa	
Final Bias Pressure:	-2.69 Pa	
Average Bias Pressure:	-2.82 Pa	
Initial Temperature:	indoors: 20 C	outdoors: 5 C
Final Temperature:	indoors: 20 C	outdoors: 5 C
Barometric Pressure	99.780 kPa	from Direct measurement

Test Analysis			
Coefficient of Determination, r^2:	0.9991	95% confidence limits	
Slope, n:	0.702	0.67732	0.72629
Intercept, C_{env} [m³/h/Pa^n]:	57.228	52.14	62.82
	Results	Uncertainty	
Air flow at 50 Pa, Q_{50} m³/h	901.83	+/-1.0%	
Air changes, n_{50}:	3.844	+/-1.0%	
Equivalent leakage area at 50 Pa [cm²]	184.1	+/-1.0%	
Permeability at 50 Pa, AP_{50} [m³/h/m²]	3.8672	+/-1.0%	

Measured pressure [Pa]		-24.7	-32.9	-42.9	-50.8	-58.4	-66.7	-74.9					
Induced Pressure [Pa]		-21.8	-30.1	-40.1	-48.0	-55.6	-63.9	-72.0					
#1, Range B2	Fan Pressure [Pa]	115.4	177.5										
	Flow [m³/h]	511.9	653.9										
#1, Range B4	Fan Pressure [Pa]			60.2	74.9	89.9	106.5	122.3					
	Flow [m³/h]			805.5	903.7	999.1	1098	1188					
Total Flow, Q_c [m³/h]		511.922	653.895	805.452	903.738	999.084	1098.33	1188.30					
Corrected Flow, Q_{env} [m³/h]		491.944	628.376	774.019	868.469	960.092	1055.46	1141.93					
Error [%]		-1.3%	0.8%	1.4%	0.3%	0.0%	-0.3%	-0.8%					

7 induced pressures each taken for 20 of the required 20 seconds.

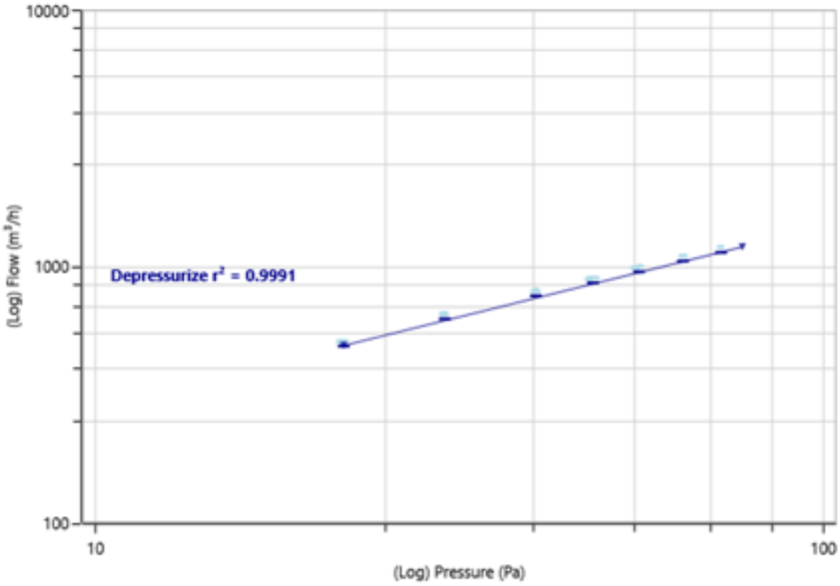
7 baseline pressures each taken for 10 of required 10 seconds.

Average Baseline, ΔP: -2.82 Pa

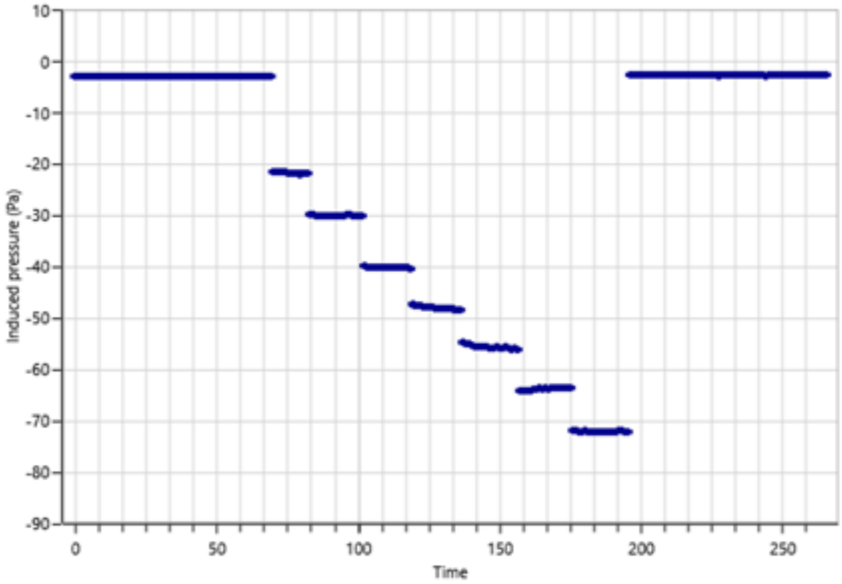
Static Pressure Averages:			
Average Baseline [Pa]	ΔP -2.82		
initial [Pa]	ΔP01 -2.95	ΔP01- -2.95	ΔP01+ 0.00
final [Pa]	ΔP02 -2.69	ΔP02- -2.69	ΔP02+ 0.00

Baseline, initial [Pa]	-2.97	-2.90	-2.97	-2.96	-2.99	-2.93	-2.96						
Baseline, final [Pa]	-2.64	-2.67	-2.70	-2.72	-2.72	-2.70	-2.69						

Flow vs Induced Pressure (Depressurize Set)



Building Gauge Pressure (Depressurize Set)



Pressurize Data Set

Test Dataset Date: 2023-03-06
Start time: 12:01:12

Test was carried out under Method B (method A, B or C).

Environmental Conditions		
Wind speed:	0	from the
Operator Location:	Inside the building	
Initial Bias Pressure:	-2.99 Pa	
Final Bias Pressure:	-2.84 Pa	
Average Bias Pressure:	-2.91 Pa	
Initial Temperature:	indoors: 20 C	outdoors: 5 C
Final Temperature:	indoors: 20 C	outdoors: 5 C
Barometric Pressure:	99.780 kPa	from Direct measurement

Test Analysis			
Coefficient of Determination, r^2:	0.9985	95% confidence limits	
Slope, n:	0.706	0.67393	0.73756
Intercept, C_{env} [m³/h/m²]:	61.279	54.07	69.45
	Results	Uncertainty	
Air flow at 50 Pa, Q_{50} m³/h	964.67	+/-1.1%	
Air changes, n_{50}:	4.112	+/-1.1%	
Equivalent leakage area at 50 Pa [cm²]	193.6	+/-1.1%	
Permeability at 50 Pa, AP_{50} [m³/h/m²]	4.1367	+/-1.1%	

Measured pressure [Pa]		25.6	32.1	42.8	49.8	58.4	68.4	74.3					
Induced Pressure [Pa]		28.6	35.0	45.7	52.7	61.3	71.3	77.2					
#1, Range B2	Fan Pressure [Pa]	195.4	252.7										
	Flow [m³/h]	639.1	734.8										
#1, Range B4	Fan Pressure [Pa]			119.3	140.1	165.8	197.1	215.8					
	Flow [m³/h]			912.0	999.0	1101	1220	1287					

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Document1

Total Flow, Q_c [m³/h]		639.111	734.785	911.965	998.954	1100.84	1219.75	1287.16					
Corrected Flow, Q_{env} [m³/h]		649.057	746.219	926.156	1014.50	1117.98	1238.73	1307.19					
Error [%]		-0.5%	-0.9%	1.9%	0.9%	-0.1%	-0.5%	-0.7%					

7 induced pressures each taken for 20 of the required 20 seconds.

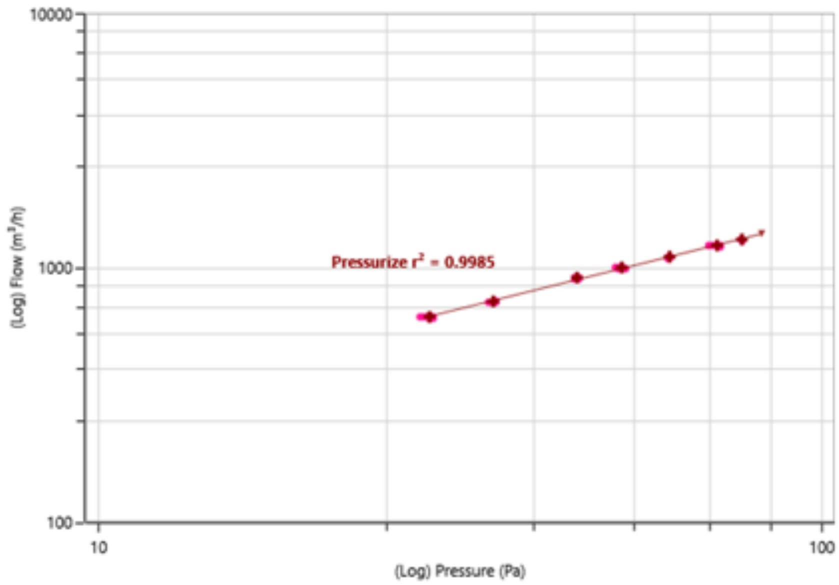
7 baseline pressures each taken for 10 of required 10 seconds.

Average Baseline, ΔP: -2.91 Pa

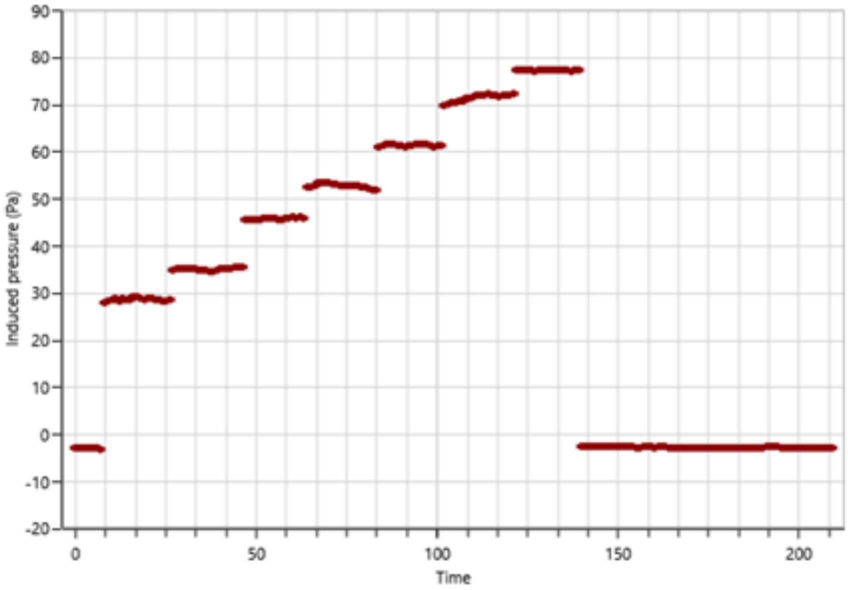
Static Pressure Averages:			
Average [Pa]	ΔP -2.91		
initial [Pa]	ΔP01 -2.99	ΔP01- -2.99	ΔP01+ 0.00
final [Pa]	ΔP02 -2.84	ΔP02- -2.84	ΔP02+ 0.00

Baseline, initial [Pa]	- 2.99	- 3.00	- 2.99	- 2.94	- 2.91	- 2.93	- 3.13					
Baseline, final [Pa]	- 2.70	- 2.74	- 2.83	- 2.90	- 2.90	- 2.82	- 2.98					

Flow vs Induced Pressure (Pressurize Set)



Building Gauge Pressure (Pressurize Set)



Test Equipment

The following test equipment was used in the performance of the air leakage tests.

	Fan	Fan serial	Fan location	Gauge	Gauge serial	Gauge Calibration
#1	Retrotec 5000		EH2 Bellway	DM32	405420	

Fan Calibration Certificate Retrotec 5000:

Retrotec 5000 Fan last calibrated: (Flow Equation Parameters - B1) . . CFM							
Range	**n**	**K**	**K1**	**K2**	**K3**	**K4**	**MF**
Open	0.498	548	0	0.3	0	1	10
A	0.502	287	0	0.4	0	1	20
B8	0.54	113.25	0	0.7	0	1	40

Polynomial Range	**g**	**f**	**a**	**b**	**c**	**d**	**K2**	**MF**
B4	29	-0.19	0.000007943	-0.00864	4.9	206	0.8	40
B2	30	0.1	0.00000088	-0.0029	2.15	90	1	50
B1	30	0	0.0000005	-0.00128	1.02	54	1	60
B74	25	0.15	0.000000796	-0.00095	0.59	18	0.8	35
B47	25	0.09	0.000000269	-0.0003591	0.2435	12.05	1	50
B29	25	-0.02	0.000000111	-0.000149	0.092	4.4	0.6	50

Fan Pressure (FP) is the measured fan pressure when using a self-referenced fan or when Room Pressure (RP) is negative. If using a fan which is not self-referenced, and Room Pressure is positive, Fan Pressure is calculated by subtracting the measured Room Pressure from the Absolute Value of the Fan Pressure.

If PrA>0 and fan is not self-referencing: FP = |PrB|-PrA
If PrA<0 or fan is self-referencing: FP = PrB

Flow calculations are not valid if Fan Pressure is less than either MF or (K2 x |RP|).

Flow in CFM using the above coefficients is calculated as follows for standard Ranges:

$$flow = (FP - (|RP| \times K1))^{N} \times (K + (K3 \times FP))$$

Flow in CFM using the above polynomial coefficients is calculated as follows:

$$flow = (a \times FP^{3}) + (b \times FP^{2}) + (c \times FP) + d + ((g - |RP|) \times f)$$

16.Annex F. Pulse Test

Air Permeability Test Report

PULSE

University Of Salford Allerton Building Frederick Road Salford M6 6PU	Air Permeability @ 4Pa **0.6** m³/m²h	Air Changes @ 4Pa **0.6** 1/h

Report Date	Unique Reference
21 April 2023	**36072145-7406-4327-B22C-D2A7AE7A843C**

Test Date	21 Apr 2023 - 10:15	**Test Method**	Low Pressure Pulse
Technician	Anestis Sitmalidis	**Registration No.**	-
Company Name	University Of Salford		
Company Address	-		

Building Reference	Bellway - Future Home		
Building Type	House / Bungalow	**Envelope Area**	233.2 m²
Building Age	L (2012 onwards)	**Volume**	234.6 m³
Wall Construction	Timber Frame		

Result

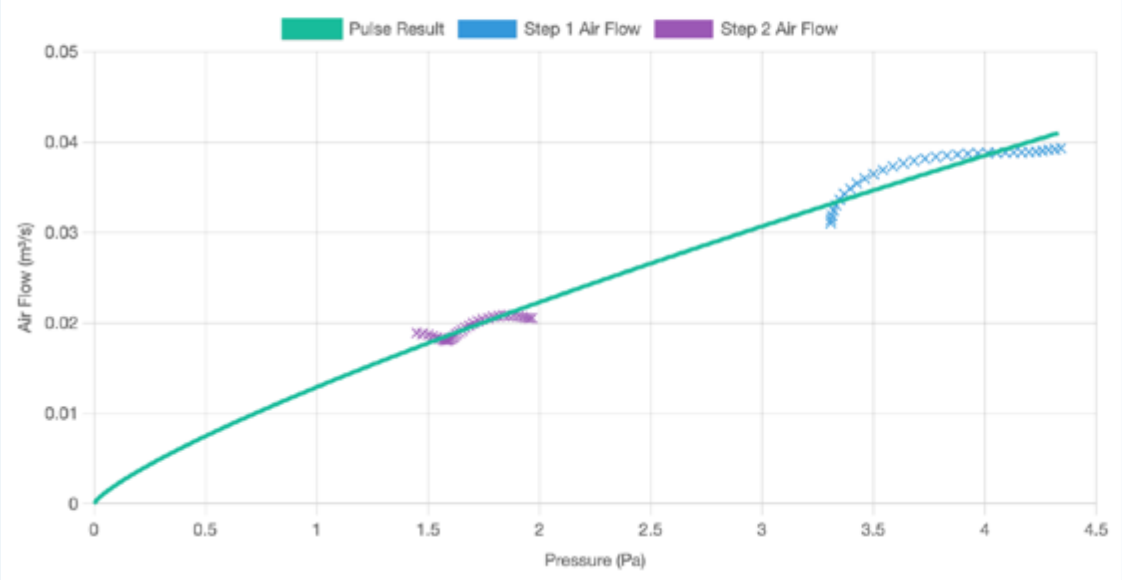
	Measured @ 4Pa			Extrapolated @ 50Pa		
Air Leakage Rate	**Q4**	139	m³/h	**Q50**	758	m³/h
Air Permeability	**AP4**	0.59	m³/m²h	**AP50**	3.25	m³/m²h
Air Changes per Hour	**N4**	0.59	1/h	**N50**	3.23	1/h
Equivalent Leakage Area		0.01	m²		0.02	m²
Calculation Uncertainty		1	±%		4	±%

Test Status	Valid		
Number of Tanks	1	**Pulse Duration**	1.5 secs
Number of Steps	2	**Steps Used**	1, 2

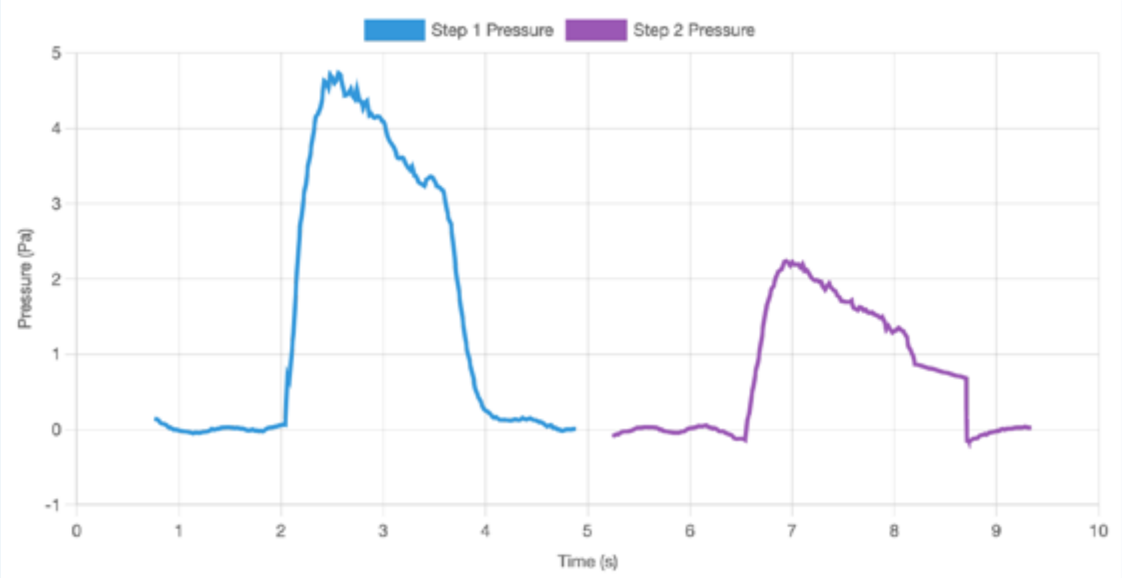
https://reports.buildtestsolutions.com/accounts/f1868633-53ce-43ae-bde8-ab32cddc2ff4/pulse/36072145-7406-4327-b22c-d2a7ae7a843c Page 1 of 4

Calculation Details		Test Conditions	
Achieved Pressure Range	1.4 - 4.3 Pa	Atmospheric Pressure	101,325 Pa

Air Flow Chart



Air Pressure Chart



The Low Pressure Pulse (LPP) method has been approved as an airtightness testing method under Part L building regulations. Full test prodedure and airtightness testing methodology are detailed in CIBSE TM23.

17.Annex G. HFP Thermography locations

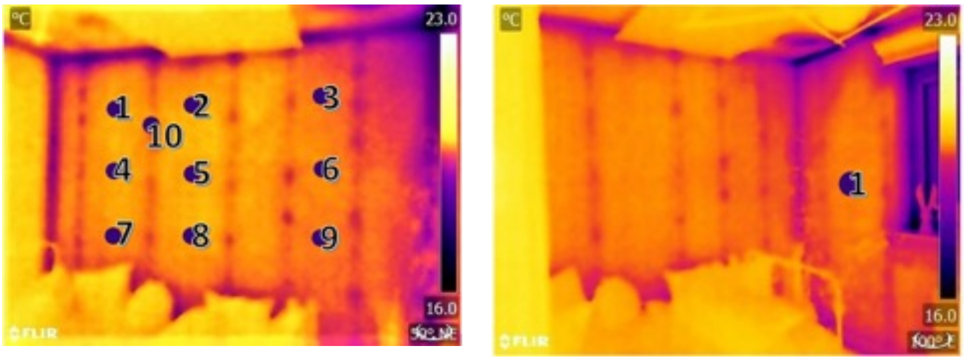


Figure 31. Thermogram showing locations of external wall in-situ U-value measurements. (a) bedroom 2 grid (b)rendered wall location.

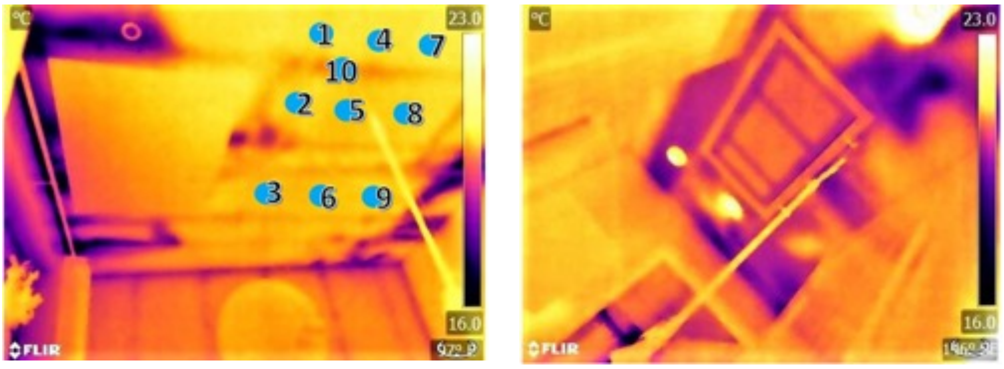


Figure 32.Thermogram showing locations of ceiling in-situ U-value measurements (a) ceiling (b)landing.

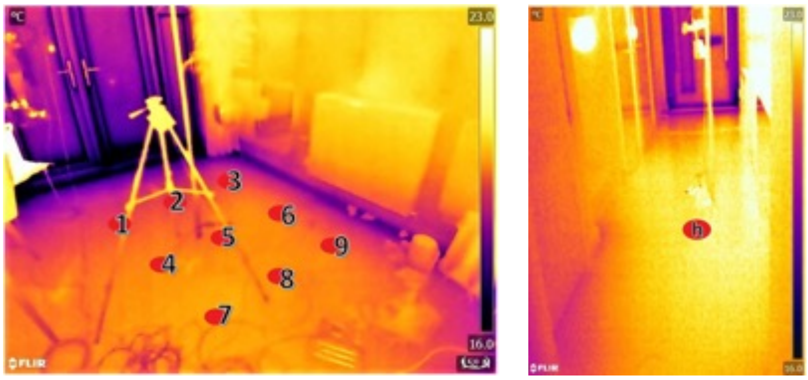


Figure 33. Thermogram showing locations of floor in-situ U-value measurements (a) Kitchen (b)Hall.

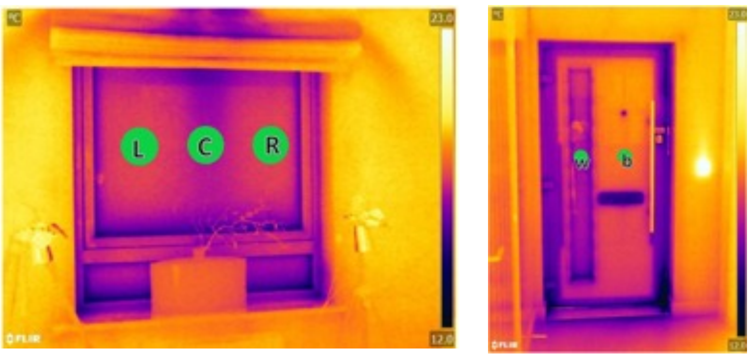


Figure 34. Thermogram showing locations of windows and door in-situ U-value measurements. (a) bedroom 3 window (b)door.

18.Annex H. QUB test

Bellway Homes
Plot No A

Salford EH3
Frederick Road Campus
University of Salford
Salford

M6 6PU

As Designed

SAP Entry	Unit	Value
total floor area	m2	92.82
dweling volume	m3	235.76
air permeability q50	m3/h/m2	**2.50**
total fabric heat loss	W/K	68.14
ventilation heat losses	W/K	38.90
Heat Losses attributed to Infiltration	W/K	9.67
Heat Losses attributed to Ventilation	W/K	29.23
HTC	W/K	**107.04**
HLP	W/m2/K	**1.15**
QUB	W/K	**77.81**

As Tested

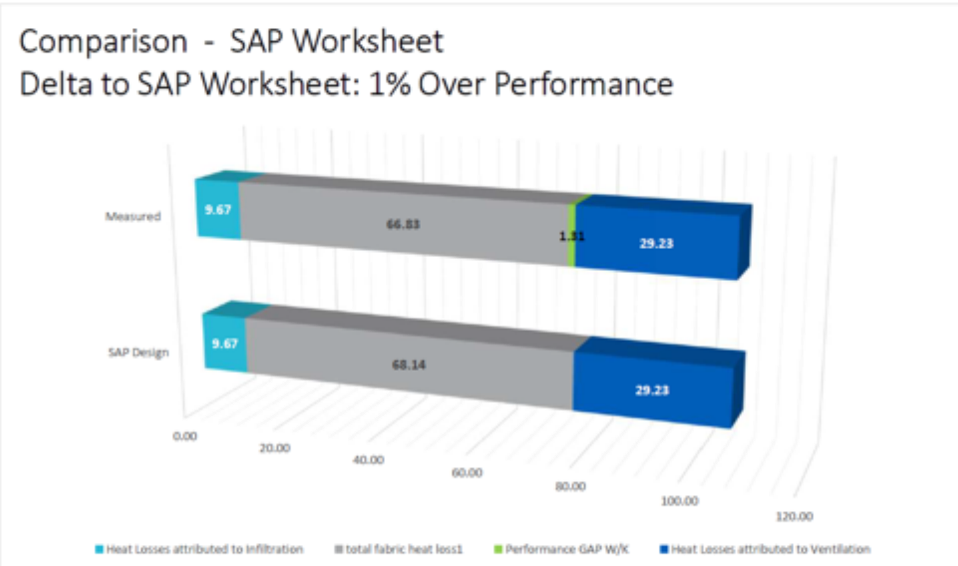
SAP Entry	Unit	HTC	
total floor area	m2	92.82	
dweling volume	m3	235.76	
air permeability q50	m3/h/m2	**2.50**	
total fabric heat loss[1]	W/K	**66.83**	
ventilation heat losses	W/K	38.90	
Heat Losses attributed to Infiltration	W/K	9.67	
Heat Losses attributed to Ventilation	W/K	29.23	
HTC[2]	W/K	**105.73**	
HLP[3]	W/m2/K	**1.14**	
QUB as measured	W/K	**76.50**	**+/- 6.1**

Calculations used based on the QUB measurement result

$^{1}\,\textbf{total fabric heat loss} = QUB - (\text{Heat Loss Attributed to Infiltration})$

$^{2}\,\textbf{HTC} = QUB + (\text{Heat Loss Attributed to Ventilation})$

$$^{3}\textbf{HLP} = \frac{QUB + (\text{Heat Loss Attributed to Ventilation}}{\text{total floor area}}$$



Report Date: 26/05/2023 QUB by Saint Gobain Issued by : Bill Parker

19.Annex I. Veritherm test

Test Credentials			
Issued by:	Veritherm UK		
Address:	Malvern Hills Science Park,	Technician:	-
	Geraldine Road, Malvern,	Registered No:	RED-002
	WR14 3SZ	Qualification:	-
Telephone:	-		
Email:	admin		
Report Reference:	ID 411		
Client:	University of Salford EH2		
Client Contact:	Heidi Diaz Hernandez	Role:	Research Fellow

Building Details			
Building identifier:	ritual.basin.toxic		
Address:	Bellway Energy House 2.0 Frederick Road Campus, University of Salford, Manchester M6 6PU		
Type:	Dwelling	Description:	detached
Status:	TestStatus.Review	Construction:	brick
Contractor:	Bellway Homes	Heating Source:	electricity
SAP reference:	111	SAP software:	Other
Floor area (m^2):	92.82	Property height (m):	5.08
Envelope (m^2):	233.9424	Volume (m^3):	235.7628
Air Perm (m^3/hm^2@50PA):	2.5 (designed)	4.002 (measured)	
Number of ring mains:	2	Passive Property?	-

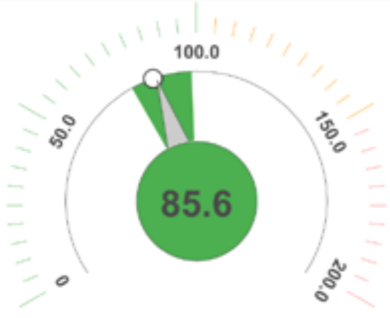
Test Details			
Date:	23-05-2023		
Heating Phase:	17:00 UTC - 22:30 UTC	Cooling Phase:	22:30 UTC - 04:00 UTC
External Conditions:	Average 9.3°C (min 8.6°C, max 11.4°C), max 10.1kmph winds, 0.0mm precipitation		
Temporary Sealing:	Temporary seals in place		
Notes:	NOTE - two minor drops in the heat load were observed during the heating phase, please reference power graphs. The external weather data API can be ignored due to testing within a controlled climate chamber.		

Test Results		
This is to certify that the above named building has been tested by an approved Veritherm Testing Engineer.		
Measured Veritherm Result:	**85.6 W/K**	
Confidence Range:	76.1 W/K - 98.1 W/K	
	Designed	**Measured**
Fabric	68.137 W/K	69.5 W/K
Air Infiltration	10.1 W/K	16.1 W/K
Ventilation	28.8 W/K	
Heat Transfer Coefficient	107.04 W/K	114.4 W/K

Enquiries should be made to Veritherm, Priebe Building, Redbarn Drive, Hereford, HR4 9DX
or visit www.veritherm.co.uk

Veritherm

Result Summary (HTC)



Result Breakdown

Measured

Ventilation *
28.8 W/K

ι

Fabric
69.5 W/K

Veritherm Measured Result (Fabric + Infiltration)
85.6 W/K

76.1 98.1

Designed

HTC (Fabric + Infiltration + Ventilation)
107.0 W/K

Δ

Ventilation
28.8 W/K

ι

Fabric
68.1 W/K

ι Infiltration: 16.1 W/K **

Δ Performance Gap: 1.4 W/K (-7%)

* Ventilation not measured by Veritherm, figure supplied from design information

** Infiltration is calculated from provided air permeability data

Thermal Efficiency Rating

Very energy efficient - lower running costs

(0-1) VERY GOOD

(1-2) GOOD < This property (1.2)

(2-3) POOR

(3+) VERY POOR

Not energy efficient - higher running costs

Performance Gap

-7%

Average U-Value:	0.30 W/m²K

20.Annex J. SAP Summary

Summary for Input Data

elmhurst energy

Property Reference	Coppersmith EH2.0	Issued on Date	05/04/2023
Assessment Reference	EH2.0 Fab A DAP 2.5	Prop Type Ref	Coppersmith EH2.0
Property			

SAP Rating	82 B	DER	4.03	TER	11.67
Environmental	96 A	% DER < TER			65.47
CO_2 Emissions (t/year)	0.35	DFEE	38.82	TFEE	41.31
Compliance Check	See BREL	% DFEE < TFEE			6.02
% DPER < TPER	30.26	DPER	42.50	TPER	60.94

Assessor Details	Mr. Jamie Bursnell	Assessor ID	Z504-0001
Client			

SUMMARY FOR INPUT DATA FOR: New Build (As Designed)

Orientation	South
Property Tenture	ND
Transaction Type	6
Terrain Type	Urban
1.0 Property Type	House, Detached
2.0 Number of Storeys	2
3.0 Date Built	2020
4.0 Sheltered Sides	1
5.0 Sunlight/Shade	Average or unknown
6.0 Thermal Mass Parameter	Precise calculation

7.0 Electricity Tariff	Standard
Smart electricity meter fitted	No
Smart gas meter fitted	No

7.0 Measurements

	Heat Loss Perimeter	Internal Floor Area	Average Storey Height
Ground floor:	27.78 m	46.41 m²	2.39 m
1st Storey:	27.78 m	46.41 m²	2.69 m

8.0 Living Area 14.99 m²

9.0 External Walls

Description	Type	Construction	U-Value (W/m²K)	Kappa (kJ/m²K)	Gross Area(m²)	Nett Area (m²)	Shelter Res	Shelter	Openings	Area Calculation Type
External Wall 1	Timber Frame	Timber framed wall (one layer of plasterboard)	0.18	9.00	141.12	121.03	0.00	None	20.09	Calculate Wall Area

9.2 Internal Walls

Description	Construction	Kappa (kJ/m²K)	Area (m²)
Internal Wall 1	Plasterboard on timber frame	9.00	222.00

10.0 External Roofs

Description	Type	Construction	U-Value (W/m²K)	Kappa (kJ/m²K)	Gross Area(m²)	Nett Area (m²)	Shelter Code	Shelter Factor	Calculation Type	Openings
External Roof 1	External Plane Roof	Plasterboard, insulated at ceiling level	0.09	9.00	46.41	0.00	None	0.00	Calculate Wall Area	0.00

10.2 Internal Ceilings

Description	Storey	Construction	Area (m²)
Internal Ceiling 1	Lowest occupied	Plasterboard ceiling, carpeted chipboard floor	46.41

11.0 Heat Loss Floors

Description	Type	Storey Index	Construction	U-Value (W/m²K)	Shelter Code	Shelter Factor	Kappa (kJ/m²K)	Area (m²)
Heat Loss Floor 1	Ground Floor - Solid	Lowest occupied	Suspended concrete floor, carpeted	0.11	None	0.00	75.00	46.41

11.2 Internal Floors

Description	Storey Index	Construction	Kappa (kJ/m²K)	Area (m²)
Internal Floor 1		Plasterboard ceiling, carpeted chipboard floor	9.00	46.41

12.0 Opening Types

Summary for Input Data

Description	Data Source	Type	Glazing	Glazing Gap	Filling Type	G-value	Frame Type	Frame Factor	U Value (W/m²K)
Windows	BFRC, BSI or CERTASS data	Window	Double glazed			0.47			1.30
Front Door	Manufacturer	Solid Door							1.00
French Doors	Manufacturer	Window	Double Low-E Soft 0.05			0.70		0.70	1.40

13.0 Openings

Name	Opening Type	Location	Orientation	Area (m²)	Pitch
Front Door	Front Door	External Wall 1	South	2.15	
Front Windows	Windows	External Wall 1	South	7.26	
Rear Windows	Windows	External Wall 1	North	4.98	
French	French Doors	External Wall 1	North	4.98	
Right	Windows	External Wall 1	East	0.72	

14.0 Conservatory None

15.0 Draught Proofing 100 %

16.0 Draught Lobby No

17.0 Thermal Bridging Calculate Bridges

17.1 List of Bridges

Bridge Type	Source Type	Length	Psi	Adjusted	Reference:	Imported
E2 Other lintels (including other steel lintels)	Independently assessed	13.40	0.05	0.05	NRG	No
E3 Sill	Independently assessed	9.99	0.03	0.03	NRG	No
E4 Jamb	Independently assessed	28.35	0.05	0.05	NRG	No
E5 Ground floor (normal)	Independently assessed	27.80	0.19	0.19	NUSPAN	No
E6 Intermediate floor within a dwelling	Independently assessed	27.80	0.06	0.06	NRG	No
E10 Eaves (insulation at ceiling level)	Independently assessed	11.18	0.08	0.08	NRG	No
E12 Gable (insulation at ceiling level)	Independently assessed	16.60	0.04	0.04	NRG	No
E16 Corner (normal)	Independently assessed	20.28	0.04	0.04	NRG	No
E18 Party wall between dwellings	Independently assessed	33.10	0.03	0.03	NRG	No

Y-value 0.05 W/m²K

18.0 Pressure Testing Yes

Designed AP_{50} 2.50 m³/(h.m²) @ 50 Pa

Test Method Blower Door

19.0 Mechanical Ventilation

Mechanical Ventilation

Mechanical Ventilation System Present	Yes
Approved Installation	No
Mechanical Ventilation data Type	Database
Type	Mechanical extract ventilation - decentralised
MV Reference Number	500755
Duct Type	Flexible
Wet Rooms	3

19.1 Mechanical extract ventilation - Decentralised

SFP	Fan/Room Type	Count
0.15	In Room Fan Kitchen	1
0.15	In Room Fan Other Wet Room	0
0.00	In Duct Fan Kitchen	0
0.00	In Duct Fan Other Wet Room	0
0.11	Through Wall Fan Kitchen	0
0.14	Through Wall Fan Other Wet Room	3

20.0 Fans, Open Fireplaces, Flues

21.0 Fixed Cooling System No

22.0 Lighting

No Fixed Lighting No

Name	Efficacy	Power	Capacity	Count
Pen	90.00	9	810	9
Down	100.00	8	800	19

24.0 Main Heating 1 Database

Percentage of Heat	100.00	%
Database Ref. No.	105525	
Fuel Type	Electricity	
In Winter	0.00	
In Summer	0.00	
Model Name	WH-MDC05J3E5	
Manufacturer	Panasonic HVAC UK Ltd	
System Type	Heat Pump	
Controls SAP Code	2207	
PCDF Controls	0	
Is MHS Pumped	Pump in heated space	
Heating Pump Age	2013 or later	
Heat Emitter	Radiators	
Flow Temperature	Enter value	
Flow Temperature Value	45.00	

25.0 Main Heating 2	None
26.0 Heat Networks	None

	Heat Source	Fuel Type	Heating Use	Efficiency	Percentage Of Heat	Heat	Heat Power Ratio	Electrical	Fuel Factor	Efficiency type
Heat source 1										
Heat source 2										
Heat source 3										
Heat source 4										
Heat source 5										

28.0 Water Heating

Water Heating	Main Heating 1
SAP Code	901
Flue Gas Heat Recovery System	No
Waste Water Heat Recovery Instantaneous System 1	Yes
Waste Water Heat Recovery Instantaneous System 2	No
Waste Water Heat Recovery Storage System	No
Solar Panel	No
Water use <= 125 litres/person/day	Yes
Cold Water Source	From mains
Bath Count	1
Immersion Only Heating Hot Water	No

28.1 Showers

Description	Shower Type	Flow Rate [l/min]	Rated Power [kW]	Connected	Connected To

28.3 Waste Water Heat Recovery System
Instantaneous System 1

Database ID	80179
Brand Model	Mira Showers, HeatCapture
Details	Year: 2012 + current Efficiency: 0 Utilisation factor: 0.972

29.0 Hot Water Cylinder	Hot Water Cylinder	
Cylinder Stat	Yes	
Cylinder In Heated Space	Yes	
Independent Time Control	Yes	
Insulation Type	Measured Loss	
Cylinder Volume	200.00	L

Loss	1.40	kWh/day
In Airing Cupboard	No	

31.0 Thermal Store None

34.0 Small-scale Hydro None

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

35.0 Special Features

Energy Saved	Fuel Saved	Energy Used	Fuel Used	Description	Monthly Air Change Rates	Special Technologies Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.00		0.00				CO2 saving feature												

Recommendations

Lower cost measures

None

Further measures to achieve even higher standards

Typical Cost	Typical savings per year	Ratings after improvement SAP rating	Environmental Impact
£4,000 - £6,000	£51	B 84	A 97
£3,500 - £5,500	£218	A 92	A 99
		0	0

21.Annex K. Thermal Bridging Calculations

Thermal assessment – Energy House (Junctions)

Report prepared for Bellway Homes Ltd

Document information:	**Prepared for:** Bellway Homes Limited (Group Office) Woolsington House Woolsington Newcastle upon Tyne NE13 8BF	**Date of issue:** 12.08.22 **Issue number:** 1 **Our reference:** 235TB – Energy House (Psi-values)
Assessment information:	Prepared by: George Higgs	

+44(0)7793677215 info@buildingnrg.co.uk buildingnrg.co.uk

Contents

1. Introduction

The client has supplied constructional cross-sectional drawings of the junction(s) to be assessed. The purpose of this project is to establish: a) The linear thermal transmittance (Ψ-value), and; b) The surface temperature factor (f_{Rsi}) of each junction.

2. Methodology

The thermal bridging analysis of each junction has been undertaken in accordance with EN 10211 : 2017 and the guidance in BR497, using Physibel's heat flow program, TRISCO v15 (64-bit). Flanking element U-values have been established in accordance with EN ISO 6946 or EN 10211, as appropriate. Where necessary:

- fenestration framing, glazing and panelling have been assessed in accordance with EN ISO 10077-2, using Physibel's heat flow program, BISCO v12;
- underfloor temperatures have been established via the heat balance equations described in Annex G of EN ISO 13370;

Results for Ψ-values may be compared to those in SAP 2012, while f_{Rsi} values are compared to the critical values in IP1/06 (for the building type in question).

3. Assumptions

Original drawings:

- 'Energy House 2-0 - Timber Frame (E) --Sheet - 20-AC-01 - Section A-A.dxf' dated 7th June 2022;
- 'Energy House 2-0 - Timber Frame (E) --Sheet - 20-AC-03 - Sections C-C & D-D.dxf' dated 7th June 2022;
- 'Energy House 2-0 - Timber Frame (E) --Sheet - 20-AC-04 - Timber Frame Window Details.dxf' dated 7th June 2022;
- 'The Coppersmith - Energy House 2-0 - Rev E --Sheet - 10-AC-03 - Timber Frame Fixing Details.dwg' dated 23 May 2022;
- 'Energy House 2-0 - Timber Frame (H) - Sheet - 10-AC-01 - Ground Floor Setting Out Plan.dxf' dated 22 July 2022;

External wall (cavity unfilled): The external wall is an insulated timber frame construction with internal sheathing insulation, build-up as follows (from external to internal): 102.5mm brickwork (or rendered 100mm dense block), 63mm residual cavity, 9mm OSB, 89mm timber frame filled with insulation (specification $\lambda=0.035Wm^{-1}K^{-1}$), 40mm PIR insulated sheathing (specification $\lambda=0.022Wm^{-1}K^{-1}$, $\varepsilon=0.05$), 25mm low-E service cavity, 12.5mm plasterboard.

External wall (cavity filled): The external wall is an insulated timber frame construction with internal sheathing insulation and filled cavity, build-up as follows (from external to internal): 102.5mm brickwork (or rendered 100mm dense block), 63mm cavity filled with blown mineral fibre (specification $\lambda=0.034Wm^{-1}K^{-1}$), 9mm OSB, 89mm timber frame filled with insulation (specification

λ=0.035Wm^{-1}K^{-1}), 40mm PIR insulated sheathing (specification λ=0.022Wm^{-1}K^{-1}, ε=0.05), 25mm low-E service cavity, 12.5mm plasterboard.

Roof (insulation at ceiling level): The construction is a timber joisted cold pitched roof, build-up as follows (from internal to external): 12.5mm plasterboard, 400mm Knauf Loft roll 44 (specification λ=0.044Wm^{-1}K^{-1}), loft space.

Intermediate floor: The intermediate/party floor build-up is as follows (from top to bottom): 18mm particleboard, 300mm air void between joists, 12.5mm plasterboard.

4. Results

The thermal bridging analysis yields the results for linear thermal transmittance and surface condensation given in table 1.

Table 1: Junction ψ-values and surface condensation risk results

Junction	Drawing reference	SAP reference	63mm cavity	Constructional ψ-value	Dwelling ψ-value	Temperature factor, f_{Rsi}
				$Wm^{-1}K^{-1}$	$Wm^{-1}K^{-1}$	-
Head (interfacing eaves)	20-AC-04	E1/E2	Clear	0.046	0.046	0.91
			Mineral fibre	0.052	0.052	0.91
Sill	20-AC-04	E3	Clear	0.026	0.026	0.93
			Mineral fibre	0.020	0.020	0.94
Jamb	20-AC-04	E4	Clear	0.047	0.047	0.94
			Mineral fibre	0.031	0.031	0.95
Intermediate floor within a dwelling	20-AC-01	E6	Clear	0.062	0.062	0.95
			Mineral fibre	0.034	0.034	0.97
Eaves (insulation at ceiling level)	20-AC-01	E10	Clear	0.077	0.077	0.91
			Mineral fibre	0.082	0.082	0.91
Gable (insulation at ceiling level	20-AC-03	E12	Clear	0.038	0.038	0.94
			Mineral fibre	0.037	0.037	0.94
Corner (normal)	10-AC-03	E16	Clear	0.042	0.042	0.91
			Mineral fibre	0.035	0.035	0.93
Partition wall	10-AC-01	-	Clear	0.025	0.025	0.95
			Mineral fibre	0.013	0.013	0.97

The results in table 1 indicate the performance of the junction. Results for alternate junctions with differing design or flanking element build-ups should be calculated separately.

5. Conclusions

The 'Dwelling ψ-value' should be applied to the actual junction length in SAP. The risk of surface condensation for a given junction is predicted to be low when its temperature factor, f_{Rsi} (given above), is greater than or equal to the critical temperature factor, f_{CRsi}, for the building type (for dwellings f_{CRsi}=0.75), as per BRE Information Paper IP1/06.

Disclaimer:

This report is made on behalf of BEPC. By receiving the report and acting on it, the client - or any third party relying on it - accepts that no individual is personally liable in contract, tort or breach of statutory duty (including negligence).

The results in this report are based upon the cases, drawings and specifications provided, and have been calculated in accordance with the standards mentioned. BEPC accepts no responsibility for the accuracy or validity of information provided. Any deviations to the drawing, specification or calculation method may have a detrimental effect on the performance of the system, or increase risks associated with condensation, and should therefore be re-calculated.

Appendix

Further information:

Figure A.1: E1/E2 (drawing 20-AC-04) – technical drawing

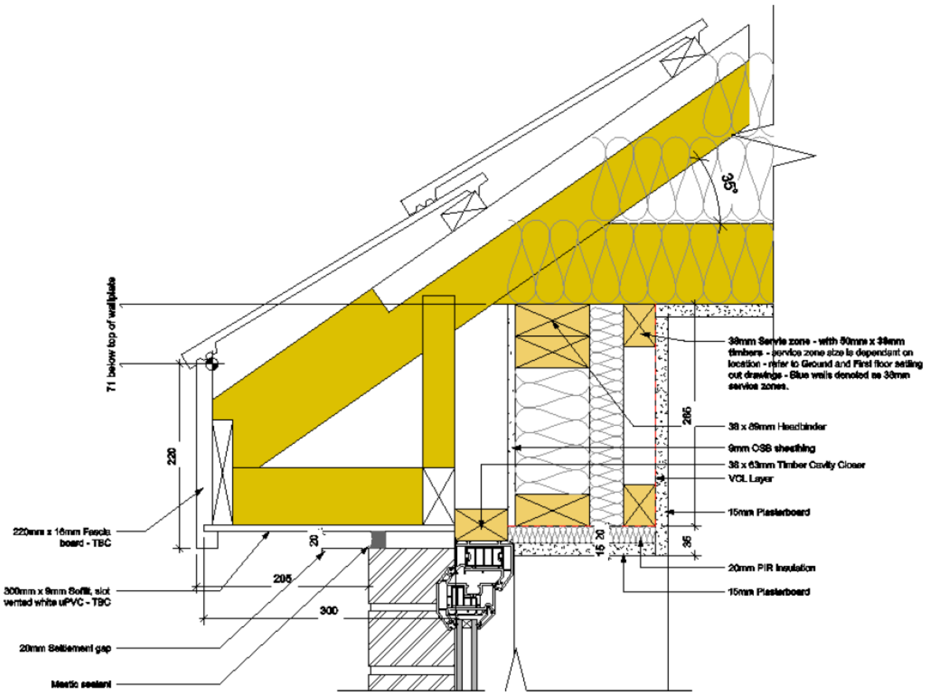


Figure A.2: E1/E2 (drawing 20-AC-04) unfilled cavity – Materials legend

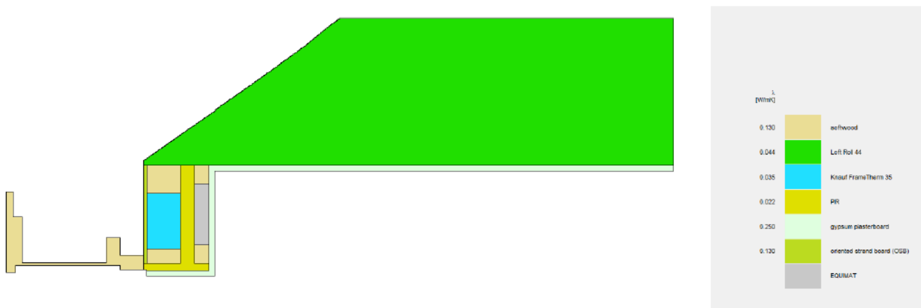


Figure A.3: E1/E2 (drawing 20-AC-04 unfilled cavity)– temperature profile & result

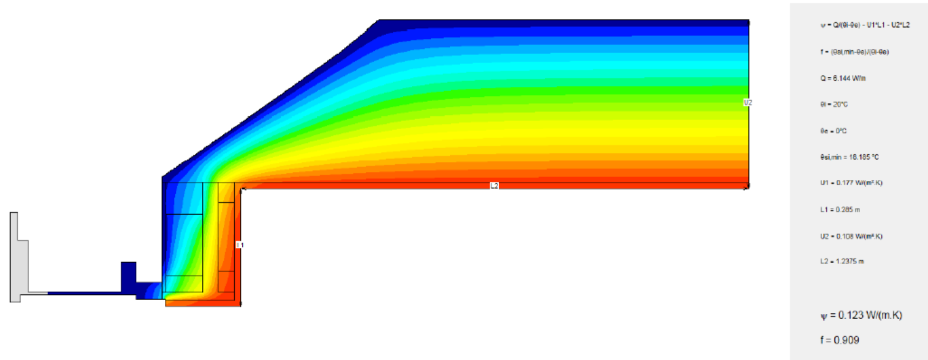


Figure A.4: E1/E2 (drawing 20-AC-04) insulated cavity – Materials legend

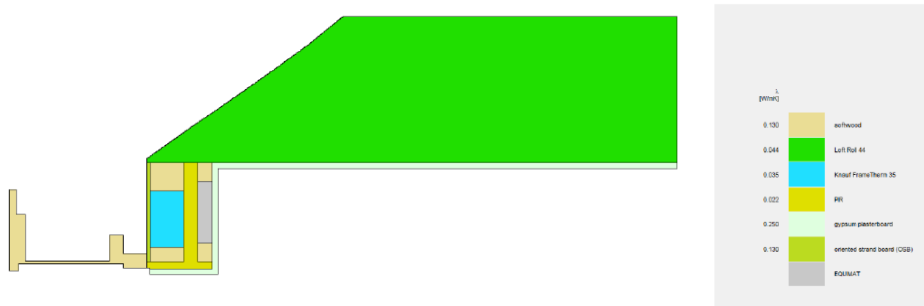


Figure A.5: E1/E2 (drawing 20-AC-04) insulated cavity – temperature profile & result

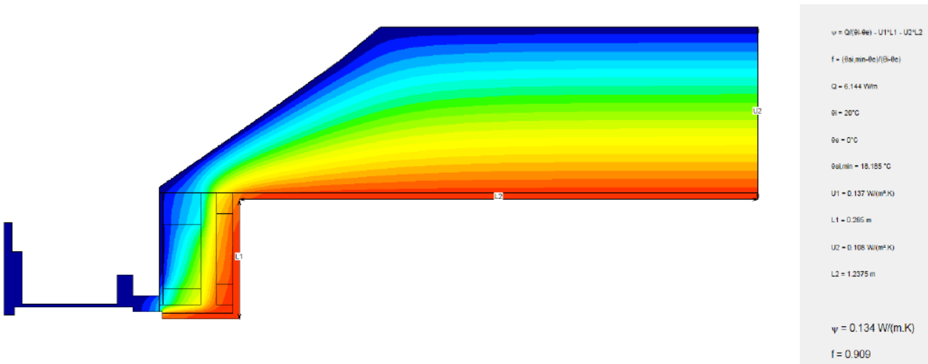


Figure A.6: E3 (drawing 20-AC-04) – technical drawing

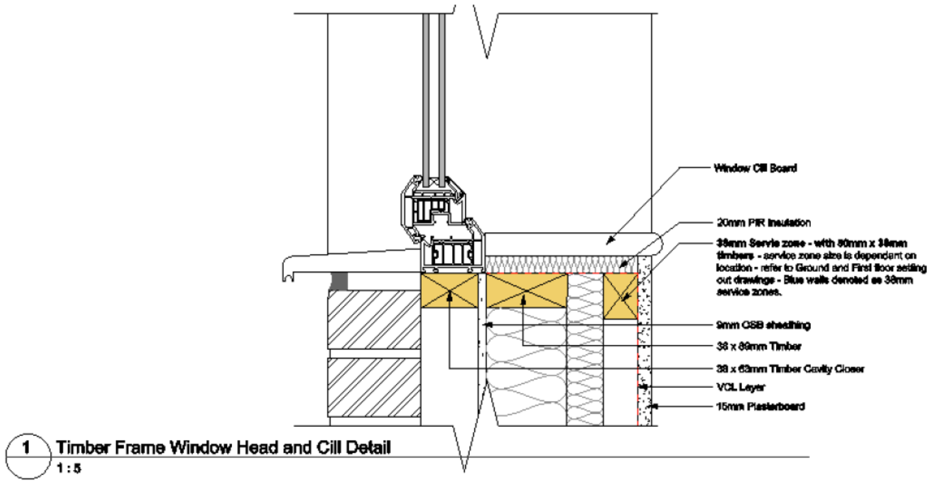


Figure A.7: E3 (drawing 20-AC-04) unfilled cavity – Materials legend

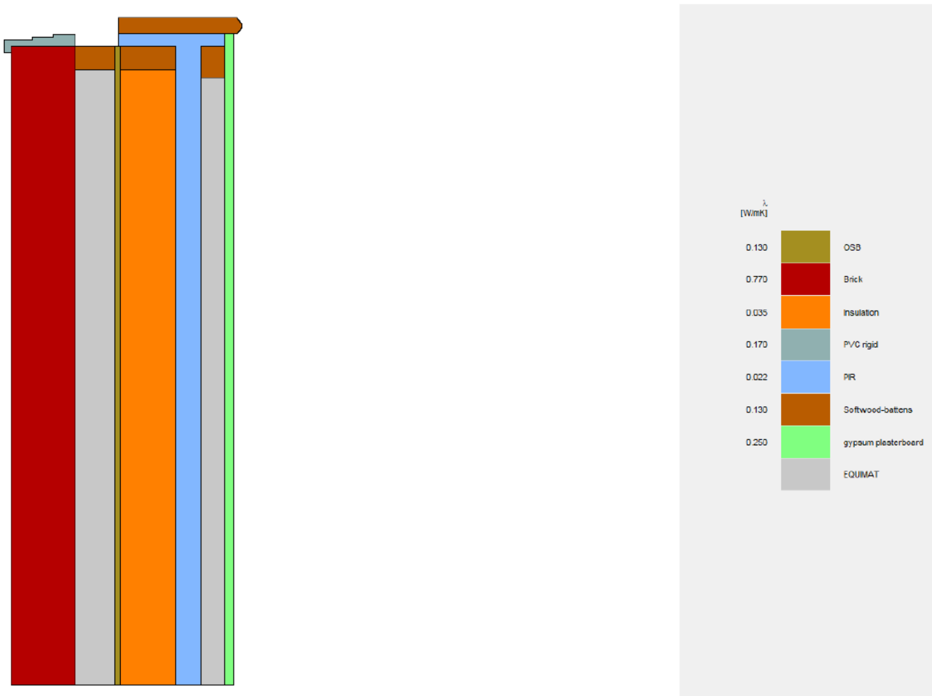


Figure A.8: E3 (drawing 20-AC-04) unfilled cavity – temperature profile

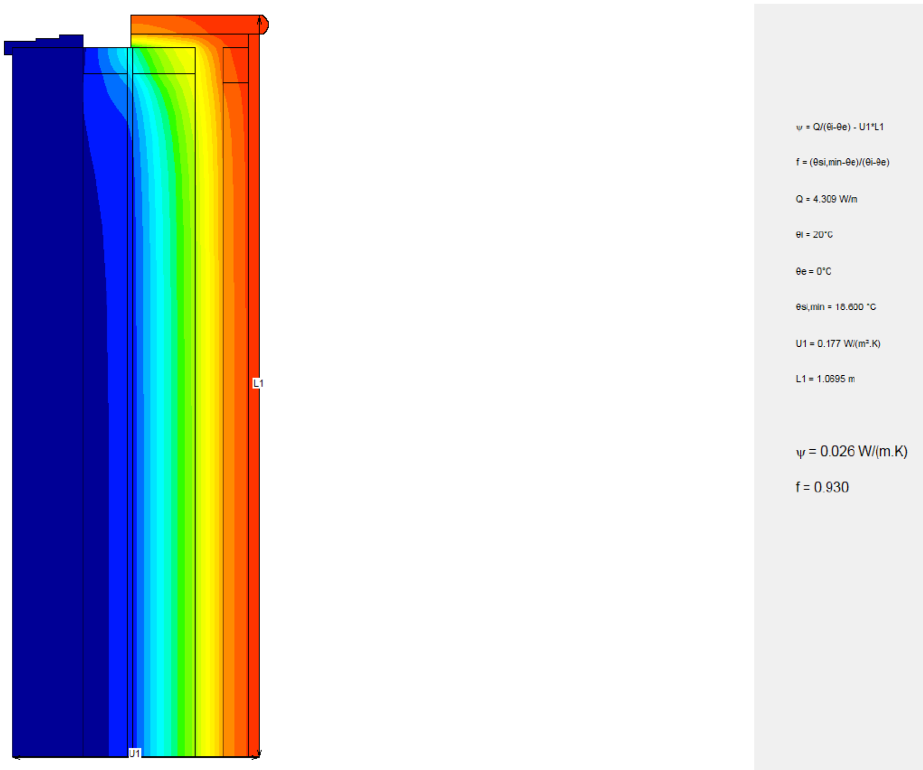


Figure A.9: E3 (drawing 20-AC-04) filled cavity – Materials legend

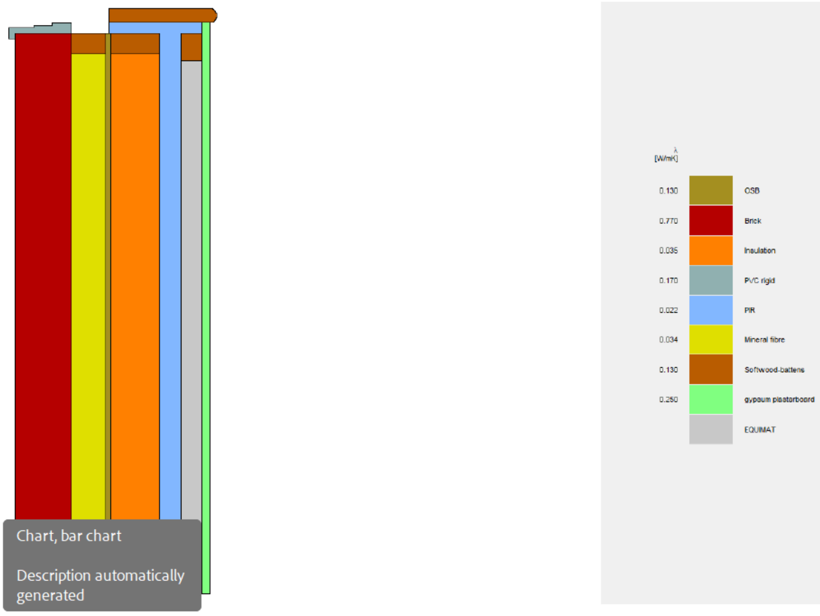


Figure A.10: E3 (drawing 20-AC-04) filled cavity – temperature profile & result

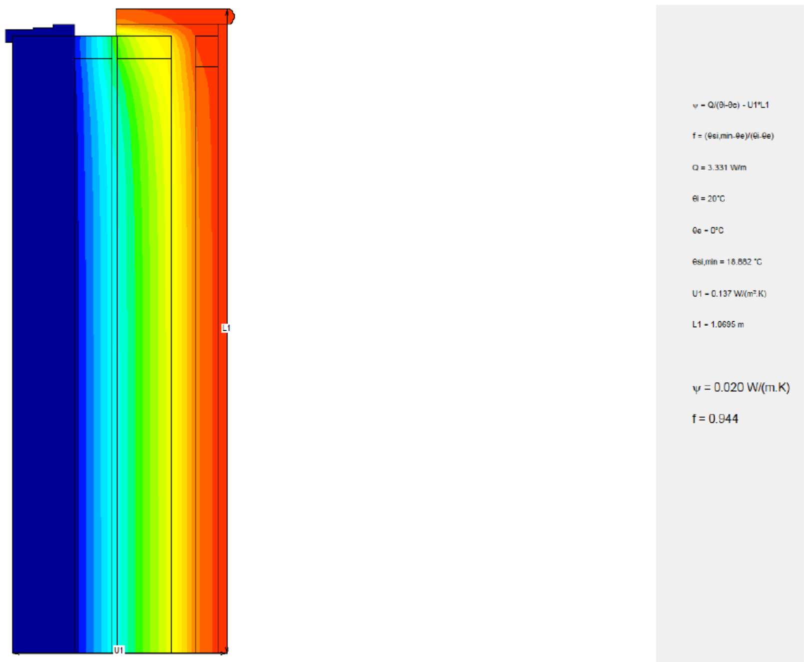


Figure A.11: E4 (drawing 20-AC-04) – technical drawing

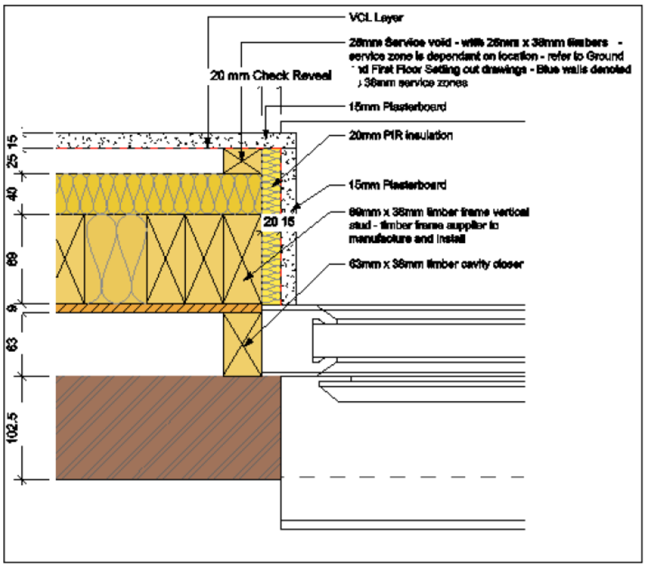


Figure A.12: E4 (drawing 20-AC-04) unfilled cavity– materials legend

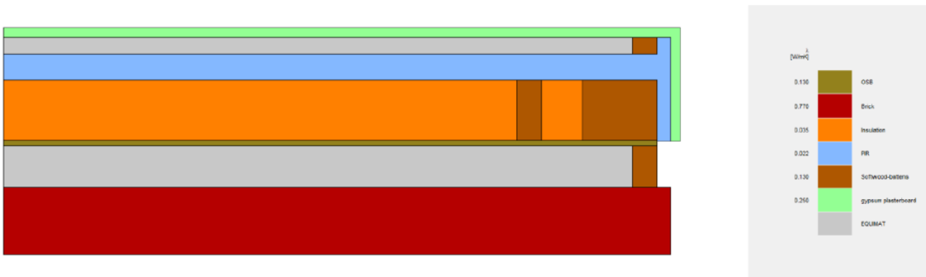


Figure A.13: E4 (drawing 20-AC-04) unfilled cavity – temperature profile & result

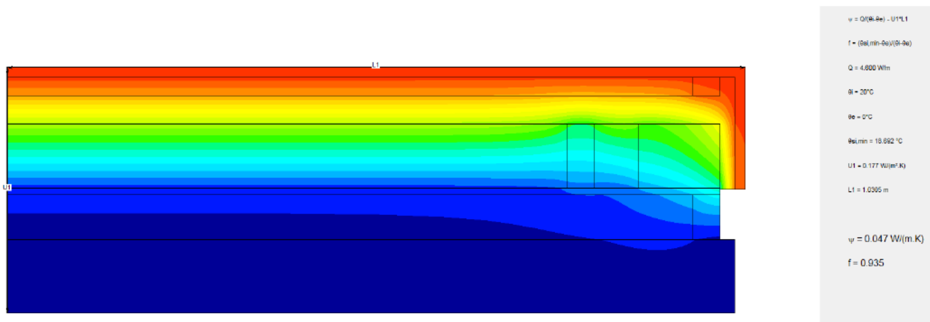


Figure A.14: E4 (drawing 20-AC-04) filled cavity– materials legend

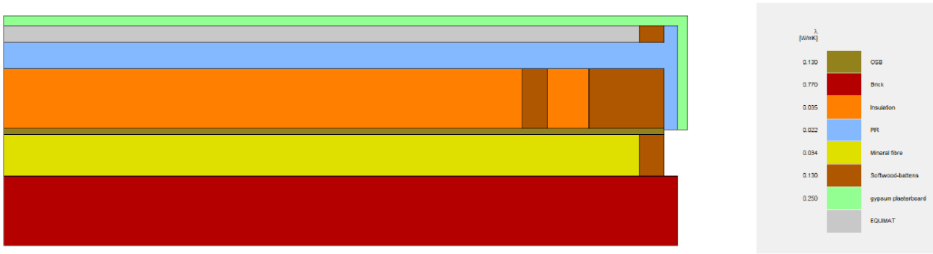


Figure A.15: E4 (drawing 20-AC-04) filled cavity – temperature profile & result

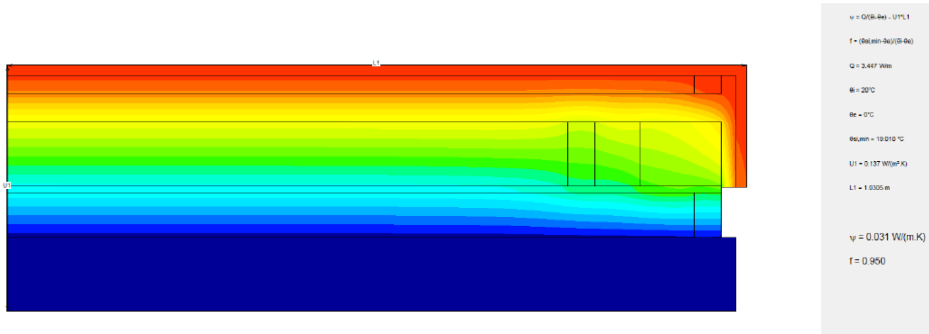


Figure A.16: E6 (drawing 20-AC-01) – technical drawing

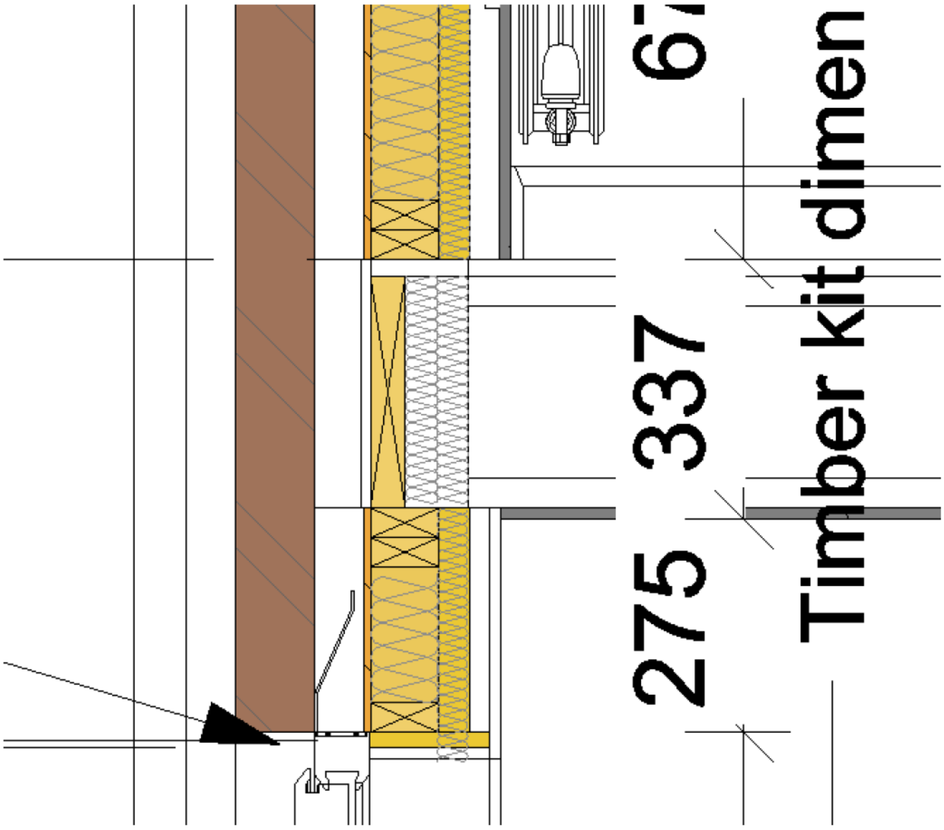


Figure A.17: E6 (drawing 20-AC-01) unfilled cavity – materials legend

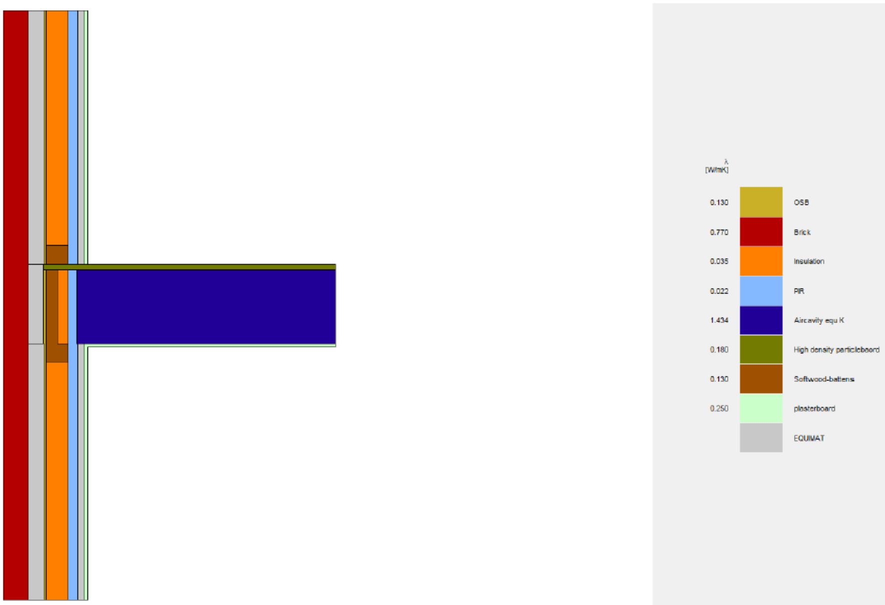


Figure A.18: E6 (drawing 20-AC-01) unfilled cavity – temperature profile & result

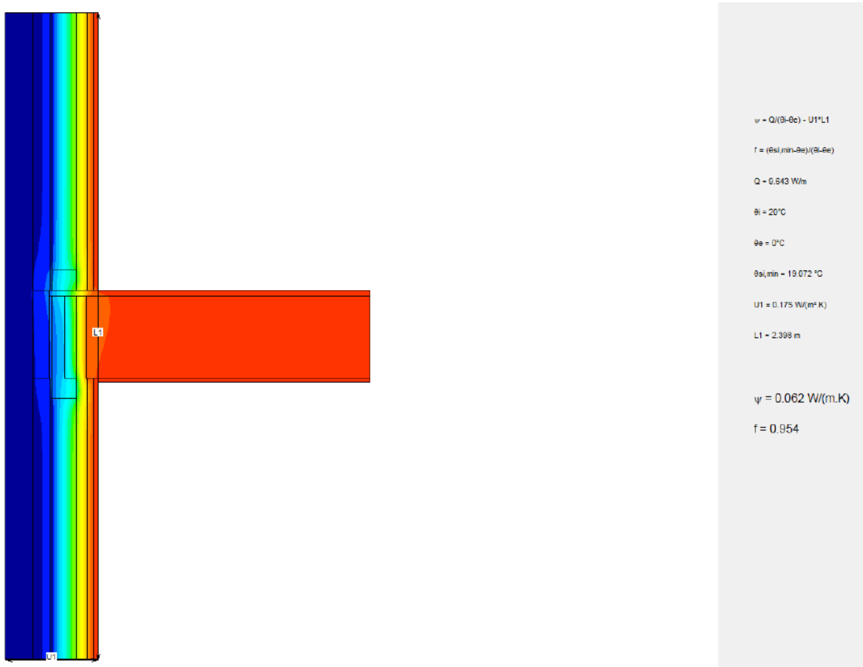


Figure A.19: E6 (drawing 20-AC-01) filled cavity – materials legend

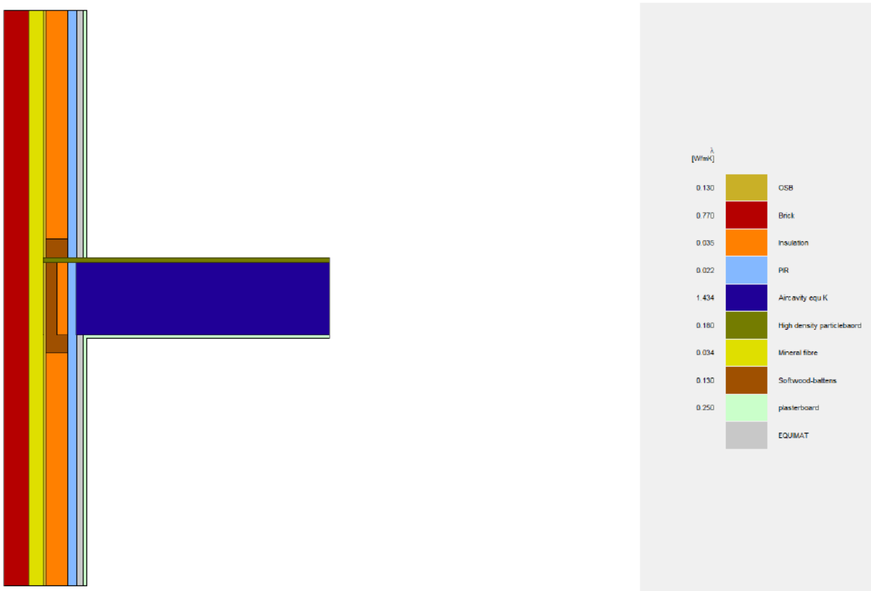


Figure A.20: E6 (drawing 20-AC-01) filled cavity – temperature profile & result

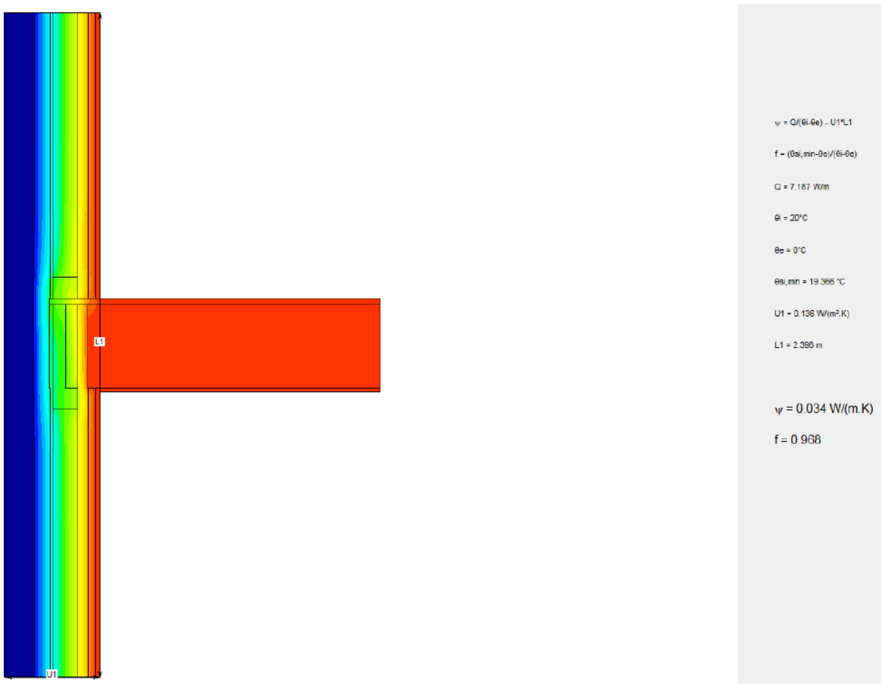


Figure A.21: E10 (drawing 20-AC-01) – technical drawing

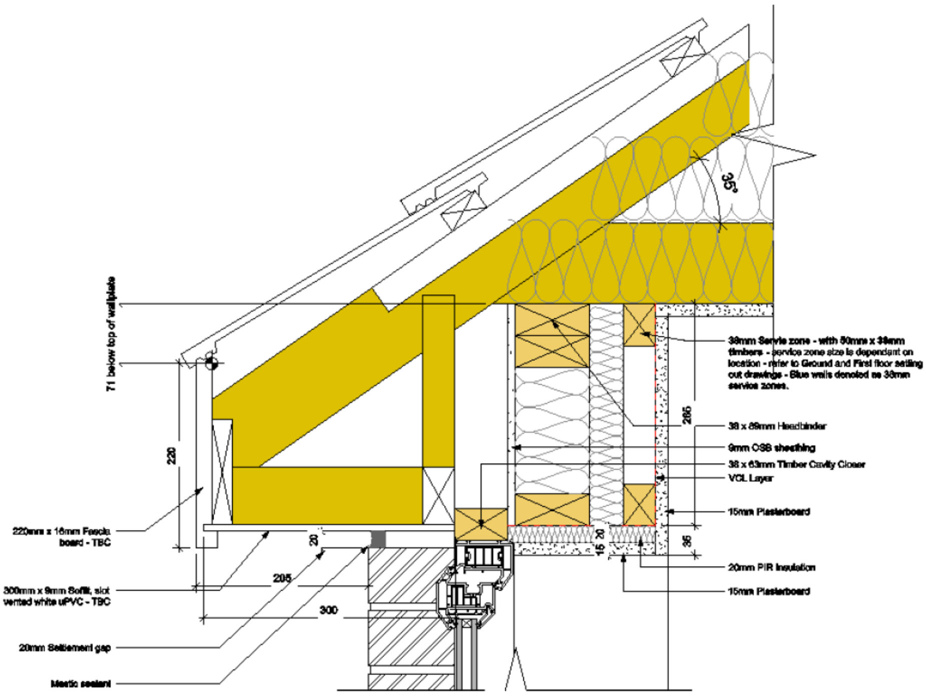


Figure A.22: E10 (drawing 20-AC-01) unfilled cavity – materials legend

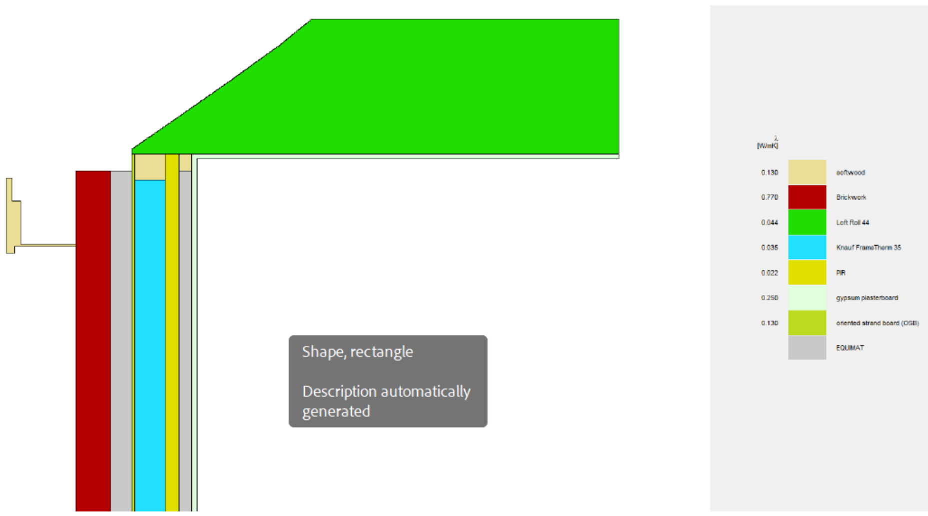


Figure A.23: E10 junction (drawing 20-AC-01) unfilled cavity – temperature profile & results

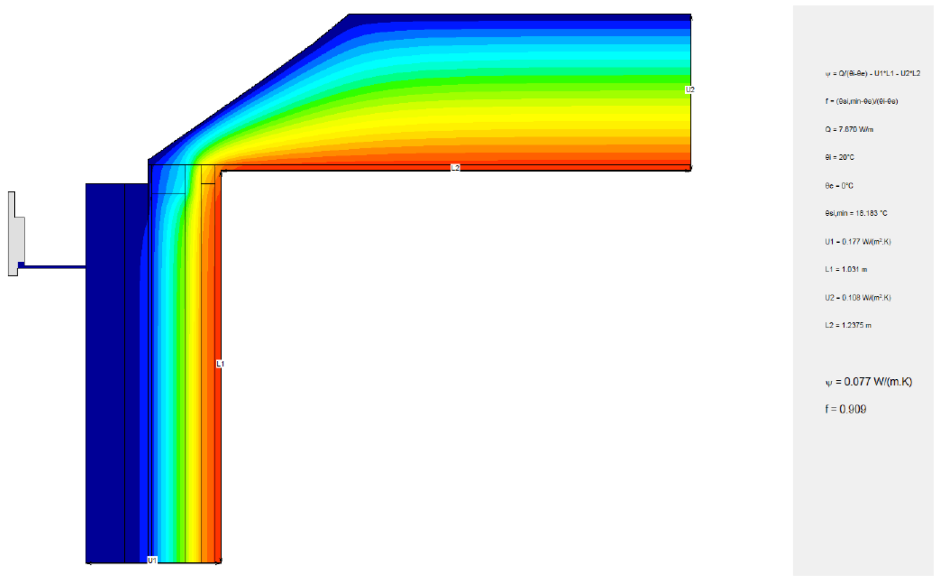


Figure A.24: E10 (drawing 20-AC-01) filled cavity – materials legend

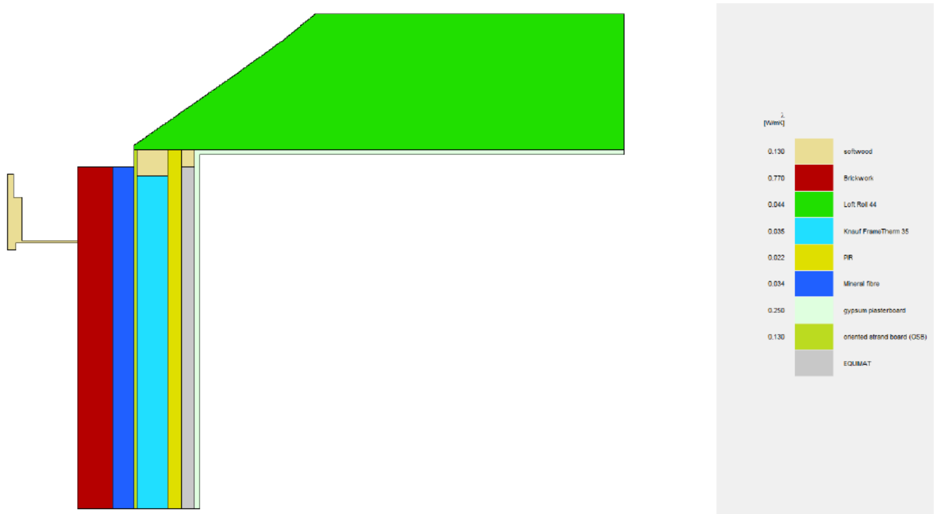
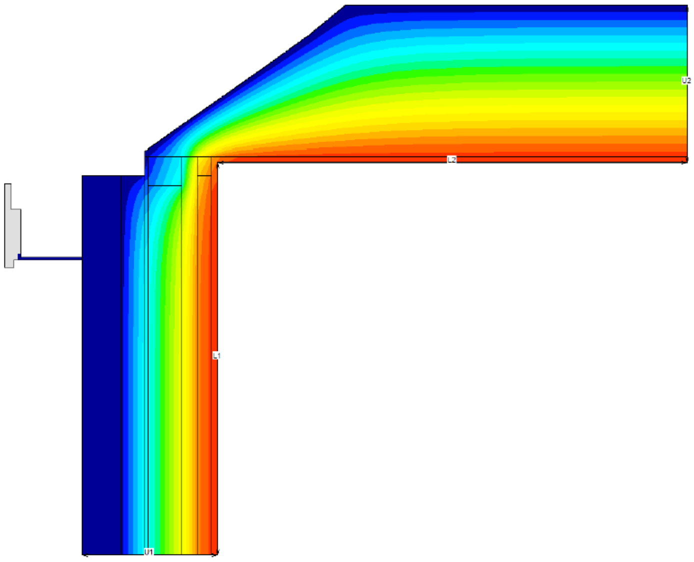


Figure A.25: E10 (drawing 20-AC-01) filled cavity – Temperature profile & results



$\psi = Q/(\theta i - \theta e) - U1*L1 - U2*L2$

$f = (\theta si,min - \theta e)/(\theta i - \theta e)$

$Q = 7.132$ W/m

$\theta i = 20°C$

$\theta e = 0°C$

$\theta si,min = 18.211$ °C

$U1 = 0.137$ W/(m².K)

$L1 = 1.031$ m

$U2 = 0.108$ W/(m².K)

$L2 = 1.2375$ m

$\psi = 0.082$ W/(m.K)

$f = 0.911$

Figure A.26: E12 (drawing 20-AC-03) – technical drawing

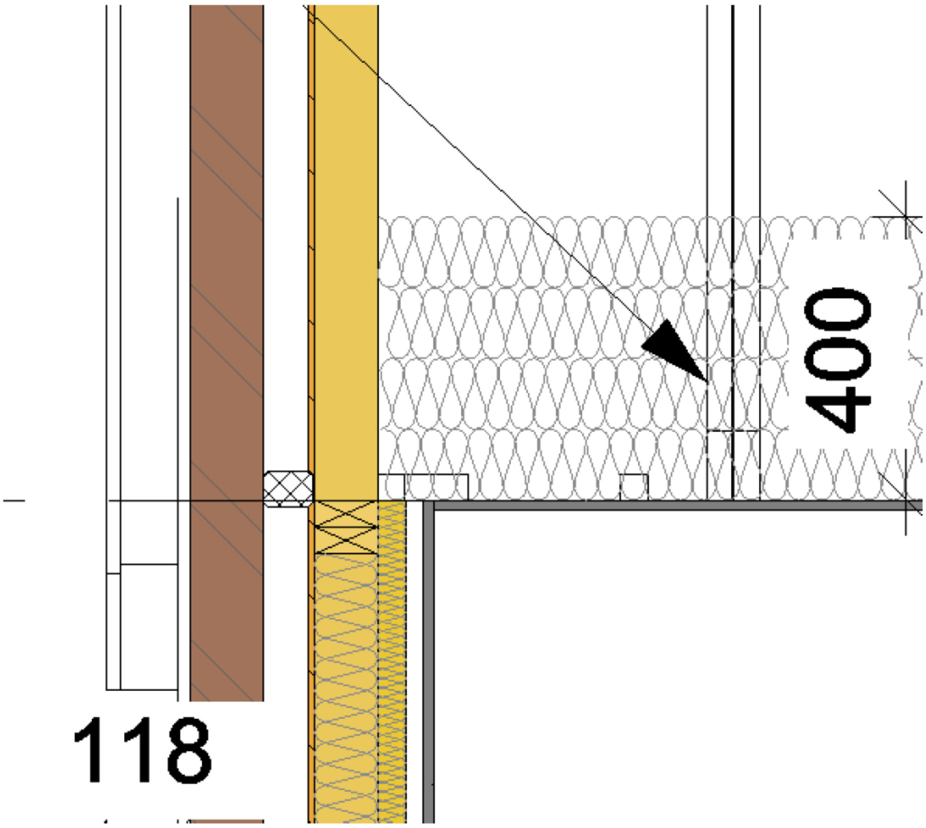


Figure A.27: E12 (drawing 20-AC-03) unfilled cavity – materials legend

Figure A.28: E12 (drawing 20-AC-03) unfilled cavity – temperature profile & results

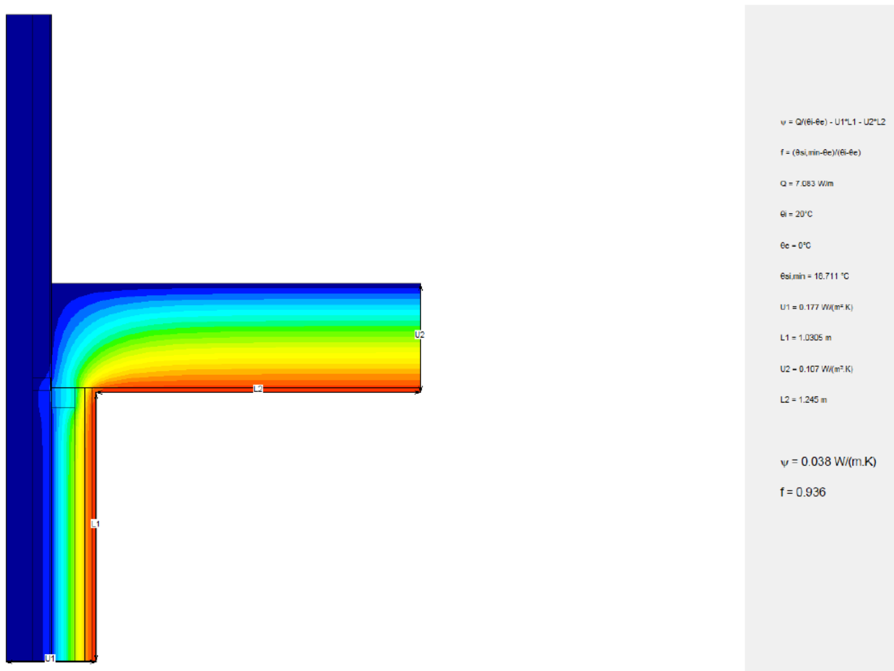


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Figure A.29: E12 (drawing 20-AC-03) filled cavity – materials legend

Figure A.30: E12 (drawing 20-AC-03) filled cavity – temperature profile & results

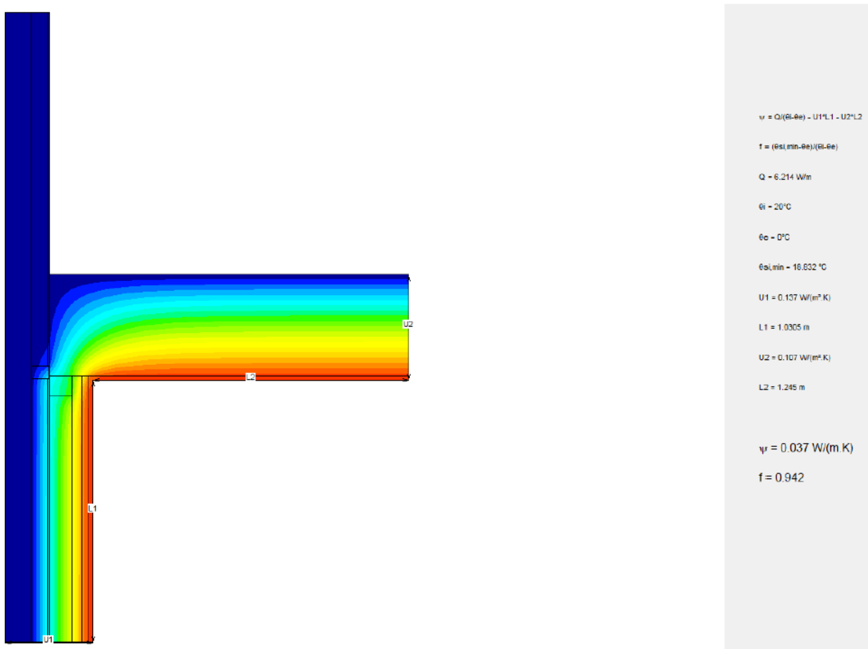


Figure A.31: E16 (drawing 10-AC-03) – technical drawing

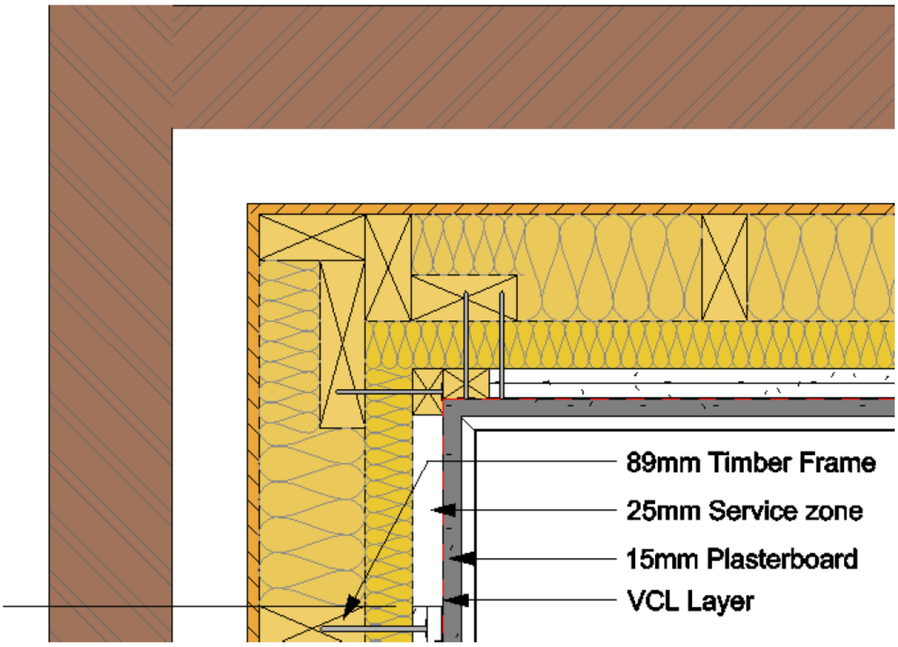


Figure A.32: E16 (drawing 10-AC-03) unfilled cavity – materials legend

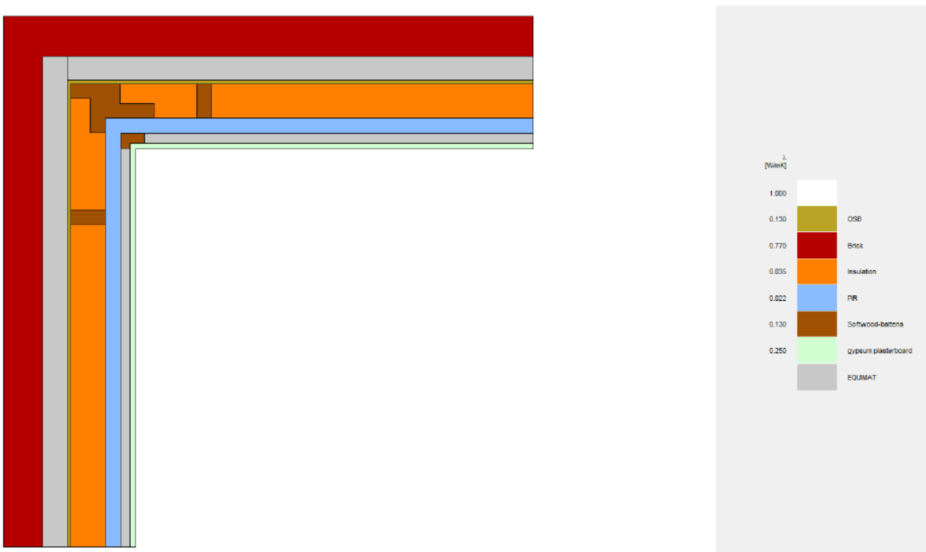


Figure A.33: E16 (drawing 10-AC-03) unfilled cavity – temperature profile

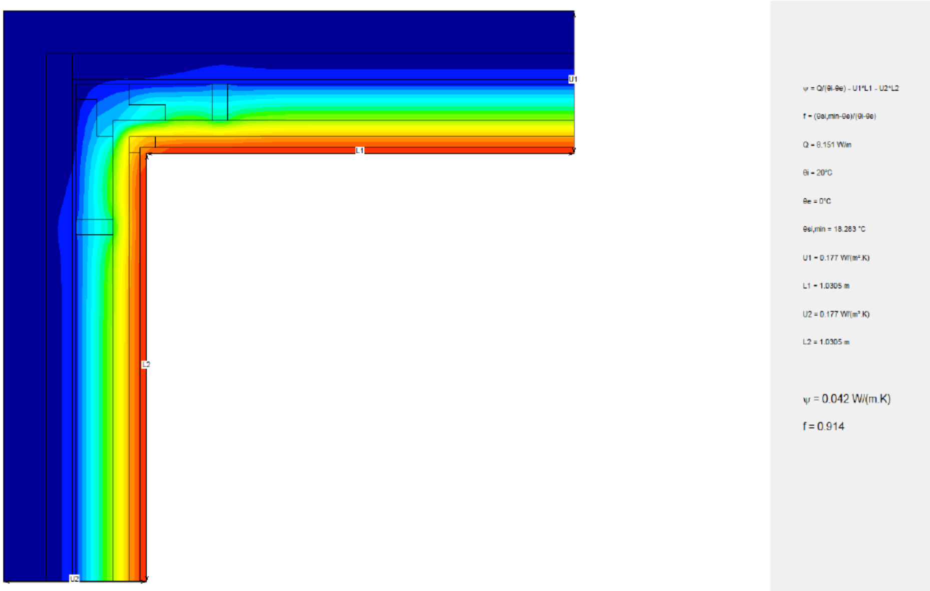


Figure A.34: E16 (drawing 10-AC-03) filled cavity – materials legend

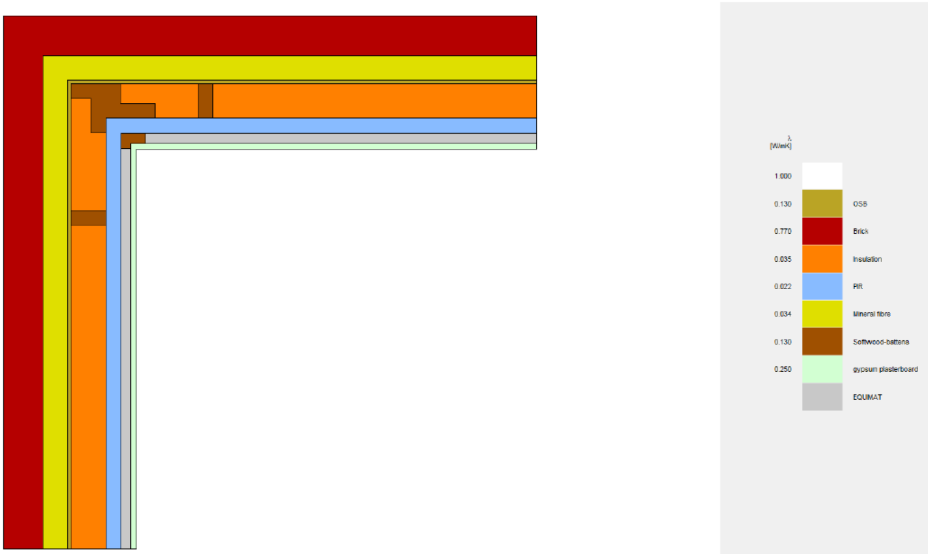


Figure A.35: E16 (drawing 10-AC-03) filled cavity – temperature profile

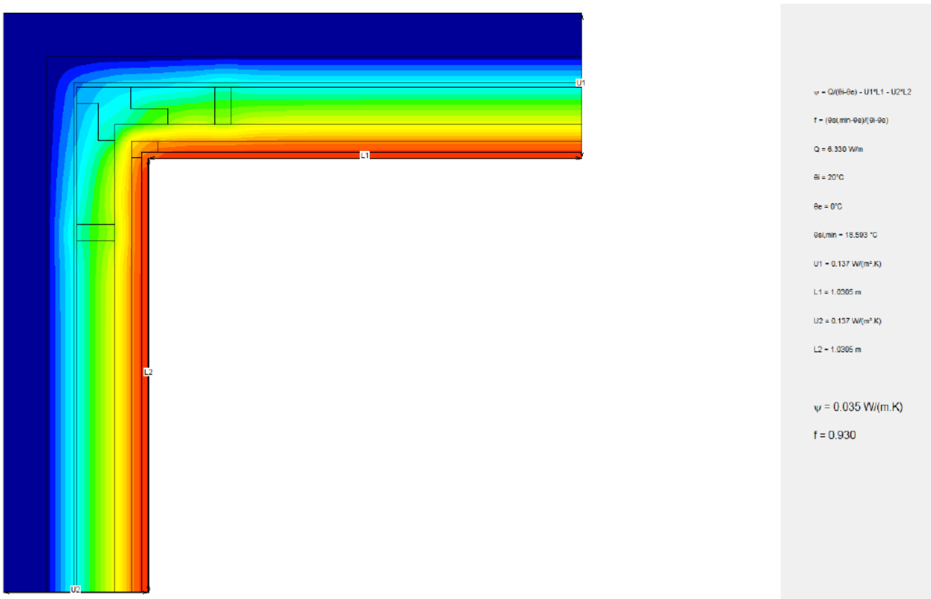


Figure A.36: Partition wall (drawing 10-AC-01) – technical drawing

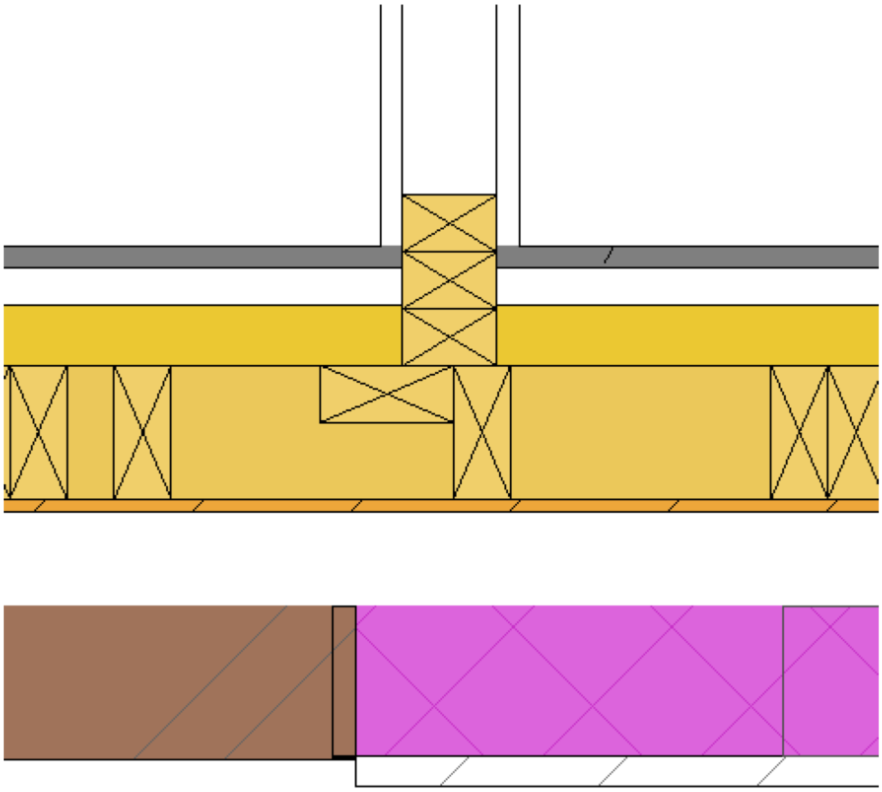


Figure A.37: Partition wall (drawing 10-AC-01) unfilled cavity – materials legend

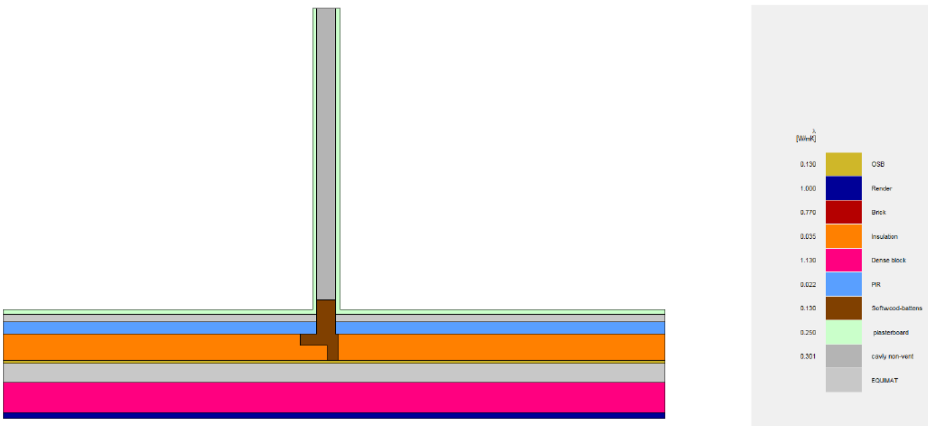


Figure A.38: Partition wall (drawing 10-AC-01) unfilled cavity – temperature profile

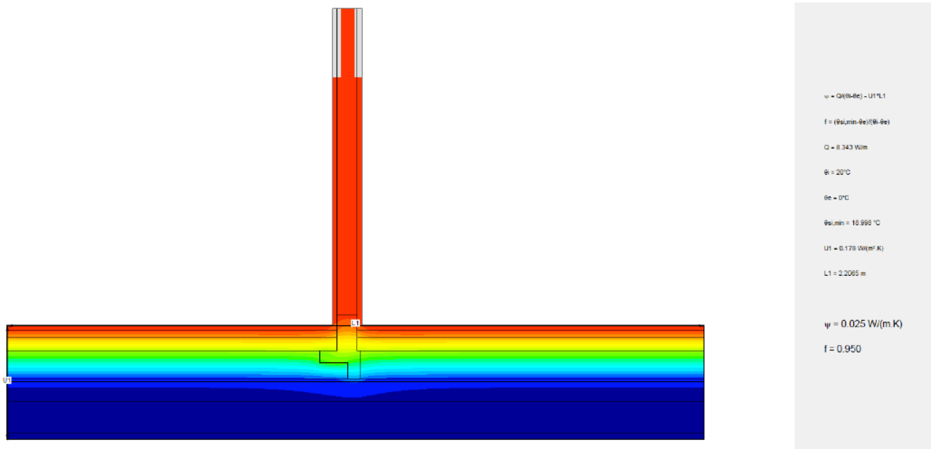


Figure A.39: Partition wall (drawing 10-AC-01) filled cavity – materials legend

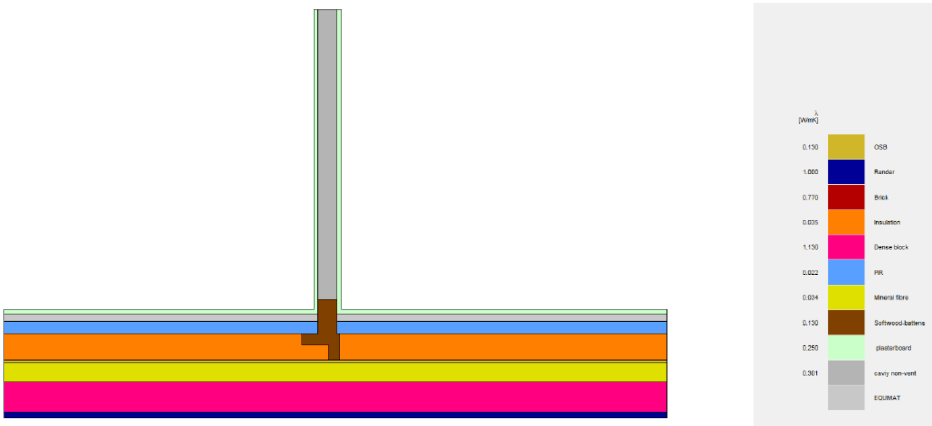
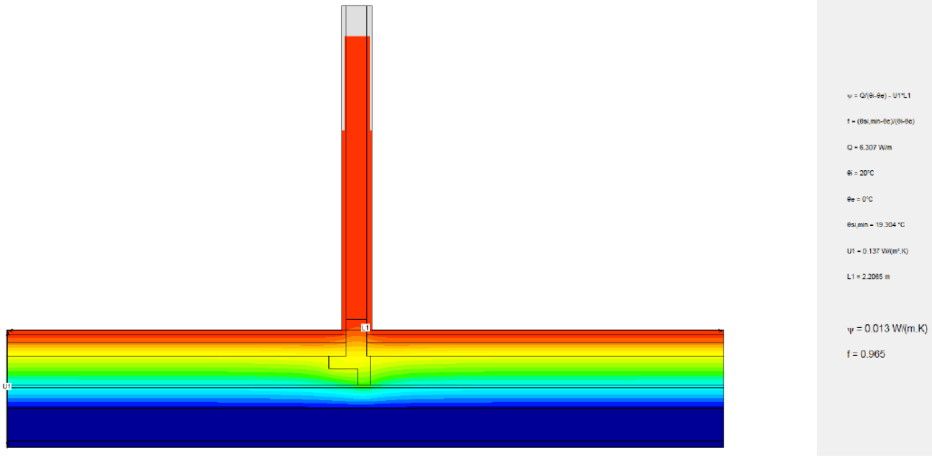


Figure A.40: Partition wall (drawing 10-AC-01) filled cavity – temperature profile



22.Annex L. Calculation of U-value with different R_{se}

The thermal transmittance of a building element is obtained by combining the thermal resistance of its component's parts and the adjacent air layers as in Equation 1.

$$U = \frac{1}{R_t} = \frac{1}{R_{si}+R_t+R_{se}} \quad \text{(eq. 1)}$$

Where U is the thermal transmittance (W/m^{2}K) R_{si} is internal surface resistance (m^{2}K/W) R_t is the sum of all the thermal resistances components (m^{2}K/W) and is the external surface resistance (m^{2}K/W).
By having a measurement, we obtain the U-value and if we assume that the R_{si} and R_t value is not affected by the wind speed we can obtain Equation 2 where R_p is the sum of R_{si} and R_t.

$$U_{measured} = \frac{1}{R_p+R_{se}} \quad \text{(eq. 2)}$$

According to CIBSE Design Guide A the external surface resistance is given by Equation 3.

$$R_{se} = \frac{1}{Eh_r+h_c} \quad \text{(eq.3)}$$

Where E is the emissivity factor, h_r is the radiative heat transfer coefficient (W/m^{2}K) and h_c is the convective heat transfer coefficient (W/m^{2}K). CIBSE Design Guide A also suggests that the correlation of h_c is given by Equation 4. Where WS is the wind speed.

$$h_c = 5.8 + 4.1 \text{ WS} \quad \text{(eq.4)}$$

The standard value of R_{se} in ISO 6946 is 0.04 m^{2}K/W for Wind speeds of 4 m/s, 0.02 m^{2}K/W for speeds of 2 m/s. If we assume a speed of 2 m/s for a R_{se} of 0.02 m^{2}K/W and calculate Eh_r, and then we substitute a new value of h_c using measured WS and recalculate R_{se} and the U value. If we compare the difference of the U value using R_{se} standard vs the measured WS value this difference is less than 1%.

23.References

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