Energy House 2.0 Systems Report

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Executive Summary

This research provides information on the performance on a large collection of different heating systems present in the Future Homes test houses at the Energy House 2.0 facility at the University of Salford. These houses were built by Bellway Homes and a partnership between Saint Gobain and Barratt developments. The report follows up on a report published in 2023 on the fabric performance of both of these homes.

The systems were selected, designed and installed by the housebuilders and their partners. The research team had no input on the design of these systems and were focussed only on the measurement of the performance of these systems, which number 28 in total, and covered a range of technologies including, infrared heat panels and air source heat pumps (floor mounted and roof mounted) different heat emitter technologies were also tested including underfloor heating, skirting board heating and radiators.

All methods of heating the home were measured in the same chamber conditions reflecting typical (5 °C) and more extreme (-5 °C) winter temperatures found in the UK. This allows for a comparison between these technologies that up to this moment has not been possible and represents unique research.

The main findings from this research are as follows:

The infrared systems proved to have the lowest system efficiency out of all the systems, yet they tended to the heat the rooms in a much quicker way with minimal stratification and good levels of thermal comfort. They also struggled to reach the required heating requirements at low chamber temperatures which simulated extreme winter conditions. This was felt to be due to under sizing rather than an issue with the technology.

The air source heat pumps performance was considered to fall in line with expectations, and performed well, but not as well as could have been expected if they were perfectly commissioned and set up. The exception to this was the R&D roof mounted system, provided by Worcester Bosch, this did not perform as well as the other heat pumps which could have been explained by its unique nature and early-stage development.

In terms of heat emitters, this was a significant point of underperformance, this could have been due to the fact that the emitters were under designed or the commissioning was not effective. This led to a significant degree of underheating in particular at the lower chamber temperature which simulated extreme winter conditions.

The key learnings for industry are:

- Heat emitter design needs to be improved, underheating during intermittent heating schedules was found throughout all emitter types.
- More commitment is needed to the installation and commissioning process, when done effectively this can lead to further efficiency in the heating systems
- Care should be taken around product submission and verification of installed equipment as incorrect equipment will lead to poorer performance

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Nomenclature

Table 1.Nomenclature

Symbol	Description
ASHP	Air Source Heat Pump
DWS	Domestic water source
MEV	Mechanical Extract Ventilation
MVHR	Mechanical Ventilation with Heat Recovery
n	Ventilation rate
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^{2}K)
ΔT	Internal to external temperature difference (K)

1. Introduction

1.1 Energy House Labs

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.

1.2 Energy House 2.0

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.

2. Fabric

2.1 The Future Homes Standard

In December 2023, the Future Homes Standard (DLUHC, 2023) consultation was released, as can be seen from Table 2 both homes that were measured, either meet or exceed the fabric standards that are given in the consultation document.

Table 2. Comparison of the Future Homes Standard to the design specification of TFH and eHome2.

	Future Home Standard		TFH	eHome2
	Option 1	Option 2	Design	Design
Roof U-value (W/m²K)	0.11	0.11	0.09	0.11
External walls U-value (W/m²K)	0.18	0.18	0.18	0.13
	0.18	0.18	0.18	0.13
	0.18	0.18	0.17	-
Floor U-value* (W/m²K)	0.13	0.13	0.11	0.11
Window U-value (W/m²K)	1.20	1.20	1.20	1.20
Door U-value (W/m²K)	1.00	1.00	1.00	1.20
Airtightness ($m^3h^{-1}m^{-2}$ @ 50Pa)	4.00	5.00	2.50	3.00

3. As-Built Performance - Overview

In a previous piece of research, the whole house aggregated heat loss was measured for both houses, this was carried out using the Coheating test method. The full details including all analysis can be found in the final reports:

- Bellway "The Future Home" Baseline Performance Report (Fitton et al., 2024a)
- Saint Gobain & Barratt Developments "eHome2" Baseline Performance Report (Fitton et al., 2024b)

4. Purpose of research

The purpose of this research is to characterise the performance of the different heating systems installed within both TFH and eHome2. Multiple heating systems were installed in both properties, more than would be installed in a typical dwelling. The research team at Energy House Labs can quickly and easily switch between them for the varying experiments.

The research considers two different heating patterns – 24h Constant heating, and the SAP heating pattern of 07:00-09:00 and 16:00-23:00, found in Table 9 of SAP 10.2 (BRE, 2021). The internal setpoint temperatures were based on SAP, with the Living Room set to 21 °C, and all other zones set to 18 °C.

All tests were conducted at both a constant 5 °C and constant -5 °C chamber temperature. The +5 °C was deemed typical of the UK average winter temperature, whereas the -5 °C was used to measure the heating system performance under more extreme UK winter conditions.

Figure 1 below illustrates the average temperatures in the UK according to Table U1 of SAP10.2 (BRE, 2021). These temperatures were used to provide a representative external temperature of the United Kingdom during the winter months (December to March).

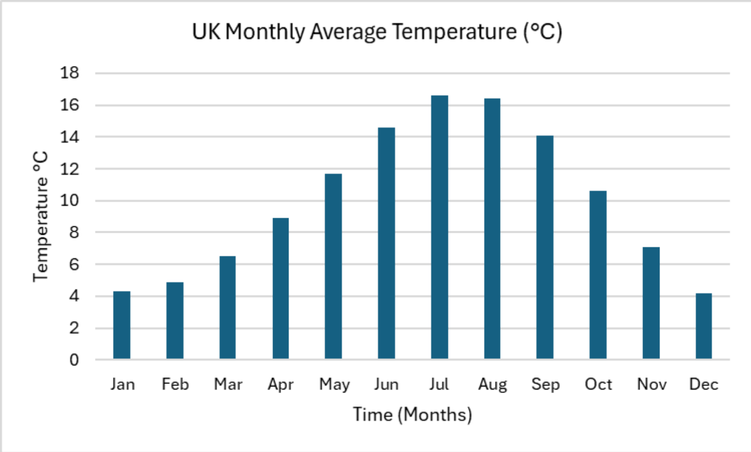


Figure 1. Average Monthly U.K. Temperature

5. Systems

Due to the variety of systems which were to be tested as part of this research project, each property has multiple heating systems, and emitters, installed simultaneously. These different systems and emitters could be opened/isolated to facilitate different tests, without the need to install/remove each system between the tests.

5.1 TFH

5.1.1 Design

The design of the building services elements studied in this work were designed by Bellway and their partners. The research team was not responsible for this design. The details of this design will be provided in the next section for reference.

5.1.1.1 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.

5.1.1.1.1 Air Source Heat Pump (1) (Panasonic -External)

The primary source of space and hot water provision is provided by a monobloc 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 design 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.

Figure 2. Panasonic ASHP

5.1.1.1.2 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.

Figure 3. Worcester Bosch ASHP Hydrotop (Left), Internal Unit (Right)

5.1.2 Heat Emitting Systems – Radiators

A combination of single and double panel compact radiators has been installed as shown in Table 3.

Table 3. 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

5.1.3 Heat Emitting Systems – Underfloor Heating

The underfloor heating (UFH) system is installed to 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.

Figure 4. Underfloor heating manifold

5.1.4 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 4. It should be noted that the system is not present in the WC, Bathroom and Ensuite.

Table 4. 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

Figure 5. Wondrwall infrared panel

5.1.5 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 5, an example is shown in Figure 6.

Table 5. 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

Figure 6. Ambion infrared panels

5.1.6 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.

Figure 7. Honeywell TRV

5.1.7 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. This is detailed below.

5.1.7.1 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 6. This is a continually running system, with the opportunity for a manual boost. **Note: An MVHR system is installed in the home but was not used in this series.**

Table 6. dMEV commissioned flow rates

Room	**Continuous Flow Measured Rate (L/s)**
Kitchen/Dining	13
WC	6
Ensuite	8
Bathroom	8

5.2 eHome2

5.2.1 Design

The building services elements studied in this work were designed by Saint Gobain & Barratt and their partners. The research team was not responsible for this design. The details of this design will be provided in the next section for reference.

5.2.1.1 Air Source Heat Pump - Vaillant Arotherm Plus

The primary source of space and hot water provision is provided by a monobloc air to water heat pump system. This is a Vaillant Arotherm Plus 5 kW running on R290 refrigerant (propane), this specification will typically provide 6.4 kW of heating with a COP of 4.07 at an outside air temperature of 2 °C, with a hot water flow temperature of 35 °C.

Figure 8. Vaillant ASHP External Unit

5.2.1.2 Heat Emitting Systems – Thermaskirt

The heat emitters attached to the heat pump are skirting board emitters. This product is called Thermaskirt (Deco range). These are controlled by addressable TRV heads. The products are sized to meet the specification below (design temperature of 45 °C flow temperature at -3 °C outside).

Table 7. Thermaskirt Specification (sized at 45 °C flow -3 °C design temperature)

Room Type	**Emitter length**	**Heat Output (according to design)**	**Model Reference**
Living Room	11.74 m x 115 mm	693 Watts	BM2
Kitchen/Dining (wall)	5.96 m x 170 mm	604 Watts	BM3
Kitchen/Dining (plinth)	4.35 m x 115 mm	257 Watts	BM2
Bedroom 1	6.41 m x 115 mm	378 Watts	BM2
Bedroom 2	5.86 m x 115 mm	346 Watts	BM2
Bedroom 3	4.55 m x 115 mm	268 Watts	BM2

Figure 9. Thermaskirt cross section

5.2.1.3 Heat Emitting Systems – Bathroom towel radiators.

The ASHP in eHome2 uses the Thermaskirt to provide the space heating, however in bathroom areas this system is not used, they are heated by towel heating radiators, as shown below in Table 8.

Table 8. Bathroom towel radiators Specification

Room Type	**Height (mm)**	**Width (mm)**	**Type**
Hall	600	500	Stelrad Compact K2
WC	1211	500	Stelrad Home Classic White Towel Rail
Bathroom	1744	500	Stelrad Home Classic White Towel Rail
Ensuite	1744	500	Stelrad Home Classic White Towel Rail

Figure 10. Bathroom towel radiator

5.2.1.4 Infrared Heating System – Curv Wall Mounted

eHome2 has an infrared heating system installed by Curv. This system provides space heating to the areas shown in Table 9. This system has been designed by Curv. This system is controlled through the Loxone system with local temperature sensors in each room.

Table 9. Infrared heating system specifications

Room	Power Rating (W)	Number of Panels	Type	Dimension (mm) (Height x Width)
Kitchen/Dining	1500	1	Flat Glass IR	1500*600
WC	250	1	IR Mirror	800*600
Living Room	750	2	Flat Glass IR	1200*600
Hall	750	1	IR Mirror	1200*600
Bathroom	550	1	IR Towel Rail	1800*350
Bedroom 1	1000	1	Flat Glass IR	1500*600
Bedroom 2	750	1	Flat Glass IR	1200*600
Bedroom 3	650	1	Flat Glass IR	1800*350
Ensuite	300	1	IR Mirror	1000*600

Figure 11. Curv infrared panel

5.2.1.5 Wet central heating system heating controls

The space heating systems in eHome2 are controlled using the Loxone building management system. Air temperature is sensed at room level and fed to the controller, where time and temperature patterns can be set at room-by-room level. The methods used to deliver this control are below:

Figure 12. ThermaSkirt control (left) and radiator TRV (right)

The Thermaskirt system is split into zones, controlled by Danfoss HP22 2-port valves. These are controlled by the Loxone control system. The towel radiators are controlled separately using Loxone TRV heads. The Thermaskirt system also has TRVs which were set to full for all tests to override.

5.2.2 Wastewater heat recovery

The shower to the main bathroom is served by a wastewater heat recover system. A Recoup Pipe Hex system (double walled copper tube heat exchanger) has been installed. This provides pre heated water from the shower waste to the shower feed supply.

5.2.3 Hot Water Systems

There are two DHW systems currently installed in eHome2: Firstly, a standalone unit generating hot water using an inbuilt ASHP (Curv system). Secondly, a 200-litre storage cylinder attached to the ASHP with a buffer vessel (Vaillant system).

5.2.3.1 Curv ASHP Hot Water Cylinder

This is a stand-alone air source hot water cylinder, designed to work alongside an infrared heating system. The model is HP250M3C, which has a capacity of 195 litres, with a quoted COP of 3.04 at 7 °C external temperature.

5.2.3.2 Vaillant Unistor

Figure 13. Curv hot water cylinder (left) and Vaillant ASHP cylinder (right)

This is a cylinder designed specifically to work with a Vaillant ASHP. It has a capacity of 200 litres and is supplied pre plumbed and is unvented. The installed version has an aroTHERM 45 litre buffer tank which can lead to less short cycling of the ASHP. The cylinder has been sized according to the Building Regulations Part L 2021 for a three-bedroom property with one bathroom and one shower room.

5.2.4 Ventilation Systems

For experimental purposes two ventilation systems are present in eHome2, these systems will be run independently depending on the test required, they will not run together, one system is a whole house system, and the second is an extract system serving the moisture generating areas of eHome2. The MEV system was used in this research work and will be described below.

5.2.4.1 Mechanical extract (MEV) system

The Vent Axia centralised mechanical extract system (MVDC-MSH 443298) system is installed in the loft and is connected generally by flexible ducting. This system is commissioned to run continuously, it has three modes: normal, boost, and purge. A humidistat will boost the system at higher levels of humidity. This system serves all the bathrooms and the kitchen.

Flow rates are shown in Table 10. **Note: An MVHR system is installed in the home but was not used in this series.**

Table 10. Flow rates for MEV system

Room	**Measured (L/s)**
Kitchen/Dining	11.6
WC	4.6
Bathroom	6.4
Ensuite	6.4
Total	**29**

6. Methodology

6.1 Test Conditions

The aim of this series of tests was to provide a series of steady state and dynamic tests of the heating systems on each house, using the same heating, ventilation and chamber temperature profiles. This was carried out with a view to obtaining the following metrics to allow a comparison to be made to the design values:

- Operative temperature
- Air temperatures
- Heat up rates
- Heat up times
- Energy output of ASHP
- Energy consumption
- Coefficient of Performance (COP)
- Running costs
- Energy Efficiency Indicator (EEI)

6.1.1 Internal and chamber environments

The tests were split into two categories, “constant” heating pattern and “SAP” heating pattern.

- **Constant**: The test houses were heated continuously over each 24h period.
- **SAP**: The test houses were heated using the SAP pattern of 07:00-09:00 and 16:00-23:00.

The internal setpoint temperatures were based on SAP/SBEM with a 21 °C setpoint in the Living Room and 18 °C setpoint in all other zones. The following test setup was followed for all tests:

- All external doors and windows were locked and shut throughout testing.
- Internal doors were closed during the heating system tests.
- All lighting and appliances were turned off for the duration of the tests.
- Measurement equipment was powered by an external source.
- The building was unoccupied.

MEV (eHome2) and dMEV (TFH) was run throughout all heating systems testing. This was commissioned by an approved contractor at the beginning of the testing, and each outlet was checked by the research team at the beginning of each test, as detailed in Table 6 and Table 10.

Table U1 of SAP10.2 (BRE, 2021) was used to select external temperatures representative of the UK average during the winter months (December to February). All tests were conducted at both a constant 5 °C and constant -5 °C chamber temperature. The 5 °C was deemed typical of the UK average winter temperature, whereas the -5 °C was used to measure the heating system performance under more extreme UK winter conditions. No solar, wind or rain was used through the testing.

6.1.2 Test duration

To minimise any thermal mass effects resulting from charging and discharging of the building fabric, each test was a minimum of 72 hours in duration. The initial 48-hour period allowed the test houses to reach a state of dynamic equilibrium[1]. The final 24-hour period for each test was the reporting period. Measurement and analysis

6.1.3 Setpoints

The aim of the tests was to compare the experimental work with the setpoints (21 °C in the Living Room, 18 °C in all other rooms) and schedules (07:00-09:00, 16:00-23:00) found in SAP (BRE, 2021).

Given the sometimes-unpredictable nature of heating systems and controls, it was difficult to attain these setpoints in each room exactly. The following method was used; The research team ran each heating system using the setpoints on the control equipment in the first instance in a constant heating schedule, for 24h. The setpoints were then adjusted in each room, to achieve the SAP setpoint temperature in the geometric centre of the rooms.

The research team found this a difficult and time-consuming task to achieve given the unpredictability of a dynamic heating system. For this reason, the task was limited to 3 days, with the offsets applied at the end of this period used for **all tests** relating to the specific heating system.

6.1.4 Measurands

The following variables were monitored throughout each test at a one-minute time interval:

- House:
  - Air temperature in seven points in each room
  - Operative temperature in seven points in each room
  - Relative humidity in the geometric centre of each room
  - Electrical energy consumption
  - Heat meter output on ASHP primary flow and return
  - Electrical energy consumption by circuit (TFH & eHome2) and by individual power outlet (eHome2)
- Chamber:
  - Air temperature at 36 points
  - Relative humidity at 36 points
  - Sub soil temperature under the centre of each house

[1] Previous tests at the Energy House Labs have shown that 24-hour periods following the initial 48-hour stabilisation period produce repeatable results thereafter (Fitton et al., 2016).

6.2 Sensor Schematic

6.2.1 Chamber Sensor Locations

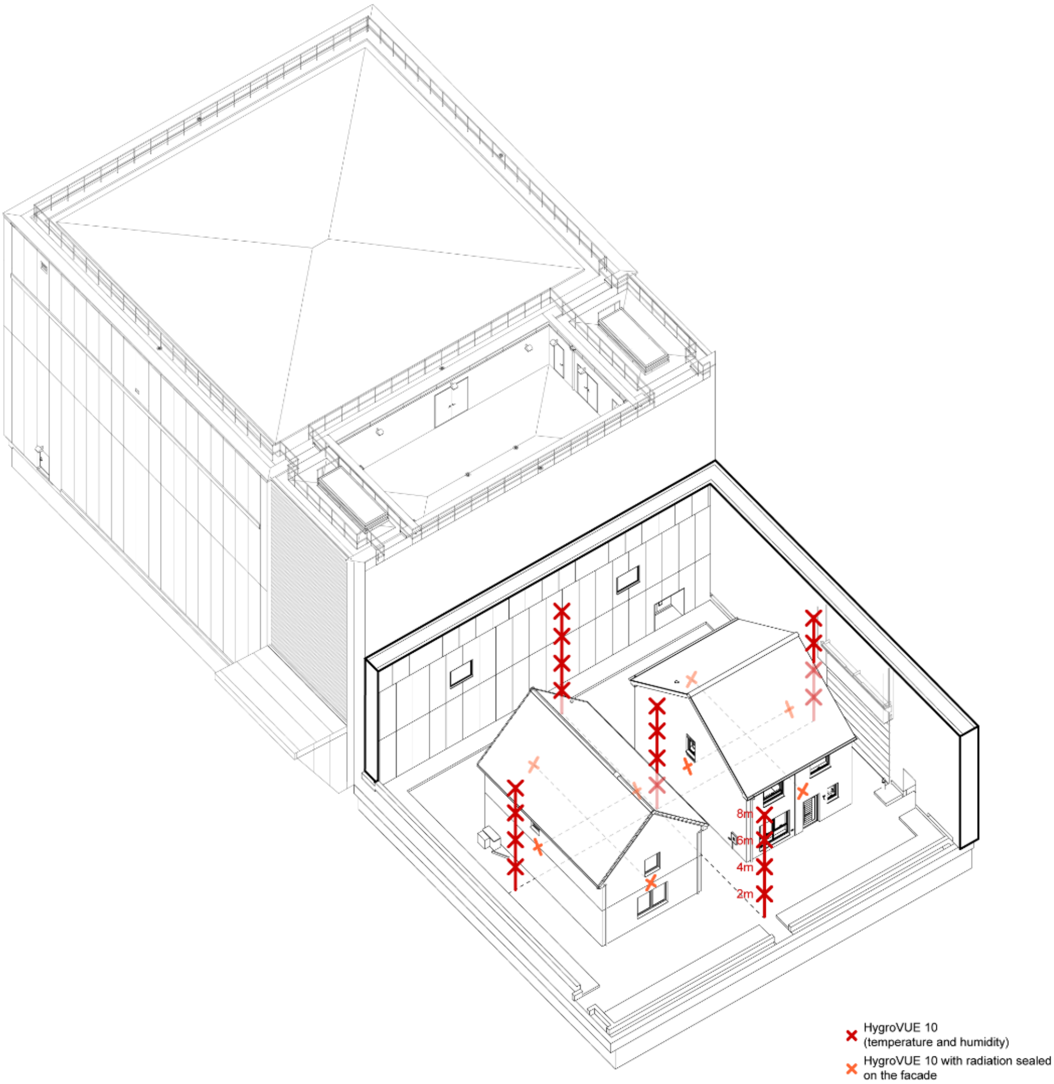


Figure 14. Diagram of air temperature and humidity sensor locations within the chambers

6.2.2 Whole House Sensor Locations

6.2.2.1 TFH

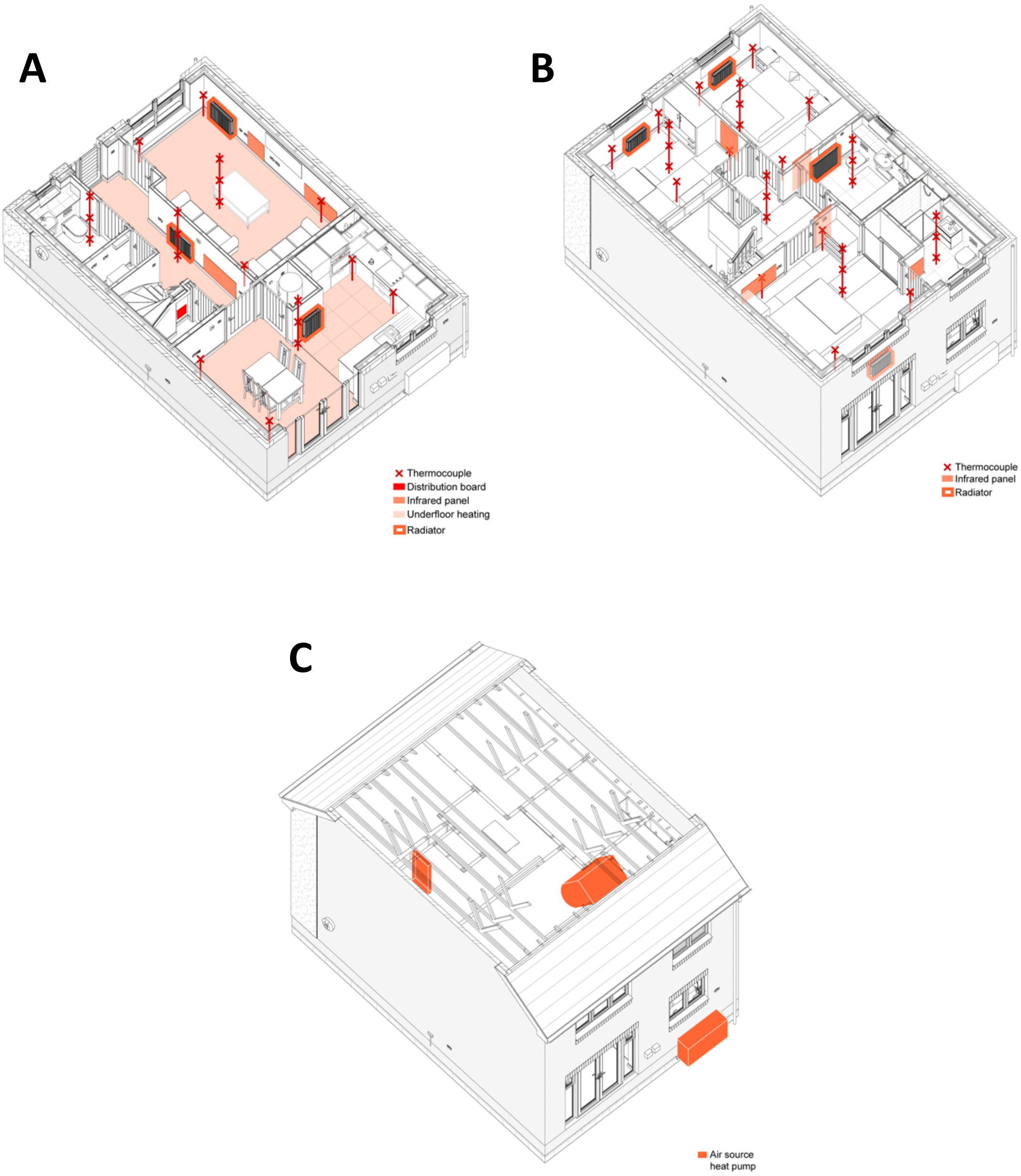
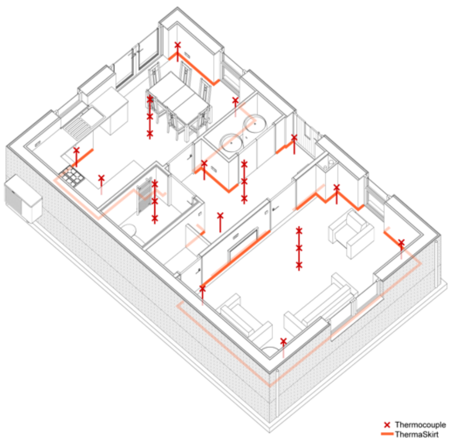


Figure 15. Heating systems and emitters in TFH. A) Radiators and UFH. B) IR Panels. C) Loft and Monobloc ASHPs.

6.2.2.2 eHome2



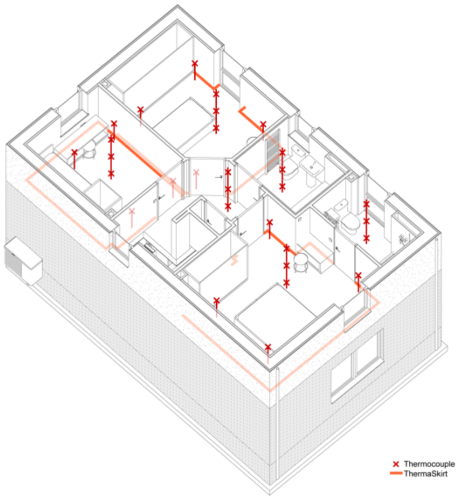
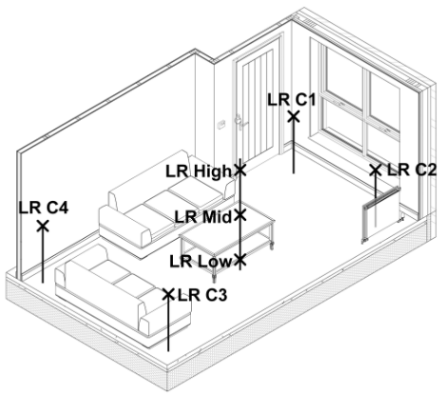


Figure 16. Heating emitters in eHome2 downstairs (left) and upstairs (right)

6.2.3 Spatial Temperature Sensors

Air and black globe temperature was measured in 7 locations in each room of the properties. The reports detail the spatial temperatures in the Living Room and Bedroom 1 of both TFH and eHome2.

The Future Home:



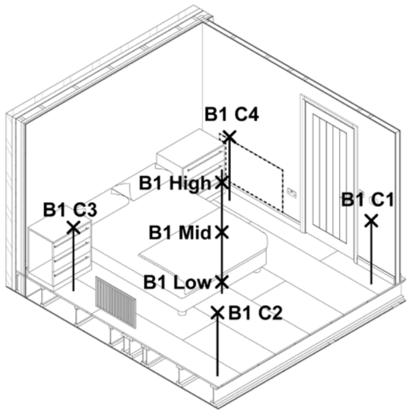


Figure 17. The Future Home Living Room (left) and Bedroom 1 (right) temperature measurement locations

eHome2:

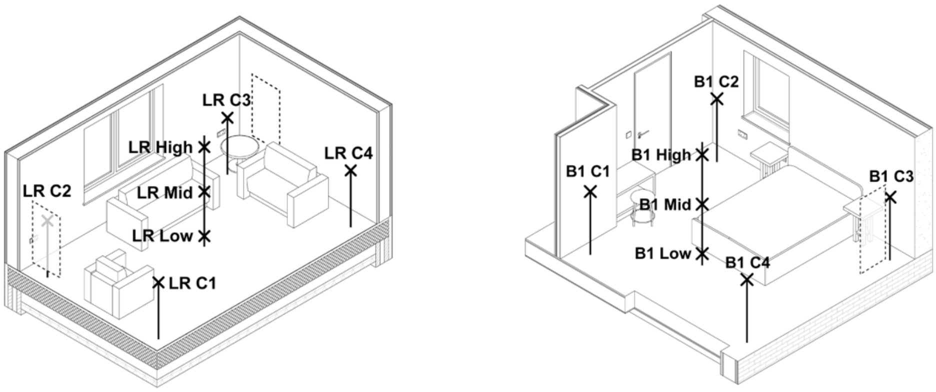


Figure 18. The Future Home Living Room (left) and Bedroom 1 (right) temperature measurement locations

6.3 Measurement Technique

All measurements were taken at one minute time intervals.

6.3.1 Internal Conditions

All temperature measurements within the homes were conducted as follows:

Air Temperature:

- 24-hour (Daily), seven-hour (Evening heating period), two-hour (Morning heating period) Averages
    - One minute temperature data averaged over the above period used in plotting and calculation of System Energy Efficiency Indicator (SEEI)

- Volume Weighted Average
    - Ratio of room volume to building volume calculated for each room to create a scaling coefficient
    - Average temperature over the period calculated for each room, then multiplied by then above coefficient.
    - This summation of these values gives the volume weighted average for each property.

Operative Temperature:

- As described in Appendix C – Operative Temperature

- 24-hour (Daily), seven-hour (Evening heating period), two-hour (Morning heating period) Averages
    - One min temperature data averaged over the above period used in plotting and calculation of SEEI

- Volume Weighted Average
    - Ratio of room volume to building volume calculated for each room to create scaling coefficient
    - Average temperature over the period calculated for each room, then multiplied by then above coefficient.
    - This summation of these values gives the volume weighted average for each property.

Electrical Energy Consumption:

- TFH
    - Measured at one-minute intervals for each circuit in TFH
    - Summed over 24h for daily figures

- eHome2
    - measured at one-minute intervals for each plug in eHome2
    - Summed over 24h for daily figures

Heat Meter output:

Heat meter energy output only increased per kWh, so was calculated for better resolution as follows:

- 1 minute flow temperature, return temperature, volume per min, and specific heat capacity value was obtained
    - Specific heat capacity value was measured at 20 °C using a refractometer and compared to manufacturers charts
- The following equation was used:

$$Q = \frac{(\dot{m} \cdot 1000) \cdot C \cdot (\mathrm{T_{Flow}} - T_{Return})}{3600000}$$

- Where:
    - Q is heat meter energy in Wh
    - $\dot{m}$ is volume flow per minute in m^3/min
    - C is the measured specific heat capacity in J/(kg.K)
    - $\mathrm{T_{Flow}}$ is the flow temperature in °C
    - $\mathrm{T_{Return}}$ is the return temperature in °C

Coefficient of Performance (COP):

The COP was based on the boundary conditions defined in the Electrification of Heat Demonstration Project report (Energy Systems Catapult, 2023). All COP's considered within this report are defined as COP_{H4}, including the ASHP unit and circulation pump and represents the performance of the entire space heating system.

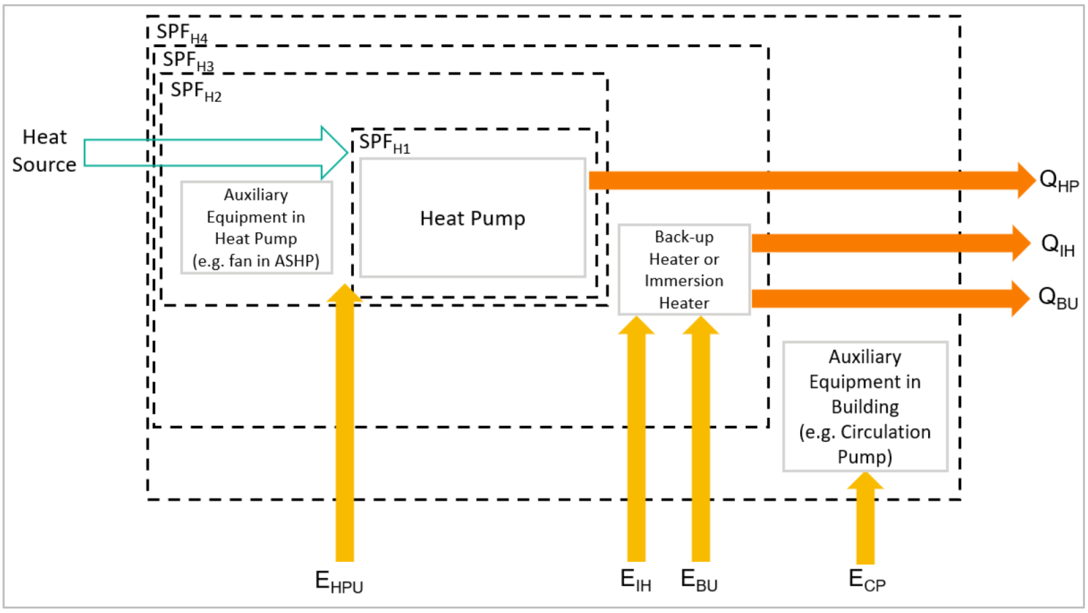


Figure 19. SPF system boundaries used to calculate coefficient of performance (COP) values. Test conditions meant that the immersion heater (E_{IH} and Q_{IH}) was not used in the systems tests at Energy House 2.0.[2].

[2]Diagram Source: (Energy Systems Catapult, 2023)

The COP was therefore calculated as:

$$COP = \frac{24h\ Heat\ Meter\ Output\ [kWh]}{24h\ System\ Electrical\ Energy\ Consumption\ [kWh]}$$

System Energy Efficiency Indicator (SEEI):

The SEEI is a metric created by the research team to attempt to compare heating systems performance, accounting both the energy consumption of the system, and the system's ability to heat the property. It indicates how much the average internal temperature of the property will increase per unit energy consumption.

The SEEI has been calculated as follows:

$$SEEI\ \left[\frac{K}{kWh}\right] = \frac{T_{Internal_{Volume\ Weighted\ Average}}\ [°C] - T_{Chamber}\ [°C]}{E_{Electric}\ [kWh]} \equiv \frac{\Delta T\ [K]}{E_{Electric}\ [kWh]}$$

6.3.2 Chamber Conditions

- Soil Temperature, Air Temperature, Relative Humidity
    - Averaged into 60 min periods, for plotting 72 h plots.
    - These 60 min averages were averaged to calculate 24 h averages.

7. Results

Table 11. TFH heating system tests

TFH System Tests	
-5 °C Wall Mounted IR TFH Constant	*5 °C Wall Mounted IR TFH Constant*
-5 °C Wall Mounted IR TFH SAP	*5 °C Wall Mounted IR TFH SAP*
-5 °C Loft ASHP Rads + UFH Constant	*5 °C Loft ASHP Rads + UFH Constant*
-5 °C Loft ASHP Rads + UFH SAP	*5 °C Loft ASHP Rads + UFH SAP*
-5 °C Loft ASHP Rads Constant	*5 °C Loft ASHP Rads Constant*
-5 °C Loft ASHP Rads SAP	*5 °C Loft ASHP Rads SAP*
-5 °C Monobloc ASHP TFH Rads + UFH Constant	*5 °C Monobloc ASHP TFH Rads + UFH Constant*
-5 °C Monobloc ASHP TFH Rads + UFH SAP	*5 °C Monobloc ASHP TFH Rads + UFH SAP*
-5 °C Monobloc ASHP TFH Rads Constant	*5 °C Monobloc ASHP TFH Rads Constant*
-5 °C Monobloc ASHP TFH Rads SAP	*5 °C Monobloc ASHP TFH Rads SAP*

Table 12. eHome2 heating system tests

eHome2 System Tests	
-5 °C Wall Mounted IR eHome2 Constant	*5 °C Wall Mounted IR eHome2 Constant*
-5 °C Wall Mounted IR eHome2 SAP	*5 °C Wall Mounted IR eHome2 SAP*
-5 °C Monobloc ASHP eHome2 Constant	*5 °C Monobloc ASHP eHome2 Constant*
-5 °C Monobloc ASHP eHome2 SAP	*5 °C Monobloc ASHP eHome2 SAP*

7.1 System Performance

7.1.1 TFH

7.1.1.1 -5°C Wall Mounted IR TFH Constant

7.1.1.1.1 Control

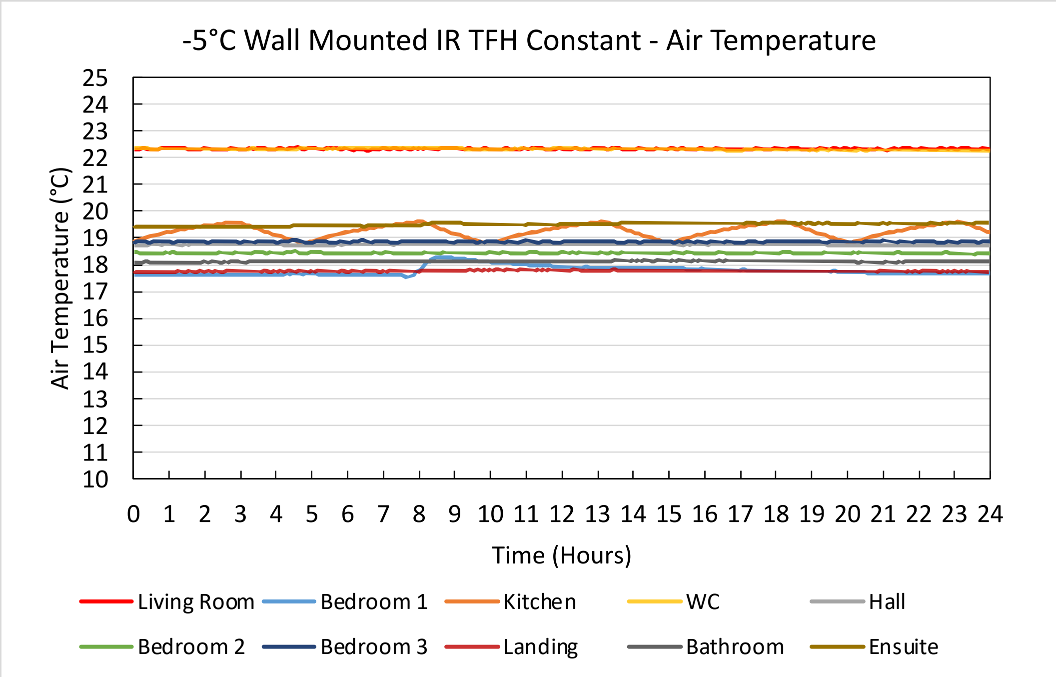


Figure 20. -5°C Wall Mounted IR TFH Constant Air Temperature Plot

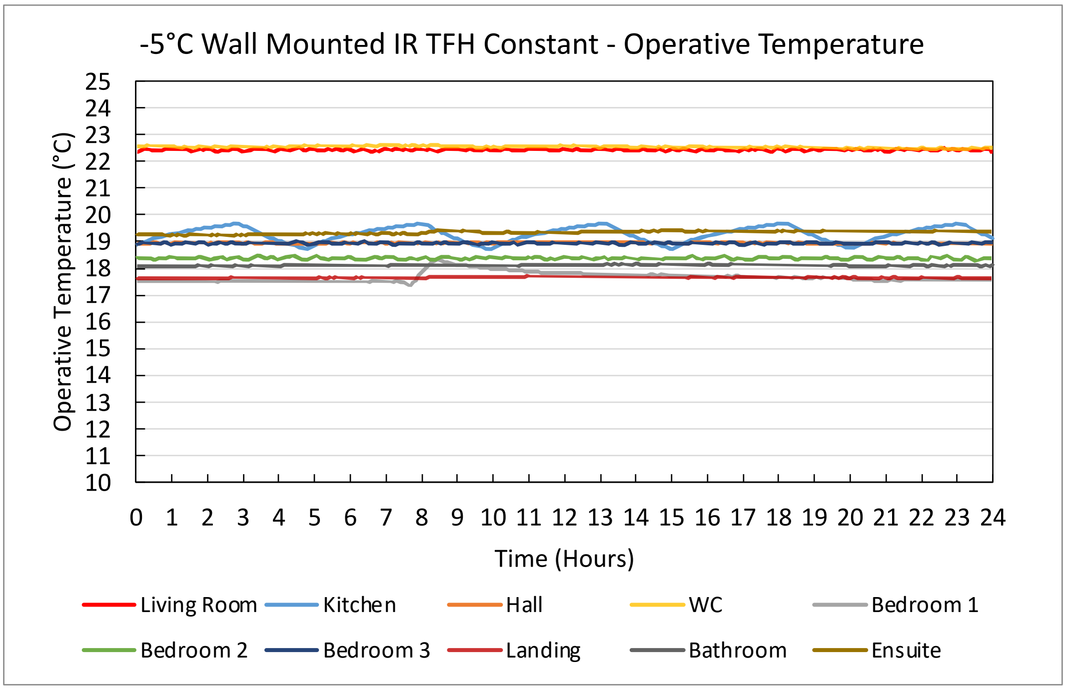


Figure 21. -5°C Wall Mounted IR TFH Constant Operative Temperature Plot

7.1.1.1.2 Spatial

-5°C Wall Mounted IR TFH Constant – Air - 7h　　-5°C Wall Mounted IR TFH Constant – Air - 7h

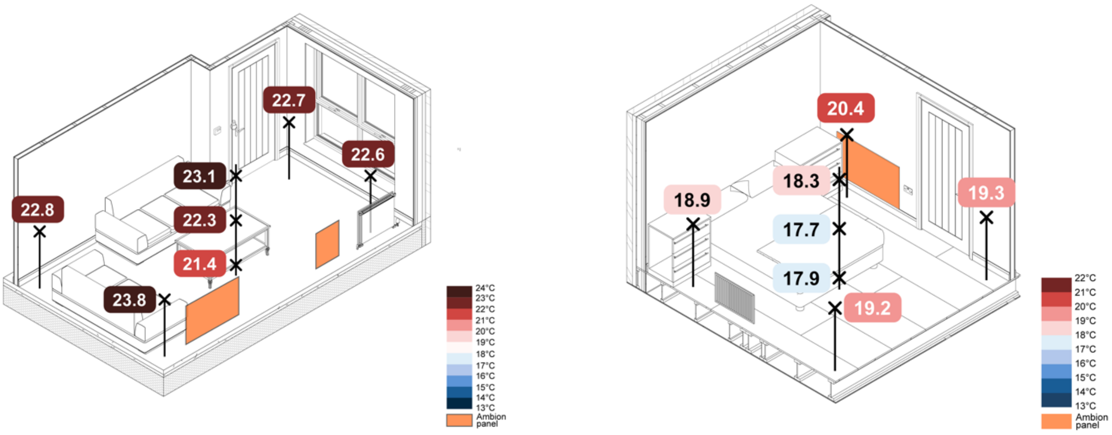


Figure 22. -5°C Wall Mounted IR TFH Constant Spatial Air Temperatures

-5°C Wall Mounted IR TFH Constant – Operative - 7h　　-5°C Wall Mounted IR TFH Constant – Operative - 7h

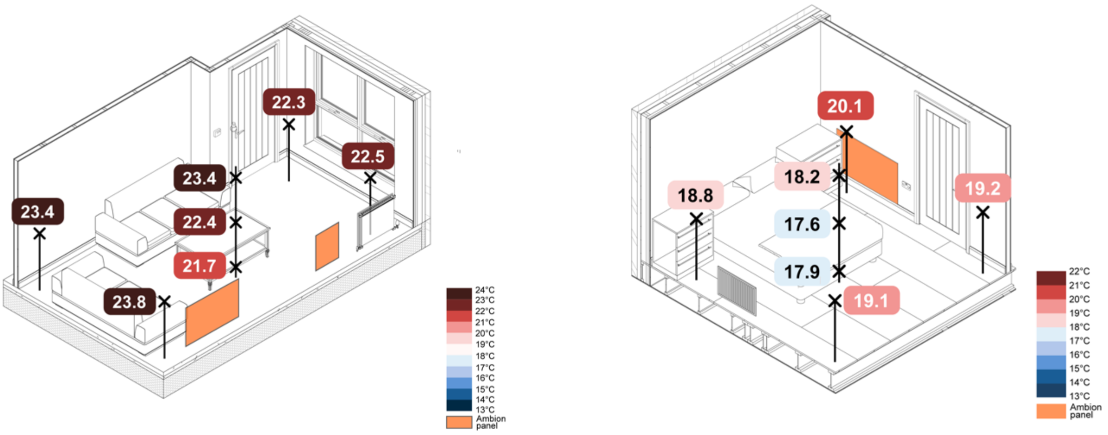


Figure 23. -5°C Wall Mounted IR TFH Constant Spatial Operative Temperatures

7.1.1.1.3 Performance Metrics

Table 13. -5°C Wall Mounted IR TFH Constant - Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.39	58.5	£14.33

7.1.1.1.4 Discussion

Setpoint

The heating setpoints were met in all rooms in the AM and PM sessions, with the exception of the WC which overheated by around 4°C , the Living Room overheated by 1 °C

- Overshoot and undershoots
    - Living room had an overshoot of 1.2 °C to the 21 °C setpoint.
    - WC overshot setpoint by 4.2 °C.
- Hysteresis
    - Generally, the hysteresis was low, with the exception of Bedroom 1 and the Kitchen, however these are relatively minor with a swing of ±~0.3 °C

Heat Distribution

- Homogenous air temperature across LR and B1 (range of ~3 °C)
- Warmest points are found closest to the wall mounted IR panels
- Little variation between operative and air temperatures (< 0.2 °C)

Energy Consumption

This 24h period had a total energy consumption of 58.5 kWh, with a running cost of £14.33.

Efficiency

The SEEI for this system test was 0.39 K/kWh.

7.1.1.2 -5°C Wall Mounted IR TFH SAP

7.1.1.2.1 Control

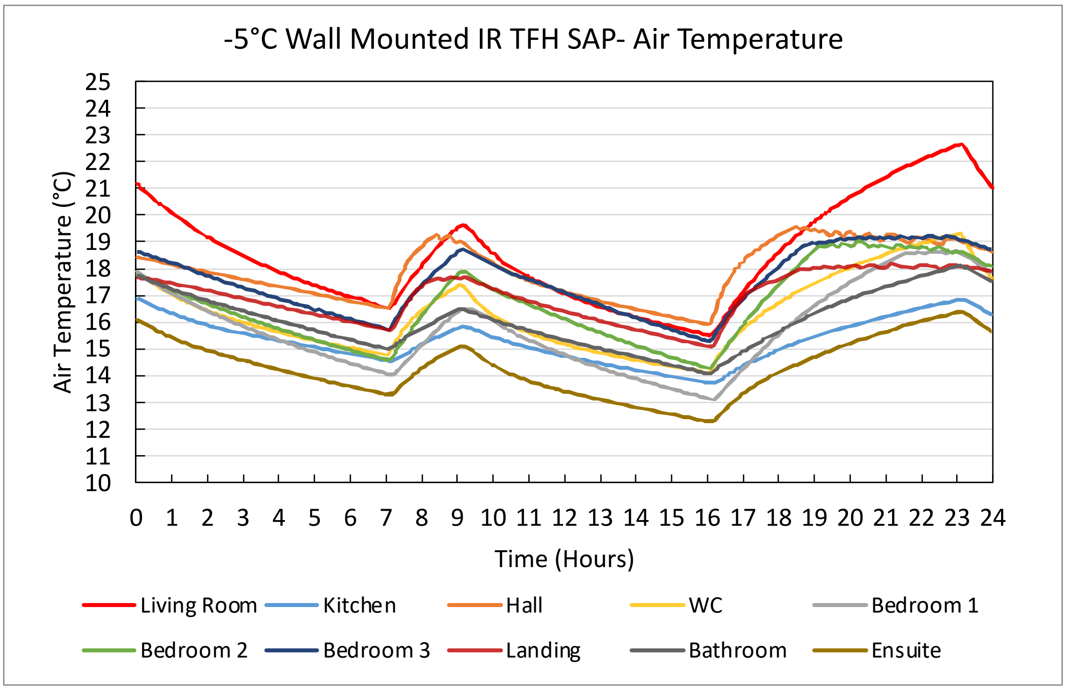


Figure 24. -5°C Wall Mounted IR TFH SAP - Air Temperature Plots

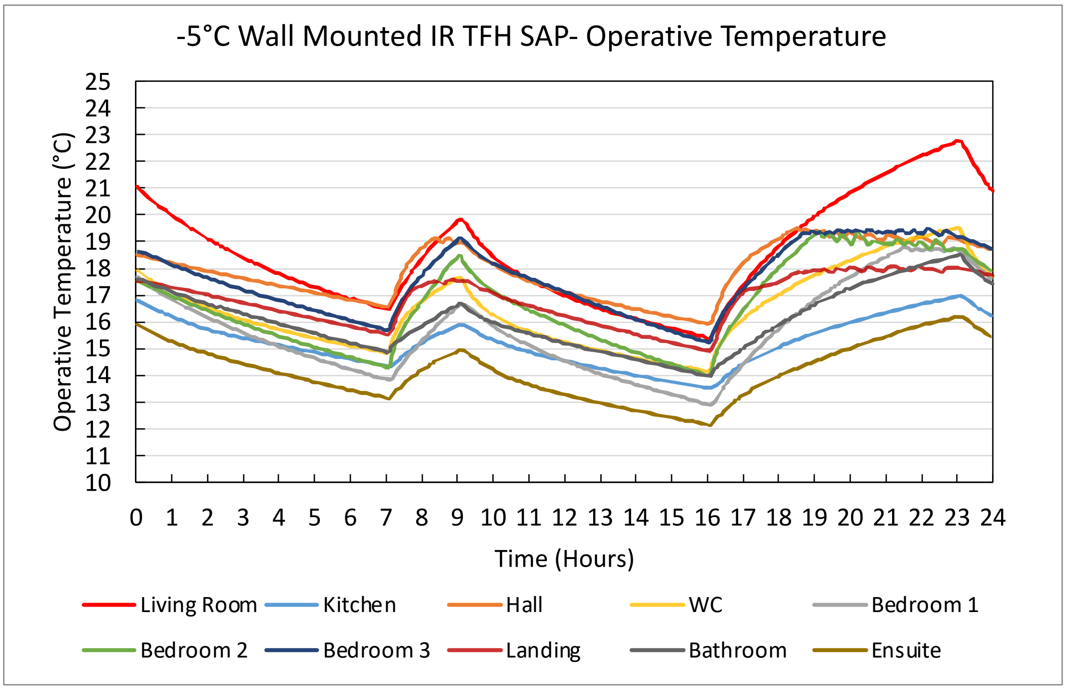


Figure 25. -5°C Wall Mounted IR TFH SAP - Operative Temperature Plots

7.1.1.2.2 Spatial

-5°C Wall Mounted IR TFH SAP – Air - 7h

-5°C Wall Mounted IR TFH SAP – Air - 7h

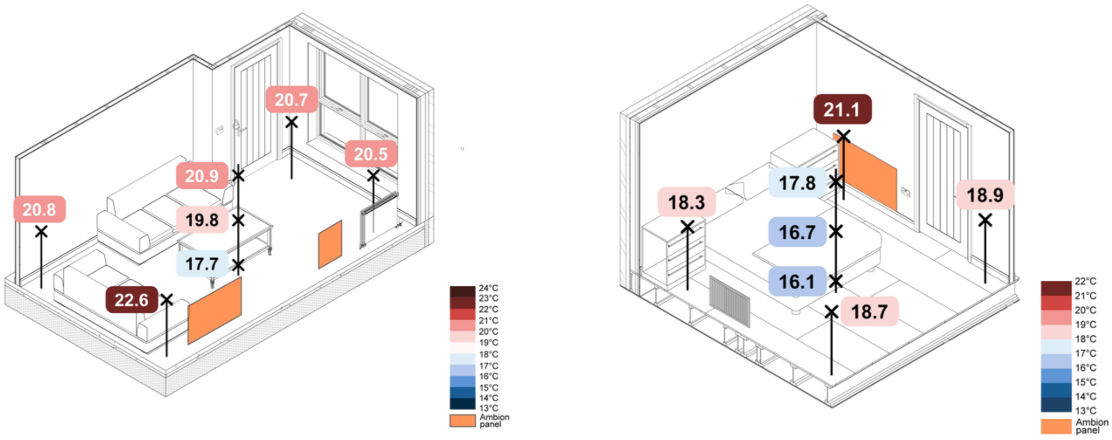


Figure 26. -5°C Wall Mounted IR TFH SAP - Spatial Air Temperatures

-5°C Wall Mounted IR TFH SAP – Operative - 7h

-5°C Wall Mounted IR TFH SAP – Operative - 7h

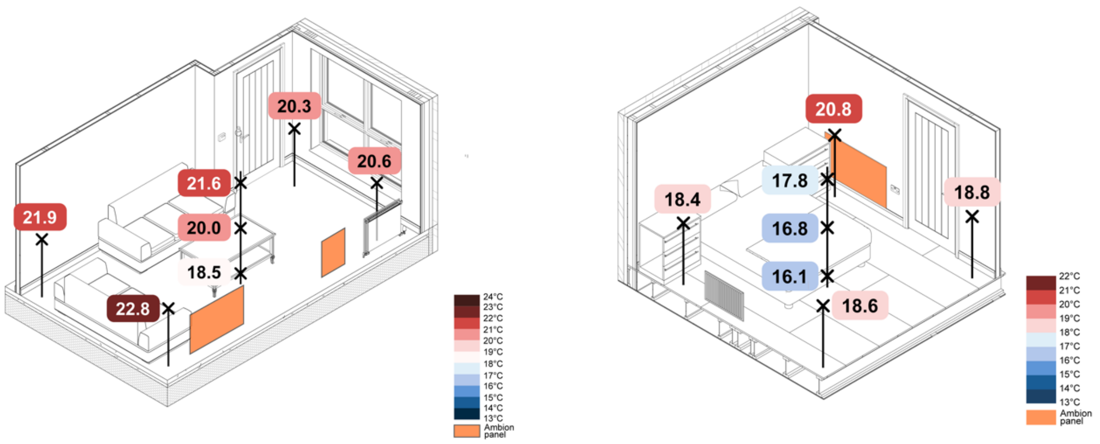


Figure 27. -5°C Wall Mounted IR TFH SAP - Spatial Operative Temperatures

7.1.1.2.3 Heat up times

Table 14. -5°C Wall Mounted IR TFH SAP - Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	15.51	21	04:23:00	1.25
Bedroom 1	12.93	17.99	04:22:12	1.16

7.1.1.2.4 Performance Metrics

Table 15. -5°C Wall Mounted IR TFH SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.48	42.0	£10.29

7.1.1.2.5 Discussion

Setpoint

- Living room temperature did not achieve setpoint (21 °C) in the morning period.
- Living room temperature takes ~3.5 hours to achieve setpoint in the evening, however does not maintain good control in this period, overheating to ~23 °C.
- Only Hall, Landing and Bedroom 3 achieve setpoint (18 °C) in the morning heating period. All remaining rooms did not achieve setpoint, with the Ensuite only achieving ~15 °C.
- Bedroom 1, 2 and 3, and the Hall all have good temperature control, however +1 °C above the setpoint.
- The Landing achieves the setpoint with good control about 18 °C.
- Bathroom achieved setpoint, however took 6h to achieve.
- Kitchen and Ensuite failed to achieve setpoint.

Heat Distribution

- Significant stratification in the centre of the room in the Living Room (range of 3.2 °C)
- Significant overheating located close to the IR panel, adjacent to the armchair.
- Overheating observed in Bedroom 1 next to IR panel.
- Significant stratification observed in the centre of Bedroom 1 (range of 1.7 °C)

Energy Consumption

This 24h period had a total energy consumption of 42.0 kWh, with a running cost of £10.29.

Efficiency

The SEEI for this system test was 0.48 K/kWh.

7.1.1.3 -5°C Loft ASHP Rads + UFH Constant

7.1.1.3.1 Control

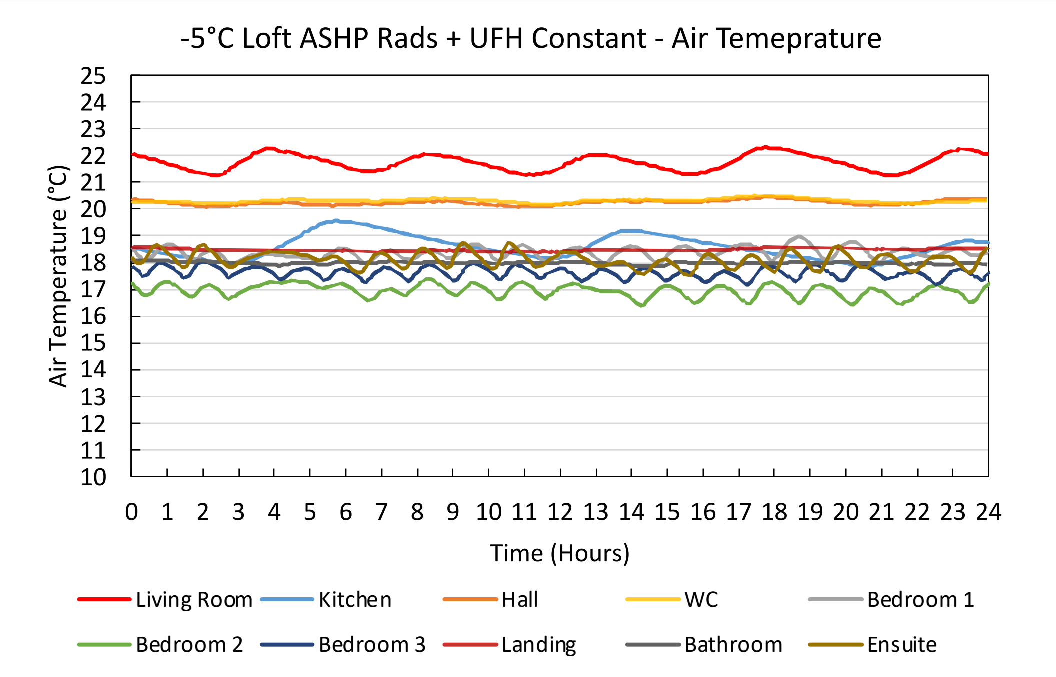


Figure 28. -5°C Loft ASHP Rads + UFH Constant - Air Temperature Plot

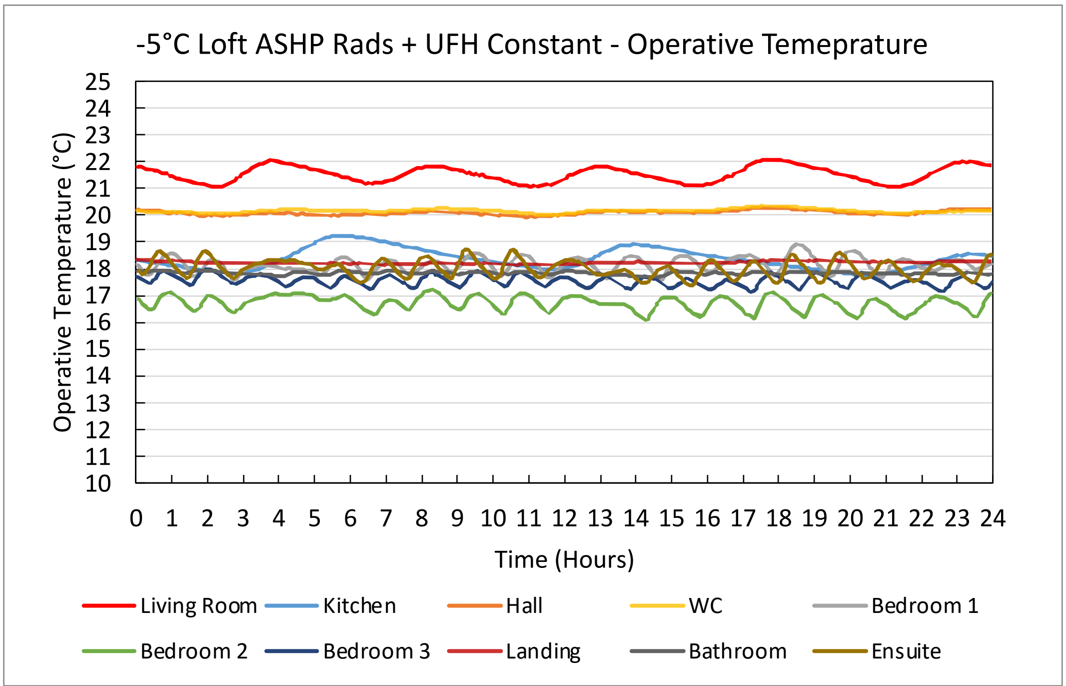


Figure 29. -5°C Loft ASHP Rads + UFH Constant - Operative Temperature Plot

7.1.1.3.2 Spatial

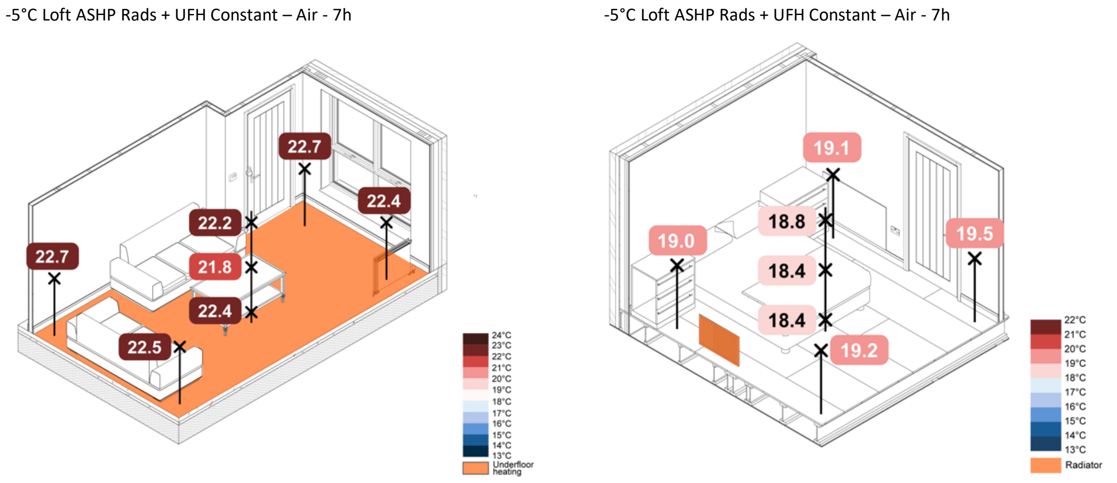


Figure 30. -5°C Loft ASHP Rads + UFH Constant - Spatial Air Temperatures

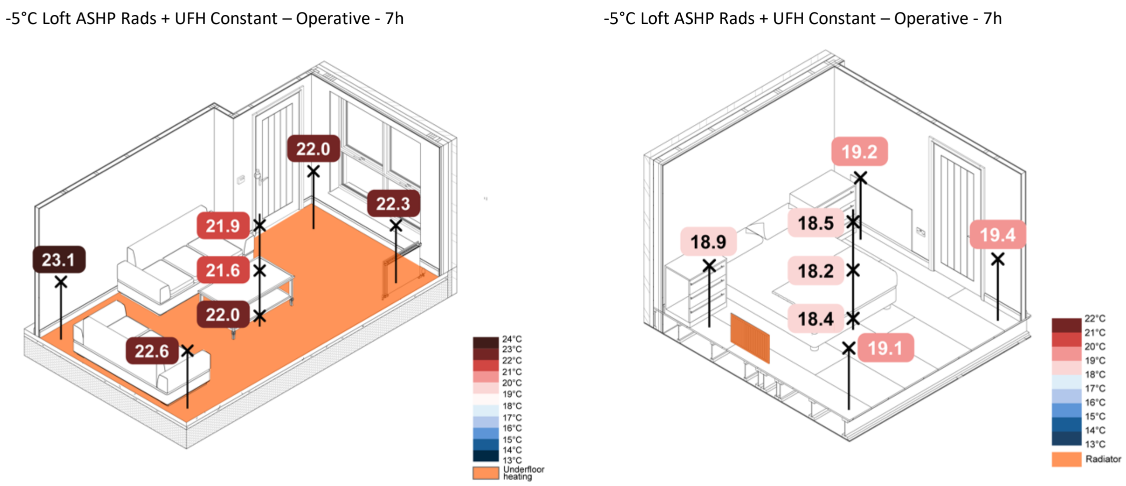


Figure 31. -5°C Loft ASHP Rads + UFH Constant - Spatial Operative Temperature Plots

7.1.1.3.3 Performance Metrics

Table 16. -5°C Loft ASHP Rads + UFH Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.4	0.49	45.6	£11.16

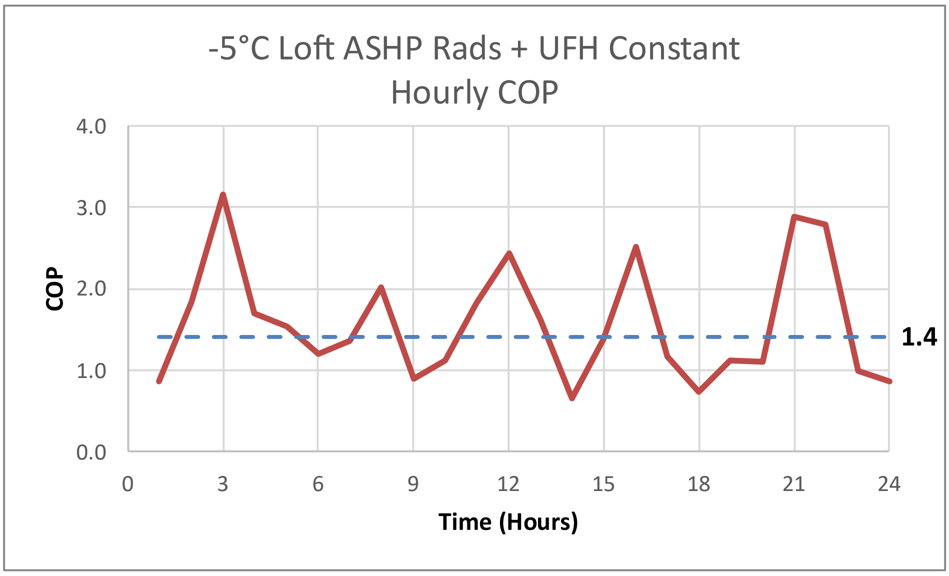


Figure 32. -5°C Loft ASHP Rads + UFH Constant – Hourly COP

7.1.1.3.4 Discussion

Issues

The ASHP had to revert to the backup heater during a large portion of the test, which could affect the COP.

Setpoint

- Living Room hysteresis is approx. ±0.5 °C, with setpoint achieved, with a slight overshoot of +0.5 °C.
- Kitchen temperature overshot setpoint by ~1.6 °C, with hysteresis of ~0.5 °C.
- Bedroom 2 did not maintain the setpoint of 18 °C, achieving ~16.9 °C.
- WC and Hall overshot by 2 °C.
- All other rooms achieved setpoint with a good level of control, with a hysteresis of ±0.3 °C.

Heat Distribution

- Homogenous air temperature across Living Room (range of 0.9 °C)
- Overheating across the Living Room of typically between ~1-2 °C
- Homogenous air temperature across Bedroom 1 (range of 1.1 °C)
- Overheating of ~1 °C in Bedroom 1, however the sensor in the geometric centre of the room is in line with the 18 °C setpoint

Energy Consumption

This 24h period had a total energy consumption of 45.6 kWh, with a running cost of £11.16.

Efficiency

The COP was 1.4, and the SEEI for this system test was 0.49 K/kWh.

7.1.1.4 -5°C Loft ASHP Rads + UFH SAP

7.1.1.4.1 Control

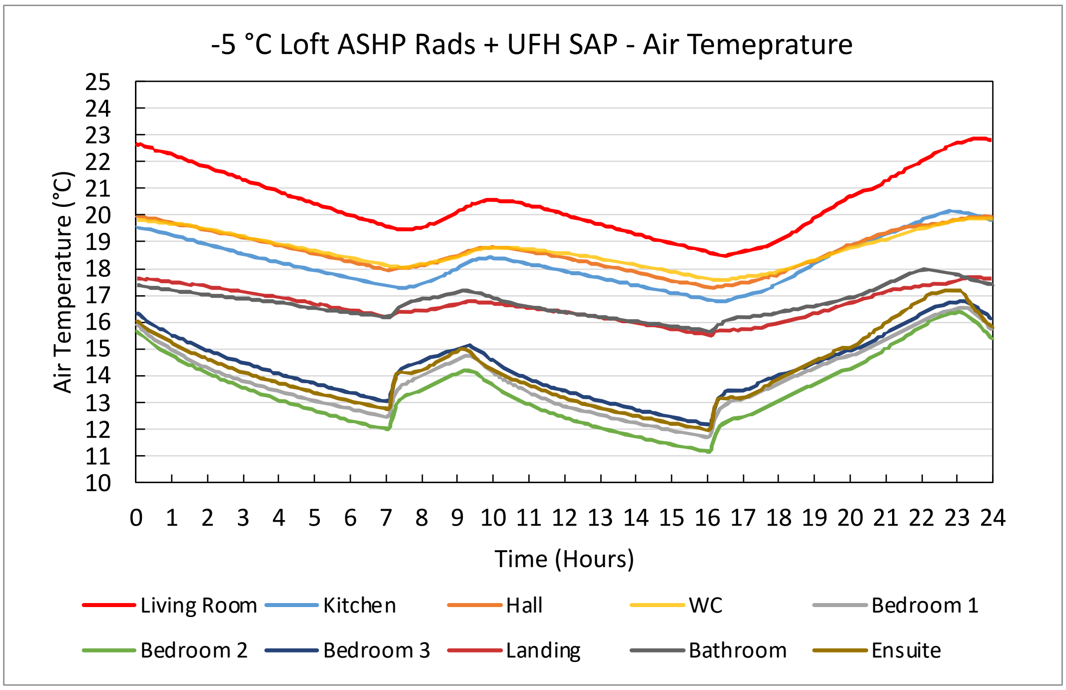


Figure 33. -5°C Loft ASHP Rads + UFH SAP – Air Temperature Plots

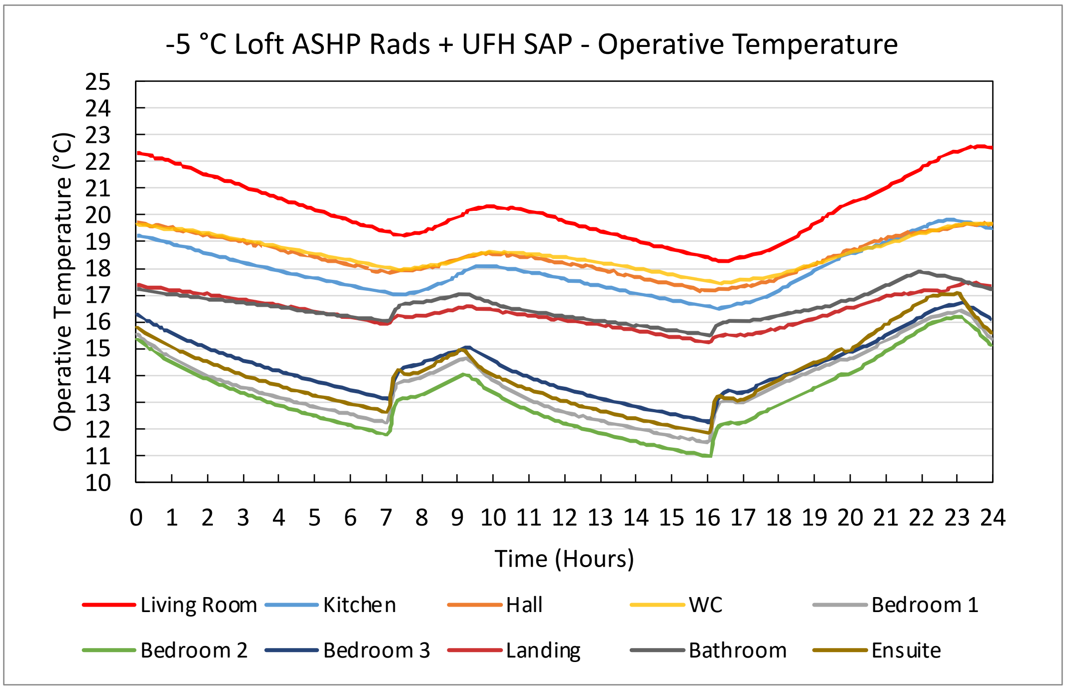
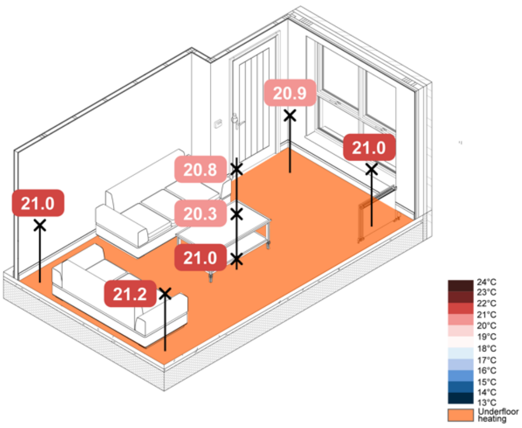


Figure 34. -5°C Loft ASHP Rads + UFH SAP – Operative Temperature Plots

7.1.1.4.2 Spatial

-5°C Loft ASHP Rads + UFH SAP – Air - 7h



-5°C Loft ASHP Rads + UFH SAP – Air - 7h

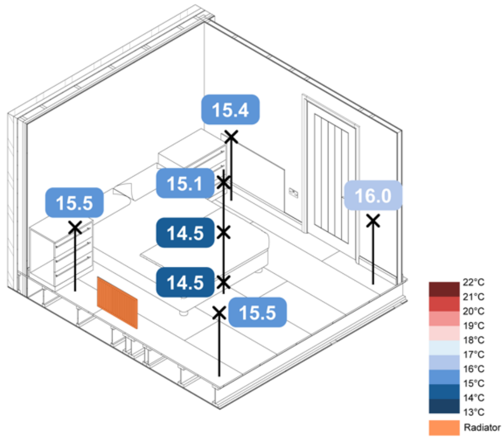
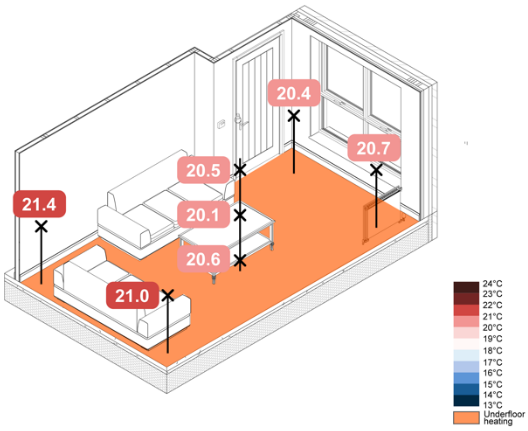


Figure 35. -5°C Loft ASHP Rads + UFH SAP – Spatial Air Temperatures

-5°C Loft ASHP Rads + UFH SAP – Operative - 7h



-5°C Loft ASHP Rads + UFH SAP – Operative - 7h

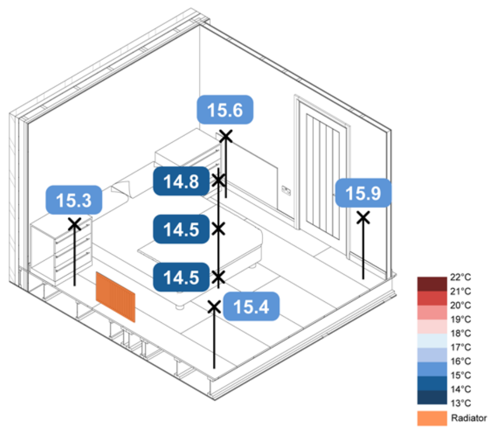


Figure 36. -5°C Loft ASHP Rads + UFH SAP – Spatial Operative Temperatures

7.1.1.4.3 Heat up times

Table 17. -5°C Loft ASHP Rads + UFH SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	18.63	21	04:35:00	0.52
Bedroom 1	11.69	16.54	07:05:00	0.68

7.1.1.4.4 Performance Metrics

Table 18. -5°C Loft ASHP Rads + UFH SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.4	0.48	41.9	£10.27

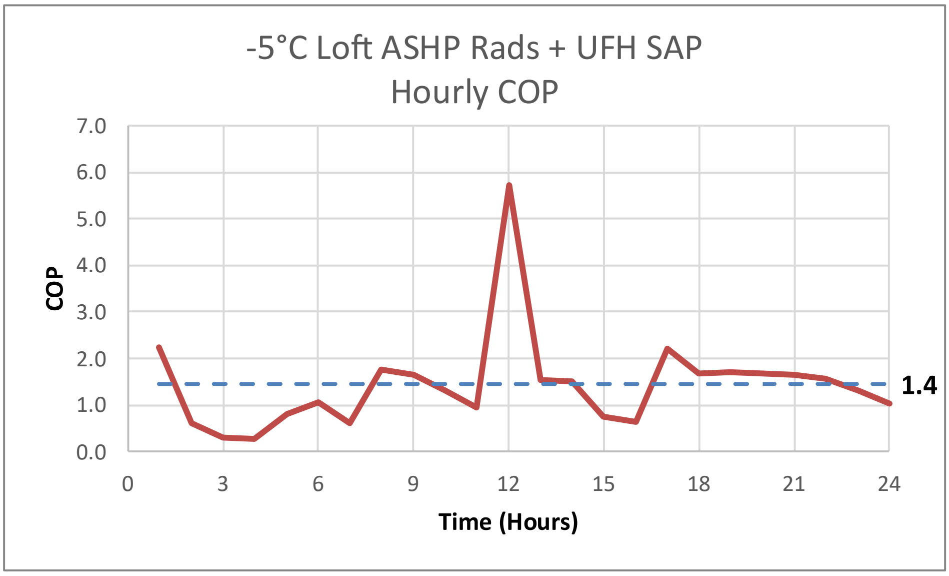


Figure 37. -5°C Loft ASHP Rads + UFH SAP – Hourly COP

7.1.1.4.5 Discussion

Issues

The ASHP had to revert to the backup heater during a large portion of the test, which could affect the COP.

Setpoint

- Setpoint not achieved in Living Room during the morning heating period. Setpoint achieved in the evening heating period after 5 hours.
- WC, Kitchen and Hall achieved setpoint in both heating periods.
- Bathroom fails to achieve setpoint in the morning heating period, and only reaches 18 °C towards the end of the evening heating period.
- All other rooms fail to achieve setpoint temperatures, with some only reaching 15 °C in the morning heating period.
- Outside of the heating periods, temperatures dropped to between 11-12 °C in some areas of the house.

Heat Distribution

- Living Room temperature was homogenous with minimal stratification (~0.9 °C), with all temperatures close to the 21 °C setpoint.
- Bedroom 1 did not achieve setpoint, particularly in the centre of the room, typically 3 °C below.

Energy Consumption

This 24h period had a total energy consumption of 41.9 kWh, with a running cost of £10.27.

Efficiency

The COP was 1.4, and the SEEI for this system test was 0.48 K/kWh.

7.1.1.5 -5 °C Loft ASHP Rads Constant

7.1.1.5.1 Control

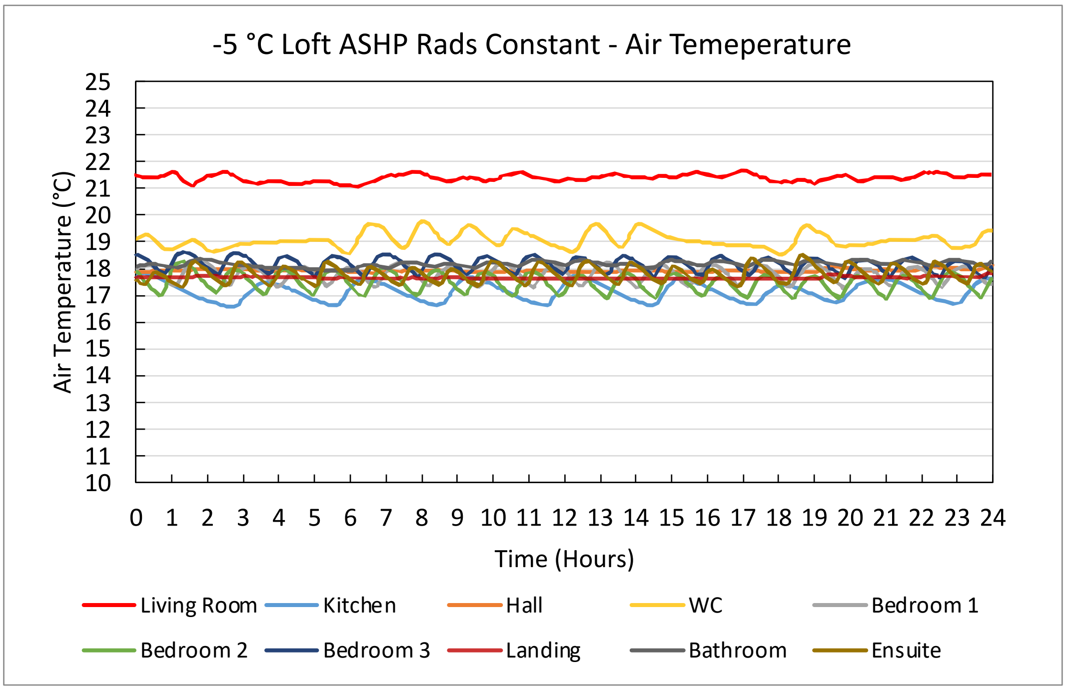


Figure 38. -5 °C Loft ASHP Rads Constant – Air Temperature Plots

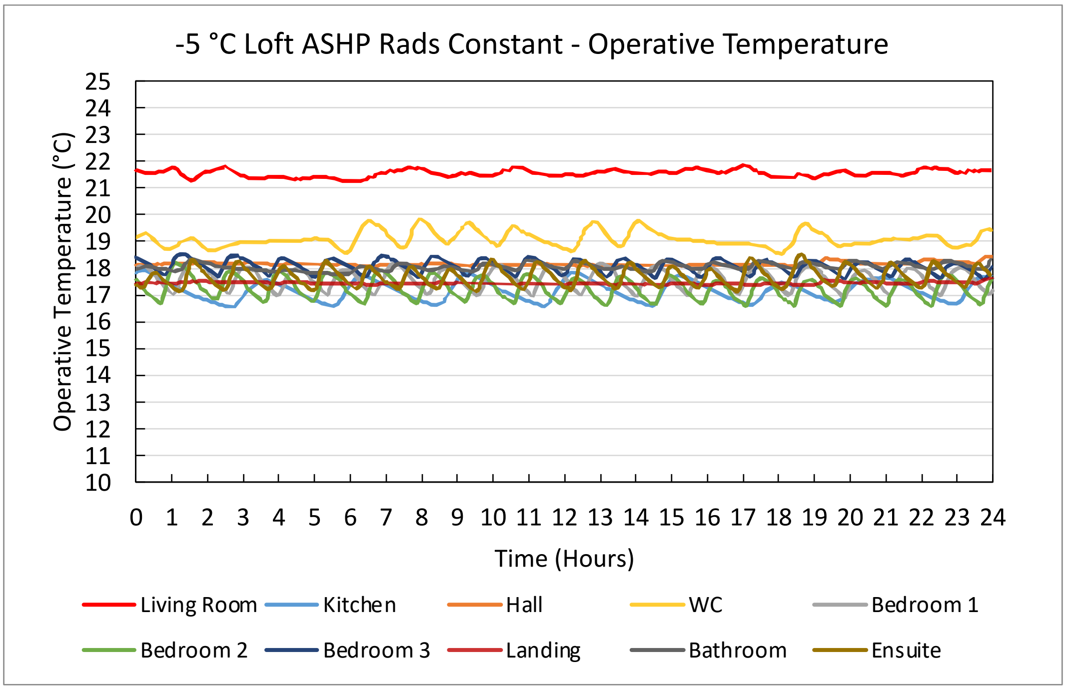


Figure 39. -5 °C Loft ASHP Rads Constant – Operative Temperature Plots

7.1.1.5.2 Spatial

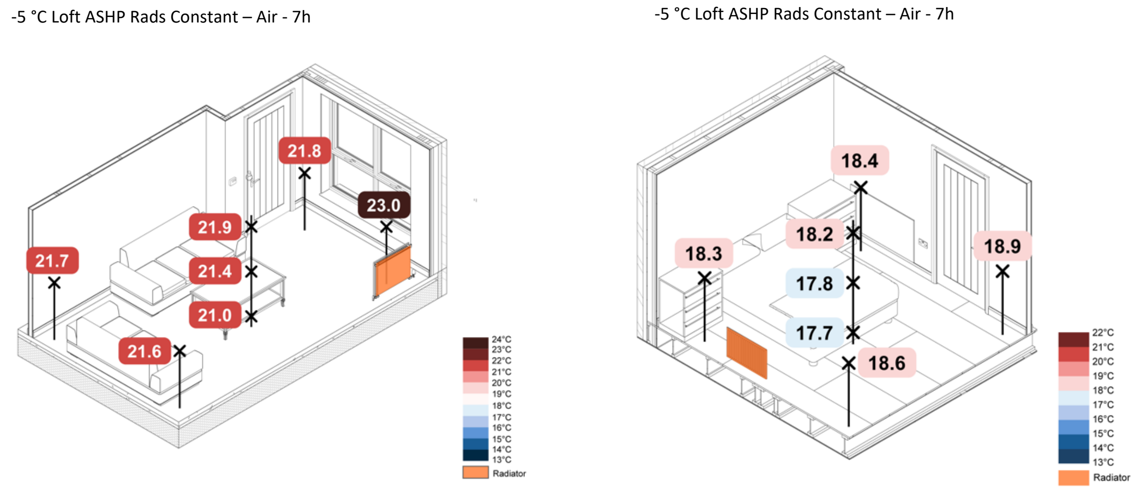


Figure 41. -5 °C Loft ASHP Rads Constant - Spatial Air Temperatures

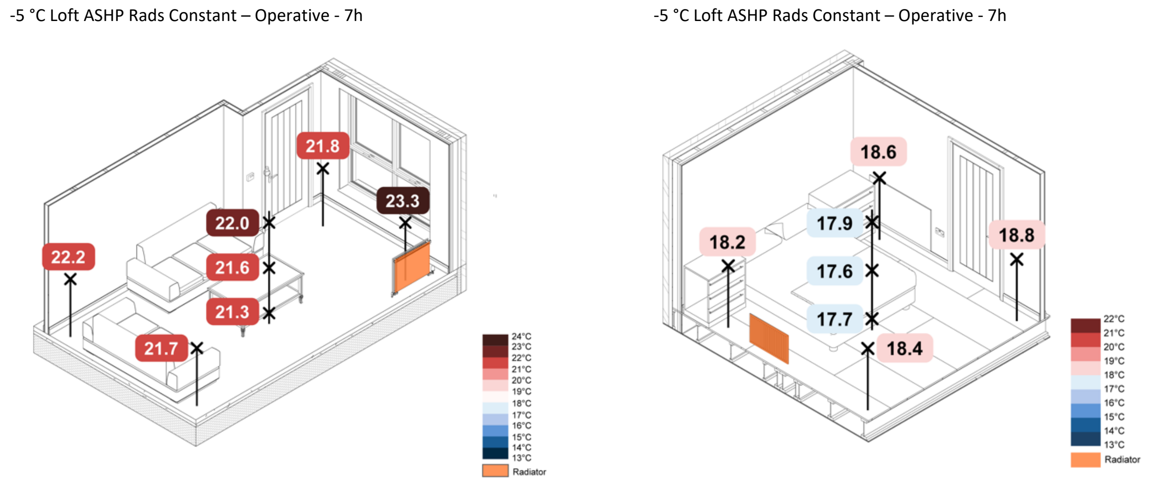


Figure 40. -5 °C Loft ASHP Rads Constant - Spatial Operative Temperatures

7.1.1.5.3 Performance Metrics

Table 19. -5 °C Loft ASHP Rads Constant - Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.0	0.35	63.0	£15.43

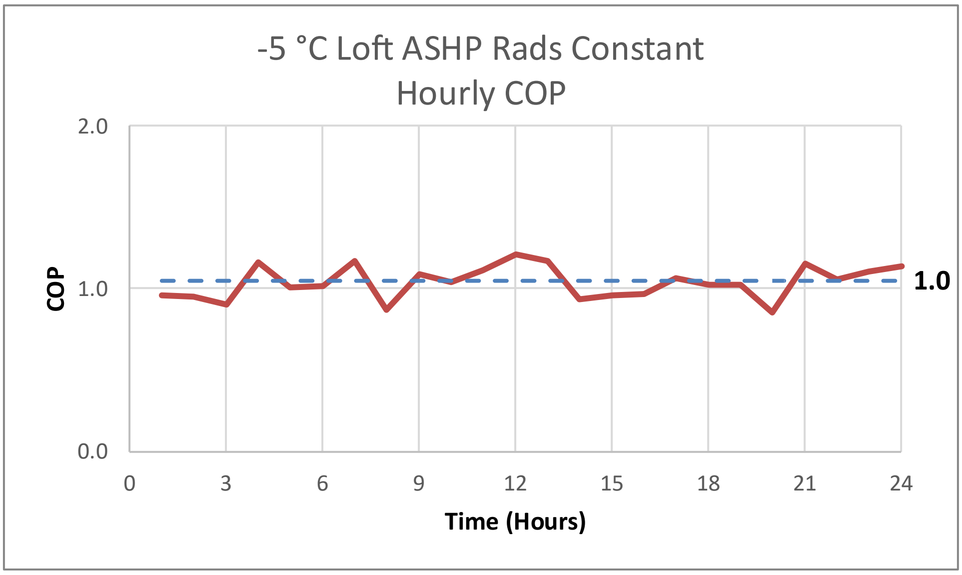


Figure 42. -5 °C Loft ASHP Rads Constant – Hourly COP

7.1.1.5.4 Discussion

Issues

The ASHP had to revert to the backup heater during a large portion of the test, which could affect the COP.

Setpoint

- Living Room temperatures achieved setpoint with low levels of hysteresis.
- WC overheated by 1 °C, with sporadic control and hysteresis.
- All other rooms achieved setpoint with a low levels of hysteresis.

Heat Distribution

- Homogenous temperature distribution across the Living Room, apart from the sensor adjacent to the radiator.
- Living room stratification was low, with a range of ~0.9 °C in air temperature.
- Homogenous temperature distribution in Bedroom 1, with low levels of stratification.

Energy Consumption

This 24h period had a total energy consumption of 63.0 kWh, with a running cost of £15.43.

Efficiency

The COP was 1.0, and the SEEI for this system test was 0.35 K/kWh.

7.1.1.6 -5 °C Loft ASHP Rads SAP

7.1.1.6.1 Control

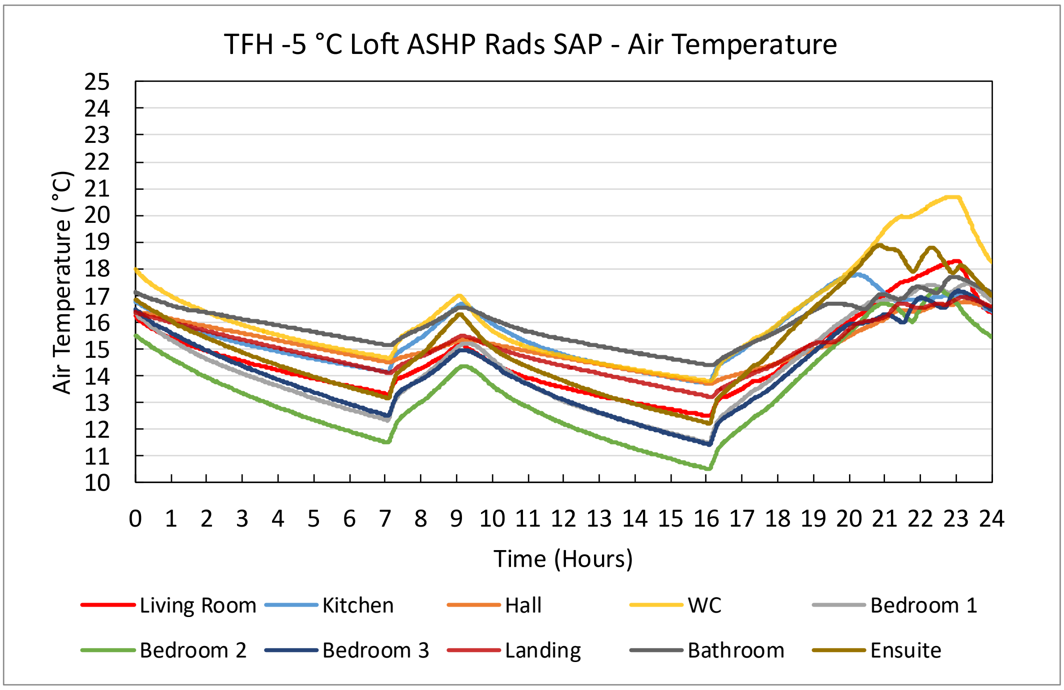


Figure 43. -5 °C Loft ASHP Rads SAP – Air Temperature Plots

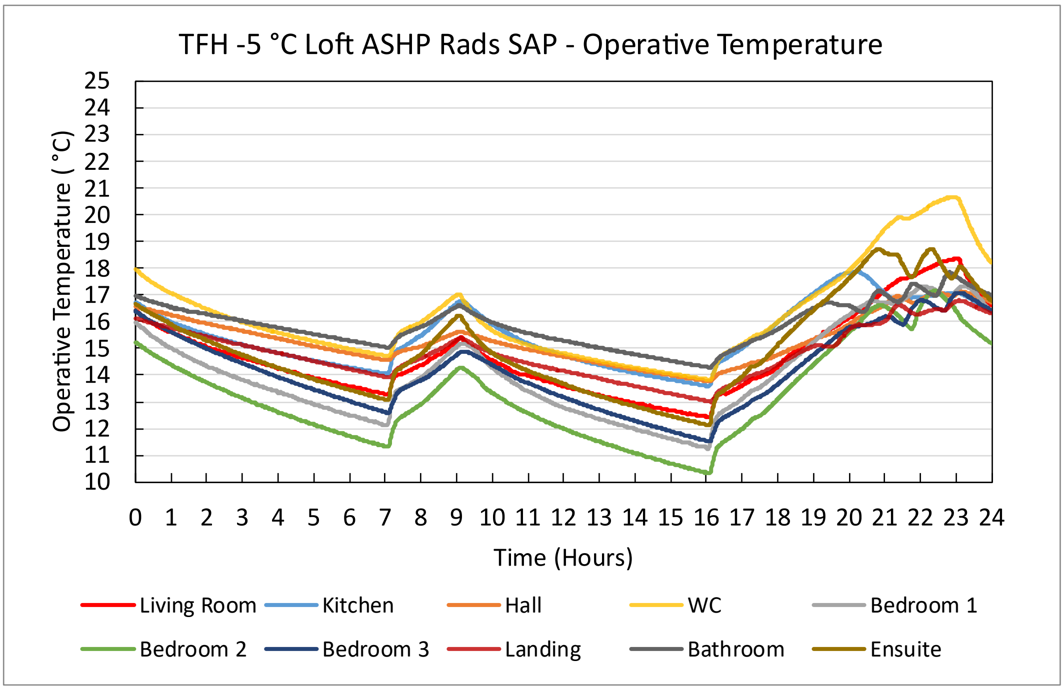


Figure 44. -5 °C Loft ASHP Rads SAP – Operative Temperature Plots

7.1.1.6.2 Spatial

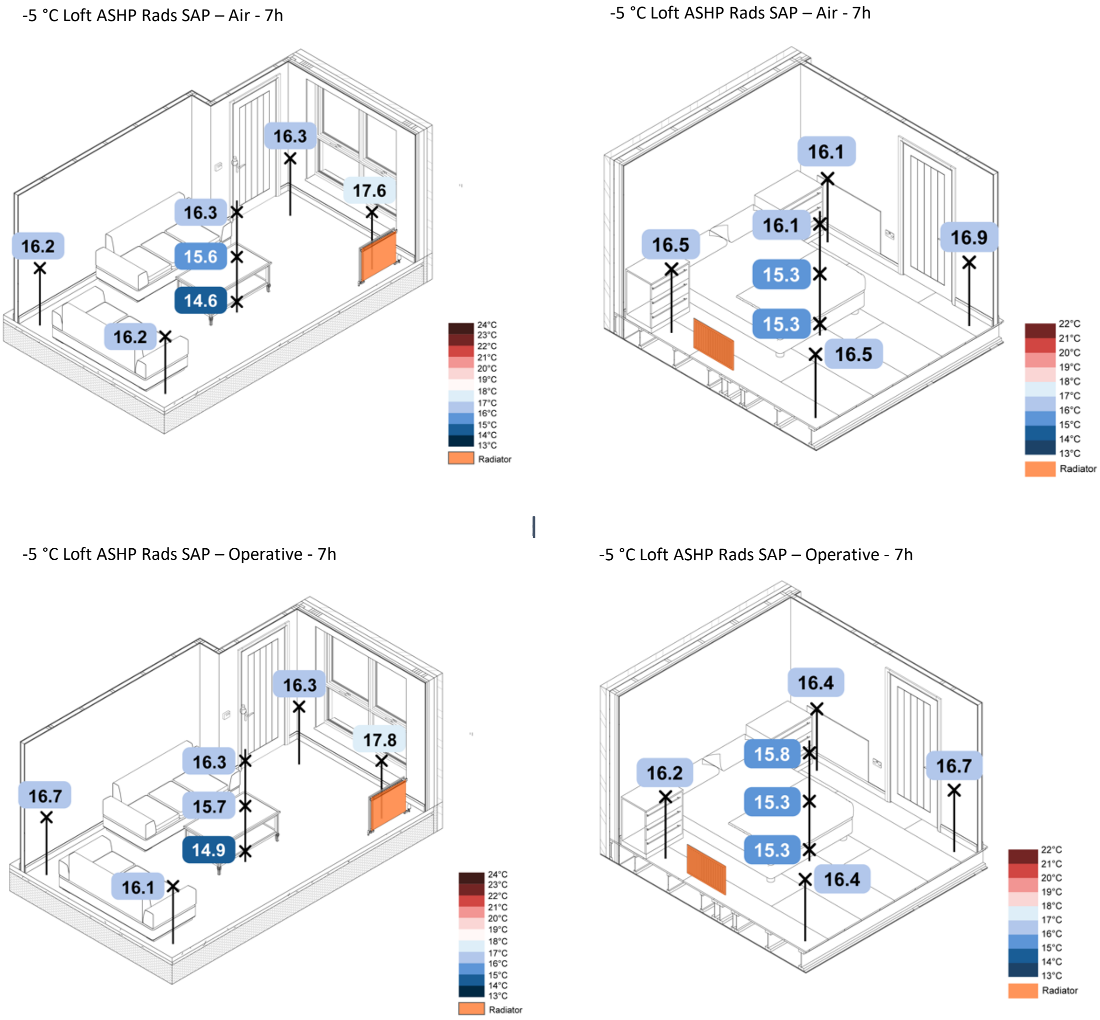


Figure 46. -5 °C Loft ASHP Rads SAP – Spatial Operative Temperatures

7.1.1.6.3 Heat up times

Table 20. -5 °C Loft ASHP Rads SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	12.51	18.29	07:01:00	0.82
Bedroom 1	11.49	17.43	07:15:00	0.82

7.1.1.6.4 Performance Metrics

Table 21. -5 °C Loft ASHP Rads SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.2	0.43	43.4	£10.64

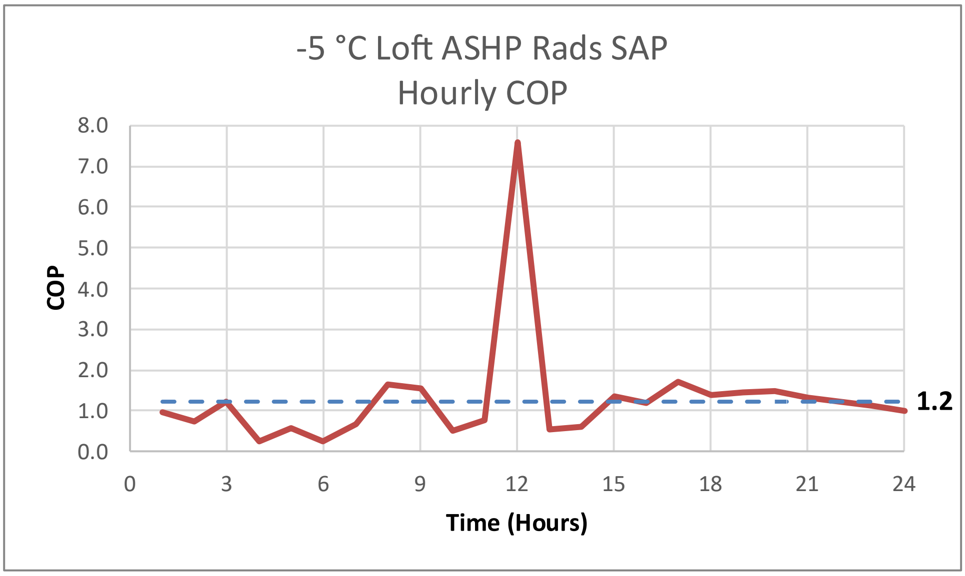


Figure 47. -5 °C Loft ASHP Rads SAP – Hourly COP

7.1.1.6.5 Discussion

Issues

The ASHP had to revert to the backup heater during a large portion of the test, which could affect the COP.

Setpoint

- Living Room failed to achieve setpoint temperatures, reaching a maximum of ~15.2 °C and ~18.3 °C in the morning and evening heating periods respectively.
- WC, Ensuite and Bathroom achieved setpoint during the evening heating period. However, the Bathroom only achieved setpoint towards the end of the evening heating period.
- No rooms achieved setpoint temperature during the morning heating period.
- Temperatures at the end of the longest period of no heating ranged from 10.3-14.3 °C

Heat Distribution

- Living Room failed to achieve setpoint in any location, with the coolest portion of the room in the centre, with the warmest point adjacent to the radiator at 17.6 °C.
- Bedroom 1 also failed to achieve setpoint, with 16.9 °C being the warmest point adjacent to the door. The coolest point was located next to the bed, measuring 15.3-15.8 °C.

Energy Consumption

This 24h period had a total energy consumption of 43.4 kWh, with a running cost of £10.64.

Efficiency

The COP was 1.2, and the SEEI for this system test was 0.43 K/kWh.

7.1.1.7 -5 °C Monobloc ASHP TFH Rads + UFH Constant

7.1.1.7.1 Control

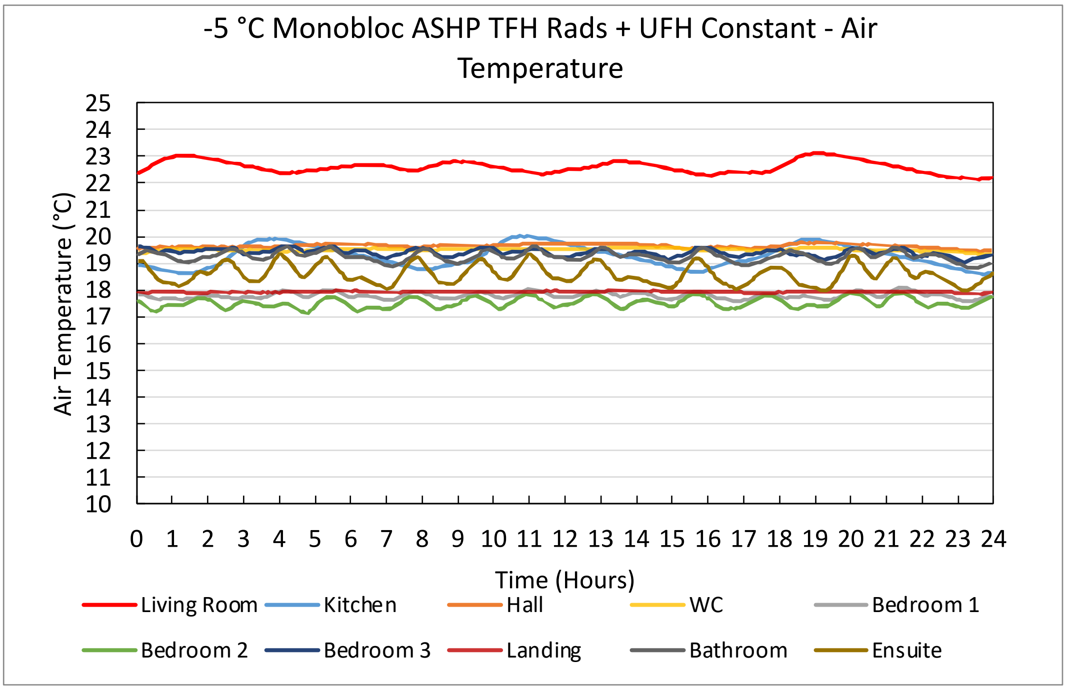


Figure 48. -5 °C Monobloc ASHP TFH Rads + UFH Constant – Air Temperature Plots

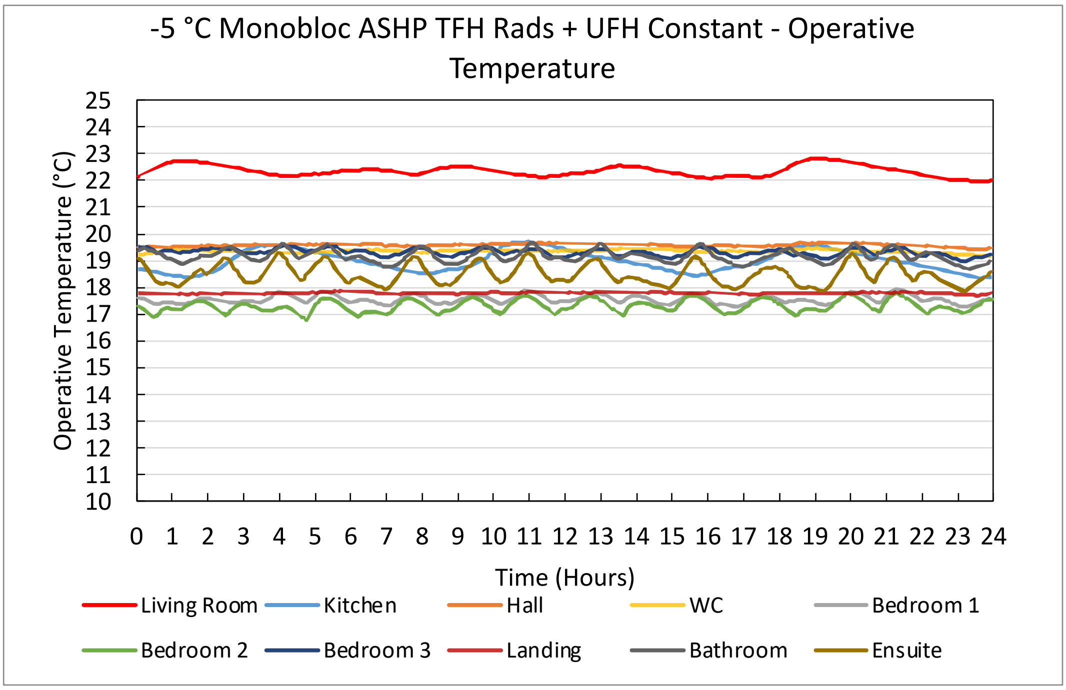


Figure 49. -5 °C Monobloc ASHP TFH Rads + UFH Constant – Operative Temperature Plots

7.1.1.7.2 Spatial

-5 °C Monobloc ASHP TFH Rads + UFH Constant – Air - 7h

-5 °C Monobloc ASHP TFH Rads + UFH Constant – Air - 7h

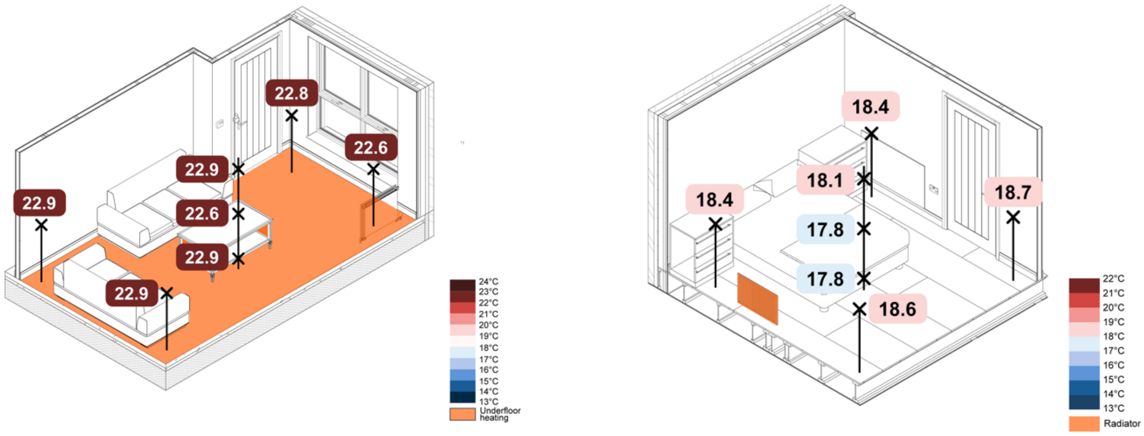


Figure 51. -5 °C Monobloc ASHP TFH Rads + UFH Constant – Spatial Air Temperatures

-5 °C Monobloc ASHP TFH Rads + UFH Constant – Operative - 7h

-5 °C Monobloc ASHP TFH Rads + UFH Constant – Operative - 7h

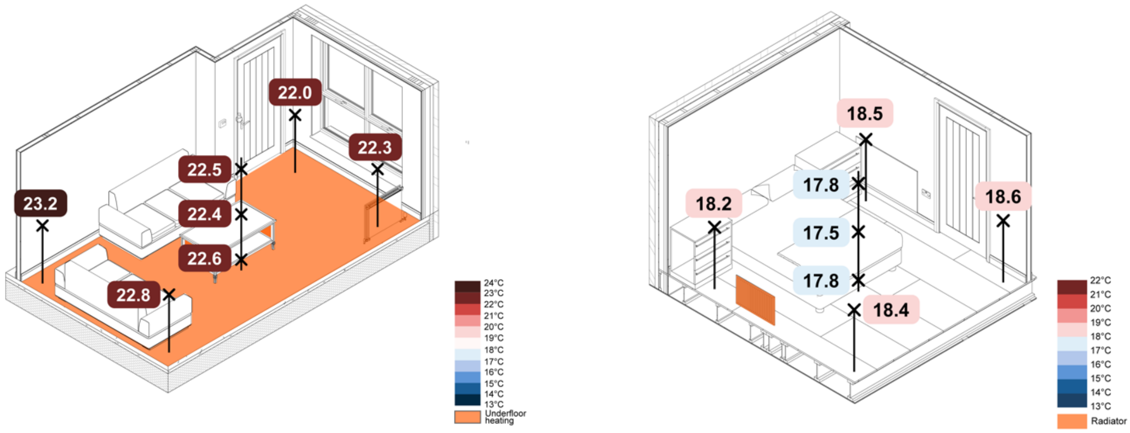


Figure 50. -5 °C Monobloc ASHP TFH Rads + UFH Constant – Spatial Operative Temperatures

7.1.1.7.3 Performance Metrics

Table 22. -5 °C Monobloc ASHP TFH Rads + UFH Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
2.3	0.87	25.9	£6.34

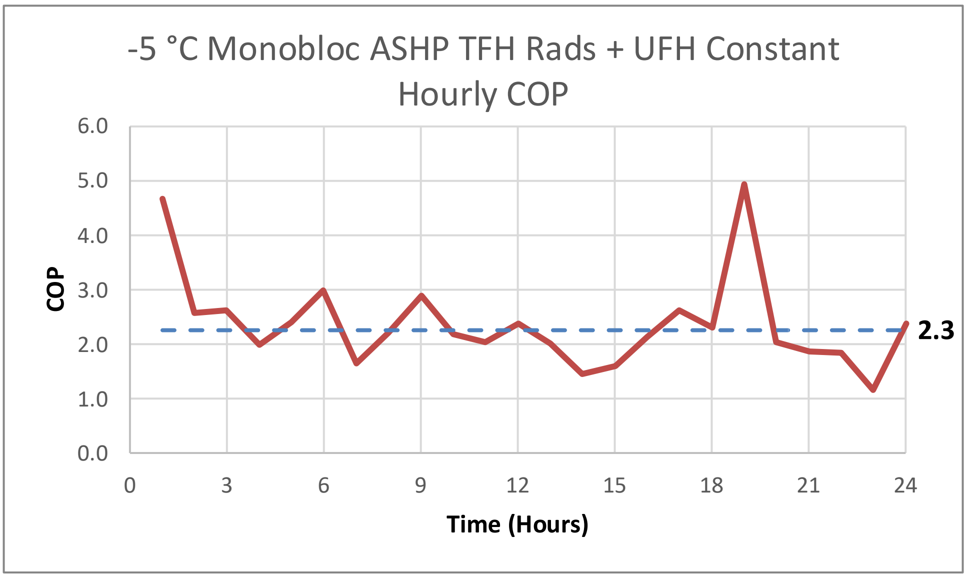


Figure 52. -5 °C Monobloc ASHP TFH Rads + UFH Constant – Hourly COP

7.1.1.7.4 Discussion

Setpoint

- Living room had an overshoot of 1.2 °C to the 21 °C setpoint.
- WC overshot setpoint by 4.2 °C.
- Generally, the hysteresis was low, with the exception of Bedroom 1 and the Kitchen, however these are relatively minor with a swing of ±~0.3 °C

Heat Distribution

- Homogenous air temperature across LR and B1 (range of ~0.5-1 °C)
- Little variation between operative and air temperatures (< 0.2 °C)

Energy Consumption

This 24h period had a total energy consumption of 25.9 kWh, with a running cost of £6.34.

Efficiency

The COP was 2.3, and the SEEI for this system test was 0.87 K/kWh.

7.1.1.8 -5 °C Monobloc ASHP TFH Rads + UFH SAP

7.1.1.8.1 Control

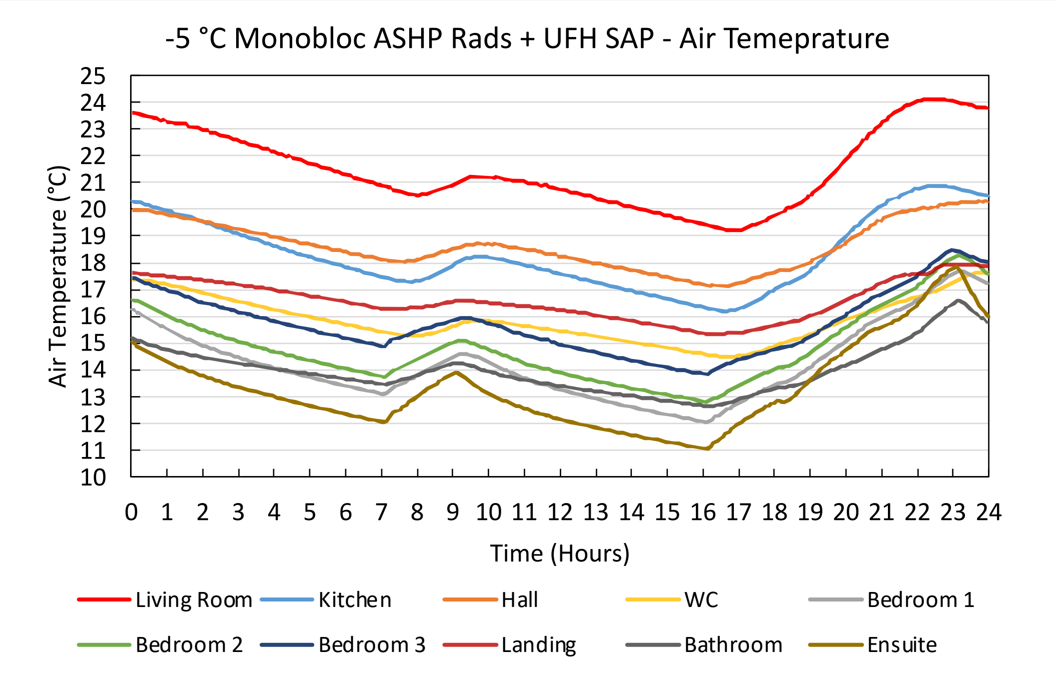


Figure 53. -5 °C Monobloc ASHP TFH Rads + UFH SAP – Air Temperature Plots

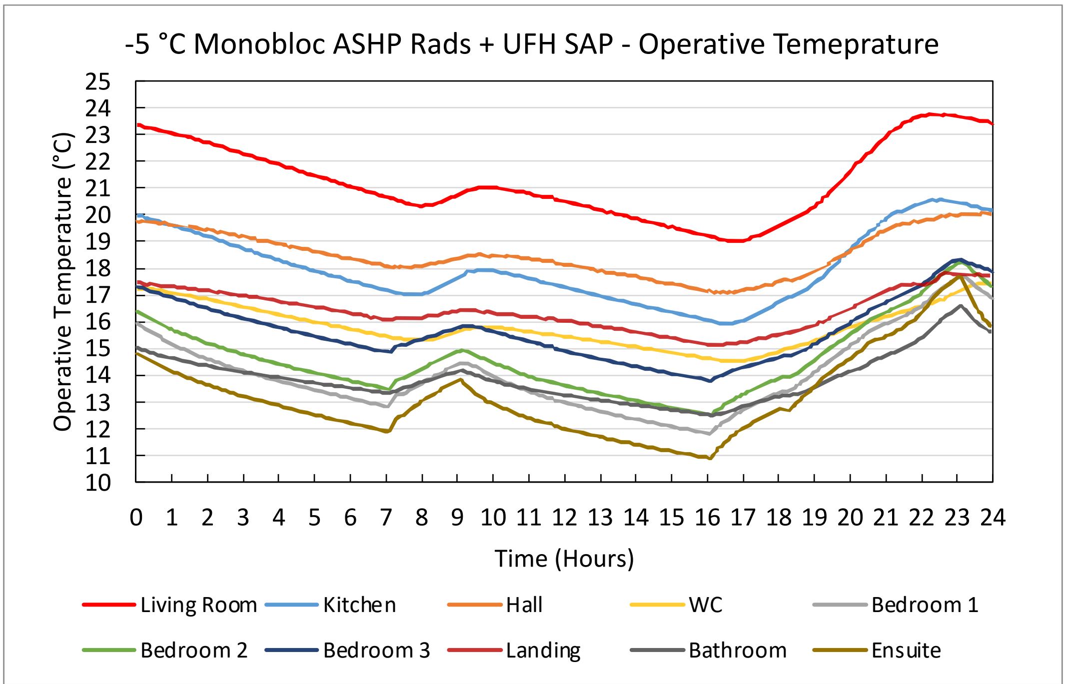


Figure 54. -5 °C Monobloc ASHP TFH Rads + UFH SAP – Operative Temperature Plots

7.1.1.8.2 Spatial

-5 °C Monobloc ASHP TFH Rads + UFH SAP – Air - 7h

-5 °C Monobloc ASHP TFH Rads + UFH SAP – Air - 7h

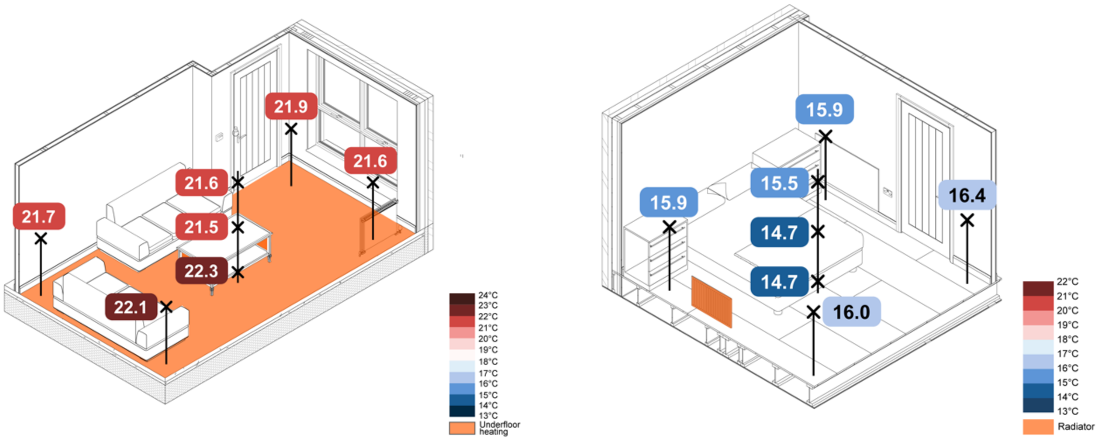


Figure 56. -5 °C Monobloc ASHP TFH Rads + UFH SAP – Spatial Air Temperatures

-5 °C Monobloc ASHP TFH Rads + UFH SAP – Operative - 7h

-5 °C Monobloc ASHP TFH Rads + UFH SAP – Operative - 7h

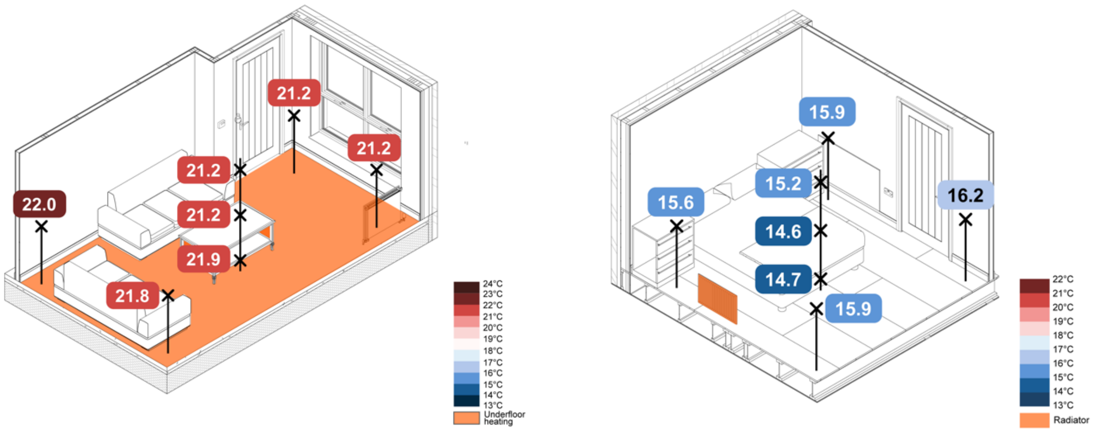


Figure 55. -5 °C Monobloc ASHP TFH Rads + UFH SAP – Spatial Operative Temperatures

7.1.1.8.3 Heat up times

Table 23. -5 °C Monobloc ASHP TFH Rads + UFH SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	19.46	21	03:23:00	0.46
Bedroom 1	12.08	17.7	07:10:00	0.78

7.1.1.8.4 Performance Metrics

Table 24. -5 °C Monobloc ASHP TFH Rads + UFH SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
3.0	1.13	18.0	£4.41

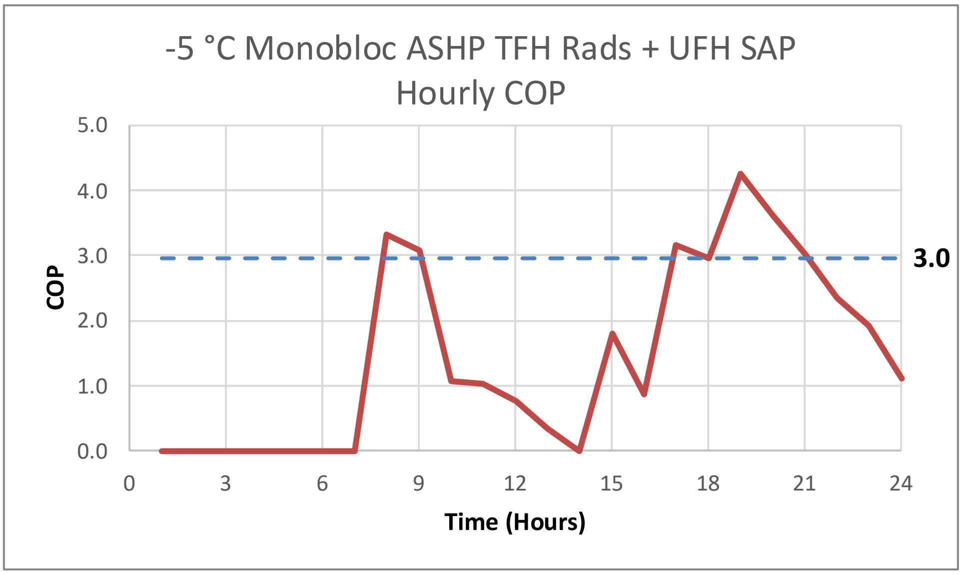


Figure 57. -5 °C Monobloc ASHP TFH Rads + UFH SAP – Hourly COP

7.1.1.8.5 Discussion

Setpoint

- Living room had an overshoot of 2.3 °C to the 21 °C setpoint, with no control about the setpoint.
- Both Kitchen and Hall overshot by ~2 °C of their 18 °C setpoint during the evening heating period.
- All other rooms failed to achieve setpoint during the morning heating period, and also failed to achieve the setpoint for a substantial portion of the evening heating period.

Heat Distribution

- Homogenous temperature distribution across the Living Room with minimal stratification
- Homogenous temperature distribution in Bedroom 1, but noticeably low temperatures, ranging from 14.7-16.4 °C

Energy Consumption

This 24h period had a total energy consumption of 18.0 kWh, with a running cost of £4.41.

Efficiency

The COP was 3.0, and the SEEI for this system test was 1.13 K/kWh.

7.1.1.9 -5 °C Monobloc ASHP TFH Rads Constant

7.1.1.9.1 Control

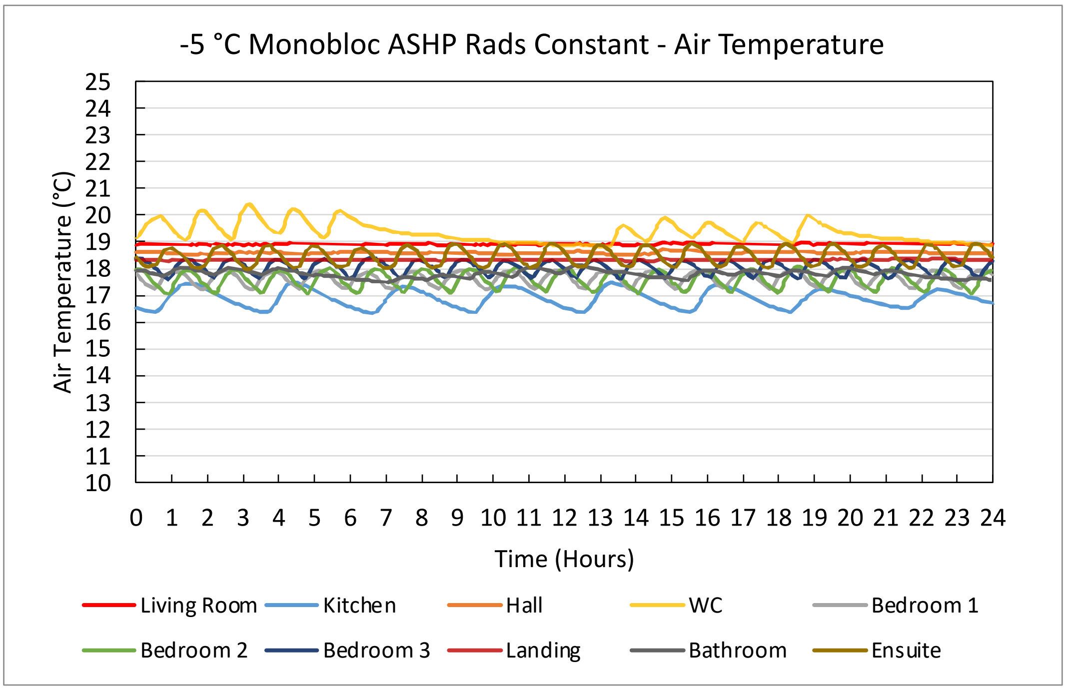


Figure 58. -5 °C Monobloc ASHP TFH Rads Constant – Air Temperature Plots

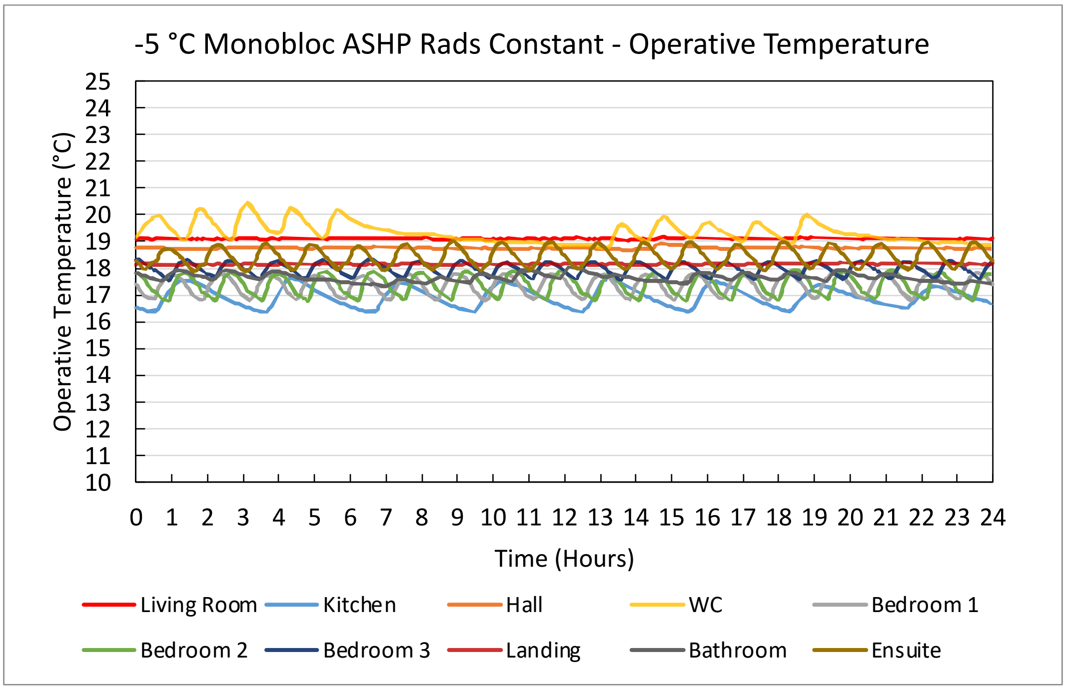


Figure 59. -5 °C Monobloc ASHP TFH Rads Constant – Operative Temperature Plots

7.1.1.9.2 Spatial

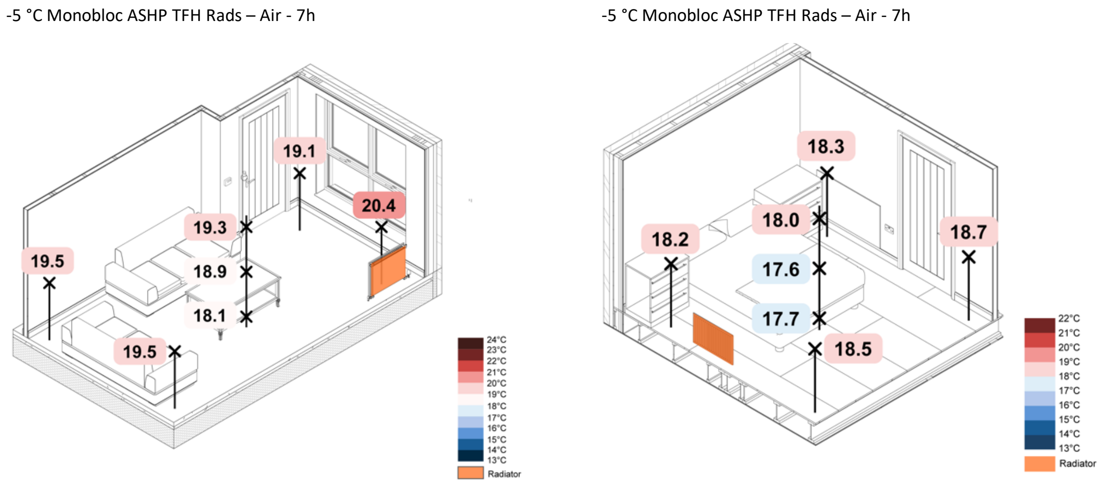


Figure 61. -5 °C Monobloc ASHP TFH Rads Constant – Spatial Air Temperatures

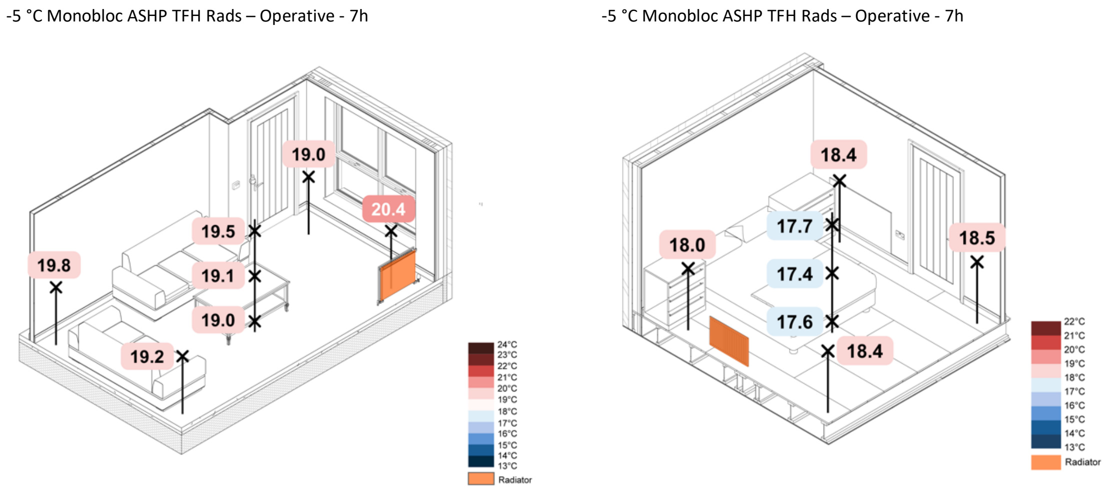


Figure 60. -5 °C Monobloc ASHP TFH Rads Constant – Spatial Operative Temperatures

7.1.1.9.3 Performance Metrics

Table 25. -5 °C Monobloc ASHP TFH Rads Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.7	0.62	34.4	£8.43

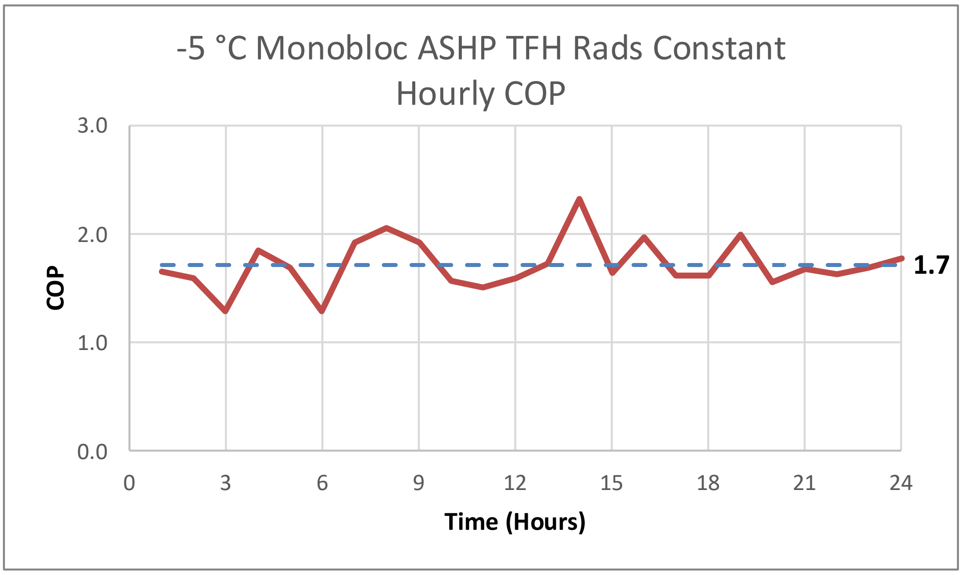


Figure 62. -5 °C Monobloc ASHP TFH Rads Constant – Hourly COP

7.1.1.9.4 Discussion

Setpoint

- Living Room failed to achieve the 21 °C setpoint temperature by ~2 °C
- WC overheated at time by up to ~2 °C, and had a sporadic pattern of control
- All other rooms were in the region of the setpoint by ~±1 °C, with the exception of the Kitchen.

Heat Distribution

- Homogenous temperature distribution in the Living Room, with the exception of the sensor located adjacent to the radiator, however temperatures were all below the 21 °C setpoint, ranging from 18.1-20.4 °C.
- Homogenous temperature distribution across Bedroom 1, with all temperatures within 0.6 °C of the 18 °C setpoint.

Energy Consumption

This 24h period had a total energy consumption of 34.4 kWh, with a running cost of £8.43.

Efficiency

The COP was 1.7, and the SEEI for this system test was 0.62 K/kWh.

7.1.1.10 -5 °C Monobloc ASHP TFH Rads SAP

7.1.1.10.1 Control

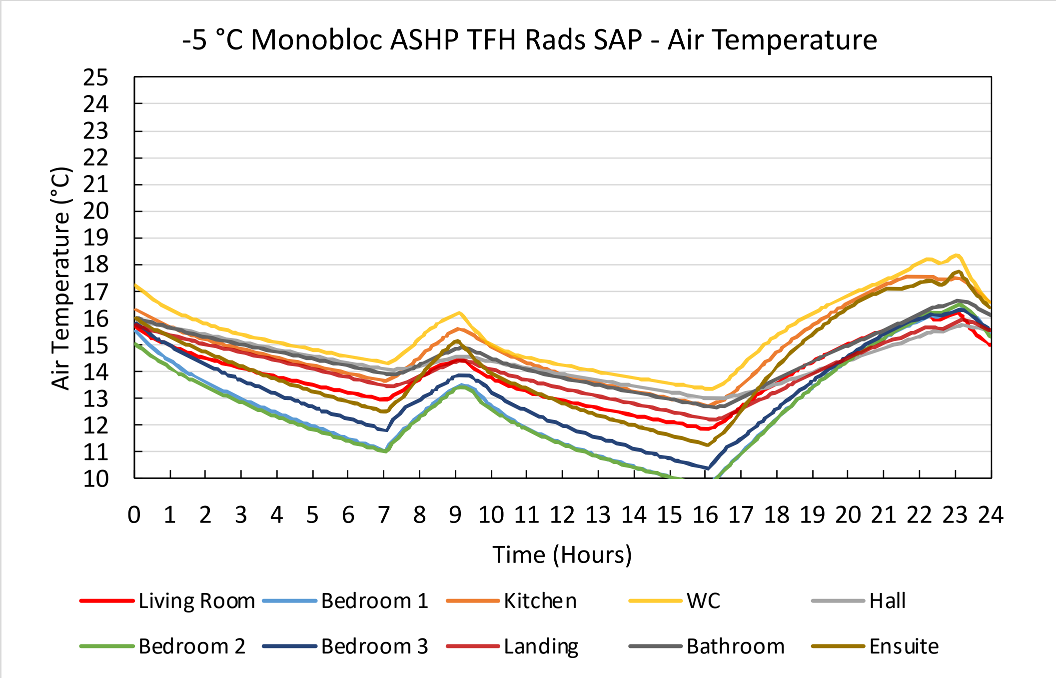


Figure 63. -5 °C Monobloc ASHP TFH Rads SAP – Air Temperature Plots

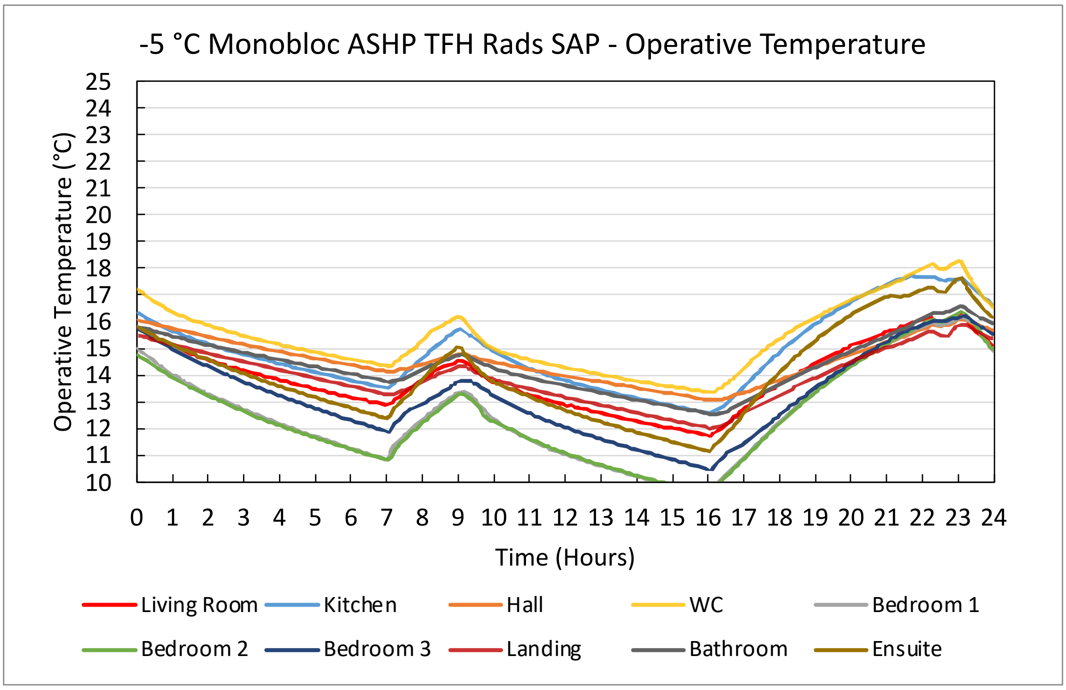


Figure 64. -5 °C Monobloc ASHP TFH Rads SAP – Operative Temperature Plots

7.1.1.10.2 Spatial

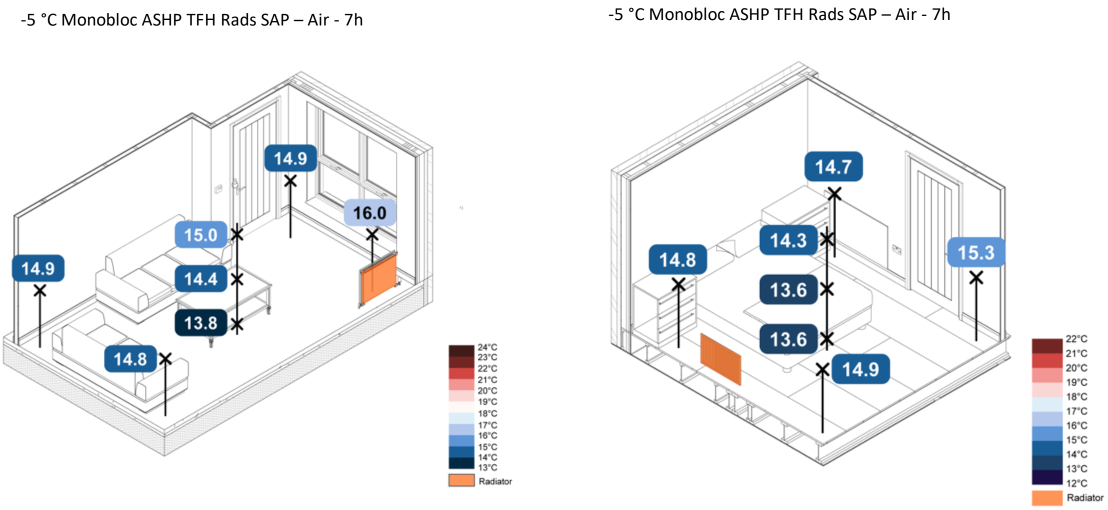


Figure 66. -5 °C Monobloc ASHP TFH Rads SAP – Spatial Air Temperatures

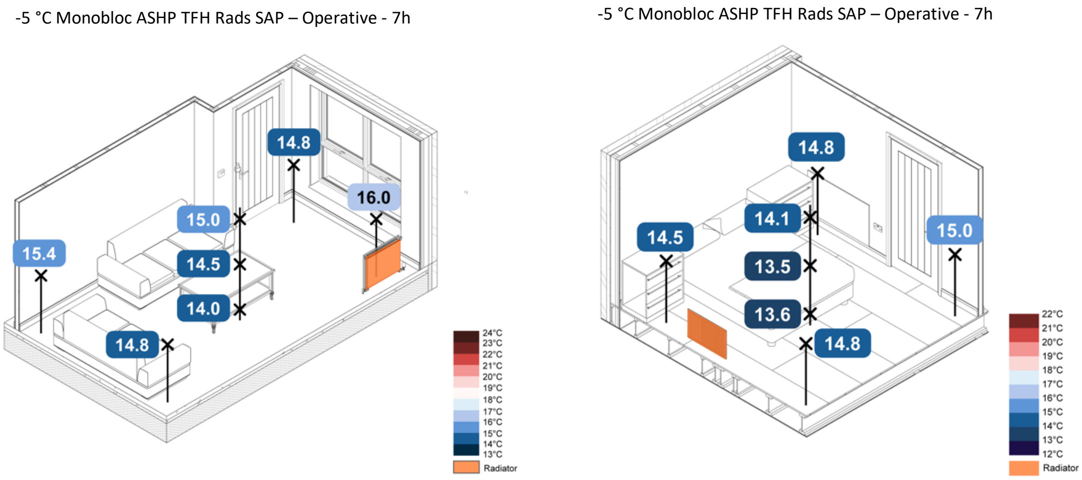


Figure 65. -5 °C Monobloc ASHP TFH Rads SAP – Spatial Operative Temperatures

7.1.1.10.3 Heat up times

Table 26. -5 °C Monobloc ASHP TFH Rads SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	12.23	16.92	07:03:00	0.67
Bedroom 1	10.44	17.07	07:07:00	0.93

7.1.1.10.4 Performance Metrics

Table 27. -5 °C Monobloc ASHP TFH Rads SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
2.5	0.90	19.6	£4.80

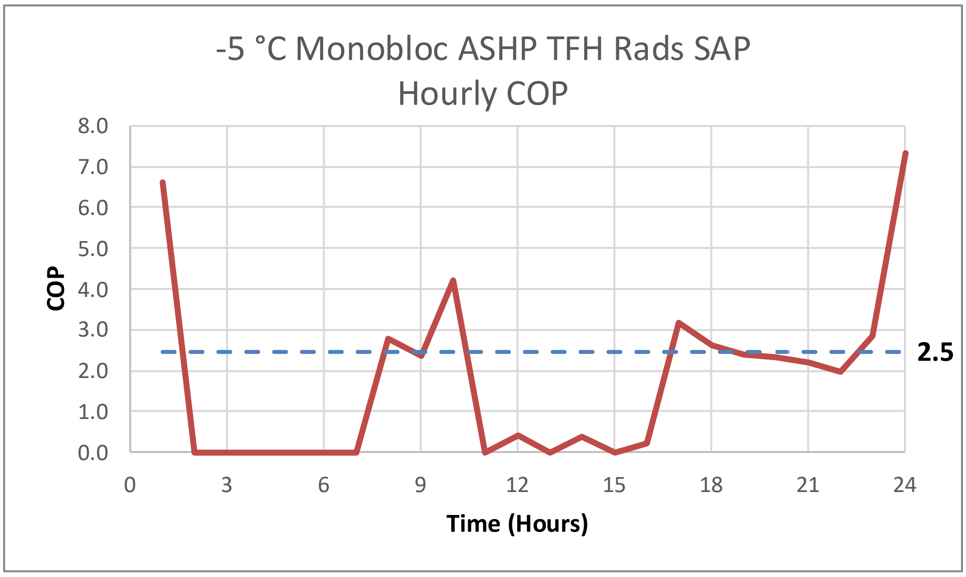


Figure 67. -5 °C Monobloc ASHP TFH Rads SAP – Hourly COP

7.1.1.10.5 Discussion

Setpoint

- All rooms failed to reach their respective setpoint temperatures.
- Both Bedroom 1 and 2 were achieving temperatures below 10 °C during the heating off periods.

Heat Distribution

- Homogenous distribution in both rooms, however both failed to achieve setpoint by ~6 °C in the Living Room and ~ 3 °C in Bedroom 1.

Energy Consumption

This 24h period had a total energy consumption of 19.6 kWh, with a running cost of £4.80.

Efficiency

The COP was 2.5, and the SEEI for this system test was 0.90 K/kWh.

7.1.1.11 5°C Wall Mounted IR TFH Constant

7.1.1.11.1 Control

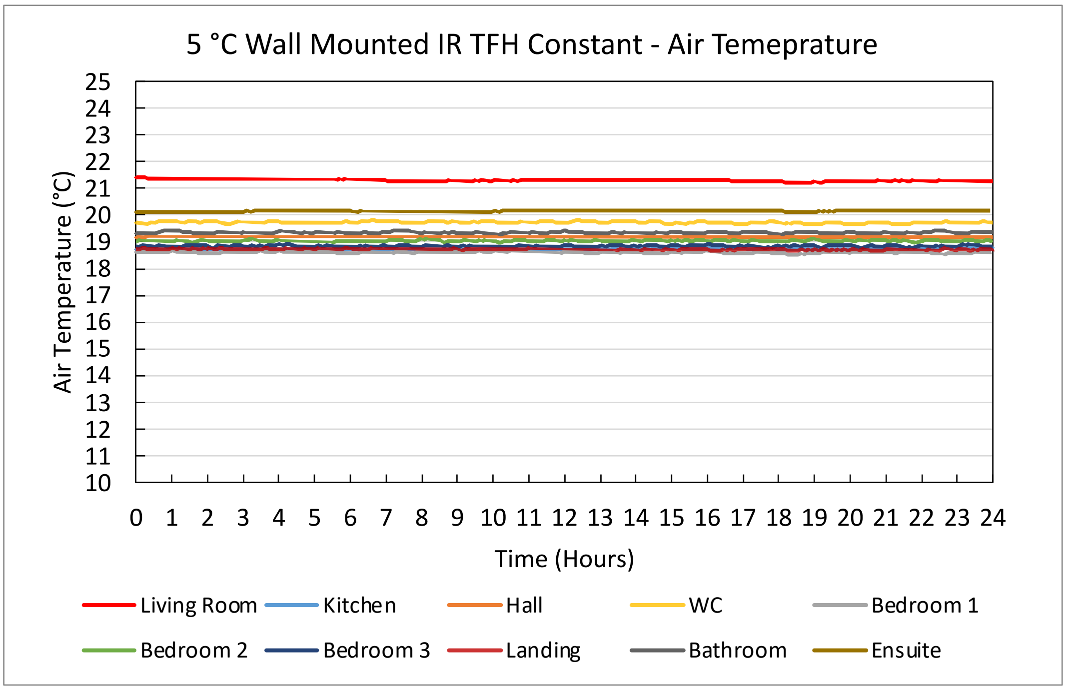


Figure 68. 5°C Wall Mounted IR TFH Constant – Air Temperature Plots

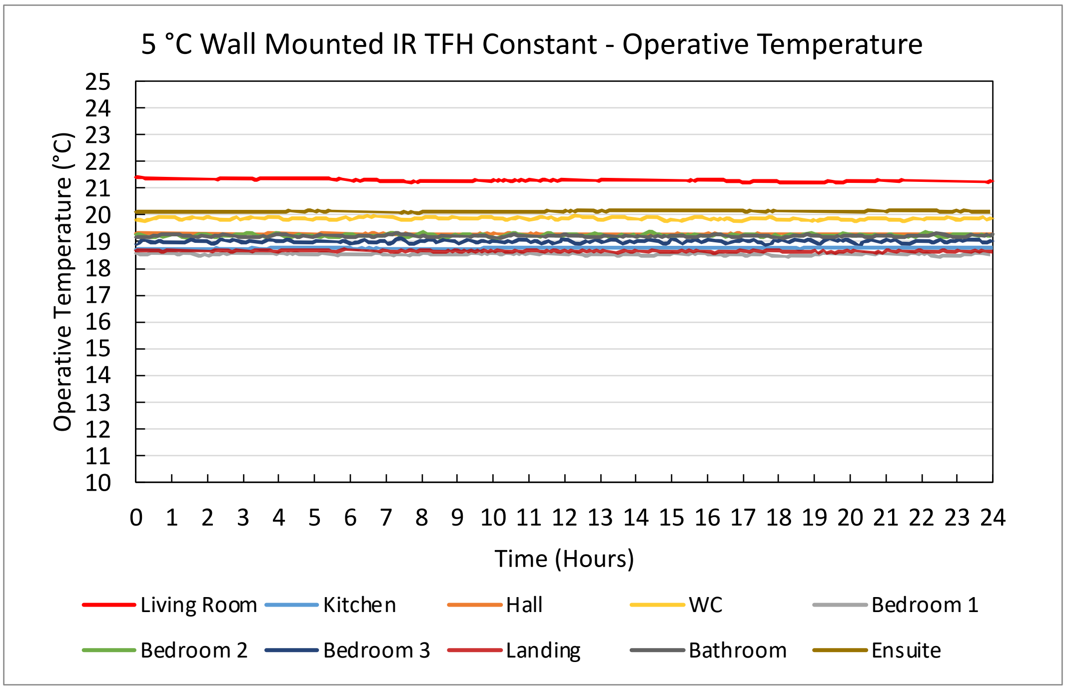


Figure 69. 5°C Wall Mounted IR TFH Constant – Operative Temperature Plots

7.1.1.11.2 Spatial

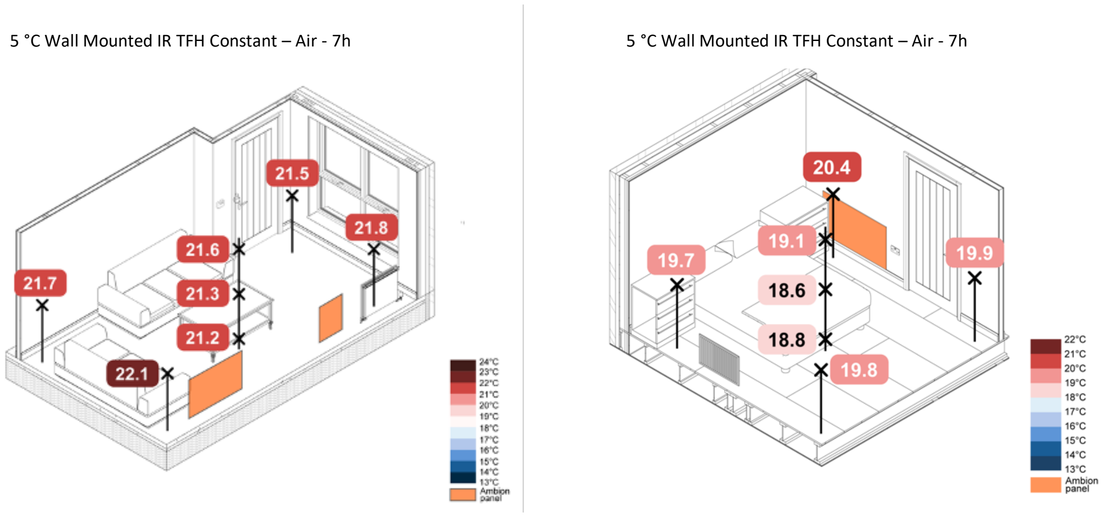


Figure 70. 5°C Wall Mounted IR TFH Constant – Spatial Air Temperatures

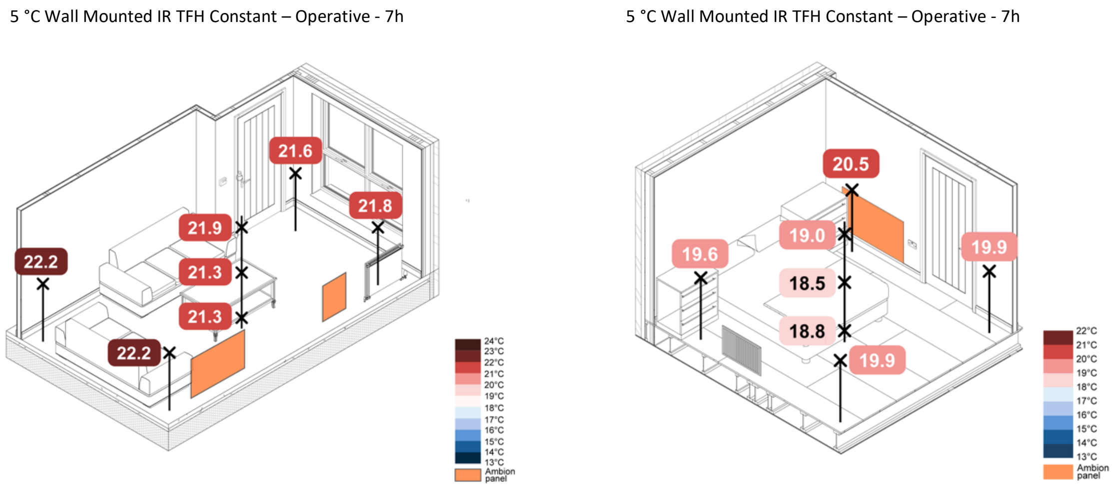


Figure 71. 5°C Wall Mounted IR TFH Constant – Spatial Operative Temperatures

7.1.1.11.3 Performance Metrics

Table 28. 5°C Wall Mounted IR TFH Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.39	30.9	£7.56

7.1.1.11.4 Discussion

Setpoint

- Low hysteresis in the Living room, and achieving setpoint temperature with ~±0.5 °C
- Low hysteresis in all rooms.
- Ensuite and WC both overshot the setpoint by ~1.5 °C
- Remaining room achieved setpoints between 18.5-19 °C.

Heat Distribution

- Homogenous temperature distribution in the Living Room (Range 21.3-22.2 °C), with slightly higher temperature adjacent to the IR heaters.
- Homogenous temperature distribution in Bedroom 1 (Range 18.5-20.5 °C), with slightly higher temperature adjacent to the IR heater.

Energy Consumption

This 24h period had a total energy consumption of 30.9 kWh, with a running cost of £7.56.

Efficiency

The SEEI for this system test was 0.39 K/kWh.

7.1.1.12 5 °C Wall Mounted IR TFH SAP

7.1.1.12.1 Control

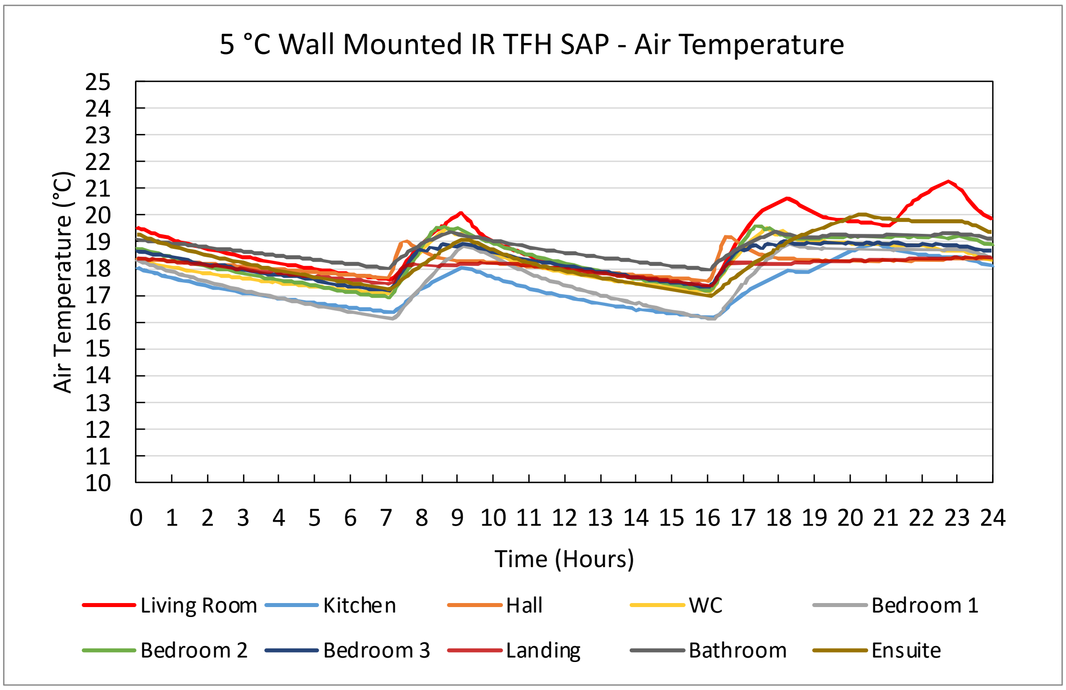


Figure 72. 5 °C Wall Mounted IR TFH SAP – Air Temperature Plots

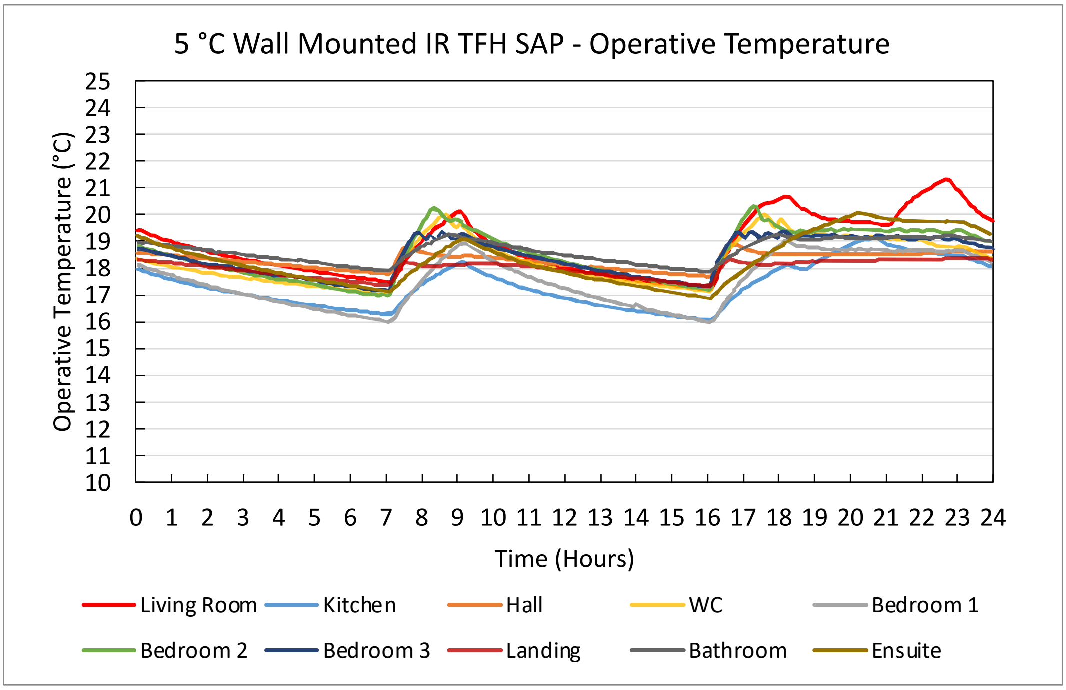


Figure 73. 5 °C Wall Mounted IR TFH SAP – Operative Temperature Plots

7.1.1.12.2 Spatial

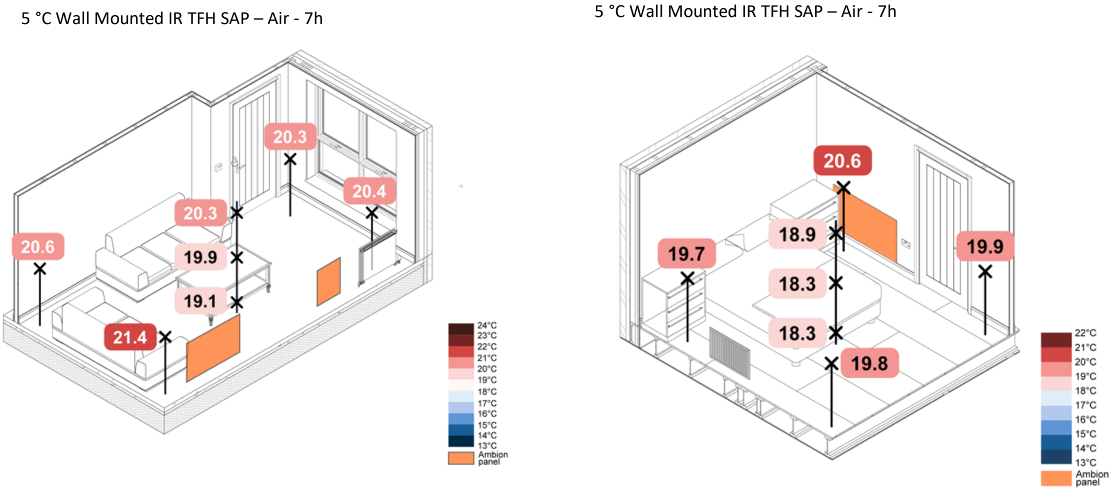


Figure 75. 5 °C Wall Mounted IR TFH SAP – Spatial Air Temperatures

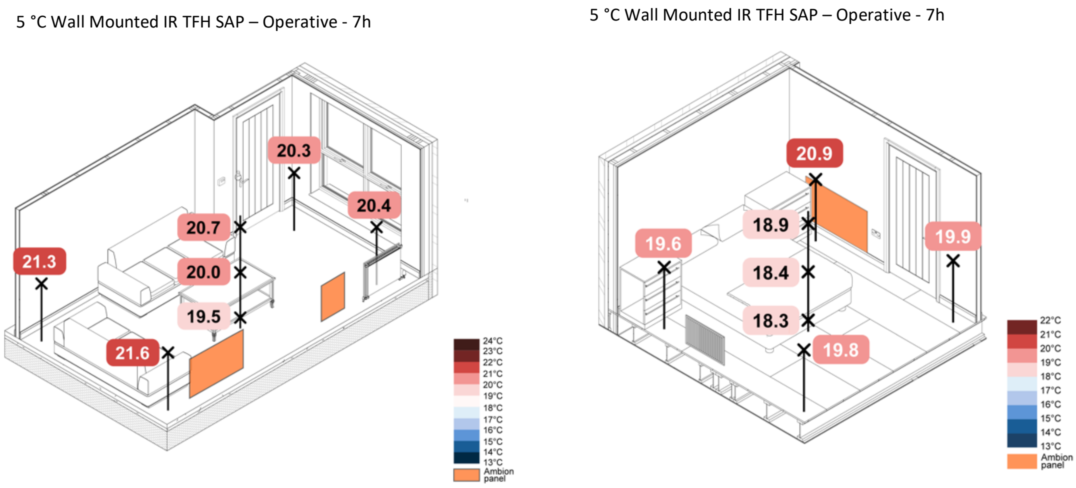


Figure 74. 5 °C Wall Mounted IR TFH SAP – Spatial Operative Temperatures

7.1.1.12.3 Heat up times

Table 29. 5 °C Wall Mounted IR TFH SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	17.31	21.00	06:18:00	0.59
Bedroom 1	16.01	18.00	01:16:48	1.55

7.1.1.12.4 Performance Metrics

Table 30. 5 °C Wall Mounted IR TFH SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.44	24.9	£6.11

7.1.1.12.5 Discussion

Setpoint

- Living Room did not achieve setpoint temperature during the morning heating period, and only achieved it for a small proportion of time during the evening heating period.
- Kitchen achieved setpoint towards the end of the morning heating period, and overshoots during the evening heating period by ~1 °C.

Heat Distribution

- Homogenous temperature distribution across the Living Room, although the average temperature was below 21 °C, with the exception of the temperature sensor adjacent to the IR heater.
- Homogenous temperature distribution in Bedroom 1, with the sensor located next to the IR heater being 20.9 °C. Excluding this sensor, the range was 18.3-19.9 °C.

Energy Consumption

This 24h period had a total energy consumption of 24.9 kWh, with a running cost of £6.11.

Efficiency

The SEEI for this system test was 0.44 K/kWh.

7.1.1.13 5 °C Loft ASHP Rads + UFH Constant

7.1.1.13.1 Control

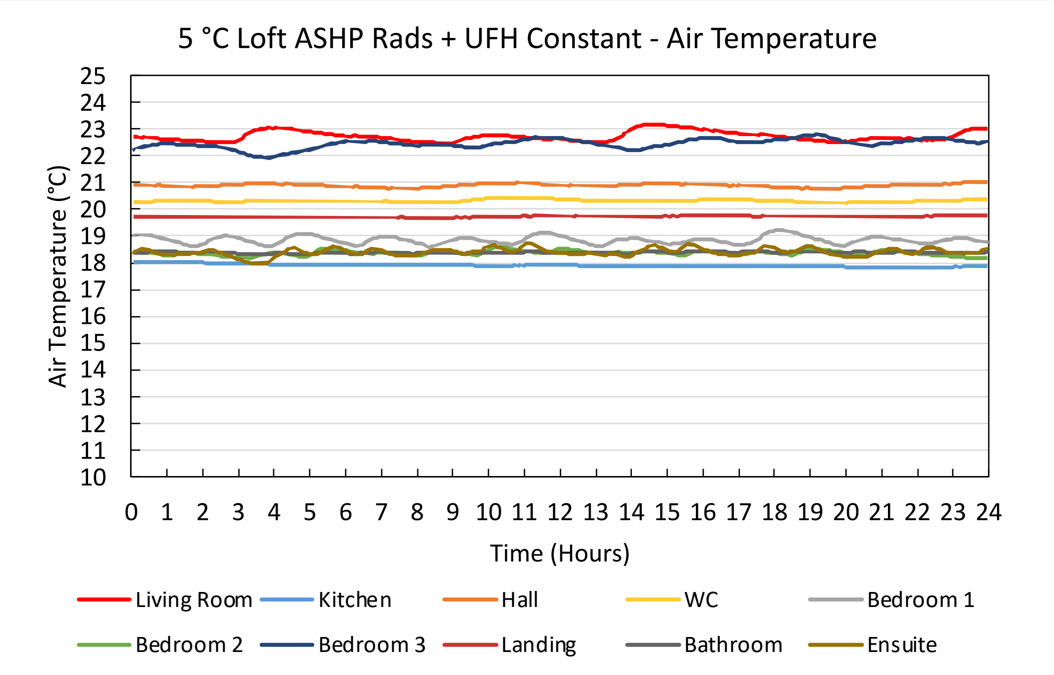


Figure 76. 5 °C Loft ASHP Rads + UFH Constant – Air Temperature Plots

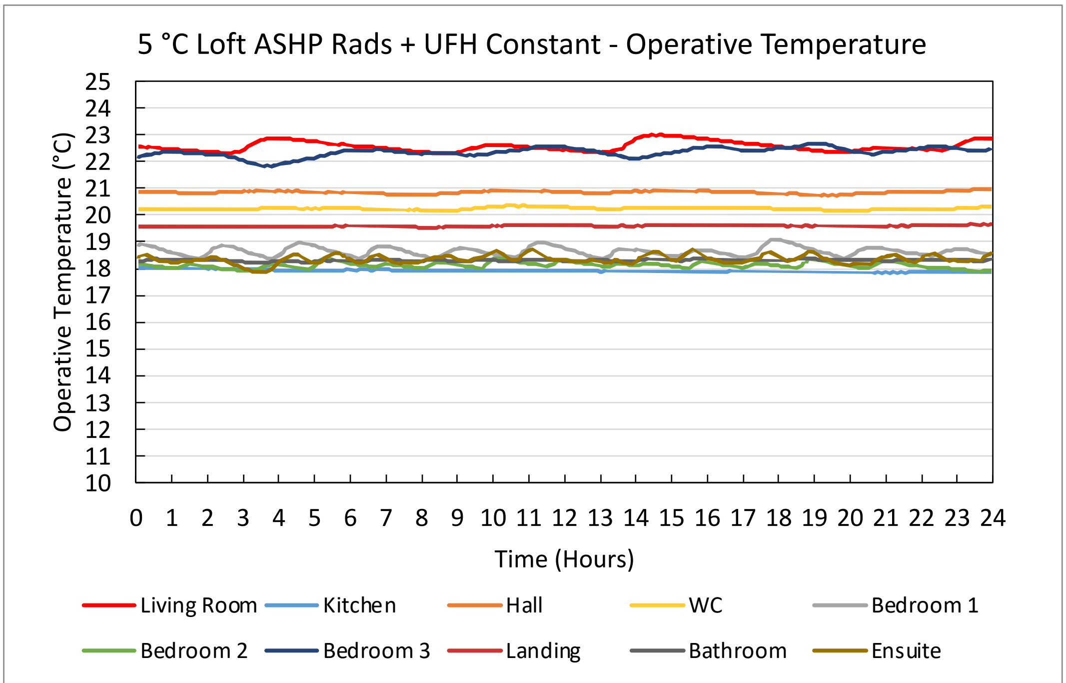


Figure 77. 5 °C Loft ASHP Rads + UFH Constant – Operative Temperature Plots

7.1.1.13.2 Spatial

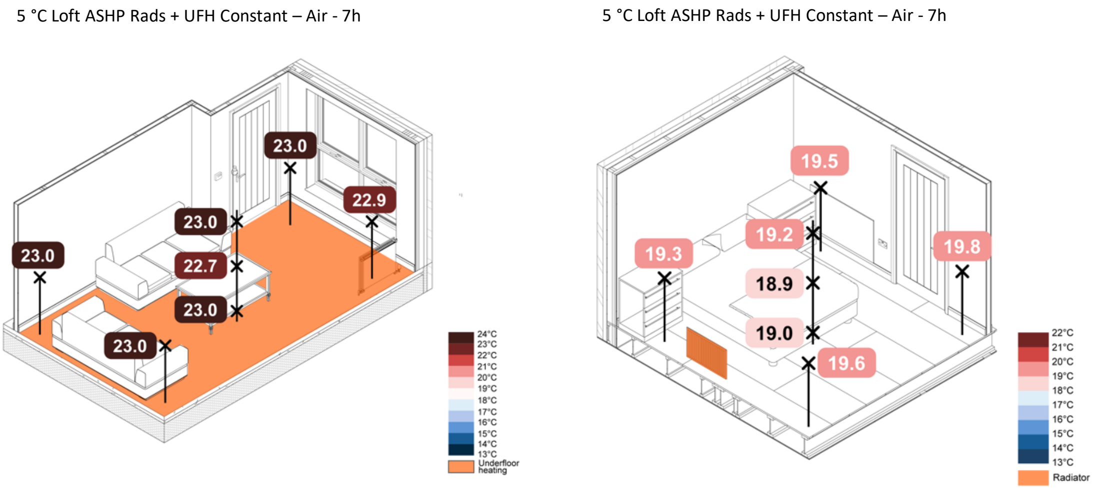


Figure 78. 5 °C Loft ASHP Rads + UFH Constant – Spatial Air Temperatures

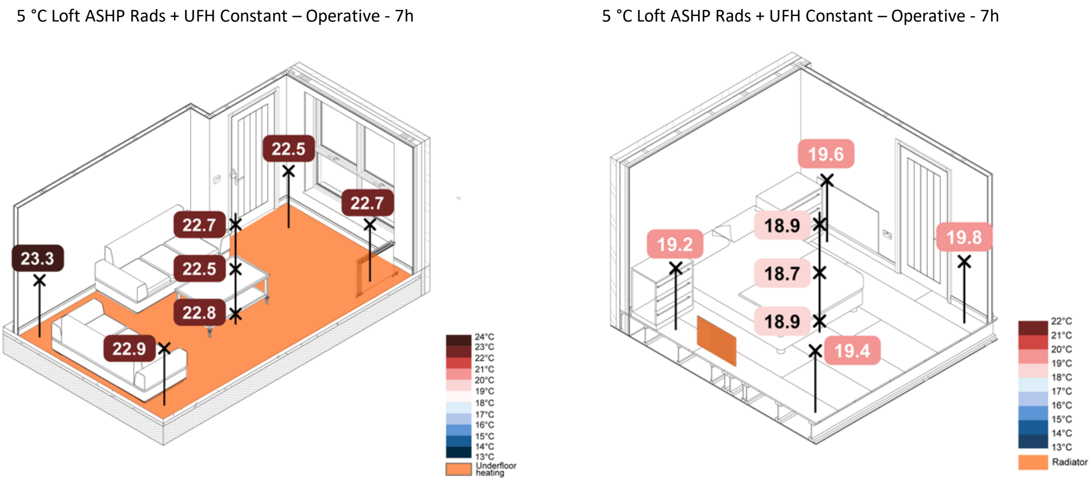


Figure 79. 5 °C Loft ASHP Rads + UFH Constant – Spatial Operative Temperatures

7.1.1.13.3 Performance Metrics

Table 31. 5 °C Loft ASHP Rads + UFH Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.3	0.39	32.9	£8.07

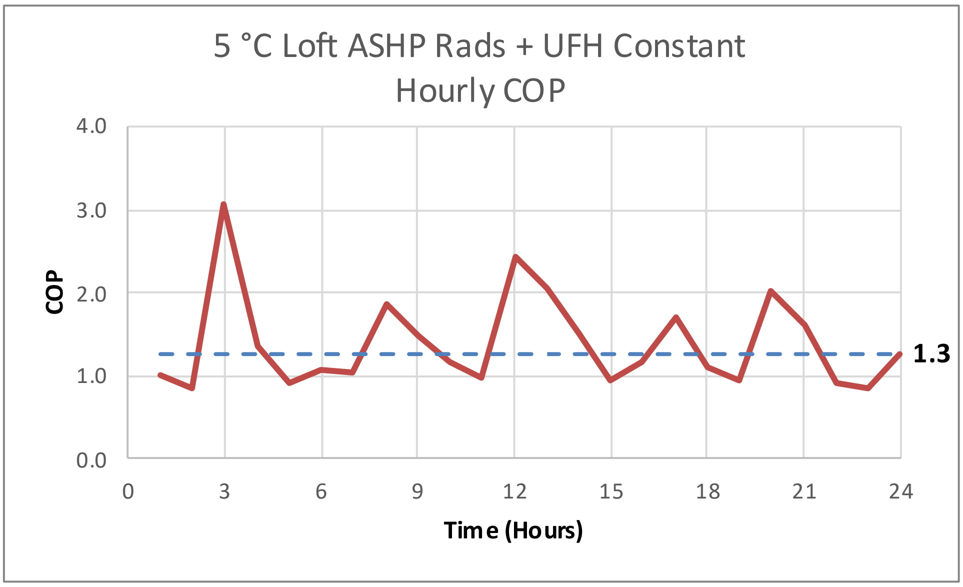


Figure 80. 5 °C Loft ASHP Rads + UFH Constant – Hourly COP

7.1.1.13.4 Discussion

Setpoint

- Living Room temperature overshot the setpoint by ~1.5 °C
- Bedroom 3 temperature overshot the setpoint ~4.5 °C
- Hall, WC and Landing all overheated between 1.5-3.0 °C
- All remaining rooms achieved setpoint within ~±0.5 °C
- All rooms showed low levels of hysteresis

Heat Distribution

- Homogenous temperature distribution across the Living Room, with a range of 22.7-23.0 °C
- Homogenous temperature distribution across Bedroom 1, with a range of 18.9-19.8 °C

Energy Consumption

This 24h period had a total energy consumption of 32.9 kWh, with a running cost of £8.07.

Efficiency

The COP was 1.3, and the SEEI for this system test was 0.39 K/kWh.

7.1.1.14 5 °C Loft ASHP Rads + UFH SAP

7.1.1.14.1 Control

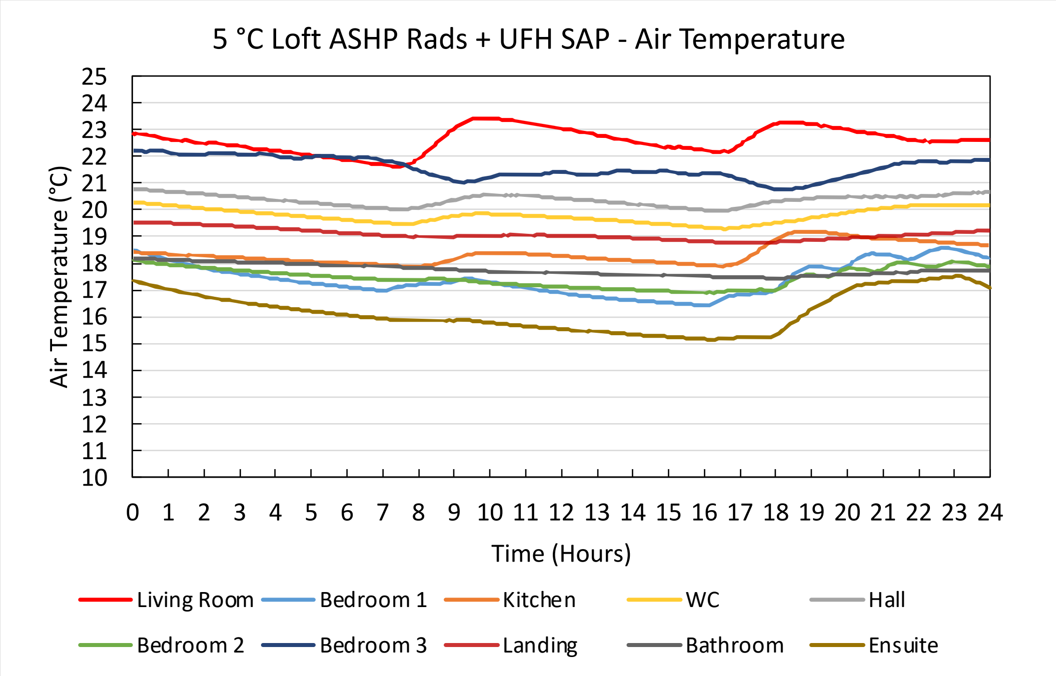


Figure 81. 5 °C Loft ASHP Rads + UFH SAP – Air Temperature Plots

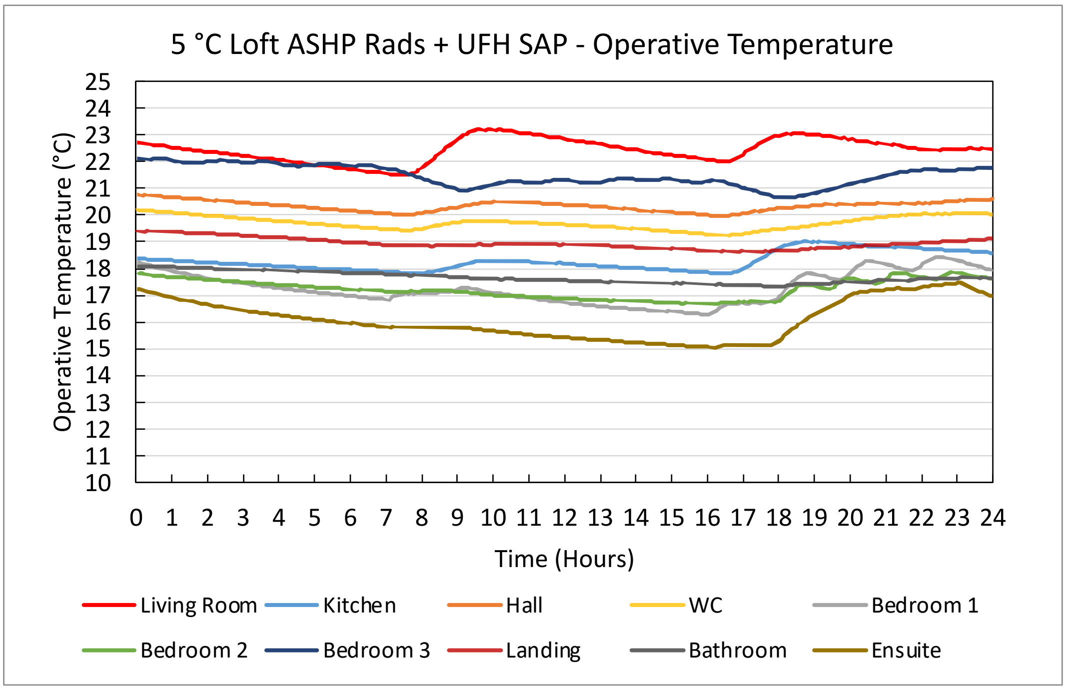


Figure 82. 5 °C Loft ASHP Rads + UFH SAP – Operative Temperature Plots

7.1.1.14.2 Spatial

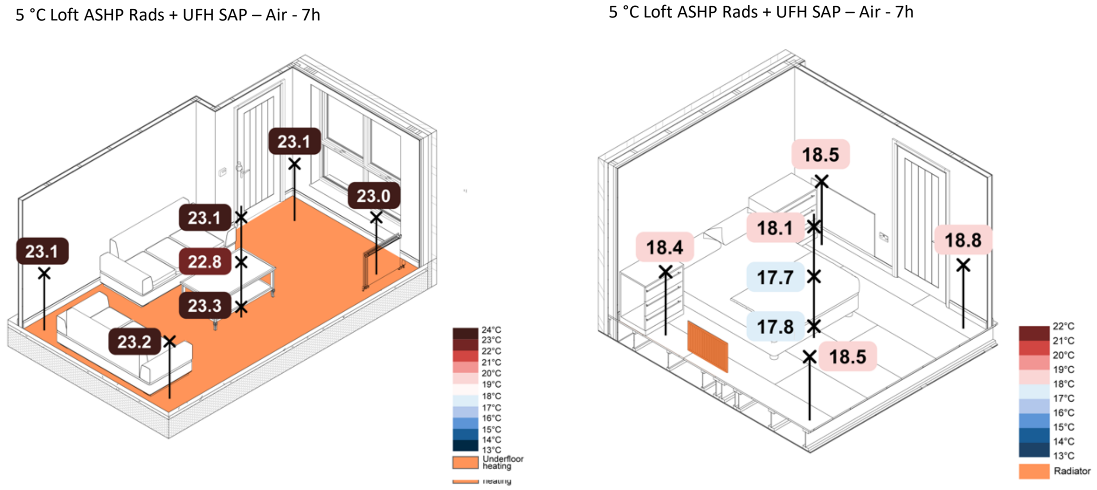


Figure 84. 5 °C Loft ASHP Rads + UFH SAP – Spatial Air Temperatures

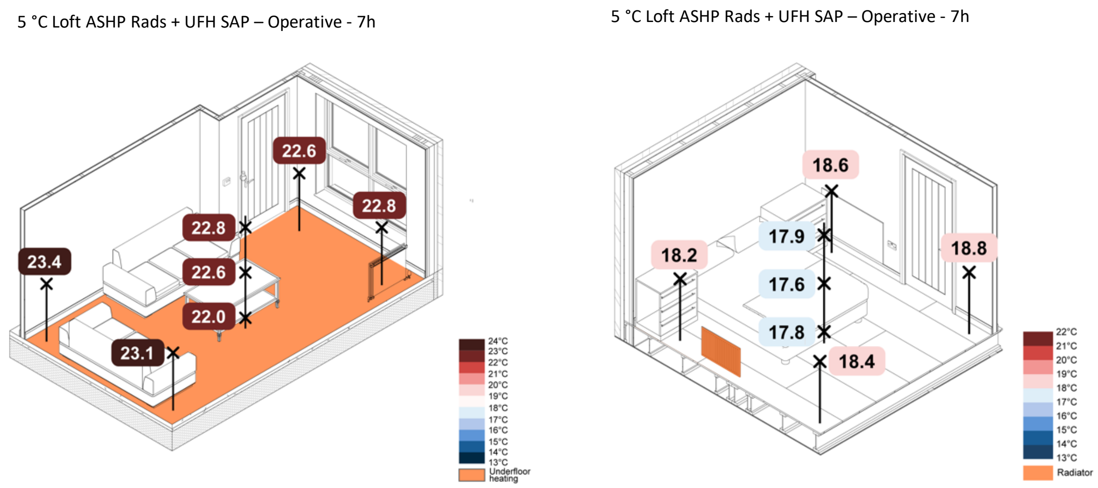


Figure 83. 5 °C Loft ASHP Rads + UFH SAP – Spatial Operative Temperatures

7.1.1.14.3 Heat up times

Table 32. 5 °C Loft ASHP Rads + UFH SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	22.45	23.29	01:16:00	0.66
Bedroom 1	16.84	18.01	02:54:12	0.40

7.1.1.14.4 Performance Metrics

Table 33. 5 °C Loft ASHP Rads + UFH SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.2	0.44	27.9	£6.83

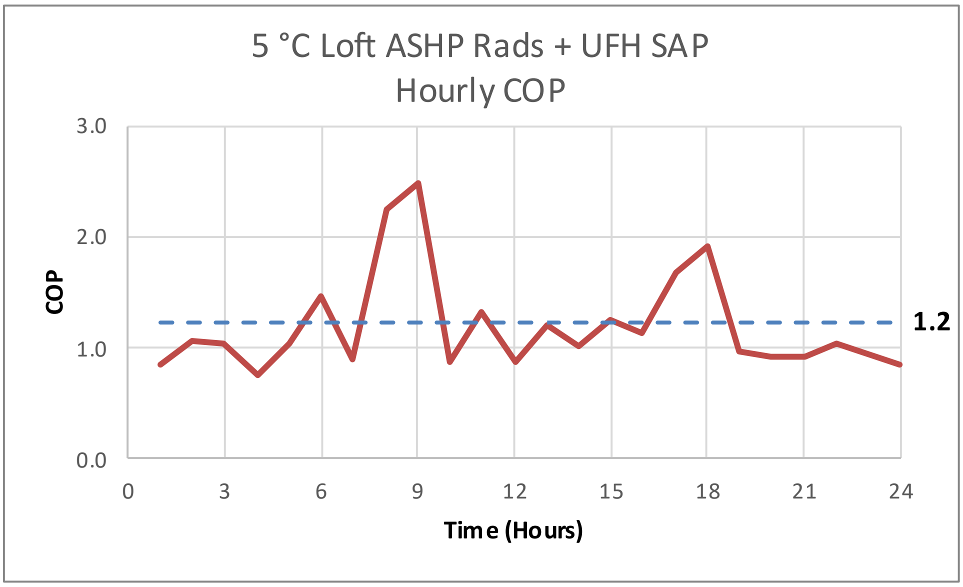


Figure 85. 5 °C Loft ASHP Rads + UFH SAP – Hourly COP

7.1.1.14.5 Discussion

Setpoint

- Living Room overshot setpoint temperature in both the morning and evening heating periods, by up to ~2 °C
- Wide temperature distribution across the different rooms (~7 °C)
- Controls patterns in some rooms were difficult to understand.
- Bedroom 1 and Bedroom 2 did not achieve setpoint during the morning heating period, and Bedroom 1 only achieved setpoint for a limited portion of time in the evening heating period.
- Bathroom and Ensuite did not achieve setpoint in either the morning or evening heating period.

Heat Distribution

- Homogenous temperature distribution in the Living Room, however overshot the setpoint, with temperatures ranging between 22.8-23.3 °C.
- Homogenous temperature distribution and setpoint achieved in Bedroom 1 within 0.3 °C, ranging between 17.7-18.8 °C.

Energy Consumption

This 24h period had a total energy consumption of 27.9 kWh, with a running cost of £6.83.

Efficiency

The COP was 1.2, and the SEEI for this system test was 0.44 K/kWh.

7.1.1.15 5 °C Loft ASHP Rads Constant

7.1.1.15.1 Control

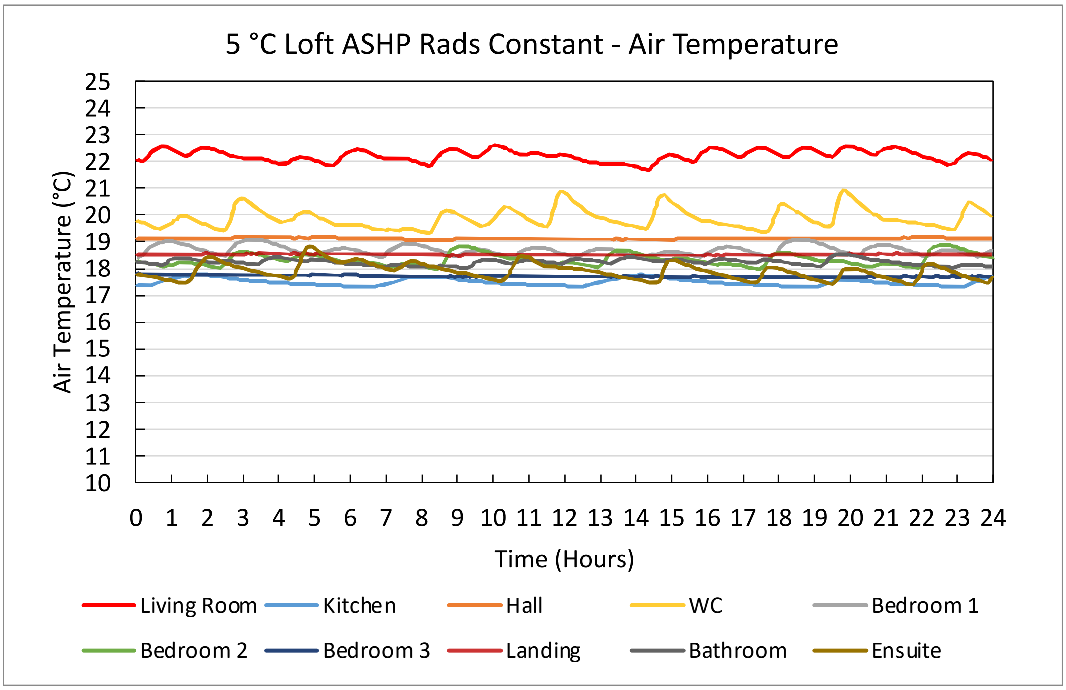


Figure 86. 5 °C Loft ASHP Rads Constant – Air Temperature Plots

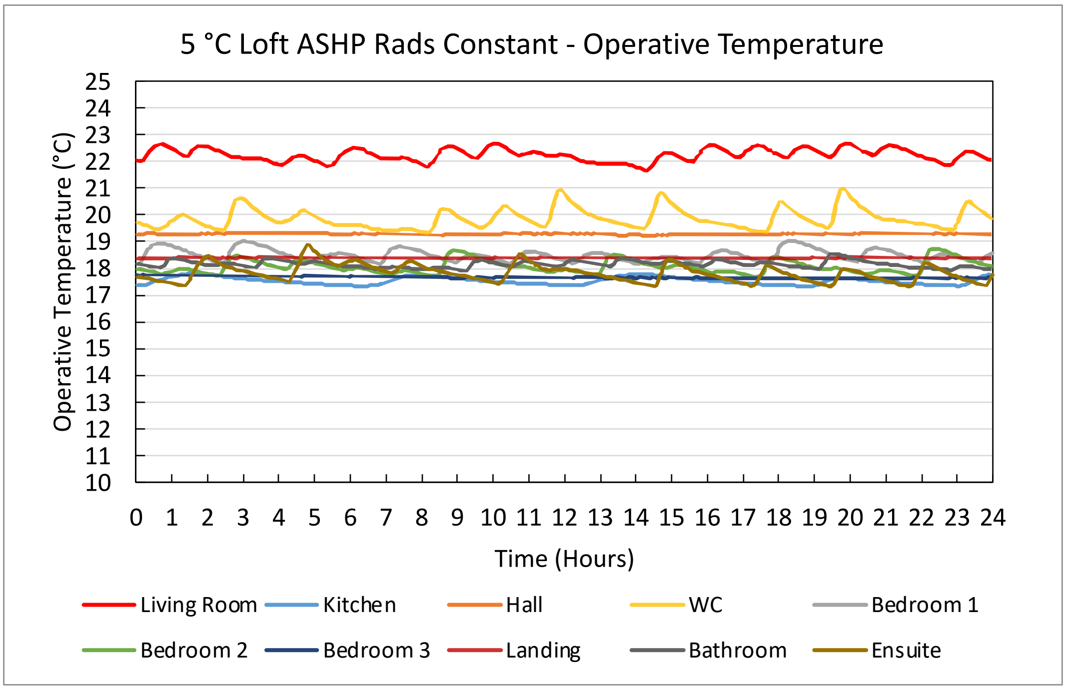


Figure 87. 5 °C Loft ASHP Rads Constant – Operative Temperature Plots

7.1.1.15.2 Spatial

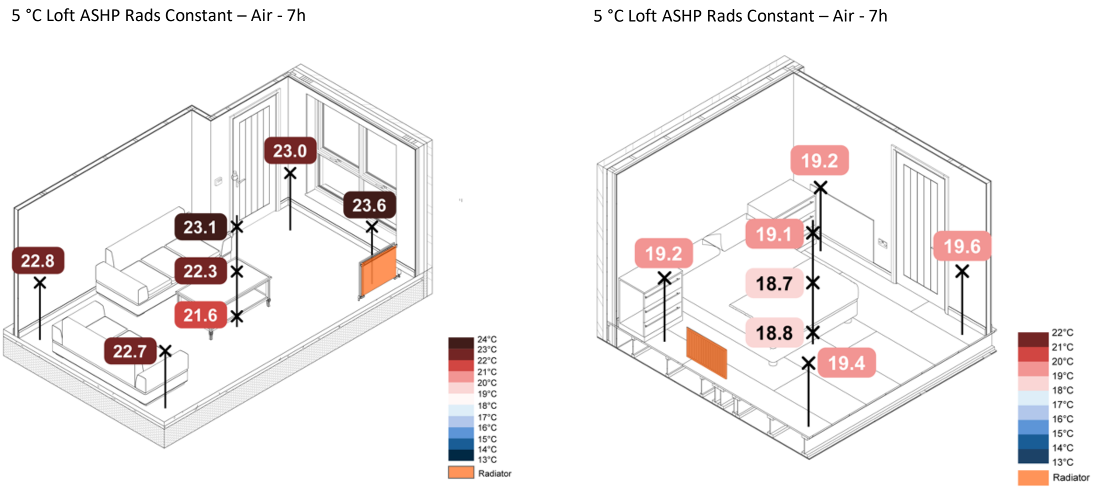


Figure 88. 5 °C Loft ASHP Rads Constant – Spatial Air Temperatures

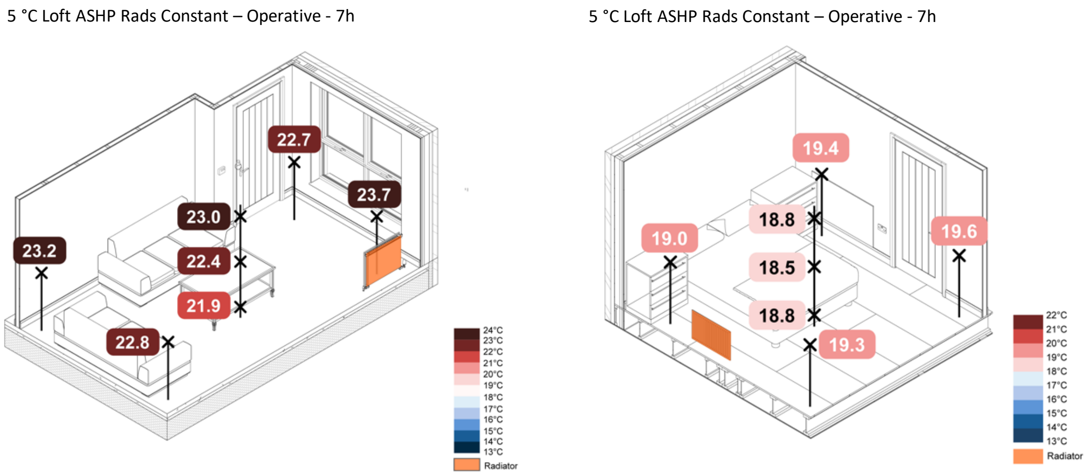


Figure 89. 5 °C Loft ASHP Rads Constant – Spatial Operative Temperatures

7.1.1.15.3 Performance Metrics

Table 34. 5 °C Loft ASHP Rads Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.1	0.40	29.9	£7.34

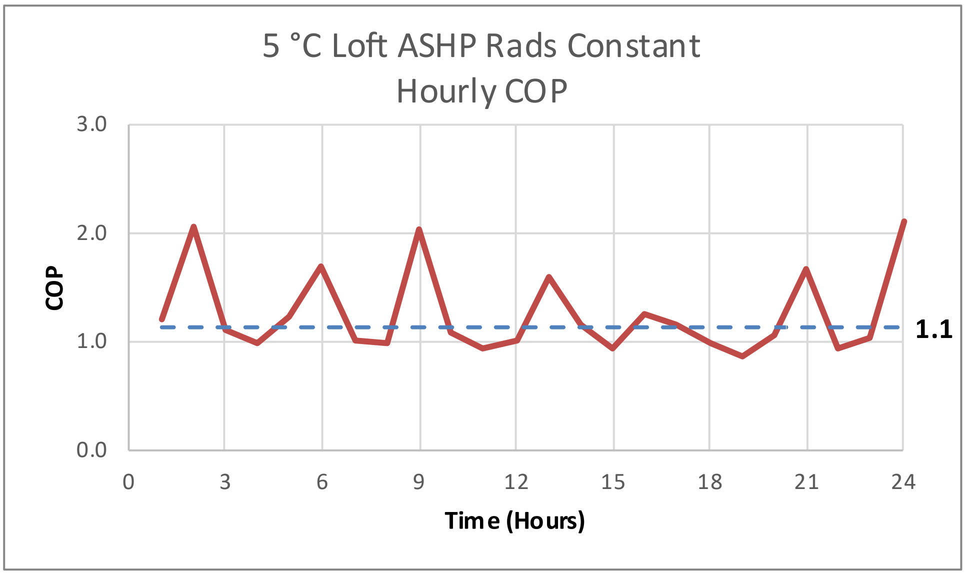


Figure 90. 5 °C Loft ASHP Rads Constant – Hourly COP

7.1.1.15.4 Discussion

Setpoint

- Living Room overshot the setpoint by ~1.2 °C
- WC overheated, achieving ~21 °C with a non-regular and sawtooth like hysteresis
- All other rooms were within ~±1.3 °C of setpoint.

Heat Distribution

- Homogenous temperature distribution across the Living Room at centre-height, although exceeding the setpoint temperature, ranging from 22.3-23.6 °C. Stratification of 1.1 °C in the centre of the room.
- Homogenous temperature distribution in Bedroom 1, with all areas achieving or exceeding setpoint, ranging between 18.7-19.6 °C

Energy Consumption

This 24h period had a total energy consumption of 29.9 kWh, with a running cost of £7.34.

Efficiency

The COP was 1.1, and the SEEI for this system test was 0.40 K/kWh.

7.1.1.16 5 °C Loft ASHP Rads SAP

7.1.1.16.1 Control

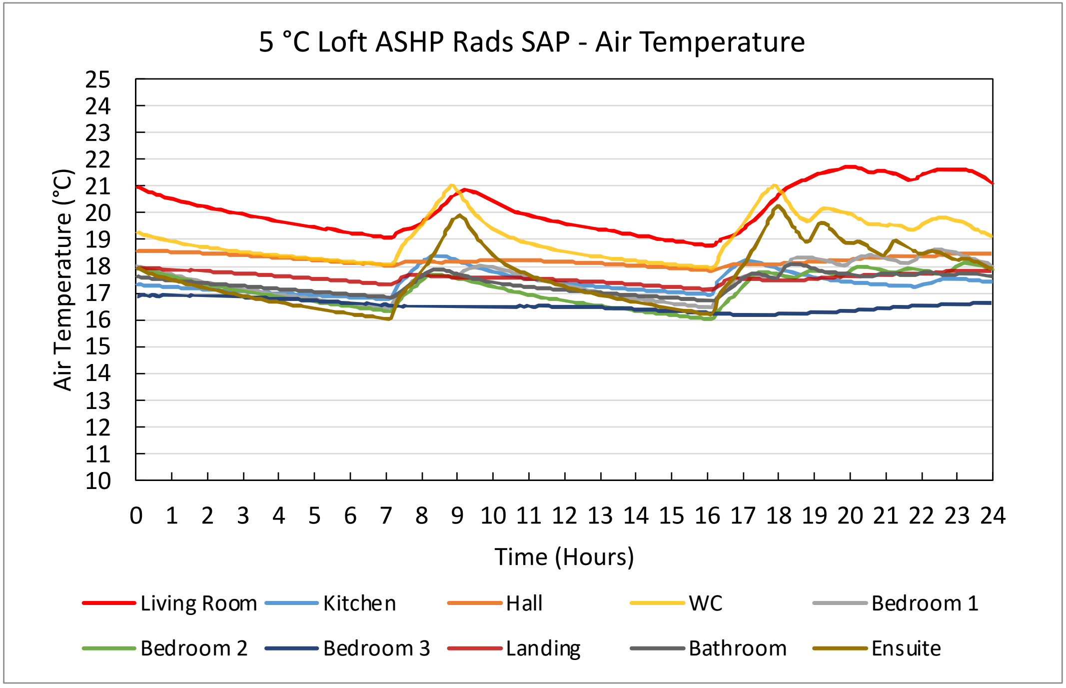


Figure 91. 5 °C Loft ASHP Rads SAP – Air Temperature Plots

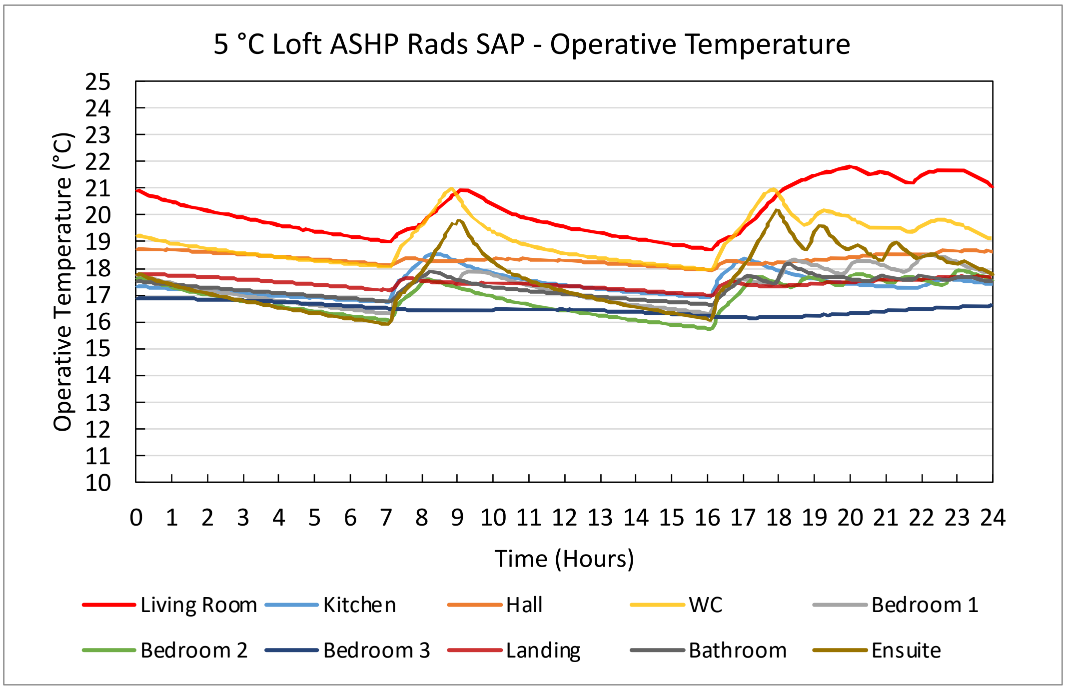


Figure 92. 5 °C Loft ASHP Rads SAP – Operative Temperature Plots

7.1.1.16.2 Spatial

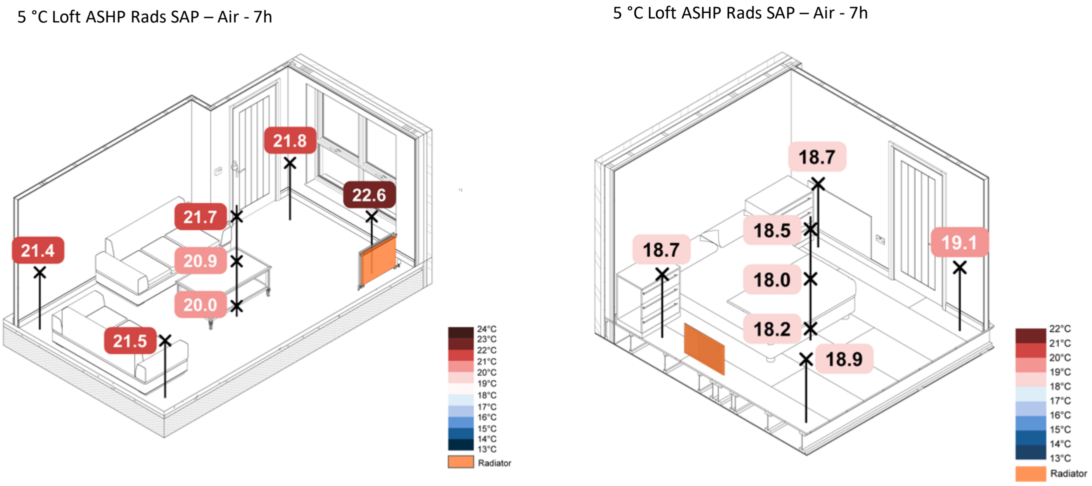


Figure 94. 5 °C Loft ASHP Rads SAP – Spatial Air Temperatures

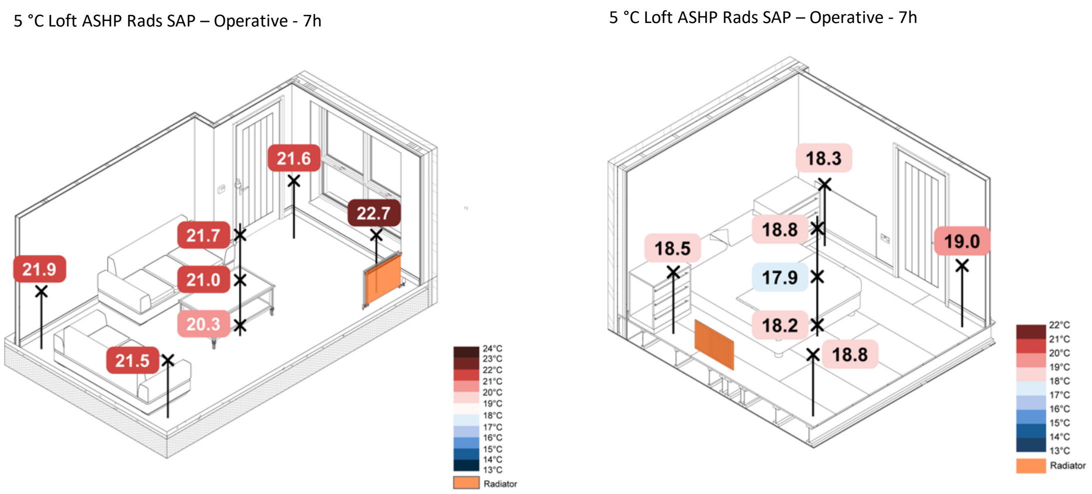


Figure 93. 5 °C Loft ASHP Rads SAP – Spatial Operative Temperatures

7.1.1.16.3 Heat up times

Table 35. 5 °C Loft ASHP Rads SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	18.78	21	02:17:00	0.97
Bedroom 1	16.46	17.99	02:10:12	0.71

7.1.1.16.4 Performance Metrics

Table 36. 5 °C Loft ASHP Rads SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
1.3	0.46	24.2	£5.92

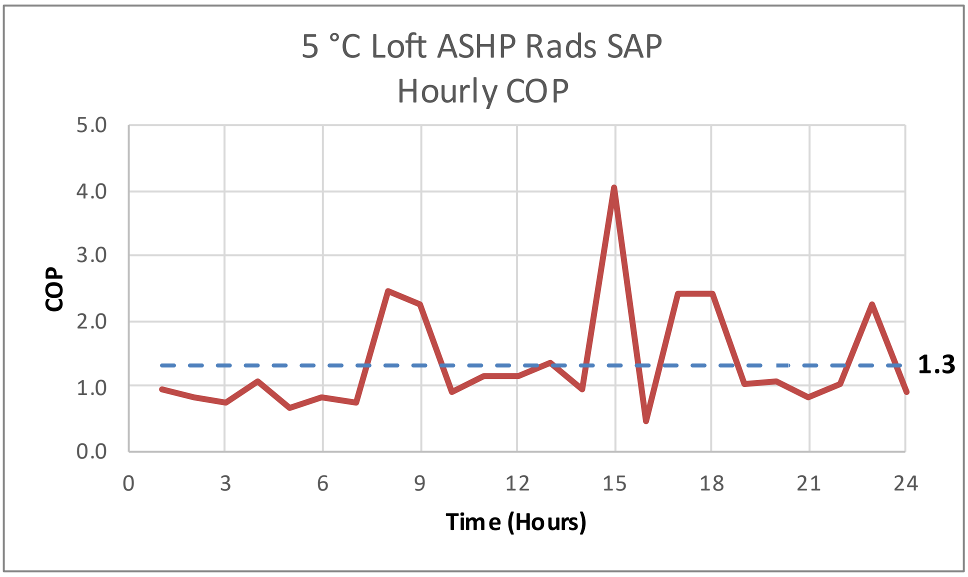


Figure 95. 5 °C Loft ASHP Rads SAP – Hourly COP

7.1.1.16.5 Discussion

Setpoint

- Living room achieved setpoint temperature in both morning and evening heating periods.
- WC overheated in both heating periods; this was less pronounced in the evening heating period.
- Bedroom 3 did not heat up as quickly as required and failed to achieve setpoint in both heating periods.

Heat Distribution

- Living Room showed homogenous temperature distribution, with the exception of the sensor located adjacent to the radiator, and the sensor located next to the ground. Stratification of 1.4 °C.
- Bedroom 1 achieved setpoint with homogenous temperature distribution ranging between 18.0-19.1 °C

Energy Consumption

This 24h period had a total energy consumption of 24.2 kWh, with a running cost of £5.92.

Efficiency

The COP was 1.3, and the SEEI for this system test was 0.46 K/kWh.

7.1.1.17 5 °C Monobloc ASHP TFH Rads + UFH Constant

7.1.1.17.1 Control

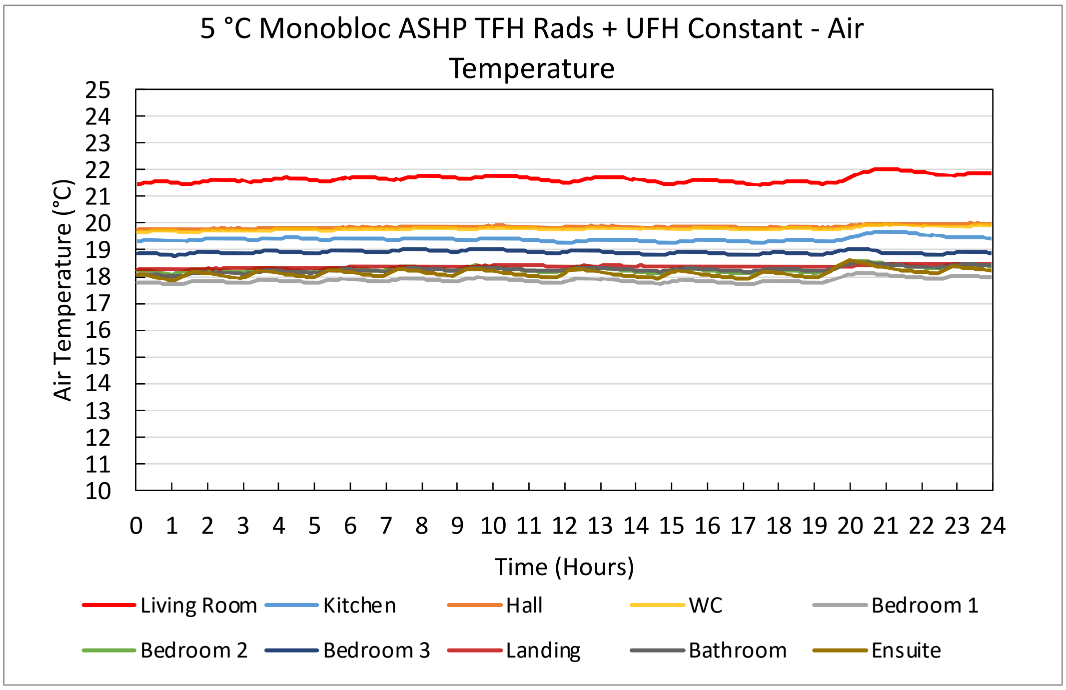


Figure 96. 5 °C Monobloc ASHP TFH Rads + UFH Constant – Air Temperature Plots

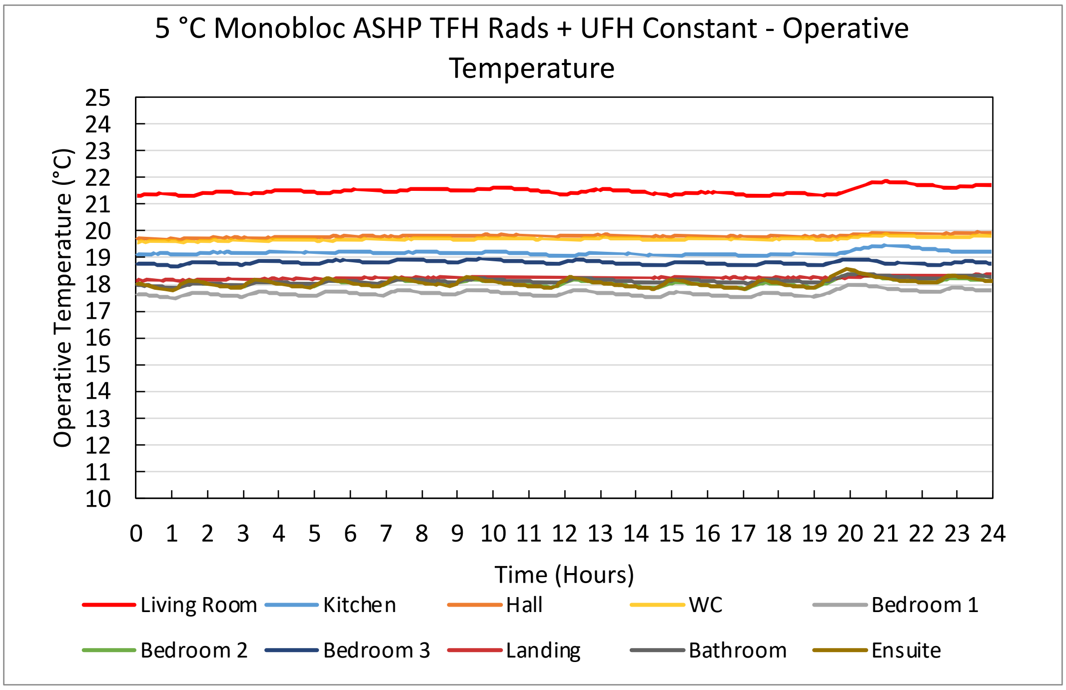


Figure 97. 5 °C Monobloc ASHP TFH Rads + UFH Constant – Operative Temperature Plots

7.1.1.17.2 Spatial

5 °C Monobloc ASHP TFH Rads + UFH Constant – Air - 7h

5 °C Monobloc ASHP TFH Rads + UFH Constant – Air - 7h

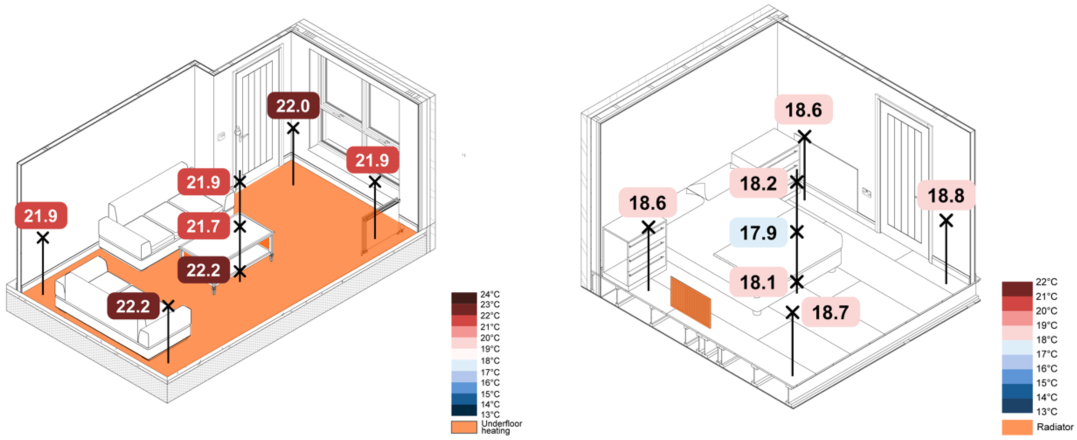


Figure 99. 5 °C Monobloc ASHP TFH Rads + UFH Constant – Spatial Air Temperatures

5 °C Monobloc ASHP TFH Rads + UFH Constant – Operative - 7h

5 °C Monobloc ASHP TFH Rads + UFH Constant – Operative - 7h

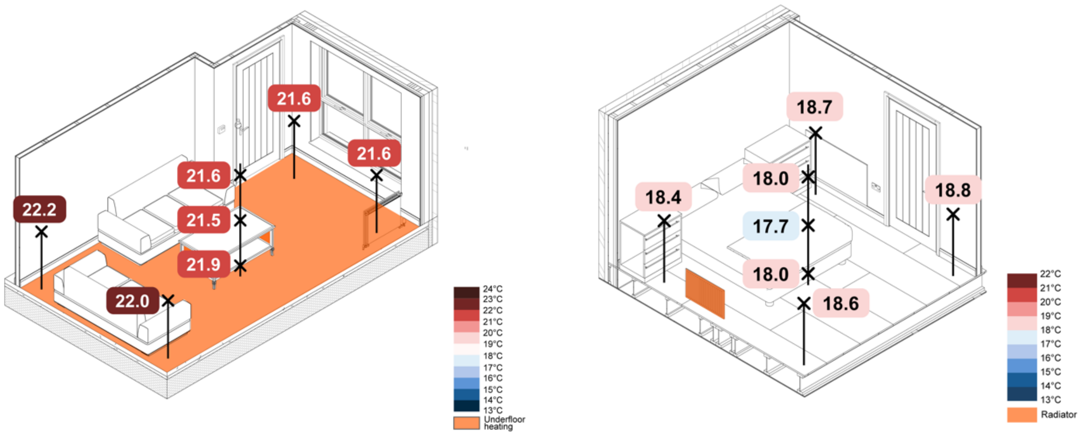


Figure 98. 5 °C Monobloc ASHP TFH Rads + UFH Constant – Spatial Operative Temperatures

7.1.1.17.3 Performance Metrics

Table 37. 5 °C Monobloc ASHP TFH Rads + UFH Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
3.7	1.31	9.4	£2.31

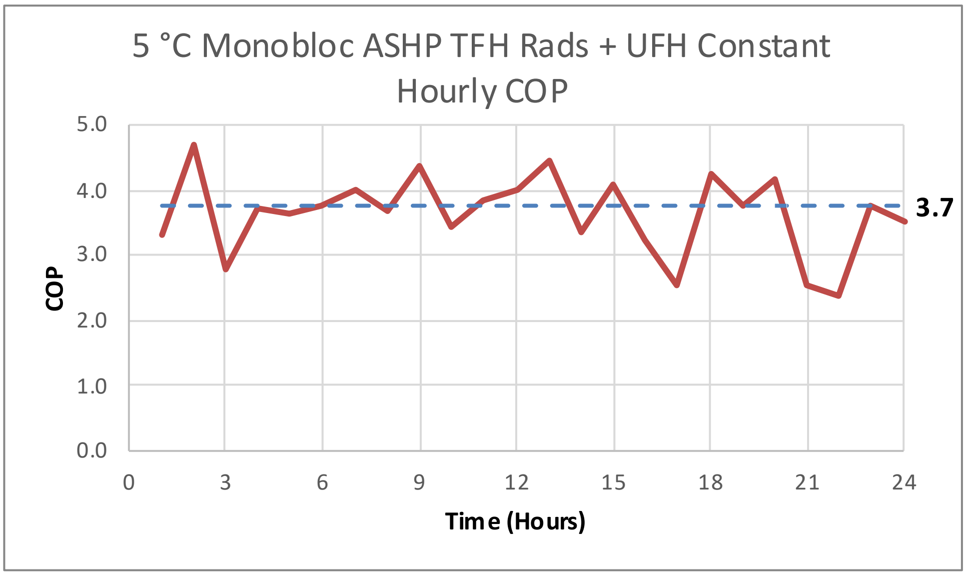


Figure 100. 5 °C Monobloc ASHP TFH Rads + UFH Constant – Hourly COP

7.1.1.17.4 Discussion

Setpoint

- Living Room achieved setpoint with 0.5 °C with low hysteresis.
- WC and Hall overshot setpoint by ~1.8 °C
- Kitchen and Bedroom 3 overshot by ~1 °C
- All other rooms were within ~0.5 °C of setpoint.

Heat Distribution

- Homogenous temperature distribution in the Living Room, although exceeding the setpoint by ~1 °C, ranging between 21.7-22.2 °C. Minimal stratification of 0.3 °C.
- Homogenous temperature distribution in Bedroom 1, achieving setpoint temperature within 1 °C, ranging between 17.9-18.8 °C. Minimal stratification of 0.4 °C.

Energy Consumption

This 24h period had a total energy consumption of 9.4kWh, with a running cost of £2.31.

Efficiency

The COP was 3.7, and the SEEI for this system test was 1.31 K/kWh.

7.1.1.18 5 °C Monobloc ASHP TFH Rads + UFH SAP

7.1.1.18.1 Control

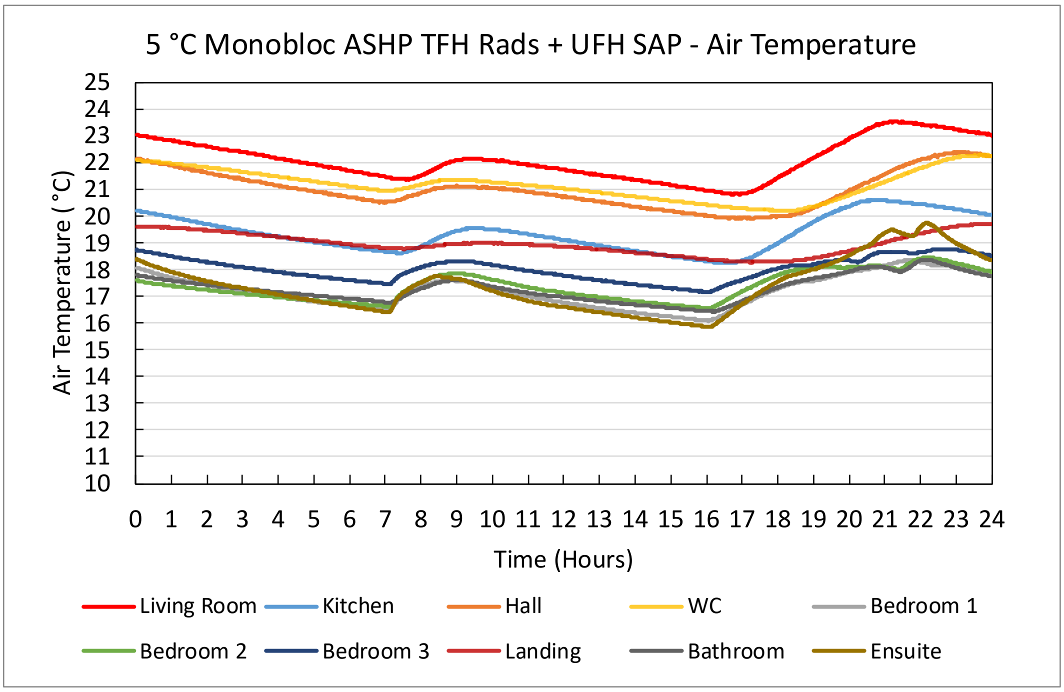


Figure 101. 5 °C Monobloc ASHP TFH Rads + UFH SAP – Air Temperature Plots

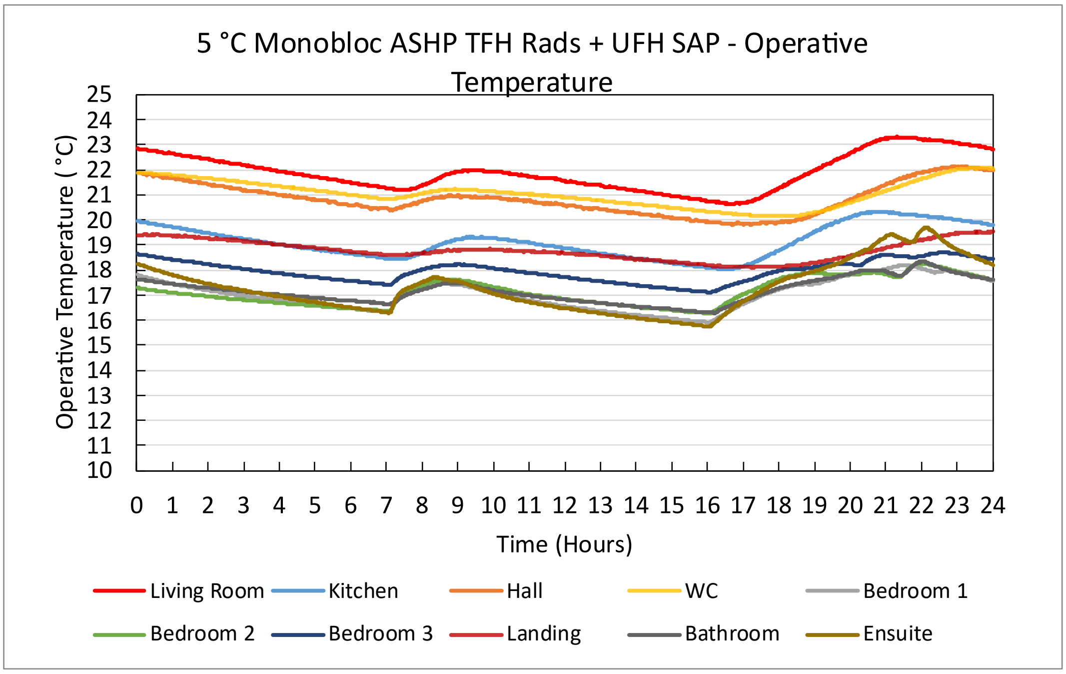


Figure 102. 5 °C Monobloc ASHP TFH Rads + UFH SAP – Operative Temperature Plots

7.1.1.18.2 Spatial

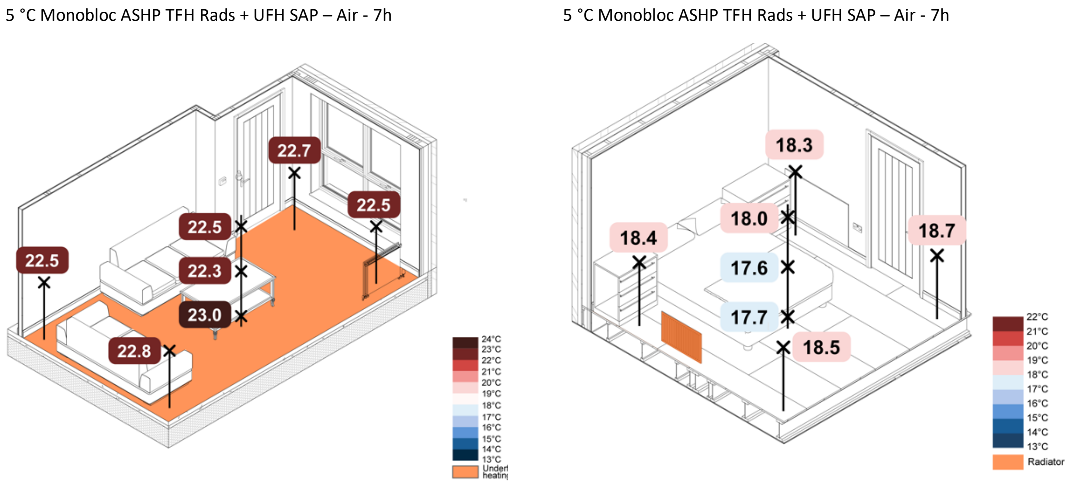


Figure 104. 5 °C Monobloc ASHP TFH Rads + UFH SAP – Spatial Air Temperatures

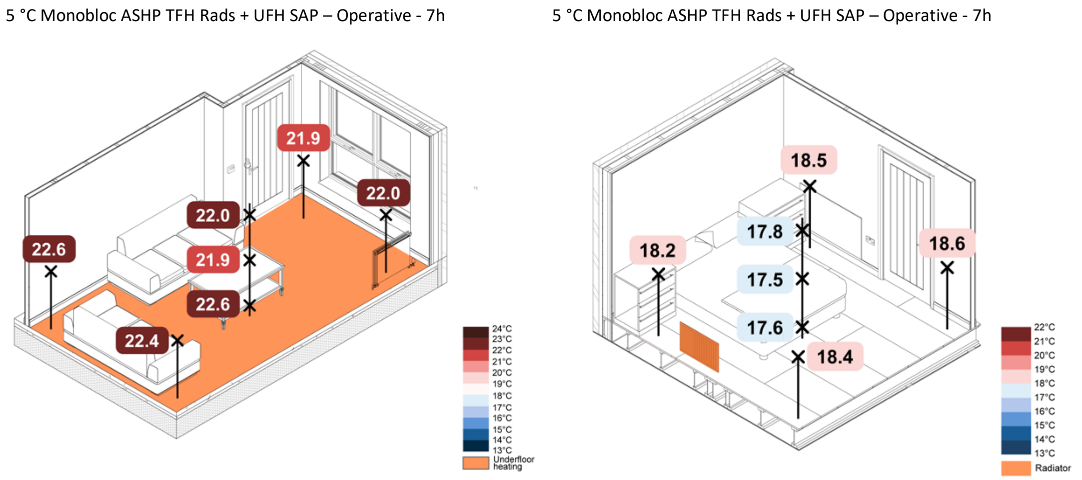


Figure 103. 5 °C Monobloc ASHP TFH Rads + UFH SAP – Spatial Operative Temperatures

7.1.1.18.3 Heat up times

Table 38. 5 °C Monobloc ASHP TFH Rads + UFH SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	20.97	21	01:03:00	0.03
Bedroom 1	15.94	17.99	05:30:00	0.37

7.1.1.18.4 Performance Metrics

Table 39. 5 °C Monobloc ASHP TFH Rads + UFH SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
3.5	1.44	8.4	£2.06

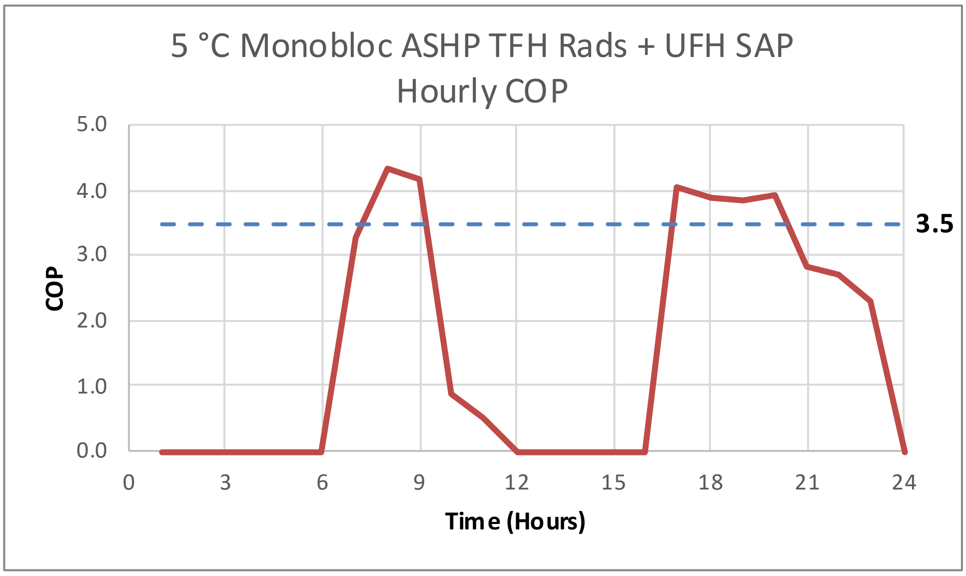


Figure 105. 5 °C Monobloc ASHP TFH Rads + UFH SAP – Hourly COP

7.1.1.18.5 Discussion

Issues

24h data was calculated using total energy consumption of TFH, due to an error with the individual circuit monitoring.

Setpoint

- Living Room overshot setpoint by ~1 °C in the morning, and ~2.2 °C in the evening heating period.
- WC and Hall overshot by up to ~3 °C in both heating periods.
- Kitchen and Landing overheated between 1-2 °C during both heating periods.
- All other rooms achieved setpoint withing ±1 °C, with the exception of the Ensuite, which overheated towards the end of the evening heating period by 1.5 °C.

Heat Distribution

- Homogenous temperature distribution in the Living Room, although exceeding the setpoint temperature, ranging from 22.4-22.9 °C. Minimal stratification of 0.2 °C.
- Homogenous temperature distribution in Bedroom 1, achieving the setpoint temperature to within 0.5 °C, ranging from 17.5-18.7 °C. Minimal stratification of 0.4 °C.

Energy Consumption

This 24h period had a total energy consumption of 8.4 kWh, with a running cost of £2.06.

Efficiency

The COP was 3.5, and the SEEI for this system test was 1.44 K/kWh.

7.1.1.19 5 °C Monobloc ASHP TFH Rads Constant

7.1.1.19.1 Control

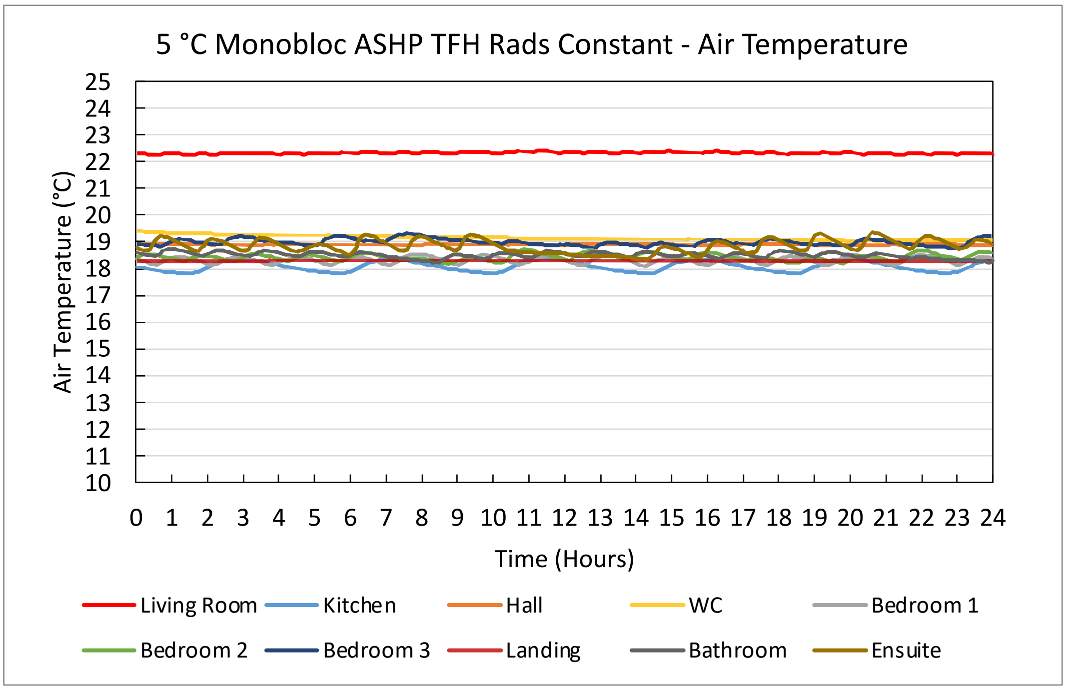


Figure 106. 5 °C Monobloc ASHP TFH Rads Constant – Air Temperature Plots

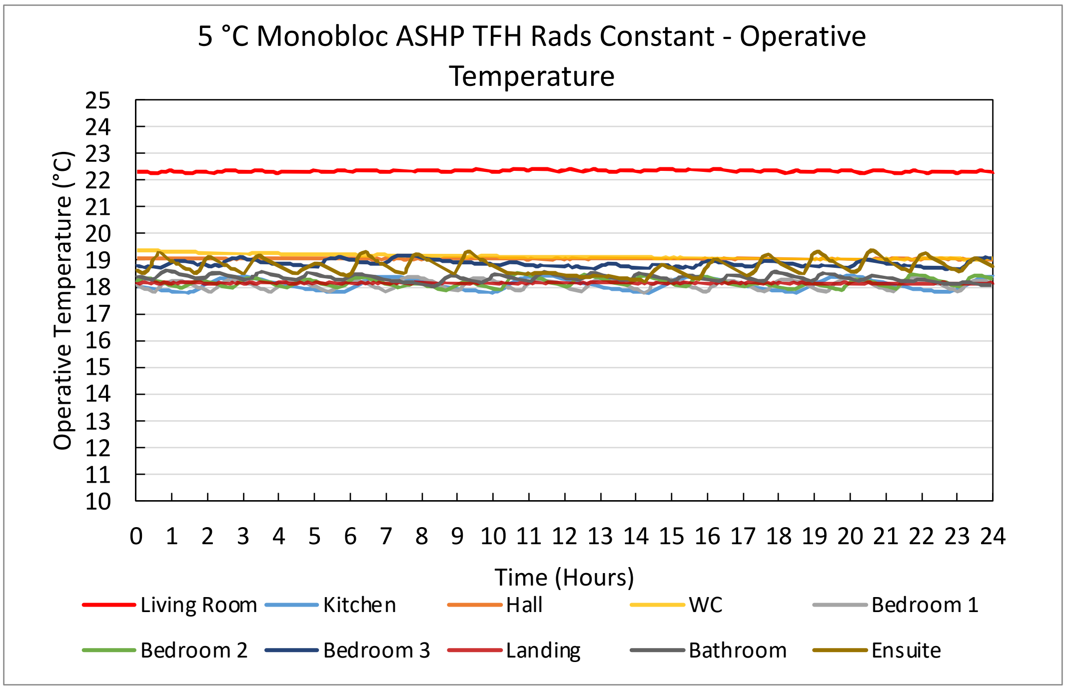


Figure 107. 5 °C Monobloc ASHP TFH Rads Constant – Operative Temperature Plots

- Living Room overheated by ~1.2 °C, with minimal hysteresis
- All other rooms were within ~1 °C of the setpoint.

7.1.1.19.2 Spatial

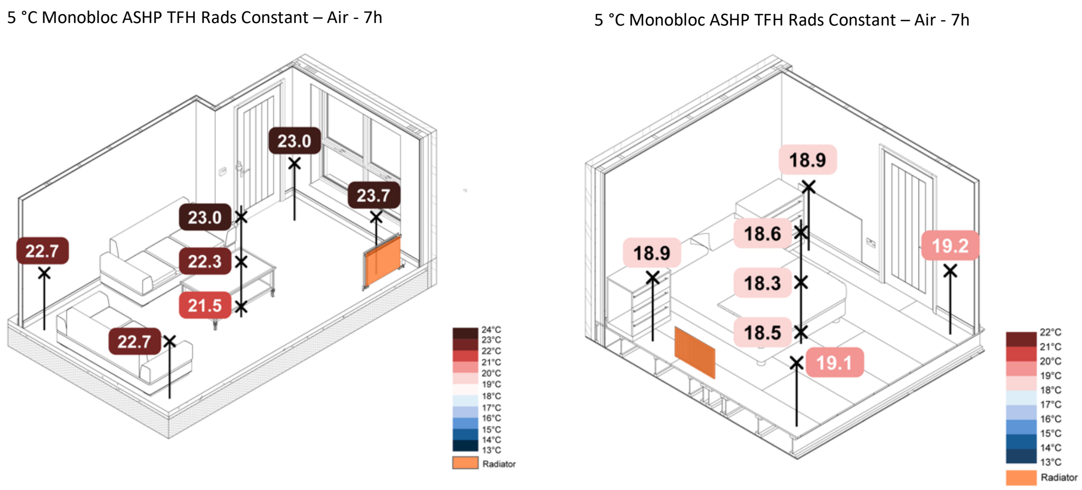


Figure 109. 5 °C Monobloc ASHP TFH Rads Constant – Spatial Air Temperatures

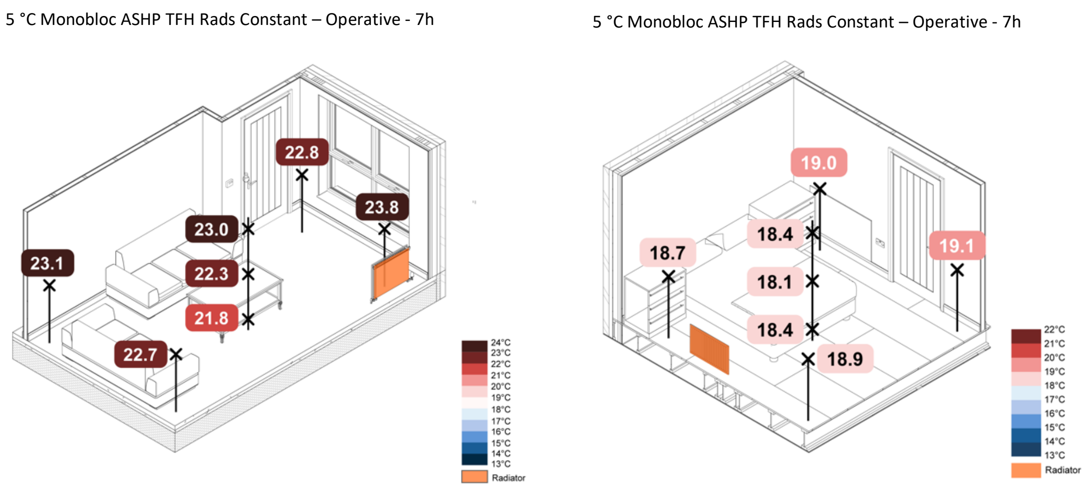


Figure 108. 5 °C Monobloc ASHP TFH Rads Constant – Spatial Operative Temperatures

7.1.1.19.3 Performance Metrics

Table 40. 5 °C Monobloc ASHP TFH Rads Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
2.5	1.05	11.8	£2.90

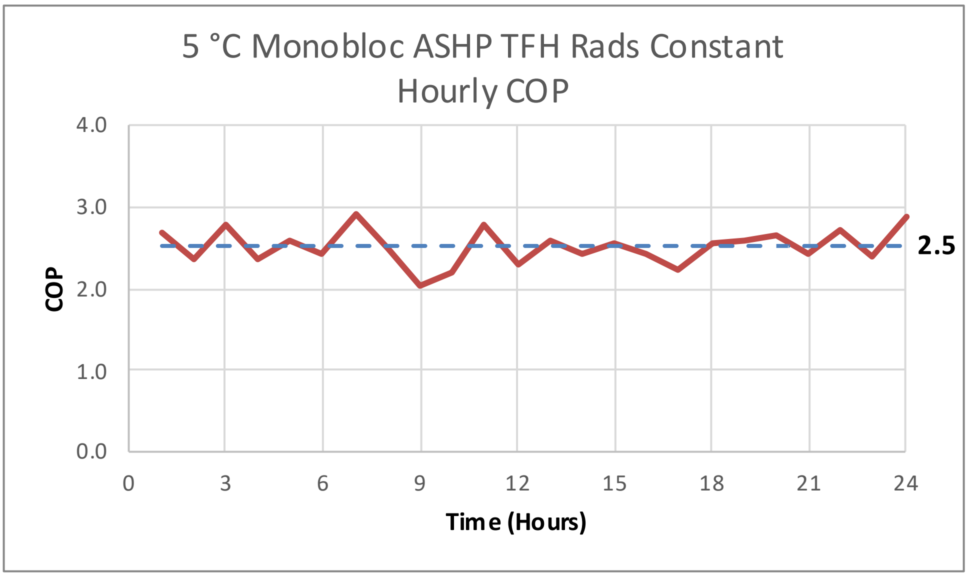


Figure 110. 5 °C Monobloc ASHP TFH Rads Constant – Hourly COP

7.1.1.19.4 Discussion

Setpoint

- Living Room overheated by ~1.2 °C, with minimal hysteresis
- All other rooms were within ~1 °C of the setpoint.

Heat Distribution

- Homogenous temperature distribution across the Living Room, with the exception of the sensor located adjacent to the radiator, ranging between 21.5-23.7 °C. Stratification of 1.5 °C.
- Homogenous temperature distribution in Bedroom 1, ranging between 18.3-19.2 °C, and minimal stratification of 0.3 °C.

Energy Consumption

This 24h period had a total energy consumption of 11.8 kWh, with a running cost of £2.90.

Efficiency

The COP was 2.5, and the SEEI for this system test was 1.05 K/kWh.

7.1.1.20 5 °C Monobloc ASHP TFH Rads SAP

7.1.1.20.1 Control

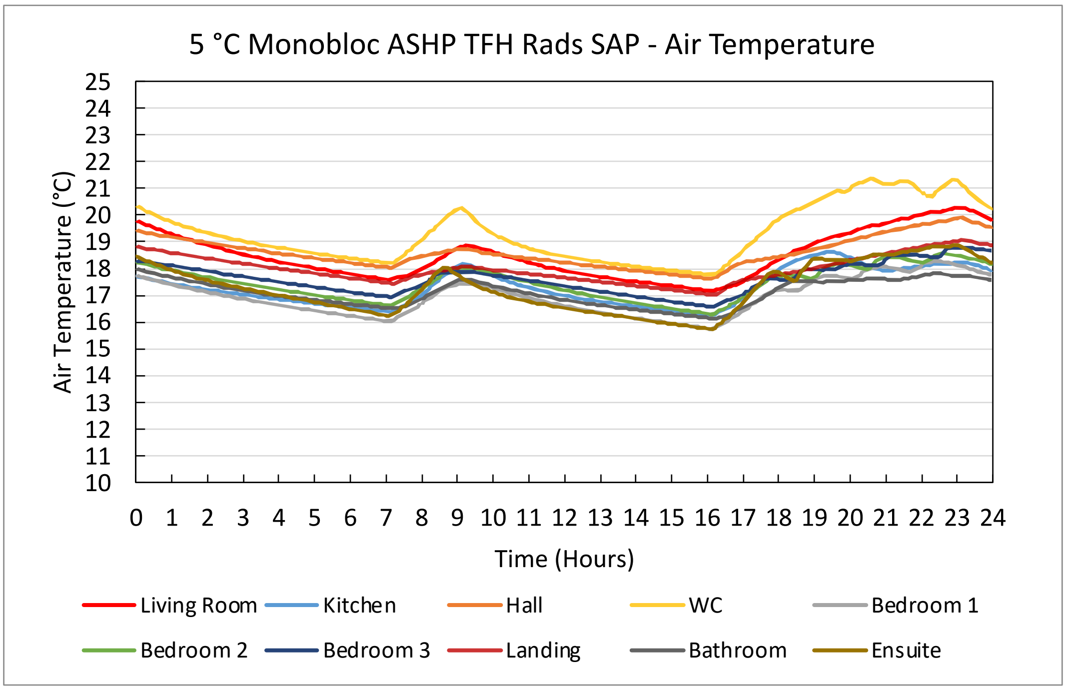


Figure 111. 5 °C Monobloc ASHP TFH Rads SAP – Air Temperature Plots

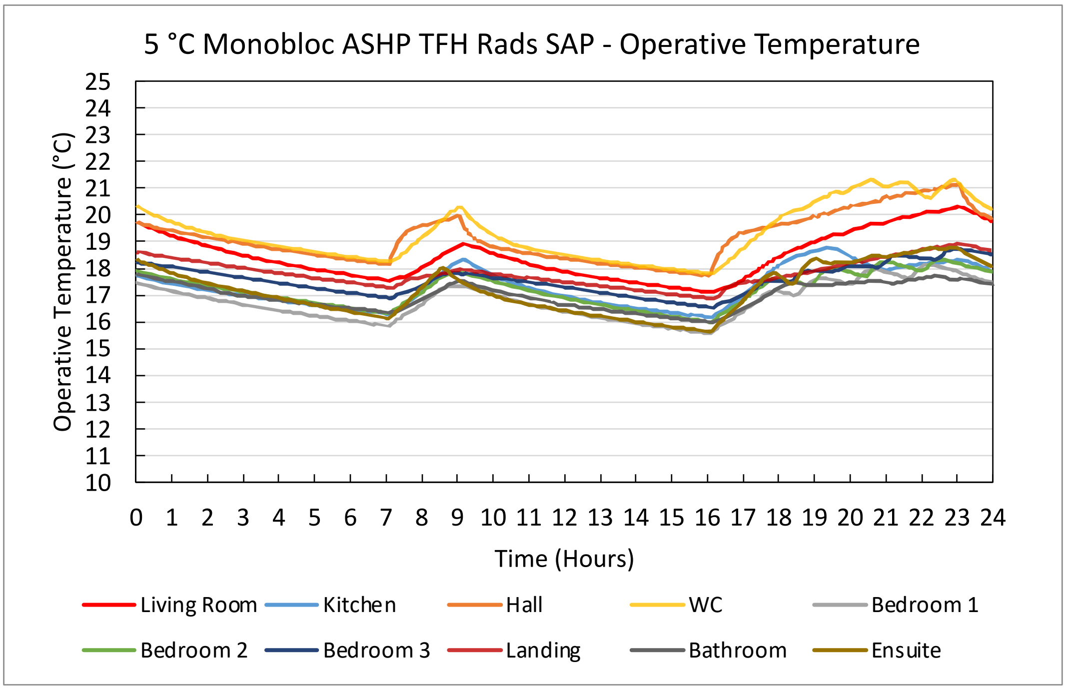


Figure 112. 5 °C Monobloc ASHP TFH Rads SAP – Operative Temperature Plots

7.1.1.20.2 Spatial

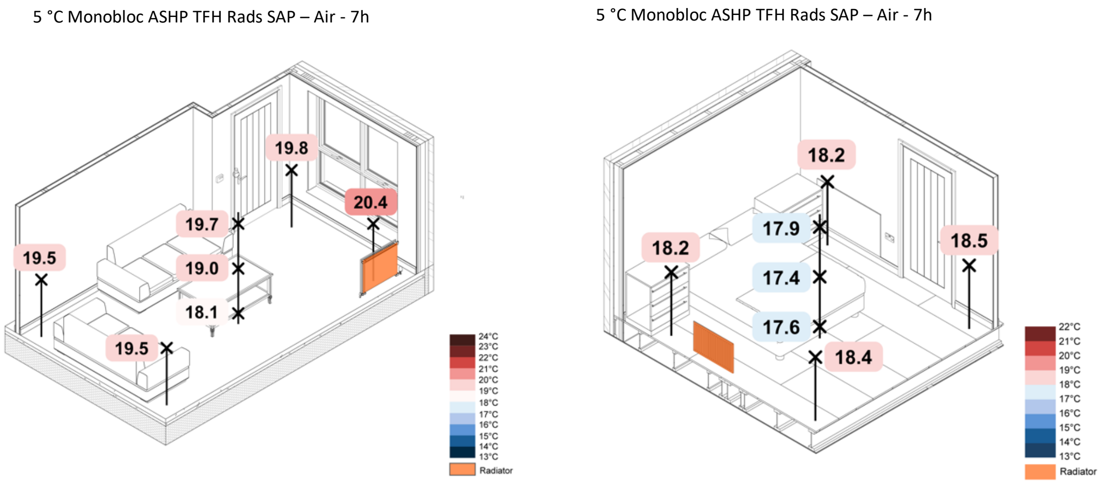


Figure 114. 5 °C Monobloc ASHP TFH Rads SAP – Spatial Air Temperatures

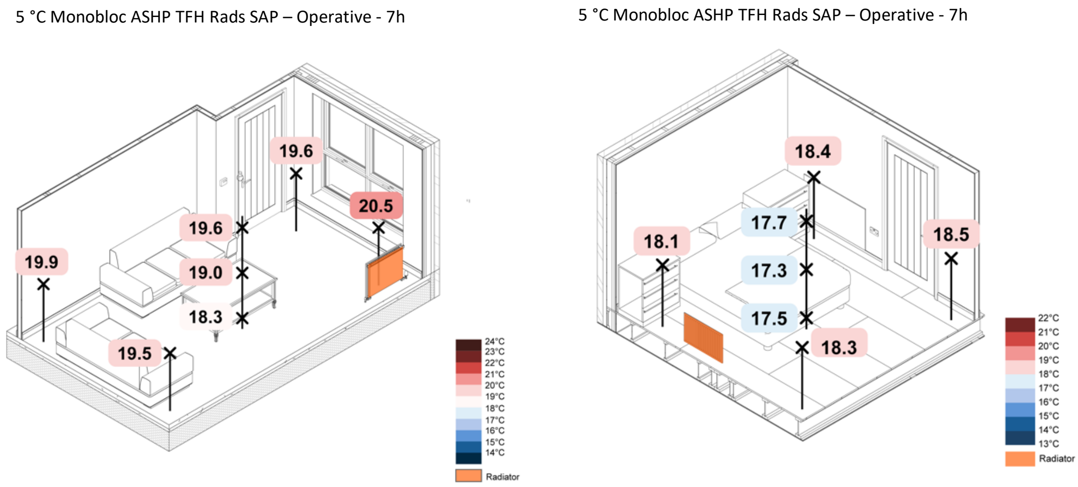


Figure 113. 5 °C Monobloc ASHP TFH Rads SAP – Spatial Operative Temperatures

7.1.1.20.3 Heat up times

Table 41. 5 °C Monobloc ASHP TFH Rads SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	17.18	20.29	07:00:00	0.44
Bedroom 1	15.75	18.00	04:33:00	0.49

7.1.1.20.4 Performance Metrics

Table 42. 5 °C Monobloc ASHP TFH Rads SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
3.2	1.47	7.5	£1.84

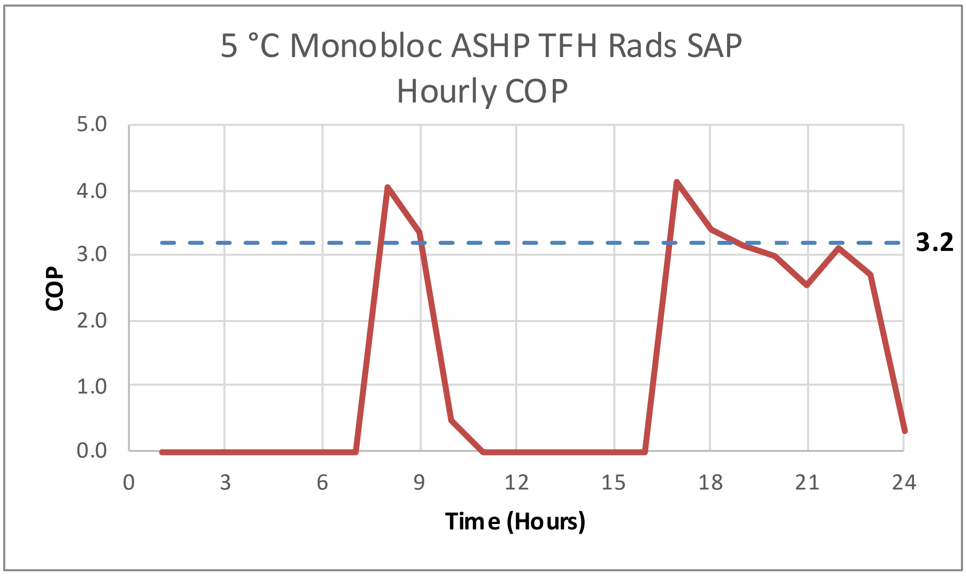


Figure 115. 5 °C Monobloc ASHP TFH Rads SAP – Hourly COP

7.1.1.20.5 Discussion

Setpoint

- Living Room failed to achieve setpoint temperature during both heating periods, achieving a maximum of ~20.2 °C.
- WC overshot the setpoint in both heating periods, achieving up to 21.2 °C.
- Hall exceeded the setpoint temperature during the evening heating period by ~2 °C.
- All other rooms achieved within ±1 °C of setpoint during both heating periods.

Heat Distribution

- Living Room failed to achieve setpoint temperature by ~2 °C in the centre of the room. Stratification in the central column of 1.6 °C.
- All Bedroom 1 temperatures were within ±1 °C of setpoint, with a stratification of 0.5 °C in the centre of the room.

Energy Consumption

This 24h period had a total energy consumption of 7.5 kWh, with a running cost of £1.84.

Efficiency

The COP was 3.2 and the SEEI for this system test was 1.47 K/kWh.

7.1.2 eHome2

7.1.2.1 -5 °C Monobloc ASHP eHome2 Constant

7.1.2.1.1 Control

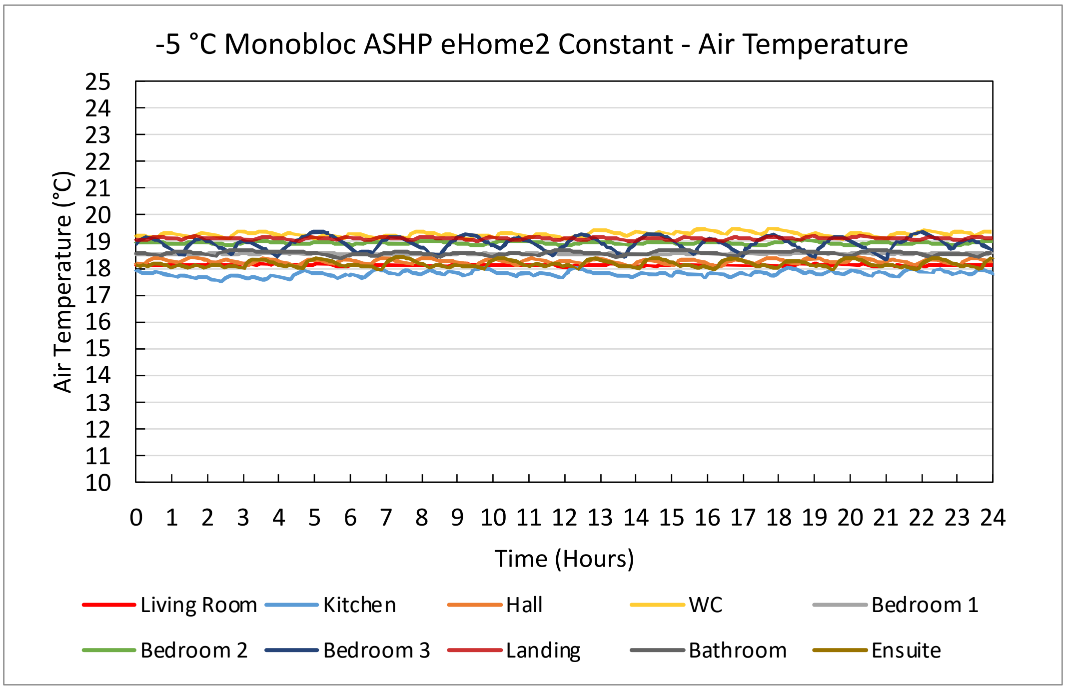


Figure 116. -5 °C Monobloc ASHP eHome2 Constant – Air Temperature Plots

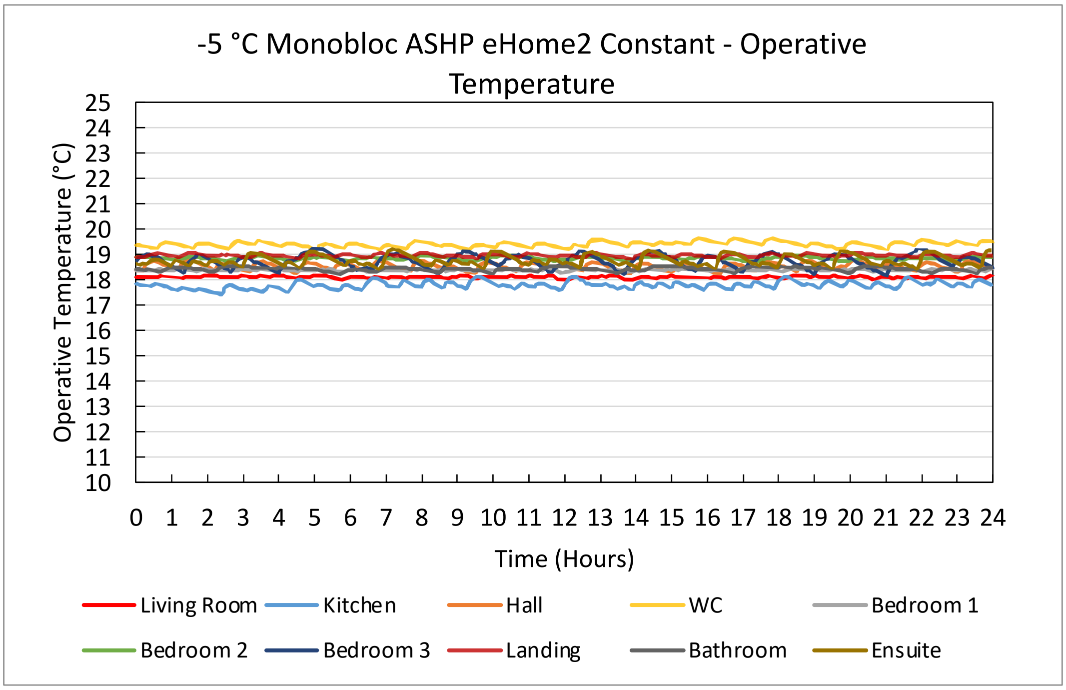


Figure 117. -5 °C Monobloc ASHP eHome2 Constant – Operative Temperature Plots

7.1.2.1.2 Spatial

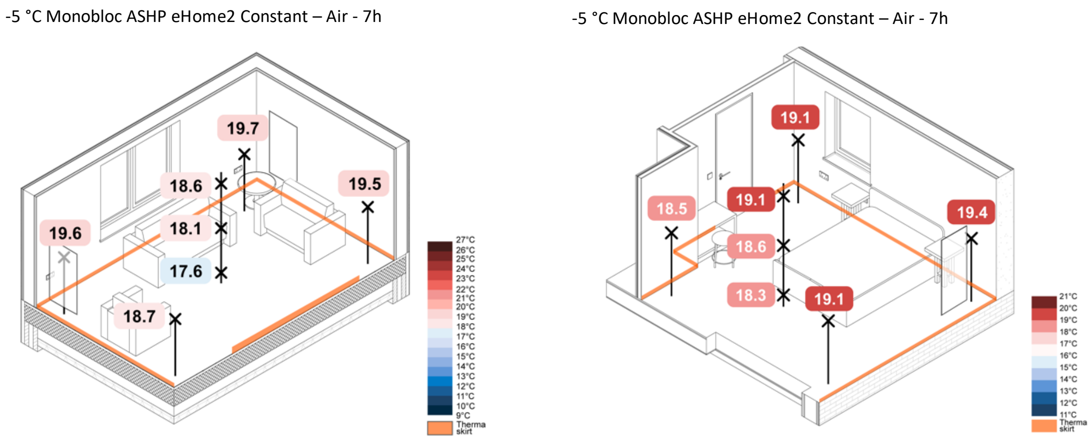


Figure 118. -5 °C Monobloc ASHP eHome2 Constant – Spatial Air Temperatures

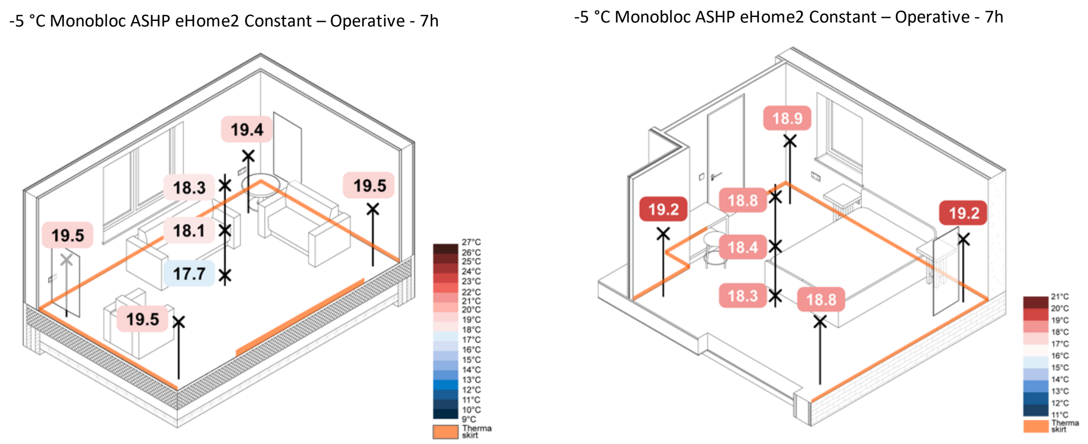


Figure 119. -5 °C Monobloc ASHP eHome2 Constant – Operative Temperature Plots

7.1.2.1.3 Performance Metrics

Table 43. -5 °C Monobloc ASHP eHome2 Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
2.3	0.94	22.5	£5.51

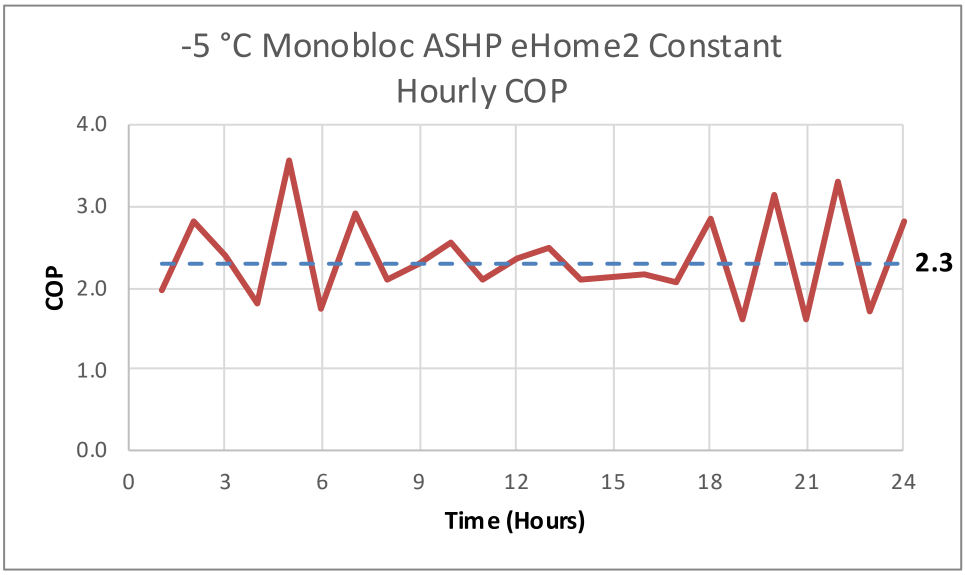


Figure 120. -5 °C Monobloc ASHP eHome2 Constant – Hourly COP

7.1.2.1.4 Discussion

Setpoint

- Living Room underheated by 3 °C.
- WC, Landing and Bedroom 2 overheated by ~1 °C.
- All other rooms were within 0.5 °C of setpoint.

Heat Distribution

- Living Room did not achieve setpoint temperature of 21 °C.
- Stratification of 1 °C in the centre of the Living Room. ~1.5 °C warmer temperature towards the corners of the Living Room.
- Bedroom 1 achieved the setpoint, with temperatures ranging between 18.3-19.4 °C. Stratification observed in the centre of the room (range = 0.8 °C). Warmer temperatures observed in the corners of the Bedroom 1.

Energy Consumption

This 24h period had a total energy consumption of 22.5 kWh, with a running cost of £5.51.

Efficiency

The COP was 2.3, and the SEEI for this system test was 0.94 K/kWh.

7.1.2.2 -5 °C Monobloc ASHP eHome2 SAP

7.1.2.2.1 Control

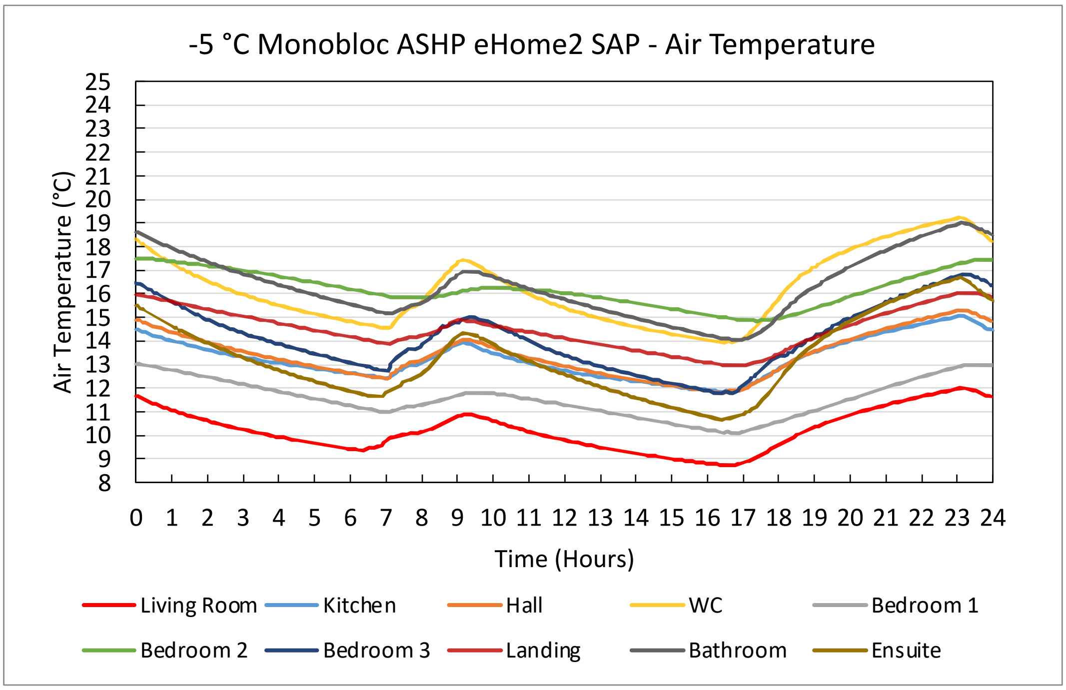


Figure 121. -5 °C Monobloc ASHP eHome2 SAP – Air Temperature Plots

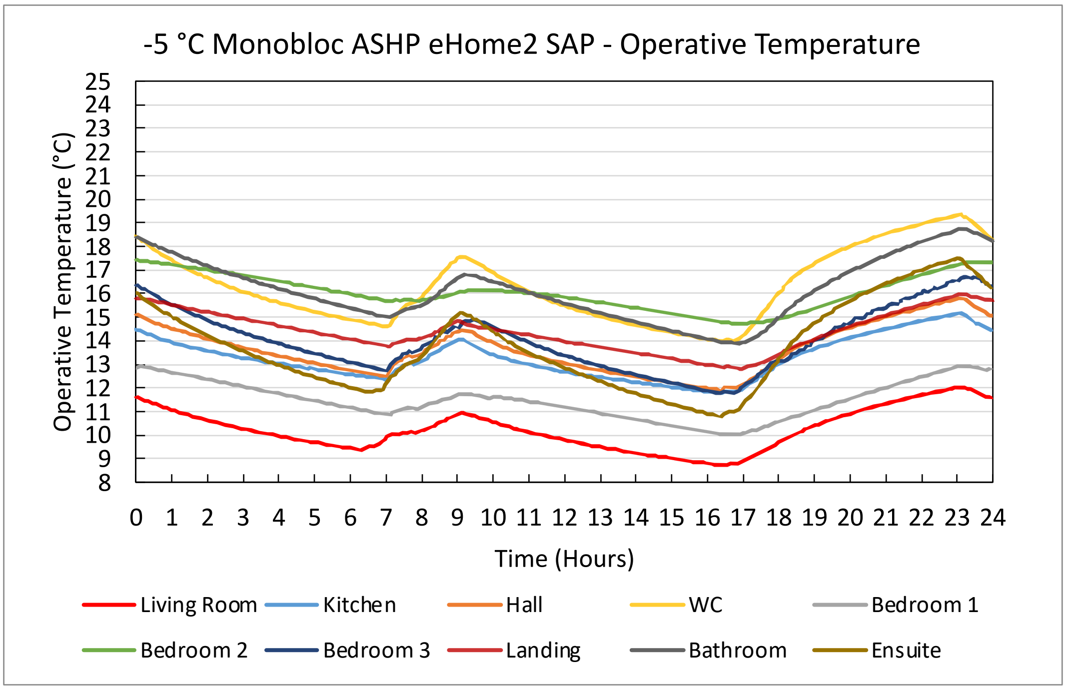


Figure 122. -5 °C Monobloc ASHP eHome2 SAP – Operative Temperature Plots

7.1.2.2.2 Spatial

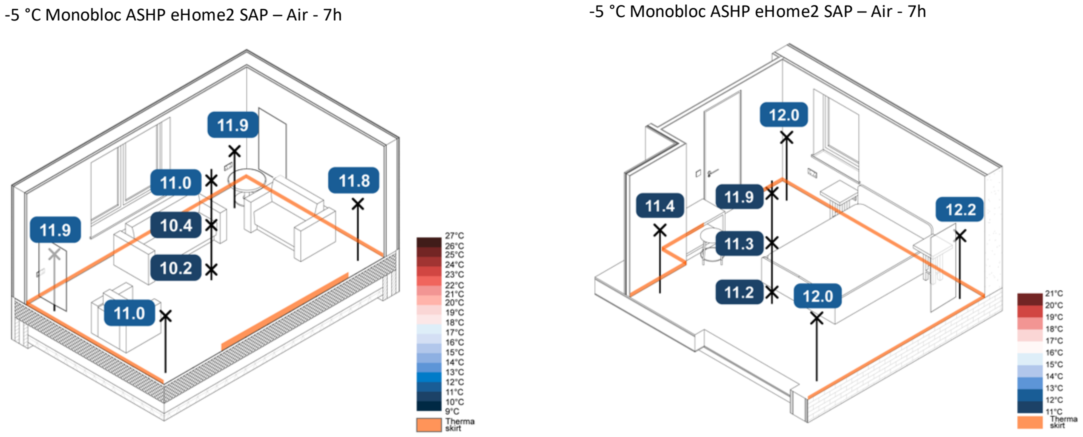


Figure 124. -5 °C Monobloc ASHP eHome2 SAP – Spatial Air Temperatures

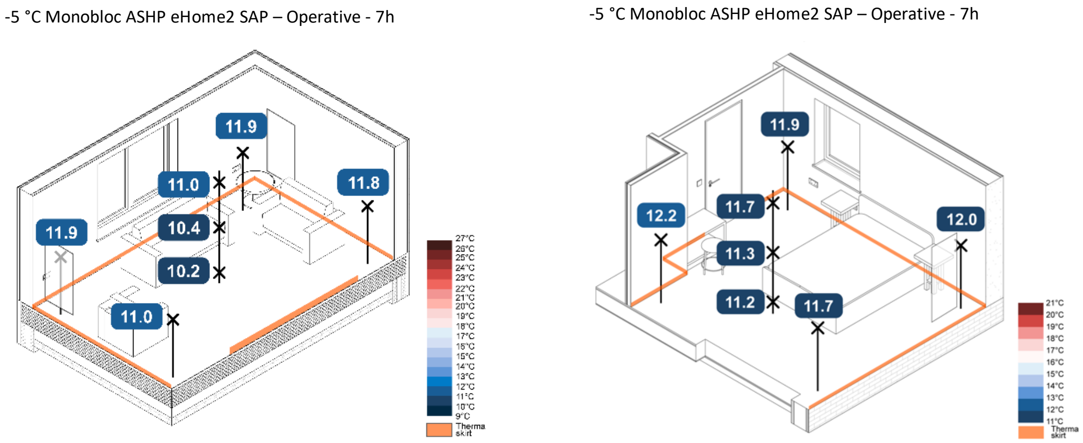


Figure 123. -5 °C Monobloc ASHP eHome2 SAP – Spatial Operative Temperatures

7.1.2.2.3 Heat up times

Table 44. -5 °C Monobloc ASHP eHome2 SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	8.8	12	07:06:00	0.45
Bedroom 1	10.23	12.99	07:20:00	0.38

7.1.2.2.4 Performance Metrics

Table 45. -5 °C Monobloc ASHP eHome2 SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
2.3	0.96	17.6	£4.30

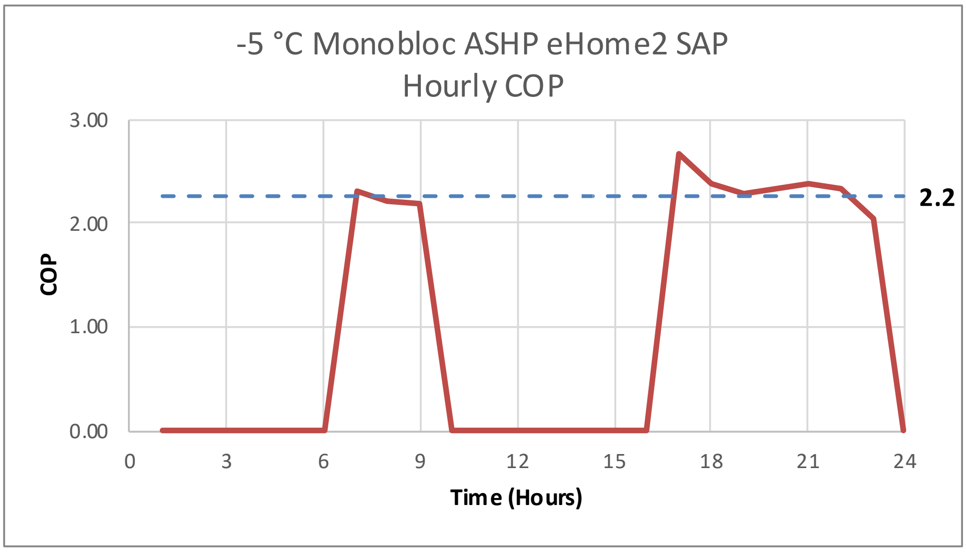


Figure 125. -5 °C Monobloc ASHP eHome2 SAP – Hourly COP

7.1.2.2.5 Discussion

Setpoint

- Living Room did not achieve setpoint, reaching a maximum of 11 °C in the morning heating period, and 12 °C in the evening.
- WC and Bathroom (heated by towel radiators) achieved setpoint in the evening heating period, with both overheating by ~1 °C.
- All other rooms failed to achieve setpoint, with temperatures ranging between 10-17 °C during the evening heating period.

Heat Distribution

- No areas of the Living room achieved the setpoint temperature of 21 °C, with temperatures ranging between 10.2 to 11.9 °C.
- Stratification of 0.6 °C was observed in the centre of the Living Room, with warmer temperatures observed towards the corners of the room.
- No areas of the Bedroom achieved the setpoint temperature of 18 °C, with temperatures ranging between 11.2 to 12.2 °C.
- Stratification of 0.7 °C was observed in the centre of Bedroom 1, with warmer temperatures observed towards the corners of the room.

Energy Consumption

This 24h period had a total energy consumption of 17.6kWh, with a running cost of £4.30.

Efficiency

The COP was 2.3, and the SEEI for this system test was 0.96 K/kWh.

7.1.2.3 -5 °C Wall Mounted IR eHome2 Constant

7.1.2.3.1 Control

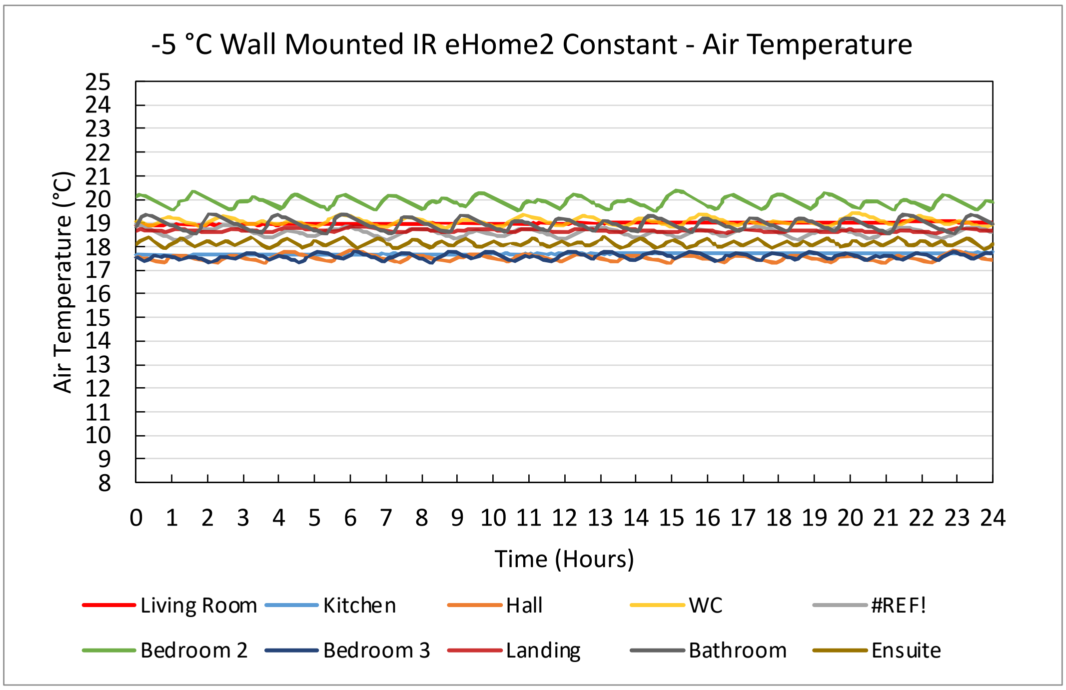


Figure 126. -5 °C Wall Mounted IR eHome2 Constant – Air Temperature Plots

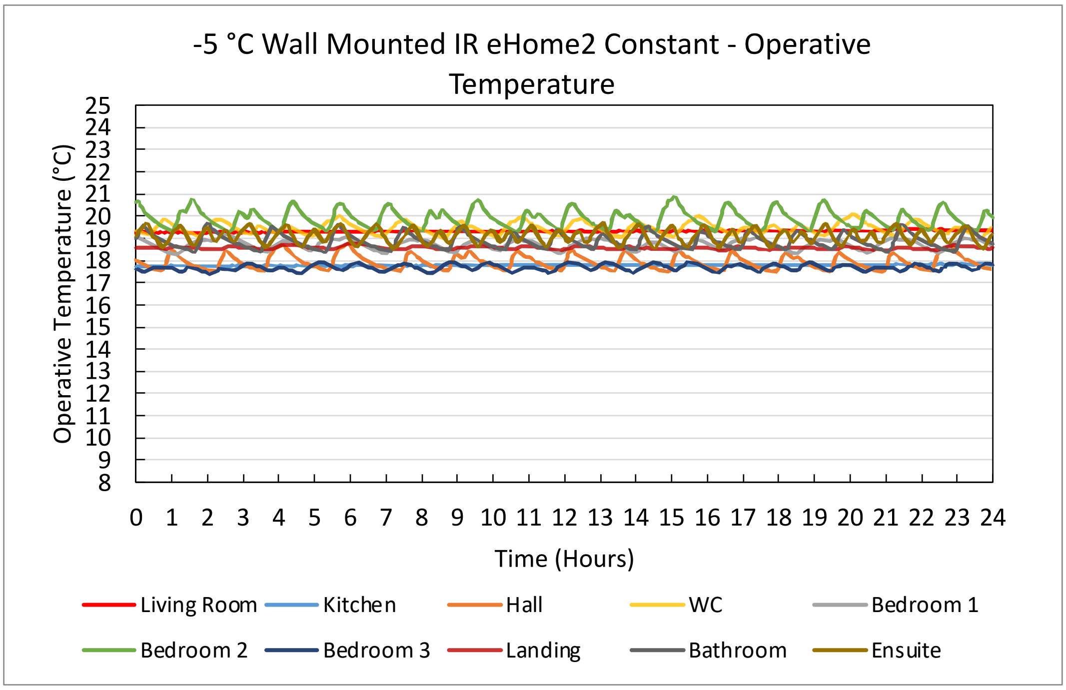


Figure 127. -5 °C Wall Mounted IR eHome2 Constant – Operative Temperature Plots

7.1.2.3.2 Spatial

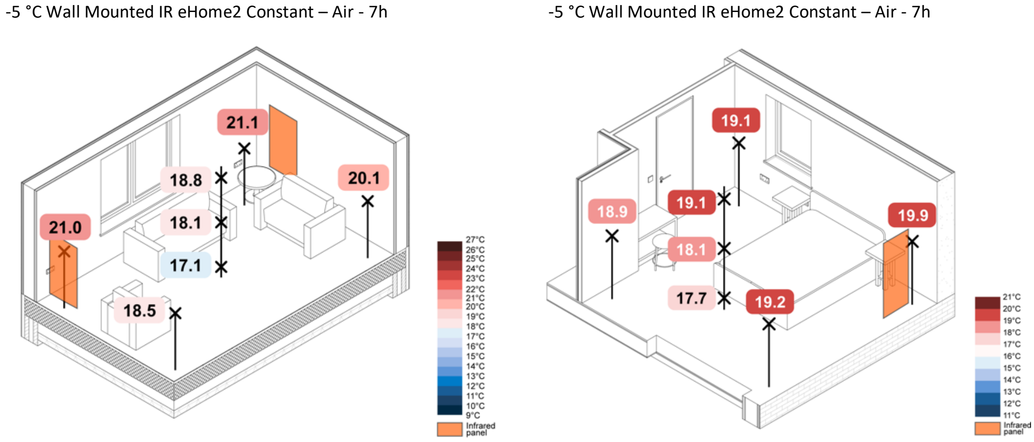


Figure 128. -5 °C Wall Mounted IR eHome2 Constant – Spatial Air Temperatures

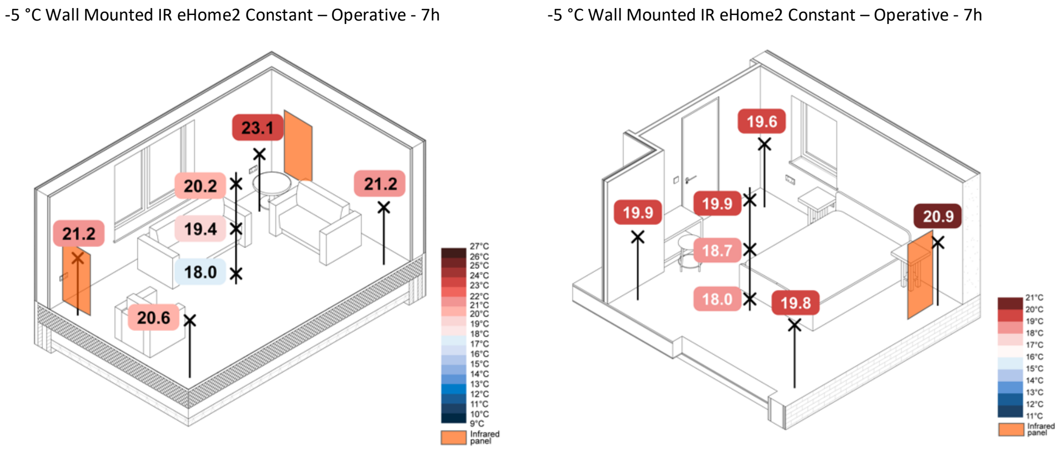


Figure 129. -5 °C Wall Mounted IR eHome2 Constant – Spatial Operative Temperatures

7.1.2.3.3 Performance Metrics

Table 46. -5 °C Wall Mounted IR eHome2 Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.39	55.7	£13.66

7.1.2.3.4 Discussion

Setpoint

- Underheating in the Living Room by ~2 °C, with a low hysteresis.
- Bedroom 2 overheating by ~2 °C.
- Ensuite, Kitchen, Bedroom 3 and Hall all achieved setpoint within ~±0.5 °C.
- WC, Bedroom 1, Landing, Bathroom all overheated by ~1 °C.

Heat Distribution

- Living Room measured stratification of 1.7 °C, and warmer temperature located closest to the IR panels. Increased operative temperature were observed across the room.
- Setpoint achieved in Bedroom 1 in all locations, with the exception of the lowest sensor in the centre of the room.
- Stratification in Bedroom 1 was found to be 1.9 °C.

Energy Consumption

This 24h period had a total energy consumption of 55.7 kWh, with a running cost of £13.66.

Efficiency

The SEEI for this system test was 0.39 K/kWh.

7.1.2.4 -5 °C Wall Mounted IR eHome2 SAP

7.1.2.4.1 Control

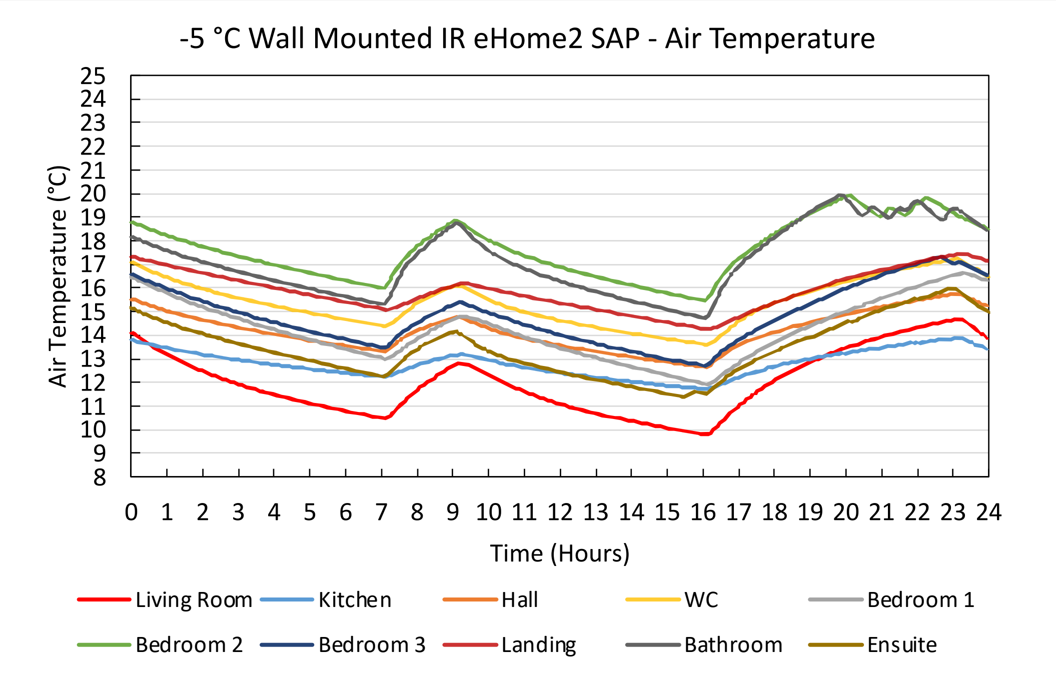


Figure 130. -5 °C Wall Mounted IR eHome2 SAP – Air Temperature Plots

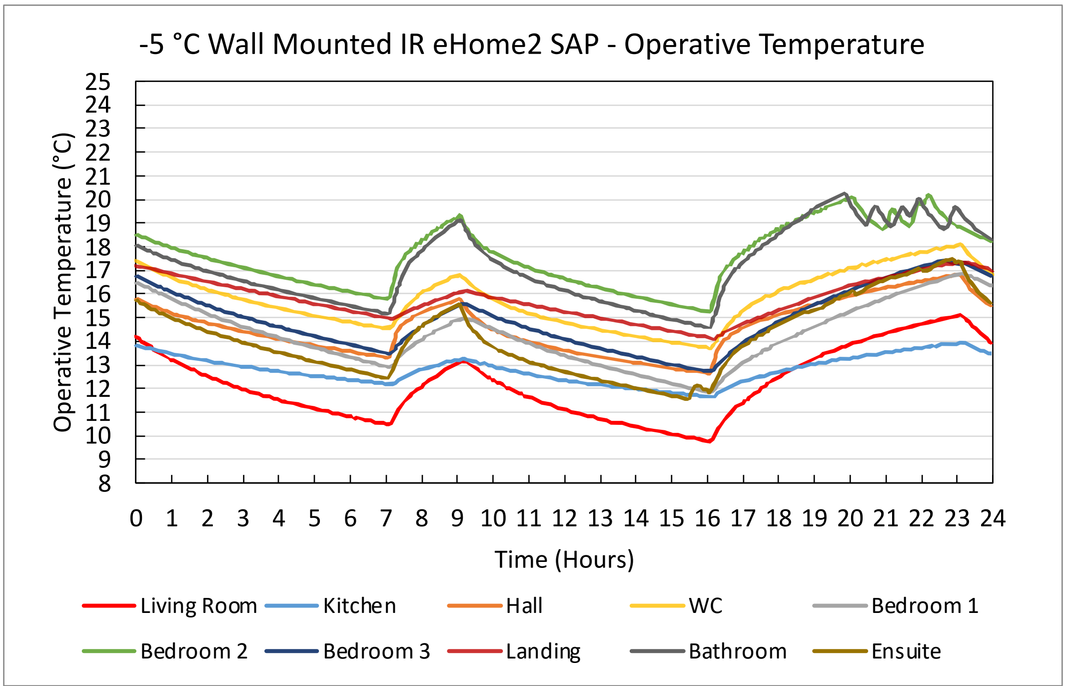


Figure 131. -5 °C Wall Mounted IR eHome2 SAP – Operative Temperature Plots

7.1.2.4.2 Spatial

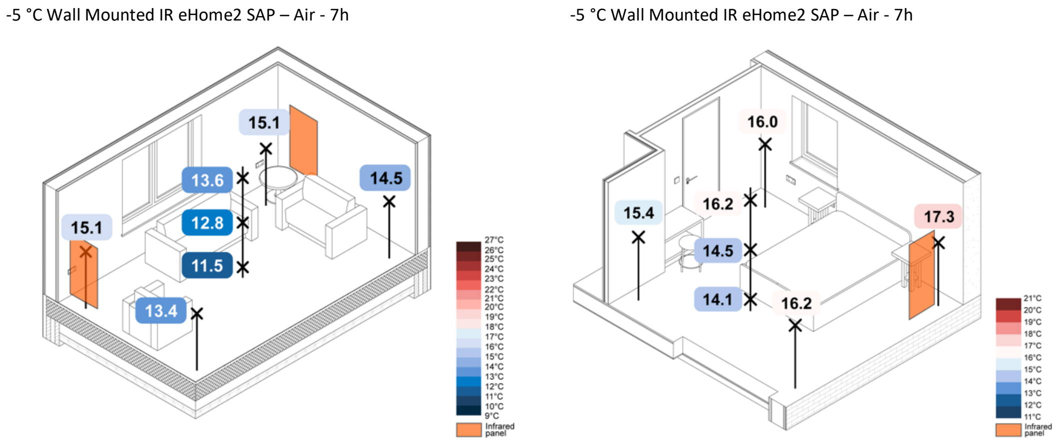


Figure 132. -5 °C Wall Mounted IR eHome2 SAP – Spatial Air Temperatures

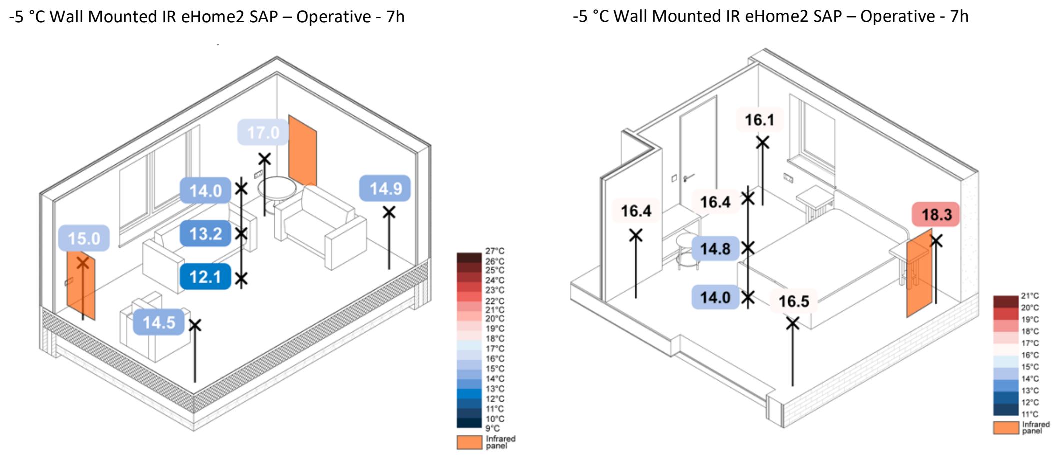


Figure 133. -5 °C Wall Mounted IR eHome2 SAP – Spatial Operative Temperatures

7.1.2.4.3 Heat up times

Table 47. -5 °C Wall Mounted IR eHome2 SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	9.78	14.7	07:05:00	0.69
Bedroom 1	11.96	16.62	07:09:00	0.65

7.1.2.4.4 Performance Metrics

Table 48. -5 °C Wall Mounted IR eHome2 SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.50	36.3	£8.88

7.1.2.4.5 Discussion

Setpoint

- The highest temperature reached in the Living Room were ~12.7 °C in the morning heating period, and ~14.6 °C in the evening heating period.
- Bathroom and Bedroom 2 achieved setpoint in both the morning and evening heating period.
- WC only achieved setpoint at the end of the evening heating period.
- All other rooms failed to achieve setpoint temperatures, ranging from 13.1-16.7 °C during the morning heating period, and 13.9-17.4 °C in the evening heating period.

Heat Distribution

- Operative temperatures were generally found to be warmer than air temperature sensors in both rooms, particularly in sensors with an unobstructed line of sight to the IR panel.
- Living Room failed to achieve setpoint, with air temperatures ranging between 11.5-15.1 °C, and stratification of 2.1 °C.
- Bedroom 1 failed to achieve setpoint, with air temperatures ranging between 14.1-17.3 °C, and stratification of 2.1 °C.

Energy Consumption

This 24h period had a total energy consumption of 36.3 kWh, with a running cost of £8.88.

Efficiency

The SEEI for this system test was 0.50 K/kWh.

7.1.2.5 5 °C Monobloc ASHP eHome2 Constant

7.1.2.5.1 Control

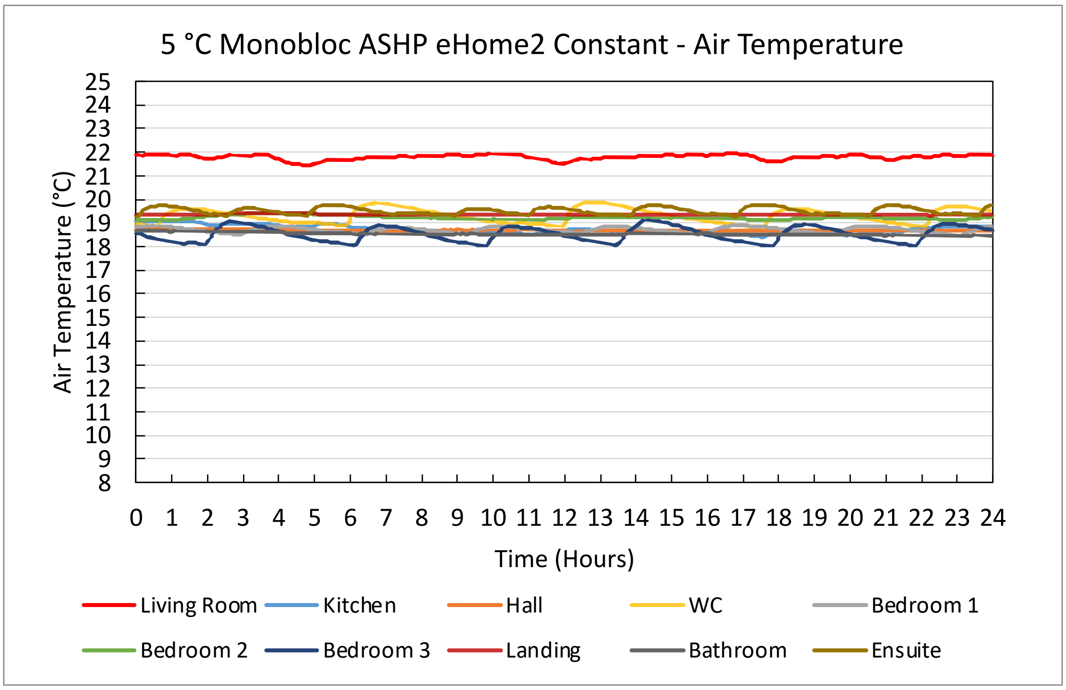


Figure 134. 5 °C Monobloc ASHP eHome2 Constant – Air Temperature Plots

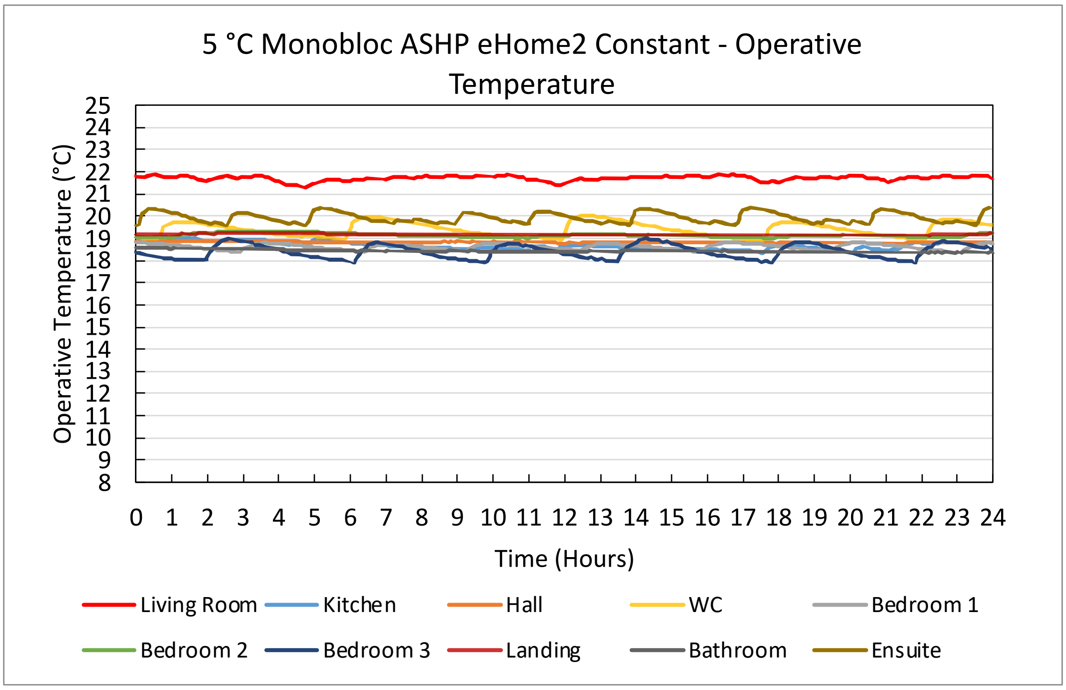


Figure 135. 5 °C Monobloc ASHP eHome2 Constant – Operative Temperature Plots

7.1.2.5.2 Spatial

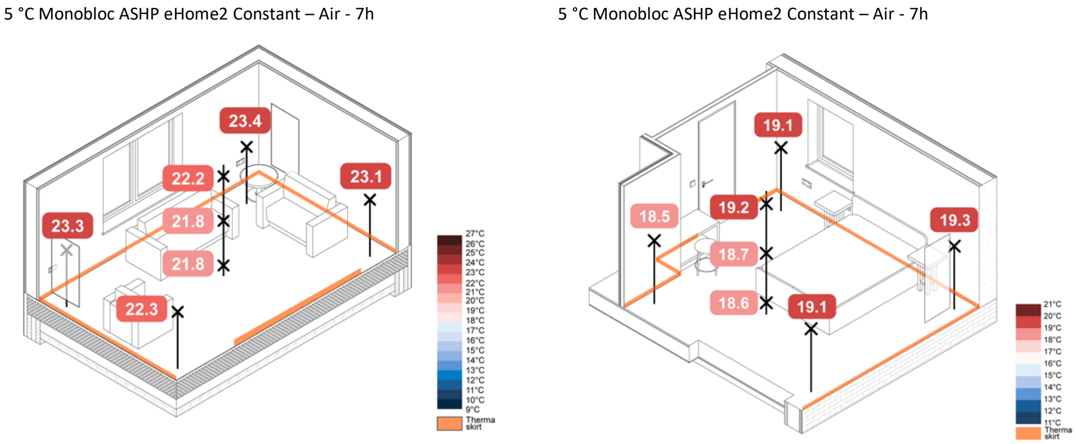


Figure 137. 5 °C Monobloc ASHP eHome2 Constant – Spatial Air Temperatures

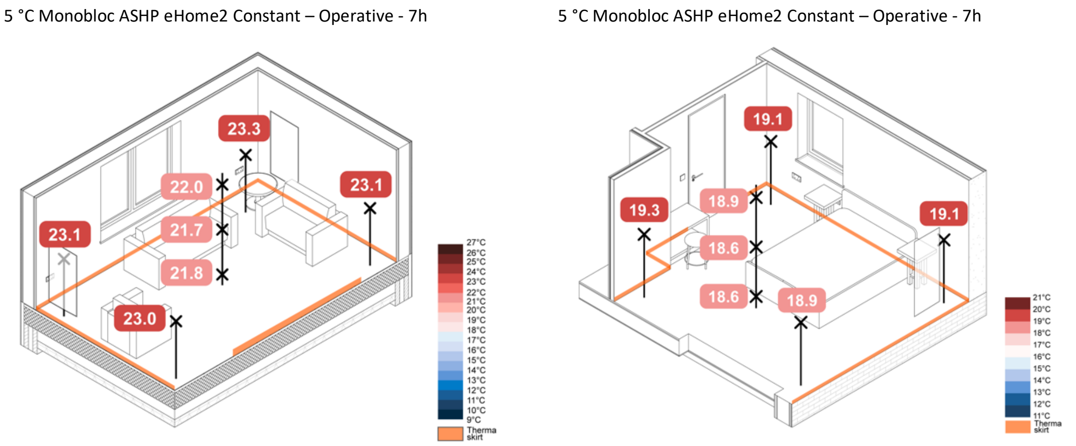


Figure 136. 5 °C Monobloc ASHP eHome2 Constant – Operative Temperature Plots

7.1.2.5.3 Performance Metrics

Table 49. 5 °C Monobloc ASHP eHome2 Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
2.6	1.10	11.6	£2.83

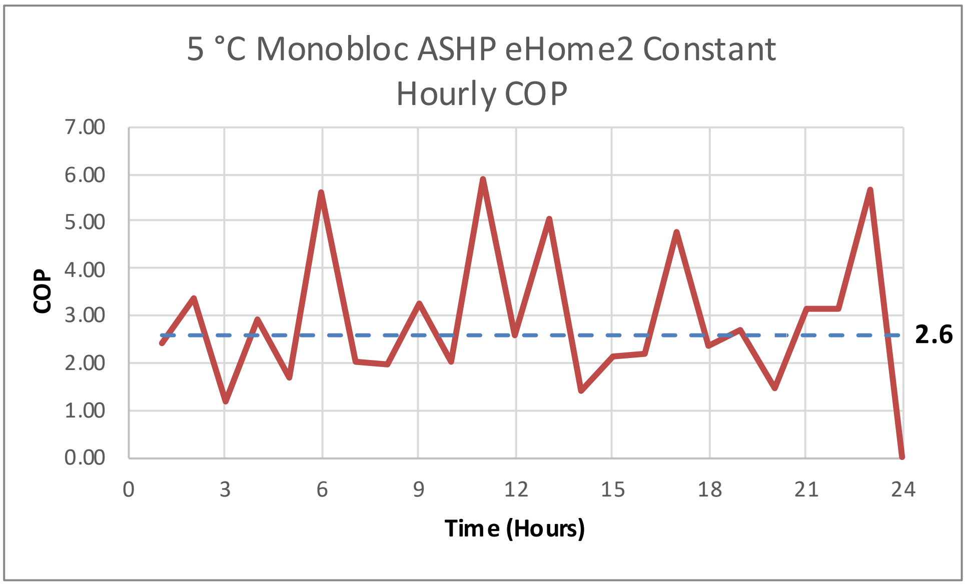


Figure 138. 5 °C Monobloc ASHP eHome2 Constant – Hourly COP

7.1.2.5.4 Discussion

Setpoint

- Living Room temperature overshot the setpoint by ~0.6 °C, with little hysteresis.
- Ensuite overheated by ~1.5 °C.
- WC Overheated between 1-2 °C
- All other rooms achieved setpoint within ~±1 °C.

Heat Distribution

- Living Room overheated towards the perimeter of the room between 1-2 °C.
- Living Room stratification of 0.4 °C in the centre of the room.
- Bedroom overheated towards the perimeter of the room by ~1 °C.
- Bedroom measured stratification of 0.6 °C in the centre of the room.

Energy Consumption

This 24h period had a total energy consumption of 11.6 kWh, with a running cost of £2.83.

Efficiency

The COP was 2.6, and the SEEI for this system test was 1.10 K/kWh.

7.1.2.6 5 °C Monobloc ASHP eHome2 SAP

7.1.2.6.1 Control

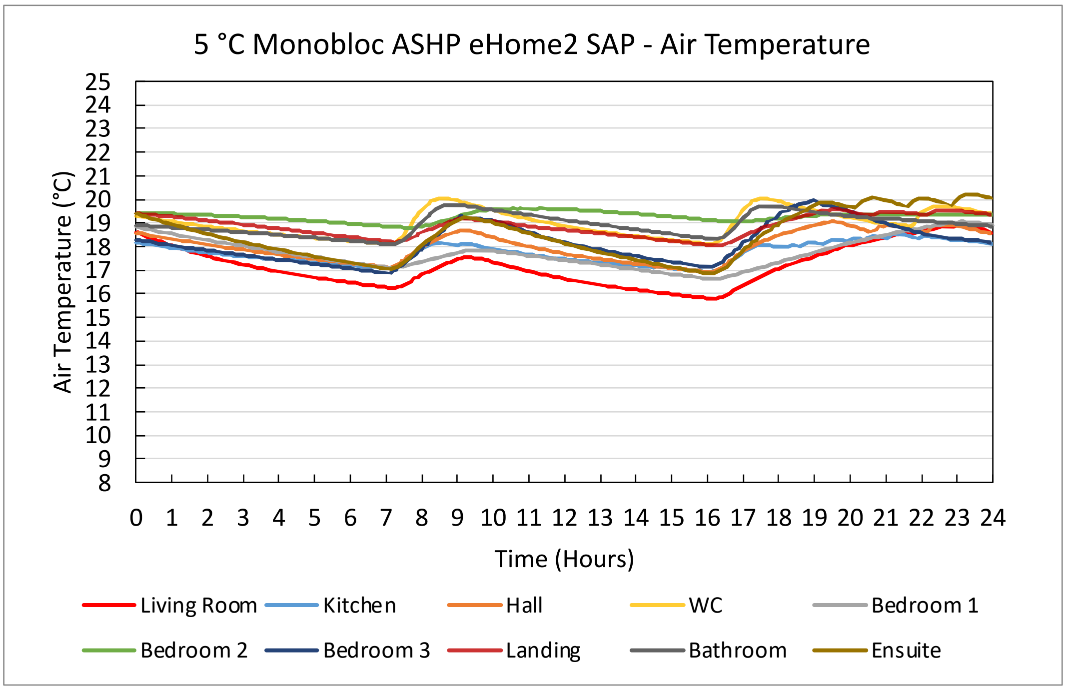


Figure 139. 5 °C Monobloc ASHP eHome2 SAP – Air Temperature Plots

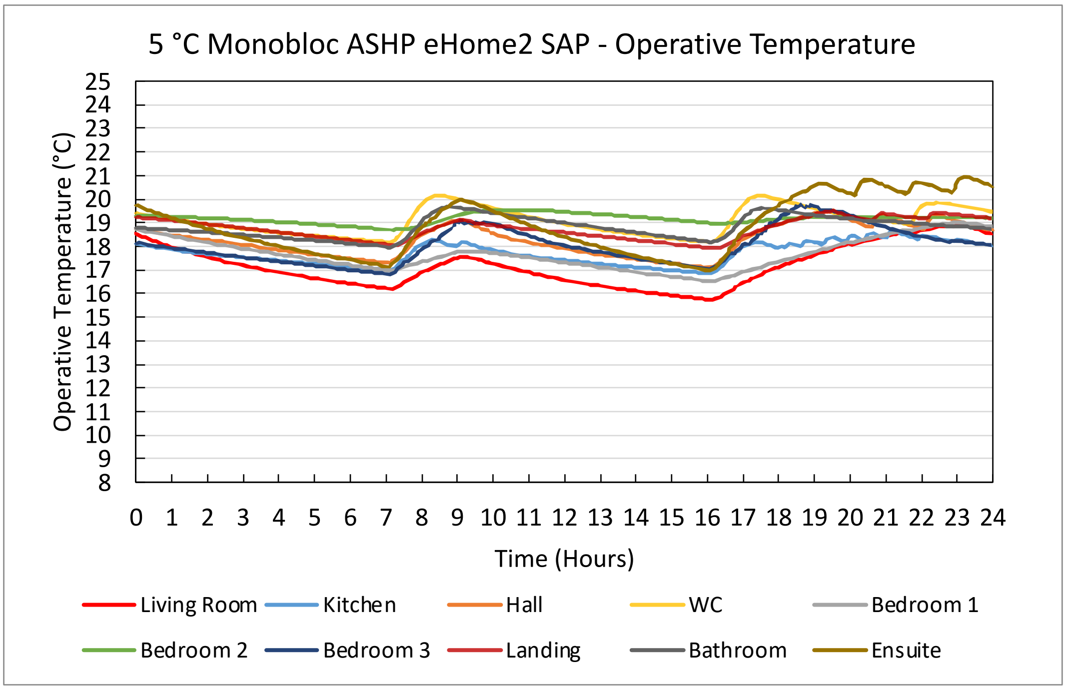


Figure 140. 5 °C Monobloc ASHP eHome2 SAP – Operative Temperature Plots

7.1.2.6.2 Spatial

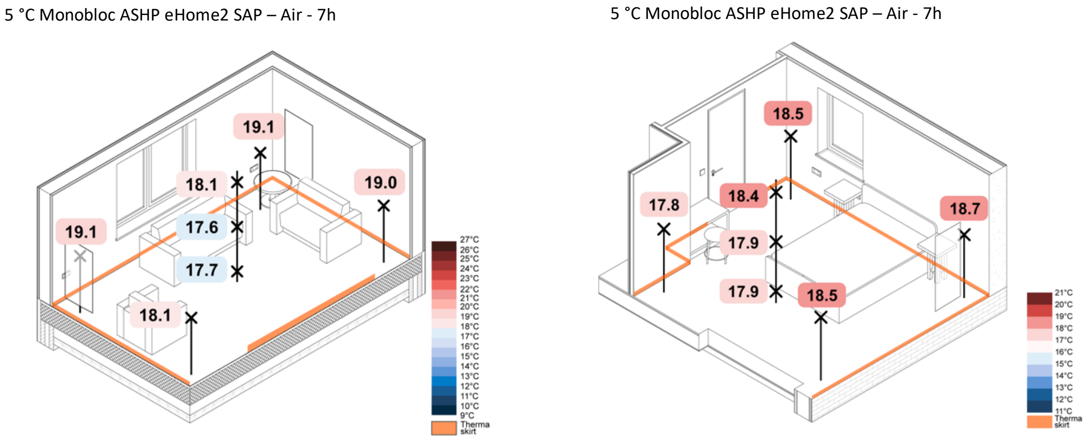


Figure 142. 5 °C Monobloc ASHP eHome2 SAP – Spatial Air Temperatures

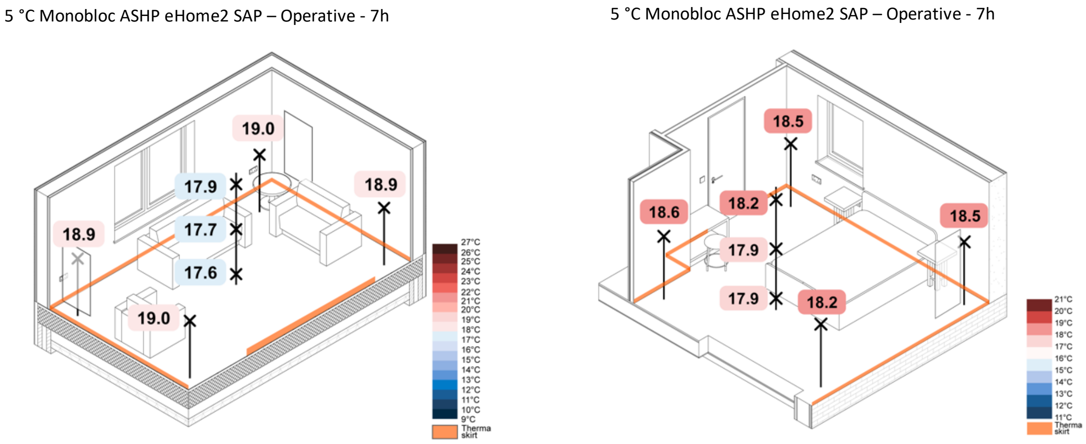


Figure 141. 5 °C Monobloc ASHP eHome2 SAP – Spatial Operative Temperatures

7.1.2.6.3 Heat up times

Table 50. 5 °C Monobloc ASHP eHome2 SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	15.81	18.92	07:04:00	0.44
Bedroom 1	16.51	18.00	03:31:48	0.42

7.1.2.6.4 Performance Metrics

Table 51. 5 °C Monobloc ASHP eHome2 SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
2.9	1.22	9.4	£2.31

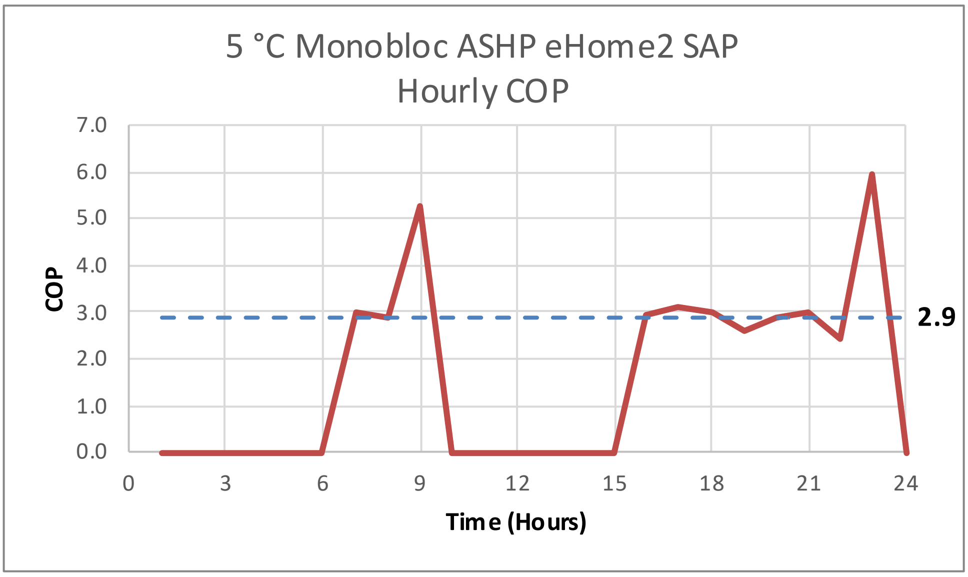


Figure 143. 5 °C Monobloc ASHP eHome2 SAP – Hourly COP

7.1.2.6.5 Discussion

Setpoint

- Living Room underheated, achieving 17.6 °C at the end of the morning heating period, and 19 °C at the end of the evening heating period.
- Controls anomaly in Bedroom 3, where it stops delivering heat at ~7pm.
- Bedroom 1 achieved setpoint at the end of the morning heating period, and achieved setpoint after 4 hours in the evening heating period.
- Kitchen shows good control in both the morning and evening heating period.
- All other rooms overshot their target setpoint.

Heat Distribution

- Living Room failed to achieve setpoint within the room. Warmer temperatures observed towards the perimeter of the room
- Living Room stratification of 0.5 °C in the centre of the room.
- Bedroom showed homogenous temperature distribution, with a measured stratification of 0.5 °C in the centre of the room.

Energy Consumption

This 24h period had a total energy consumption of 9.4 kWh, with a running cost of £2.31.

Efficiency

The COP was 2.9, and the SEEI for this system test was 1.22 K/kWh.

7.1.2.7 5 °C Wall Mounted IR eHome2 Constant

7.1.2.7.1 Control

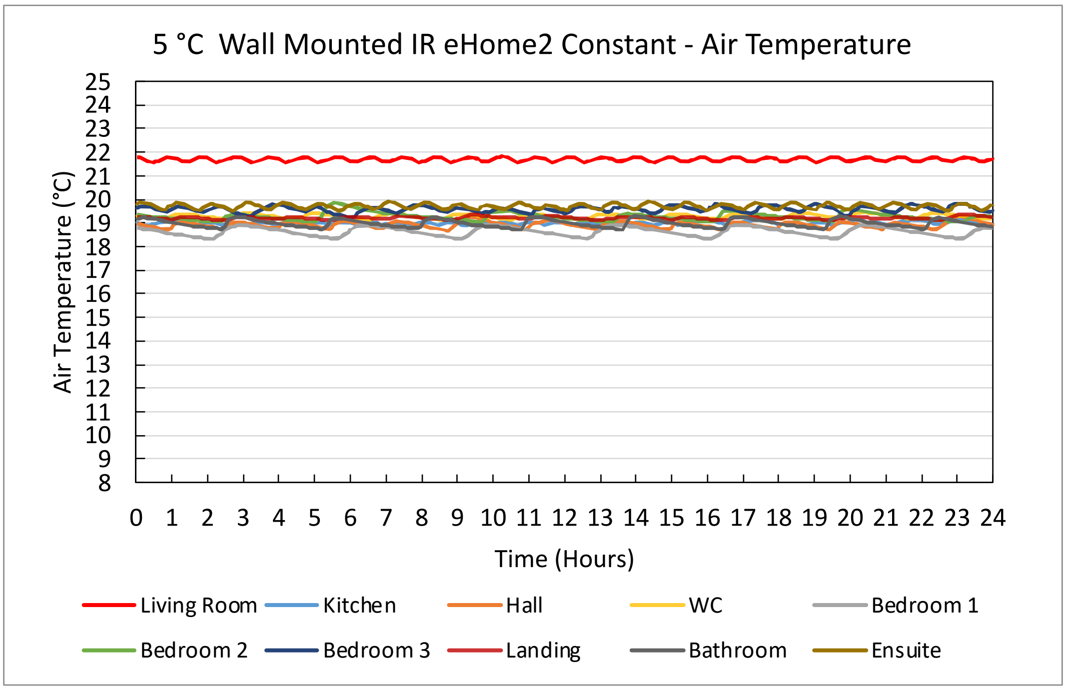


Figure 144. 5 °C Wall Mounted eHome2 Constant – Air Temperature Plots

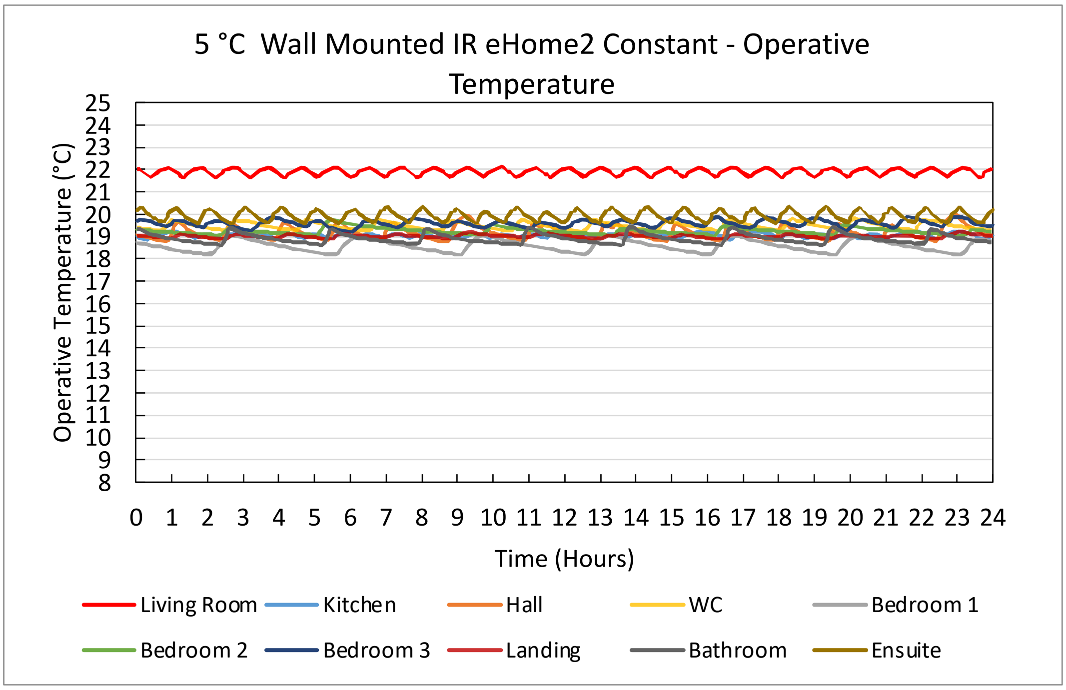


Figure 145. 5 °C Wall Mounted eHome2 Constant – Operative Temperature Plots

7.1.2.7.2 Spatial

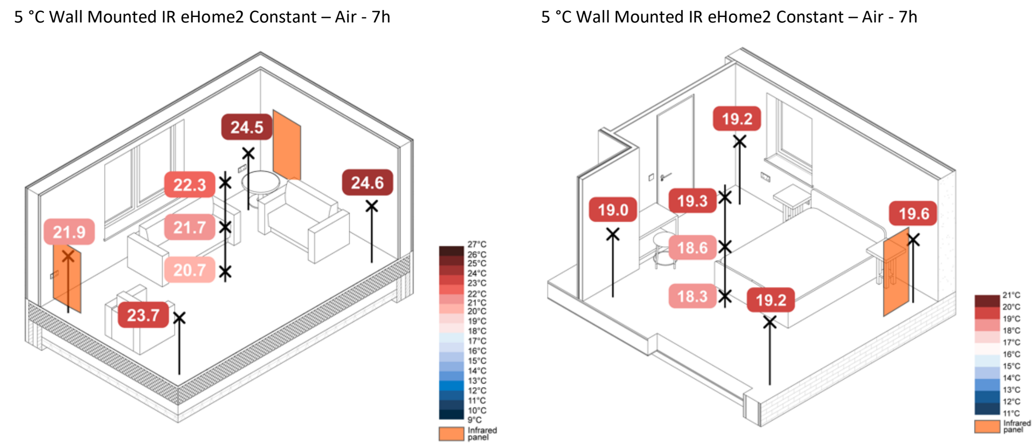


Figure 147. 5 °C Wall Mounted eHome2 Constant – Spatial Air Temperatures

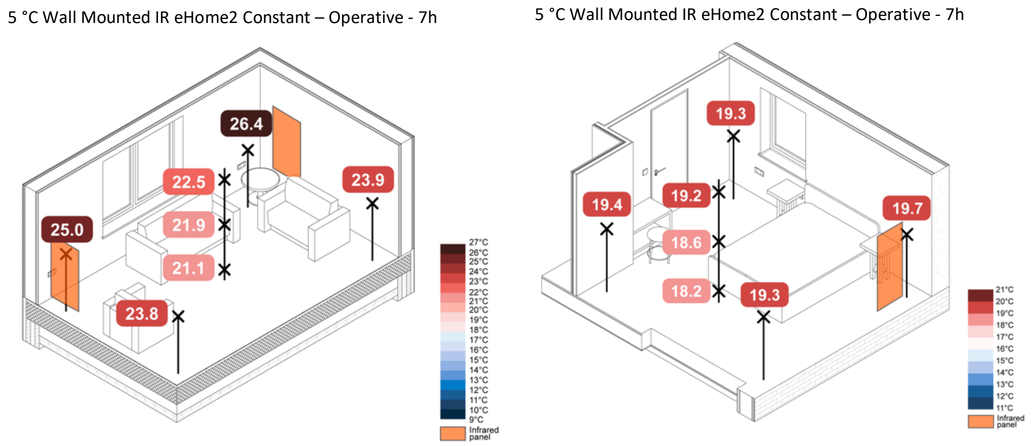


Figure 146. 5 °C Wall Mounted eHome2 Constant – Spatial Operative Temperatures

7.1.2.7.3 Performance Metrics

Table 52. . 5 °C Wall Mounted eHome2 Constant – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.36	33.0	£8.10

7.1.2.7.4 Discussion

Setpoint

- Living Room achieved the setpoint temperature within ~±0.9 °C, with little hysteresis.
- Ensuite and Bedroom 2 overshot the setpoint by ~1.5 °C
- All other rooms achieved setpoint within ~±1 °C.

Heat Distribution

- Generally, the operative temperature was higher than the air temperature.
- The Living Room showed stratification of 1.4 °C in the centre of the room.
- Living room perimeter temperatures appear warmer than those located in the centre of the room.
- Bedroom 1 measured stratification of 1 °C, with the external perimeter warmer than the centre of the room.
- Homogenous temperature distribution in Bedroom 1, with a range of 1.4 °C.

Energy Consumption

This 24h period had a total energy consumption of 33.0 kWh, with a running cost of £8.10

Efficiency

The SEEI for this system test was 0.36 K/kWh.

7.1.2.8 5 °C Wall Mounted IR eHome2 SAP

7.1.2.8.1 Control

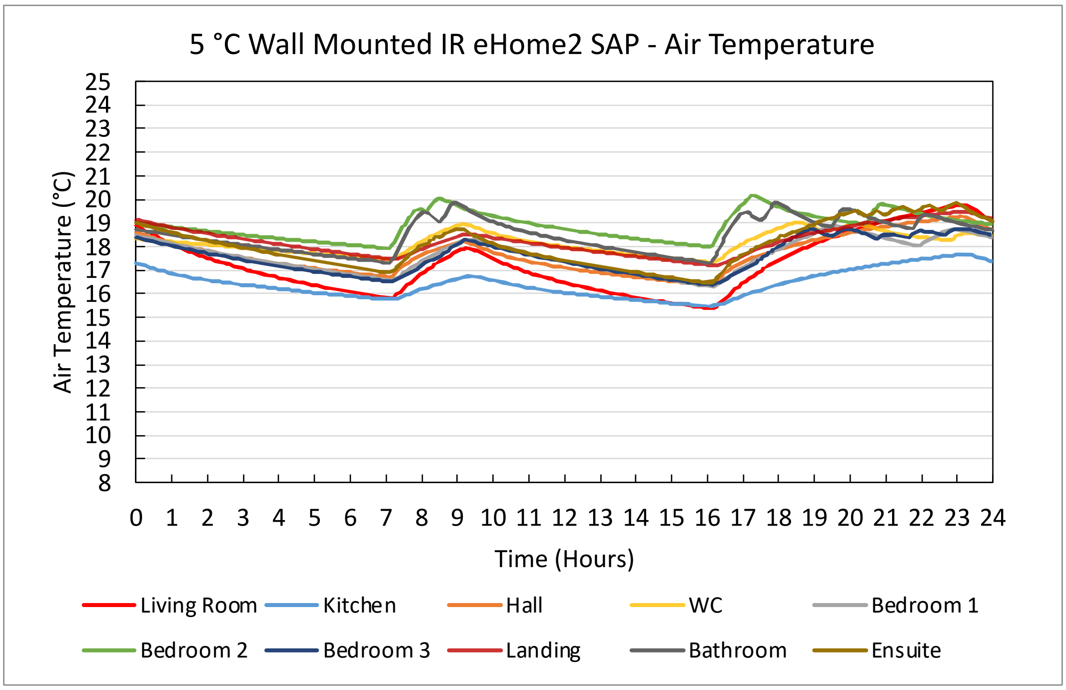


Figure 148. 5 °C Wall Mounted eHome2 SAP – Air Temperature Plots

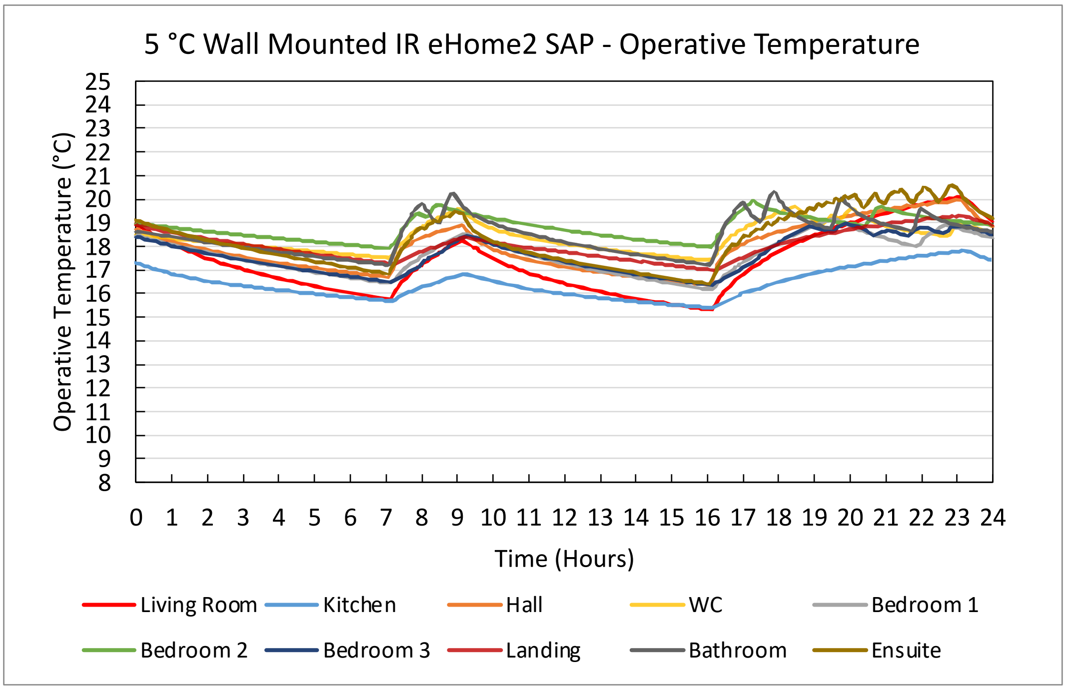


Figure 149. 5 °C Wall Mounted eHome2 SAP – Operative Temperature Plots

7.1.2.8.2 Spatial

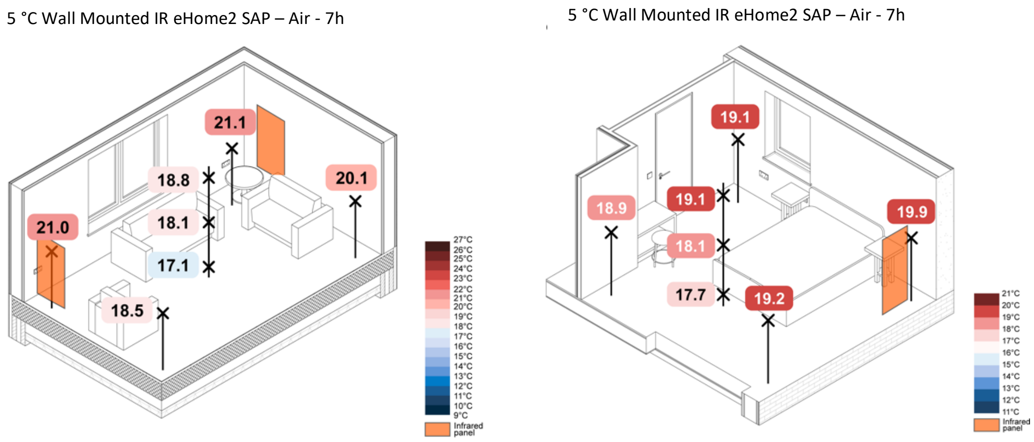


Figure 150. 5 °C Wall Mounted eHome2 SAP – Spatial Air Temperatures

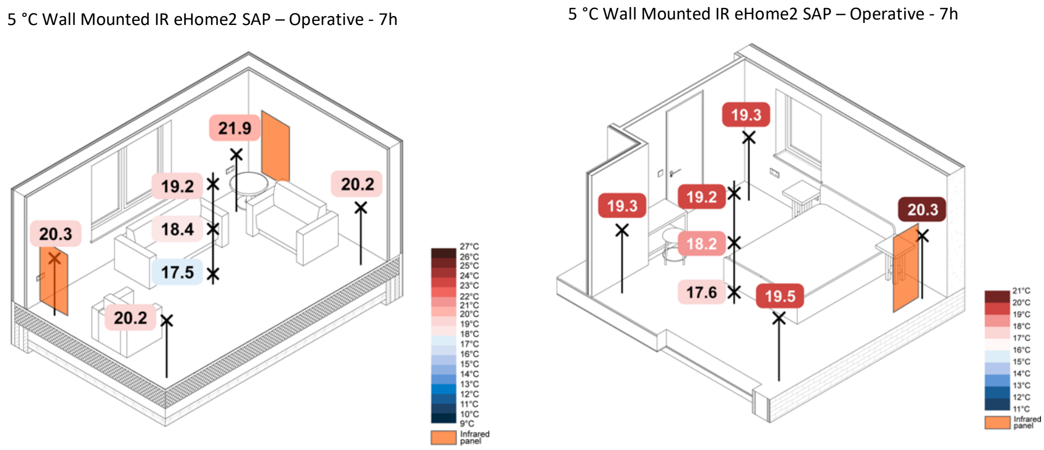


Figure 151. 5 °C Wall Mounted eHome2 SAP – Spatial Operative Temperatures

7.1.2.8.3 Heat up times

Table 53. 5 °C Wall Mounted eHome2 SAP – Heat Up Rates

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
Living Room	15.39	19.78	07:02:00	0.62
Bedroom 1	16.20	17.96	01:43:12	1.02

7.1.2.8.4 Performance Metrics

Table 54. 5 °C Wall Mounted eHome2 SAP – Performance Metrics

COP	SEEI (K/kWh)	24h Energy Consumption (kWh)	24h Running Cost
-	0.41	27.4	£6.72

7.1.2.8.5 Discussion

Setpoint

- Living Room failed to achieve setpoint in both heating periods, achieving a maximum of ~18 °C in the morning and ~20 °C in the evening.
- Kitchen failed to achieve setpoint in both heating periods, achieving a maximum of ~16.8 °C in the morning and ~17.7 °C in the evening.
- Bedroom 2 and Bathroom overheated in both the morning and evening heating periods.
- All other rooms achieved setpoint within the morning heating period (~18-19 °C), and the evening heating period (~18-20 °C)

Heat Distribution

- Setpoint only achieved in the Living Room at locations adjacent to the IR panels.
- Living Room stratification of 1.7 °C, with a room temperature range of 17.1-21.1 °C.
- Bedroom 1 operative temperatures were generally higher than the air temperature.
- Bedroom 1 achieved setpoint in all locations with the exception of the lowest sensor in the centre of the room. Stratification of 1.4 °C.

Energy Consumption

This 24h period had a total energy consumption of 27.4 kWh, with a running cost of £6.72

Efficiency

The SEEI for this system test was 0.41 K/kWh.

7.2 Average Heating Period Temperatures

The tables below show the average air temperature at the geometric centre of each room, during both the two hour morning heating period (AM), and the 7h evening heating period (PM).

7.2.1 TFH 5 °C Chamber Temperature

7.2.1.1 Constant Heating Pattern

Table 55. TFH 5 °C Chamber Temperature – Constant Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
5°C Wall Mounted IR TFH Constant	*AM*	21.3	18.6	19.0	18.8	18.7	19.2	18.7	19.3	20.1	19.8
	PM	21.3	18.6	19.0	18.8	18.7	19.2	18.7	19.4	20.2	19.7
5°C Loft ASHP Rads + UFH Constant	*AM*	22.6	18.8	18.4	22.4	17.9	20.9	19.7	18.4	18.4	20.3
	PM	22.7	18.9	18.4	22.6	17.9	20.9	19.7	18.4	18.4	20.3
5°C Loft ASHP Rads Constant	*AM*	22.3	18.6	18.5	17.7	17.6	19.1	18.5	18.1	17.9	19.8
	PM	22.3	18.7	18.4	17.7	17.4	19.1	18.5	18.2	17.8	19.9
5°C Monobloc ASHP TFH Rads + UFH Constant	*AM*	21.7	17.9	18.3	19.0	19.4	19.9	18.4	18.3	18.2	19.8
	PM	21.7	17.9	18.4	18.9	19.5	19.9	18.4	18.4	18.2	19.9
5°C Monobloc ASHP TFH Rads Constant	*AM*	22.3	18.4	18.3	19.1	18.0	18.9	18.3	18.4	19.0	19.2
	PM	22.3	18.3	18.4	19.0	18.1	18.9	18.3	18.5	19.0	19.1

7.2.1.2 SAP Heating Pattern

Table 56. TFH 5 °C Chamber Temperature – SAP Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
5°C Wall Mounted IR TFH SAP	*AM*	19.5	18.4	19.3	18.8	17.8	18.4	18.2	19.2	18.8	19.1
	PM	20.2	18.6	19.2	18.9	18.3	18.4	18.3	19.2	19.5	18.9
5°C Loft ASHP Rads + UFH SAP	*AM*	22.1	20.1	20.1	24.1	19.1	21.4	21.1	21.2	19.9	20.5
	PM	22.1	20.7	20.8	24.6	19.5	21.7	21.6	21.8	20.4	20.8
5°C Loft ASHP Rads SAP	*AM*	20.5	17.8	17.5	16.5	18.2	18.2	17.6	17.7	19.0	20.2
	PM	21.3	18.2	17.8	16.4	17.6	18.3	17.7	17.8	18.8	19.9
5°C Monobloc ASHP TFH Rads + UFH SAP	*AM*	21.6	17.3	17.9	18.1	18.9	20.4	18.6	17.4	17.4	20.7
	PM	22.7	17.9	18.3	18.5	19.9	21.7	19.3	17.9	18.5	22.0
5°C Monobloc ASHP TFH Rads SAP	*AM*	18.6	17.3	17.8	17.8	17.8	18.6	18.0	17.4	17.6	19.7
	PM	19.4	17.7	18.1	18.2	18.1	19.2	18.4	17.5	18.3	20.6

7.2.2 TFH -5 °C Chamber Temperature

7.2.2.1 Constant Heating Pattern

Table 57. TFH -5 °C Chamber Temperature – Constant Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
-5°C Wall Mounted IR TFH Constant	AM	22.3	18.2	18.4	18.9	19.2	18.8	17.8	18.1	19.5	22.3
	PM	22.3	17.7	18.4	18.9	19.3	18.7	17.8	18.1	19.6	22.3
-5°C Loft ASHP Rads + UFH Constant	AM	21.9	18.4	17.1	17.7	18.7	20.3	18.5	18.0	18.3	20.4
	PM	21.9	18.4	16.8	17.6	18.3	20.3	18.5	18.0	18.1	20.3
-5°C Loft ASHP Rads Constant	AM	21.4	17.7	17.6	18.3	17.2	17.9	17.7	18.1	17.7	19.3
	PM	21.4	17.8	17.4	18.1	17.2	18.0	17.7	18.2	17.9	19.0
-5°C Monobloc ASHP TFH Rads + UFH Constant	AM	22.7	17.8	17.5	19.4	19.1	19.7	17.9	19.3	18.7	19.5
	PM	22.6	17.8	17.6	19.4	19.3	19.6	17.9	19.2	18.5	19.5
-5°C Monobloc ASHP TFH Rads Constant	AM	18.9	17.6	17.6	18.0	16.7	18.6	18.3	17.7	18.4	19.1
	PM	18.9	17.7	17.6	18.0	16.9	18.6	18.4	17.8	18.5	19.2

7.2.2.2 SAP Heating Pattern

Table 58. TFH -5 °C Chamber Temperature – SAP Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
-5°C Wall Mounted IR TFH SAP	AM	19.0	16.1	17.3	18.3	15.6	18.9	17.5	16.2	14.8	16.9
	PM	20.7	17.3	18.3	18.8	15.9	19.1	17.9	16.9	15.2	18.0
-5°C Loft ASHP Rads + UFH SAP	AM	20.1	14.4	13.9	14.9	18.0	18.5	16.7	17.0	14.6	18.5
	PM	20.9	15.0	14.6	15.3	18.9	18.9	16.8	17.1	15.5	18.9
-5°C Loft ASHP Rads SAP	AM	14.8	14.8	13.9	14.6	16.2	15.2	15.2	16.3	15.6	16.4
	PM	16.2	16.0	15.3	15.6	16.8	15.7	15.8	16.7	17.2	18.3
-5°C Monobloc ASHP TFH Rads + UFH SAP	AM	20.9	14.3	14.9	15.8	17.9	18.5	16.5	14.1	13.5	15.6
	PM	22.2	15.4	16.0	16.5	19.1	19.0	16.8	14.6	15.0	16.1
-5°C Monobloc ASHP TFH Rads SAP	AM	13.8	13.1	13.0	13.5	15.3	14.2	14.0	14.6	14.7	15.4
	PM	15.5	15.1	15.1	15.3	16.6	14.8	14.8	15.2	16.6	16.6

7.2.3 eHome2 5 °C Chamber Temperature IR

7.2.3.1 Constant Heating Pattern

Table 59. eHome2 5 °C Chamber Temperature IR – Constant Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
5°C Wall Mounted IR eHome2 Constant	*AM*	21.7	18.6	19.2	19.6	19.0	19.0	19.2	19.0	19.7	19.3
	PM	21.7	18.6	19.3	19.6	19.0	18.9	19.2	19.0	19.7	19.3
5°C Monobloc ASHP eHome2 Constant	*AM*	21.9	18.7	19.2	18.2	18.6	18.7	19.4	18.5	19.5	19.3
	PM	21.8	18.7	19.2	18.5	18.7	18.7	19.3	18.5	19.5	19.3

7.2.3.2 SAP Heating Pattern

Table 60. eHome2 5 °C Chamber Temperature IR – SAP Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
5°C Wall Mounted IR eHome2 SAP	*AM*	17.6	18.0	19.6	17.9	16.6	18.0	18.3	19.4	18.4	18.7
	PM	18.6	18.3	19.4	18.4	17.1	18.6	18.9	19.2	19.2	18.6
5°C Monobloc ASHP eHome2 SAP	*AM*	17.3	17.7	19.3	18.9	18.1	18.5	19.0	19.6	18.9	19.8
	PM	18.1	18.2	19.3	19.0	18.2	18.7	19.3	19.3	19.7	19.5

7.2.4 eHome2 -5 °C Chamber Temperature IR

7.2.4.1 Constant Heating Pattern

Table 61. eHome2 -5 °C Chamber Temperature IR – Constant Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
-5°C Wall Mounted IR eHome2 Constant	*AM*	19.0	18.6	20.0	17.6	17.7	17.5	18.7	19.0	18.1	19.0
	PM	19.0	18.6	19.9	17.6	17.7	17.5	18.7	19.0	18.2	19.1
-5°C Monobloc ASHP eHome2 Constant	*AM*	18.1	18.6	19.0	18.9	17.9	18.3	19.1	18.5	18.1	19.2
	PM	18.1	18.6	18.9	18.9	17.9	18.3	19.1	18.6	18.2	19.3

7.2.4.2 SAP Heating Pattern

Table 62. eHome2 -5 °C Chamber Temperature IR – SAP Heating Pattern

Test	Period	Midroom Average Air Temperature (°C)									
		LR	B1	B2	B3	Kitch	Hall	Land	Bath	En	WC
-5°C Wall Mounted IR eHome2 SAP	*AM*	12.4	14.5	18.4	15.1	13.0	14.5	16.0	18.2	13.8	15.8
	PM	13.4	15.2	19.0	16.0	13.3	14.9	16.4	19.0	14.6	16.3
-5°C Monobloc ASHP eHome2 SAP	*AM*	10.6	11.6	16.1	14.7	13.6	13.8	14.7	16.5	13.8	16.9
	PM	10.9	11.7	16.1	15.1	14.0	14.1	14.8	17.2	14.7	17.7

7.3 Heat Up Rates & Time to Setpoint

7.3.1 TFH

Living room

Table 63. Heat Up Rates & Time to Setpoint for TFH Living Room

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
5°C Monobloc ASHP TFH Rads SAP	17.18	20.29	07:00:00	0.44
5°C Monobloc ASHP TFH Rads + UFH SAP	20.97	21	01:03:00	0.03
5°C Loft ASHP Rads SAP	18.78	21	02:17:00	0.97
5°C Loft ASHP Rads + UFH SAP	22.45	23.29	01:16:00	0.66
5°C Wall Mounted IR TFH SAP	17.31	21	06:18:00	0.59
-5°C Monobloc ASHP TFH Rads SAP	12.23	16.92	07:03:00	0.67
-5°C Monobloc ASHP TFH Rads + UFH SAP	19.46	21	03:23:00	0.46
-5°C Loft ASHP Rads SAP	12.51	18.285	07:01:00	0.82
-5°C Loft ASHP Rads + UFH SAP	18.63	21	04:35:00	0.52
-5°C Wall Mounted IR TFH SAP	15.51	21	04:23:00	1.25

Bedroom 1

Table 64. Heat Up Rates & Time to Setpoint for TFH Bedroom 1

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
5°C Monobloc ASHP TFH Rads SAP	15.75	18.00	04:33:00	0.49
5°C Monobloc ASHP TFH Rads + UFH SAP	15.94	17.99	05:30:00	0.37
5°C Loft ASHP Rads SAP	16.46	17.99	02:10:12	0.71
5°C Loft ASHP Rads + UFH SAP	16.84	18.01	02:54:12	0.40
5°C Wall Mounted IR TFH SAP	16.01	18.00	01:16:48	1.55
-5°C Monobloc ASHP TFH Rads SAP	10.44	17.07	07:07:00	0.93
-5°C Monobloc ASHP TFH Rads + UFH SAP	12.08	17.7	07:10:00	0.78
-5°C Loft ASHP Rads SAP	11.49	17.43	07:15:00	0.82
-5°C Loft ASHP Rads + UFH SAP	11.69	16.54	07:05:00	0.68
-5°C Wall Mounted IR TFH SAP	12.93	17.99	04:22:12	1.16

7.3.2 eHome2

Living room

Table 65. Heat Up Rates & Time to Setpoint for eHome2 Living Room

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
5°C Wall Mounted IR eHome2 SAP	15.39	19.78	07:02:00	0.62
5°C Monobloc ASHP eHome2 SAP	15.81	18.92	07:04:00	0.44
-5°C Wall Mounted IR eHome2 SAP	9.78	14.7	07:05:00	0.69
-5°C Monobloc ASHP eHome2 SAP	8.8	12	07:06:00	0.45

Bedroom 1

Table 66. Heat Up Rates & Time to Setpoint for eHome2 Bedroom 1

	$T_{Initial}$ (°C)	T_{Final} (°C)	Time to T_{Final}	Rate of change (°C/hour)
5°C Wall Mounted IR eHome2 SAP	16.20	17.96	01:43:12	1.02
5°C Monobloc ASHP eHome2 SAP	16.51	18.00	03:31:48	0.42
-5°C Wall Mounted IR eHome2 SAP	11.96	16.62	07:09:00	0.65
-5°C Monobloc ASHP eHome2 SAP	10.23	12.99	07:20:00	0.38

7.4 ASHP Coefficient of Performance (COP) measurements

The tables below show the final 24h heat meter energy output and electrical energy consumption of the ASHPs. These have been used to calculate the COP, following the methodology outline in Section 6.3.1, which is presented in the figures below.

7.4.1 TFH

Table 67. TFH ASHP Coefficient of Performance (COP)

	Heat Meter Calculated (kWh)	ASHP Consumption (kWh)	ASHP unit COP
5 °C Loft ASHP Rads + UFH Constant	41.7	32.9	1.3
5 °C Loft ASHP Rads + UFH SAP	34.6	27.9	1.2
5 °C Loft ASHP Rads Constant	33.8	29.9	1.1
5 °C Loft ASHP Rads SAP	32.2	24.2	1.3
5 °C Monobloc ASHP TFH Rads + UFH Constant	35.4	9.4	3.7
5 °C Monobloc ASHP TFH Rads + UFH SAP	29.4	8.4	3.5
5 °C Monobloc ASHP TFH Rads Constant	30.0	11.8	2.5
5 °C Monobloc ASHP TFH Rads SAP	24.0	7.5	3.2
-5 °C Loft ASHP Rads + UFH Constant	64.4	45.6	1.4
-5 °C Loft ASHP Rads + UFH SAP	60.4	41.9	1.4
-5 °C Loft ASHP Rads Constant	65.8	63.0	1.0
-5 °C Loft ASHP Rads SAP	53.0	43.4	1.2
-5 °C Monobloc ASHP TFH Rads + UFH Constant	58.6	25.9	2.3
-5 °C Monobloc ASHP TFH Rads + UFH SAP	53.3	18.0	3.0
-5 °C Monobloc ASHP TFH Rads Constant	59.0	34.4	1.7
-5 °C Monobloc ASHP TFH Rads SAP	48.0	19.6	2.5

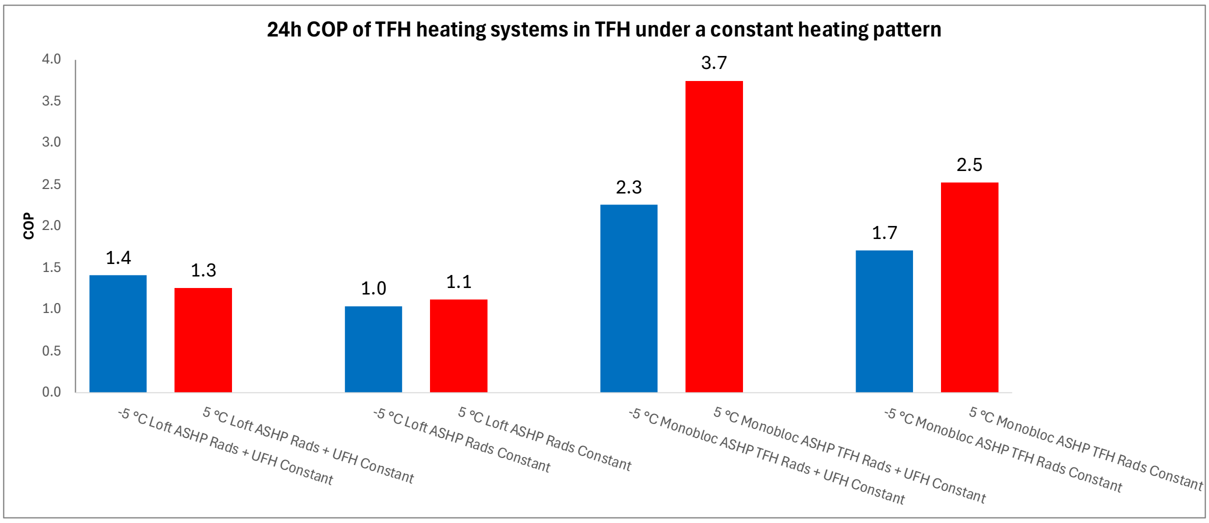


Figure 152. 24h COP of TFH heating systems under a constant heating pattern

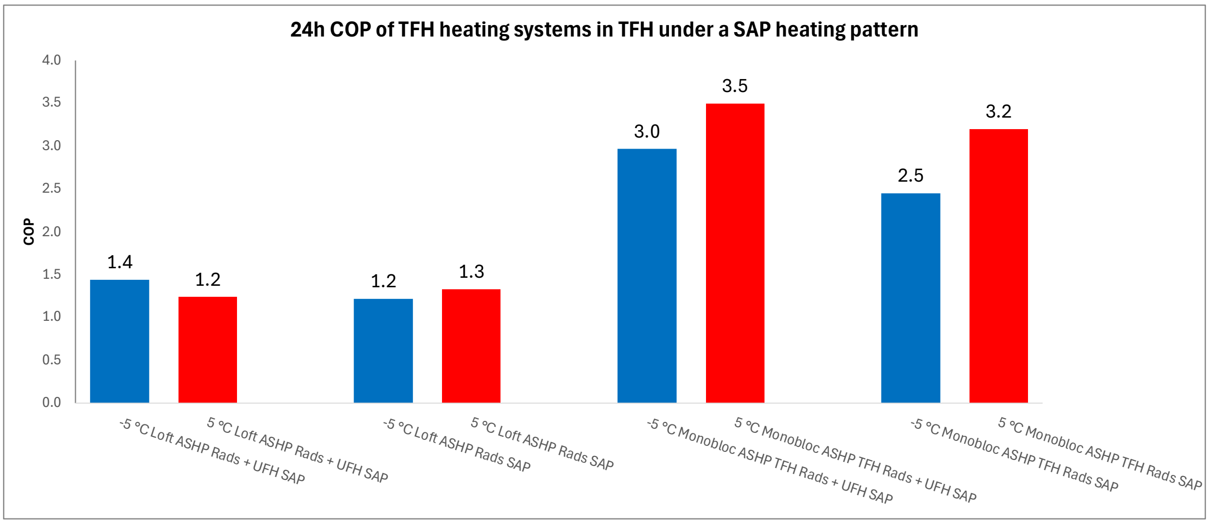


Figure 153. 24h COP of TFH heating systems under a SAP heating pattern

7.4.2 eHome2

Table 68. eHome2 ASHP Coefficient of Performance (COP)

	Heat Meter Calculated (kWh)	ASHP Consumption (kWh)	ASHP unit COP
5 °C Monobloc ASHP eHome2 Constant	29.9	11.6	2.6
5 °C Monobloc ASHP eHome2 SAP	27.4	9.4	2.9
-5 °C Monobloc ASHP eHome2 Constant	52.4	22.5	2.3
-5 °C Monobloc ASHP eHome2 SAP	40.0	17.6	2.3

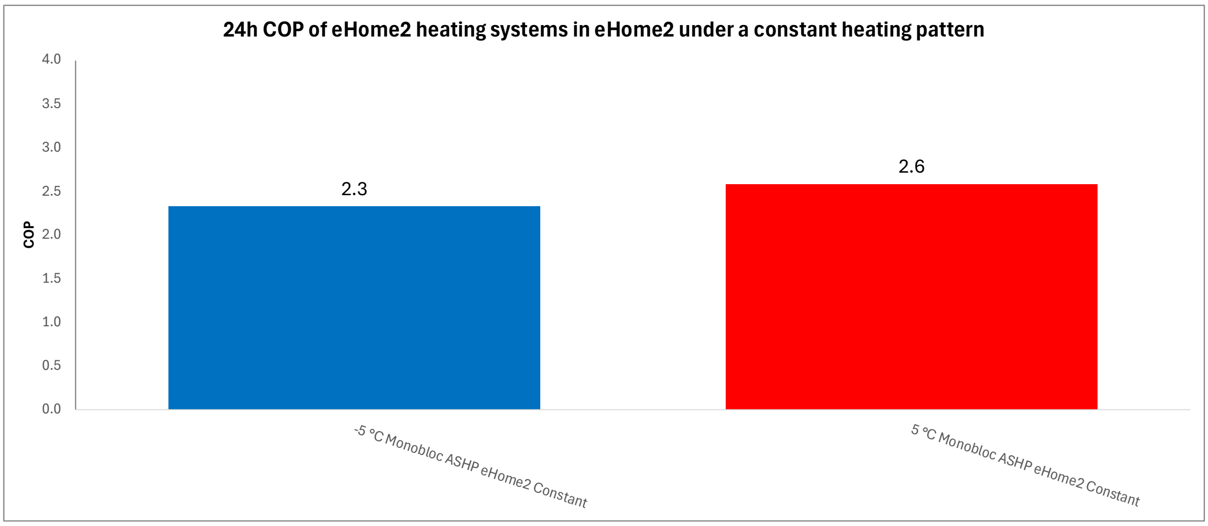


Figure 154. 24h COP of eHome2 heating systems under a constant heating pattern

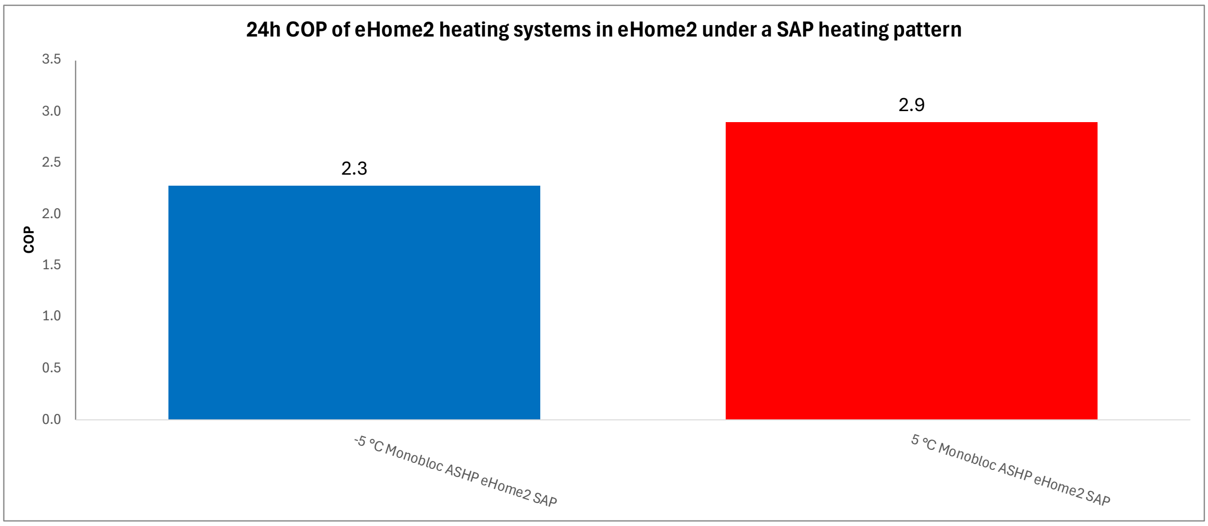


Figure 155. 24h COP of eHome2 heating systems under a SAP heating pattern

7.5 Running Costs

Energy running costs were calculated using the Ofgem electric energy price cap of 24.50p/kWh for the period 1st October to 31th December 2024 (Ofgem, 2024).

7.5.1 TFH

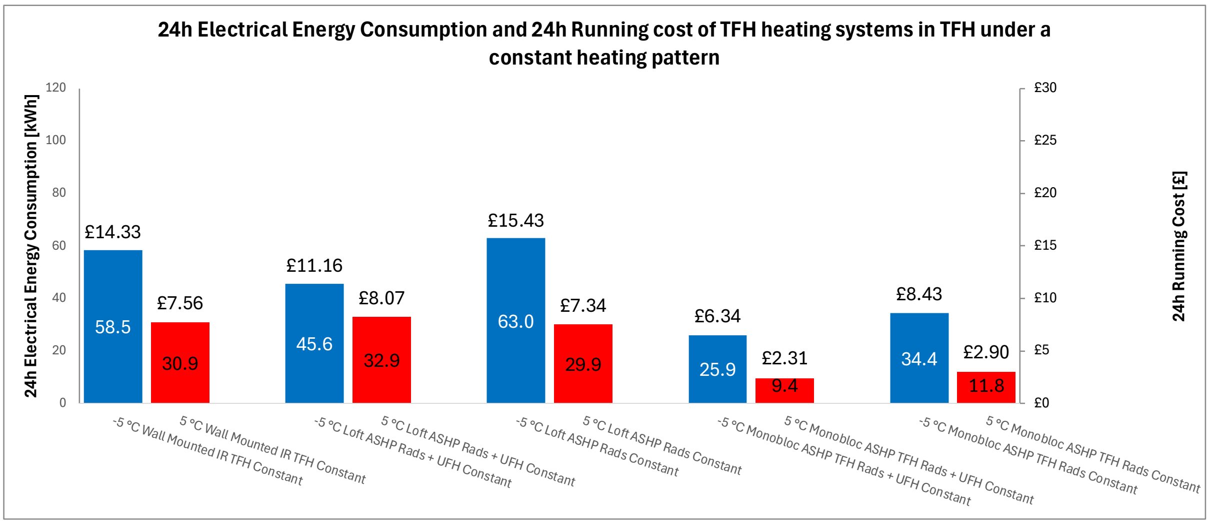


Figure 156. 24h Electrical Energy Consumption and 24h Running Cost of TFH heating system under a constant heating pattern

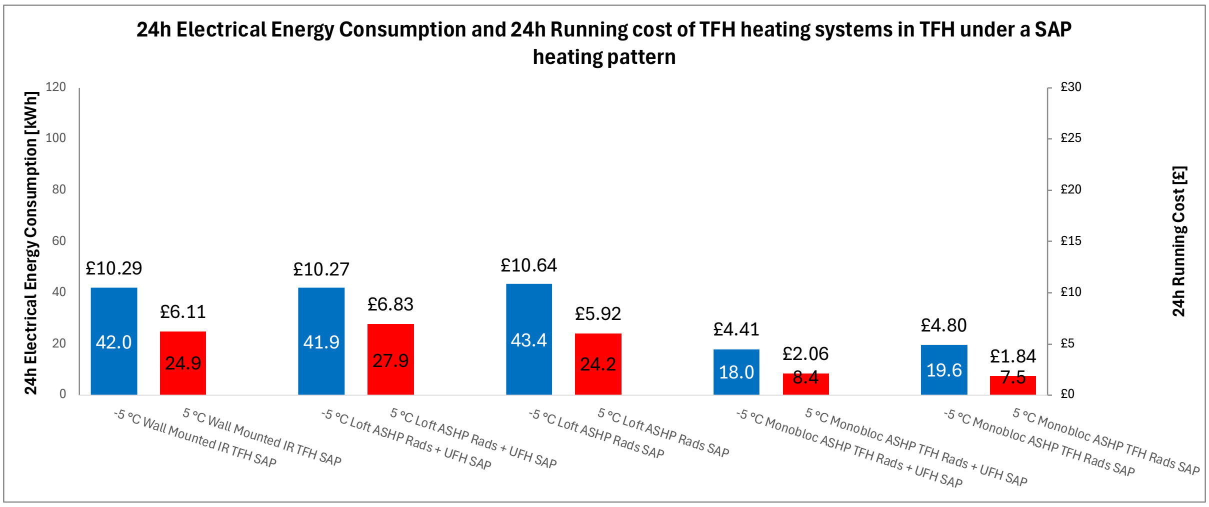


Figure 157. 24h Electrical Energy Consumption and 24h Running Cost of TFH heating system under a SAP heating pattern

- Bosch V high running cost resulting from backup heater constantly being relied on
- Ambion high running cost but good temperature control
- Panasonic achieved results that would be expected of ASHP.
  - Good control
  - Achieved setpoints in SAP test

7.5.2 eHome2

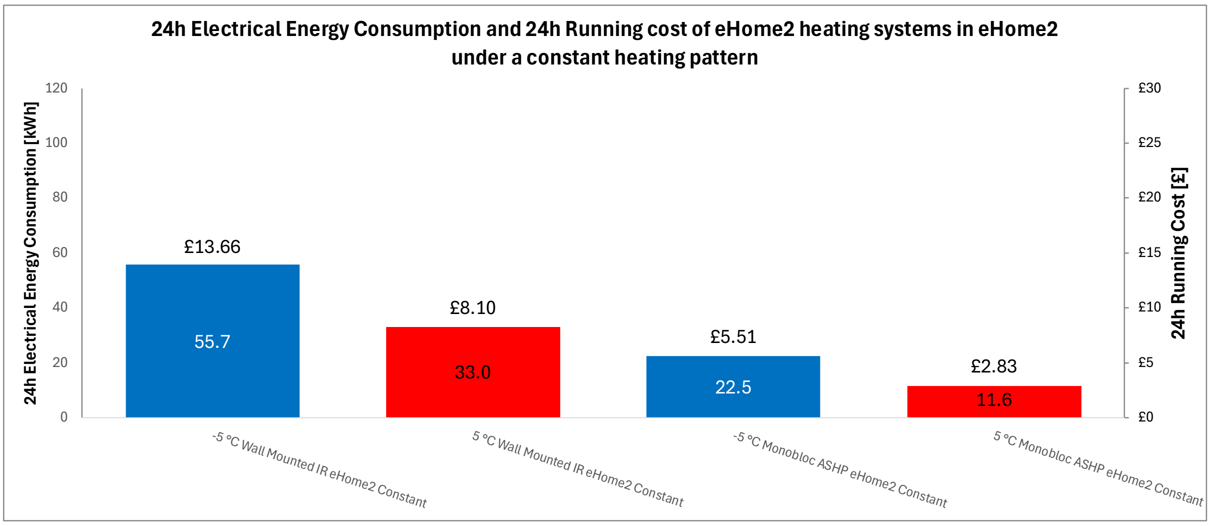


Figure 158. 24h Electrical Energy Consumption and 24h Running Cost of eHome2 heating system under a constant heating pattern

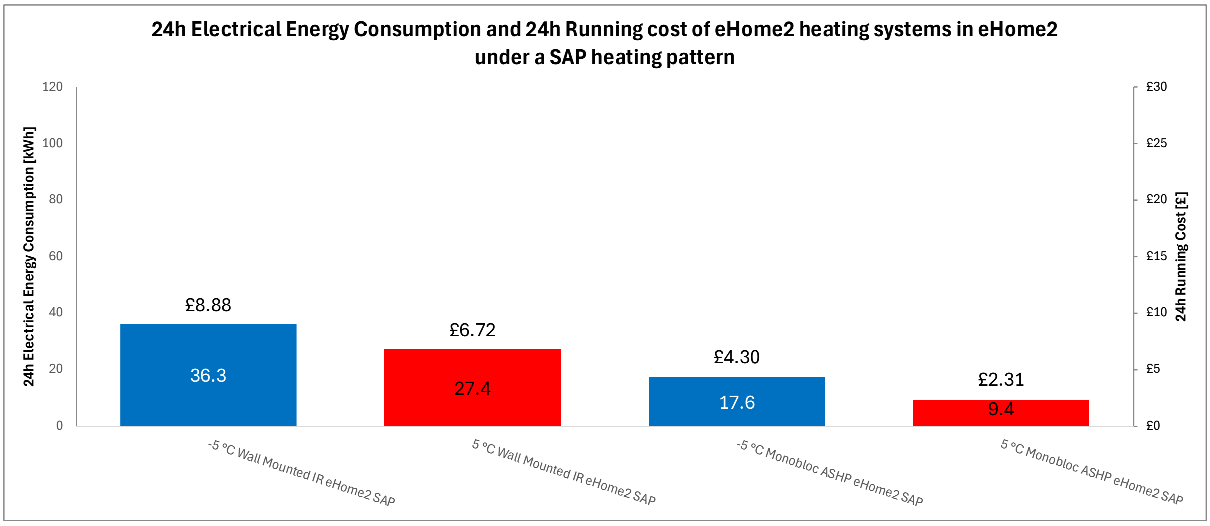


Figure 159. 24h Electrical Energy Consumption and 24h Running Cost of eHome2 heating system under a SAP heating pattern

- Thermaskirt cheaper running cost but failed to achieve setpoint in sap heating pattern.
    - Severely under achieved in -5 tests

Curv achieved temps closer to setpoint however still did not achieve.

7.6 System Energy Efficiency Indicator (SEEI)

The below plots show the SEEI for each system tested. This has been defined in Section 6.3.1.

7.6.1 TFH

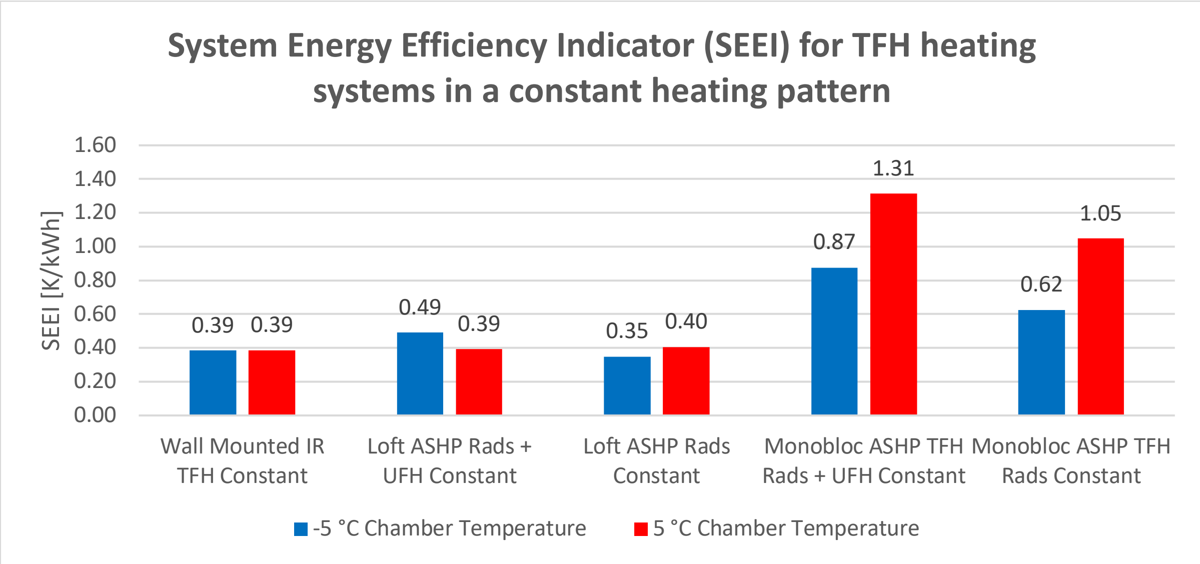


Figure 160. System Energy Efficiency Indicator (SEEI) for TFH heating system in a constant heating pattern

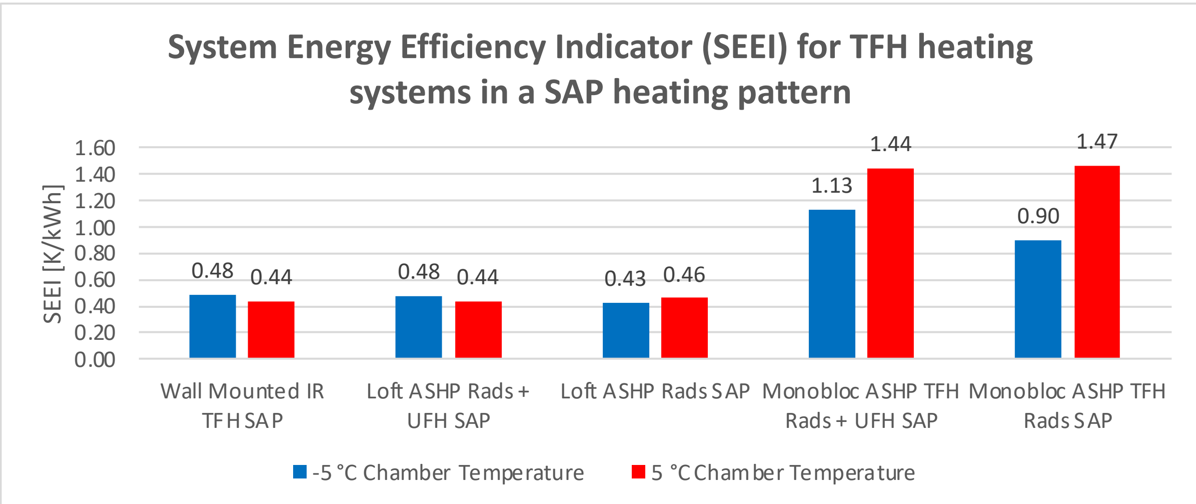


Figure 161. System Energy Efficiency Indicator (SEEI) for TFH heating system in a SAP heating pattern

7.6.2 eHome2

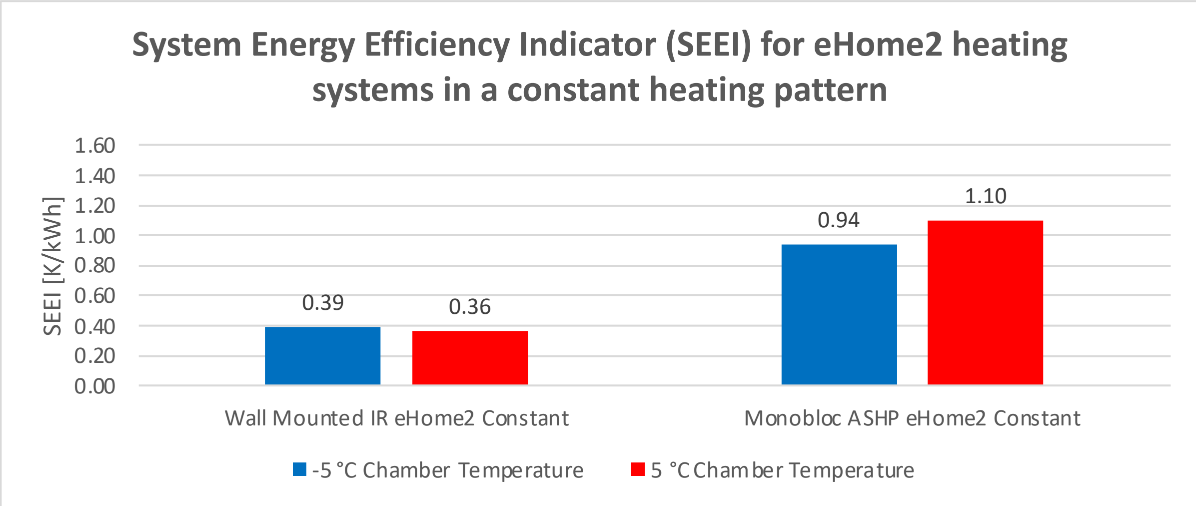


Figure 162. System Energy Efficiency Indicator (SEEI) for eHome2 heating system in a constant heating pattern

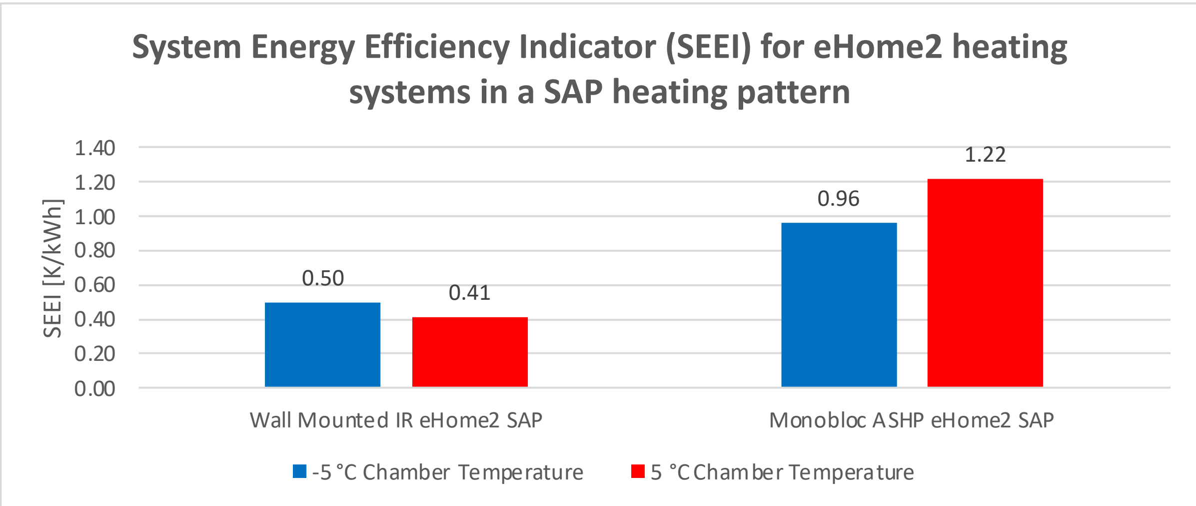


Figure 163. System Energy Efficiency Indicator (SEEI) for eHome2 heating system in a SAP heating pattern

7.7 Limitations of Research

All research has limitations, this work included tests from over six months testing, there were some issues around data collection and climatic conditions that are detailed below. These should not detract from any of the results are included for the sake of transparency.

7.7.1 Energy Data

- A small portion of minutely data monitoring systems was corrupted for the following test:
    - TFH -5 °C Loft ASHP Rads + UFH Constant

We used the following procedure to allow us to use our "Total hourly data" as a suitable substitute.

- A baseline energy consumption was measured for periods without heating
- This baseline was used to disaggregate the heating system energy consumption from the rest of house energy consumption (including appliances, measurement equipment, ventilation and control circuits).
- This baseline was verified over a period of 3 days experimentally for each test which was affected.

7.7.2 Soil Temperatures

The subsoil temperatures at 600 mm below the underside of the ground floor slab, at the centre of each house was recorded at minute intervals, the average temperature for each test is shown below. We see little variation in the 5 °C tests, but more so in the -5 °C tests. This is due to the fact that some tests had to be repeated, at the end of the test schedule, due to equipment failure, and as the chamber cools for a long period of time the ground temperature also naturally falls. We see the greatest deviation away from the mean, in tests that do not involve underfloor heating, and thus would be most affected, so this should not detract from any results.

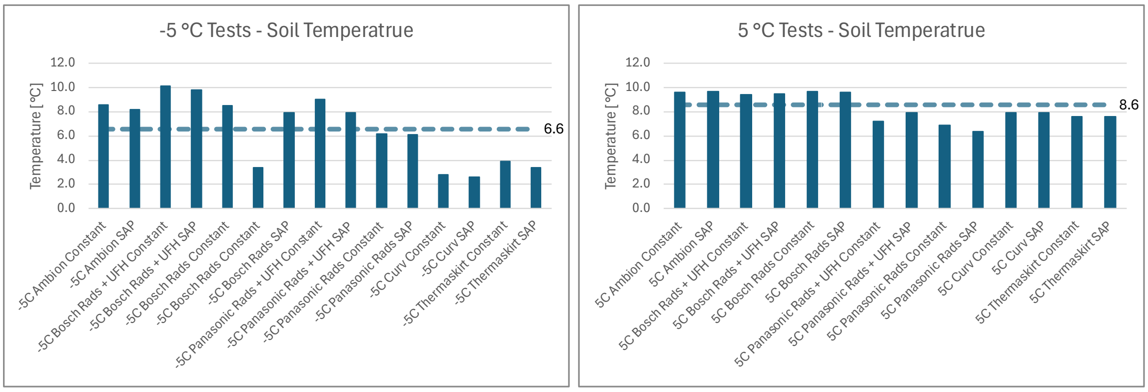


Figure 164. Soil Temperatures in -5 °C and 5 °C tests

- Range during -5 °C Chamber Tests : ±3.75 °C / Average = 6.6 °C
- Range during 5 °C Chamber Test: ± 1.65 °C / Average = 8.6 °C

7.7.3 Relative Humidity (RH)

Relative humidity is collected at 28 locations throughout the chamber, the average value is shown below. The 5°C tests are all within a range of 76% - 84%, this is an acceptable level given the length of the testing period. RH is much more difficult to control at sub-zero °C temperatures. We see a broader range here of 71% – 83%. It is difficult to quantify the effect that this will have on the ASHP in particular. This will be the focus of one of our future research projects. However, the tests with the slightly elevated RH coincide with the full round of testing of the Monobloc ASHP in TFH. As such this does not affect the results across the piece. It does however mean that the COP for this unit may have been affected. This is backed up by other experimental literature (Sahin and Adiguzel, 2022).

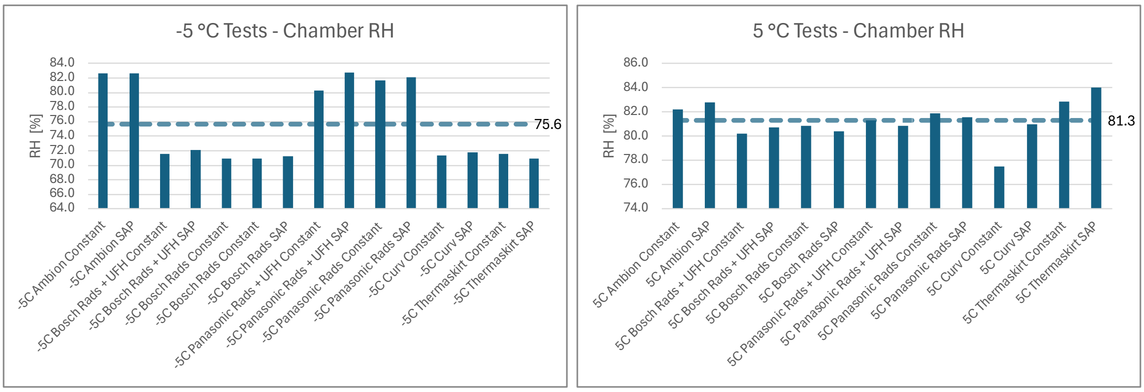


Figure 165. Chamber Humidity in -5 °C and 5 °C tests

- Range during -5 °C Chamber Tests : ±5.95% / Average = 75.6%
- Range during 5 °C Chamber Test: ± 3.25 % / Average = 81.3%

7.7.4 Chamber Temperature

Chamber temperature is measured at 28 locations throughout the chamber. The variation at both testing temperatures was minimal, as shown below.

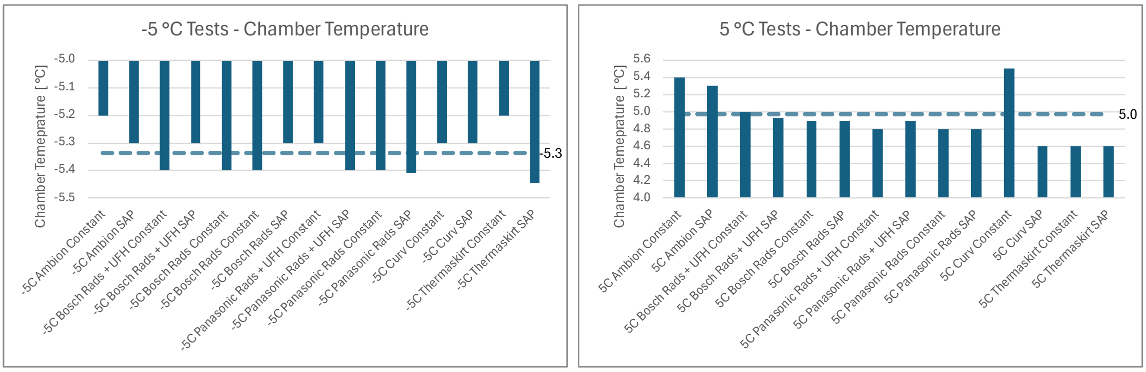


Figure 166. Chamber Temperatures in -5 °C and 5 °C tests

- Range during -5 °C Chamber Tests : ±0.10°C / Average = -5.3 °C
- Range during 5 °C Chamber Test: ± 0.45 °C / Average = 5.0 °C

7.7.5 Sensor Location

Every effort was taken to ensure the sensors were returned to the exact same positions between tests, including the use of a pre-test checklist routine. However, in the case of "TFH 5 °C Monobloc ASHP TFH Rads SAP", the black globe sensor located in the Hall was displaced closer to the heat emitter. This only affects the operative temperature measurements, which have been disregarded in our commentary in the Systems Performance (Section 7.1).

8. Discussion

8.1 System Summary

8.1.1 Infrared Heaters

Two products were tested; the Ambion wall mounted product (TFH), and the Curv wall mounted product (eHome2).

Occupant Comfort

When in a constant heating pattern, a homogenous air temperature distribution is observed, with the warmest areas being closest to the emitters and little variation between the operative and air temperatures (TFH).

In an SAP heating pattern, there is significant temperature stratification, with overheating occurring near the infrared (IR) panels. The operative temperature is often greater than the air temperature, as observed in the case of the eHome2 setup. In some rooms, the system failed to achieve the setpoint, particularly when the chamber temperature was -5 °C and during the 2-hour morning period. At -5 °C, none of the rooms reached the desired temperature. While the constant heating pattern was closer to the setpoint, the SAP pattern showed a noticeable difference.

Responsiveness

In general, the IR systems installed in both properties had the fastest heat up rate.

Running Cost

Of all the systems tested in both properties, IR had the greatest energy consumption and running costs. The had the lowest SEEI when compared to all other technologies, indicating a higher running cost than the ASHP technologies.

Installation and Commissioning

Low installation and up-front costs, with very little commissioning required. The IR panels can be easily linked with smart systems for control.

Design

During the -5 °C, in SAP, system appeared under-designed. Whereas in a constant heating pattern, it could generally achieve setpoint.

8.1.2 ASHP – Monobloc

Two Monobloc ASHPs were studied; a Panasonic (TFH), and a Vaillant (eHome2). These were both connected to three different heat emitters, which will be addressed in Section 8.1.4. The COPs of these systems were measured between 1.7-3.7.

Running Cost

Of all the systems tested in both properties, Monobloc ASHPs had the lowest energy consumption and running costs. They had the greatest SEEI when compared to all other technologies, indicating a lower running cost than the other technologies.

Installation and Commissioning

The report highlights several issues with the installation and commissioning. These include:

- Product substitution
- Poor standards of insulation
- Poor labelling

Design

During the -5 °C test, in SAP heating pattern the system appeared under-designed. Whereas in constant, it generally achieved the required setpoint. This is likely a result of the emitter design.

8.1.3 ASHP – Split/Roof

Worcester Bosch provided a split roof mounted system in TFH, which was an R+D prototype system, this was not connected the control system in the TFH. This should be viewed as prototype test setup, in which high COPs were not expected to be delivered.

Running Cost

The Split ASHP systems had the lowest COP of the ASHP's tested, ranging between 1.0-1.4. Greatest SEEI when compared to all other technologies, indicating a lower running cost than the other technologies.

Installation and Commissioning

The report highlights several issues with the installation and commissioning. These include:

- Product substitution/missing
- Poor design and justification of components
- Non-compliant installations
- Appeared to be resorting to backup heater for heat demand

It's important to note this is an R+D system, and the level of information available is not comparable to the other systems tested within this research.

Design

During the -5 °C, in SAP, system appeared under-designed. Whereas in constant, it could generally achieve setpoint. This is likely a result of the emitter design.

8.1.4 Wet Heating Emitters

8.1.4.1 Radiators

We tested the radiators in multiple configurations. In TFH, radiators were tested with both the monobloc and split ASHP system, both in a radiator only and radiator + UFH configurations. Within eHome2, radiators were used in rooms where a discrete heat solution would not have been feasible (e.g. the Hall, Bathroom, WC & Ensuite).

Occupant Comfort

In a constant heating pattern, the air temperature distribution was homogenous, with the warmest areas being closest to the radiators. The system exhibited low levels of hysteresis, though the WC experienced overheating in the eHome2 setup.

In a SAP heating pattern, the system struggled to achieve the setpoint at -5 °C, and the Living Room failed to reach the setpoint during the 5 °C test. Overall, there was insufficient heating to meet the setpoint, but when the setpoint was reached, temperature control was generally good.

Responsiveness

Heat up rate varied between heating systems used with the emitters.

Running Cost

Using radiators only tended to increase running costs of the ASHP when compared to the radiators + UFH tests. Using radiators **only** tended to reduce the SEEI of the ASHP when compared to the radiators + UFH tests.

Installation and Commissioning

Radiators in this system are designed to operate efficiently down to temperatures as low as –5 °C. However, balancing the system is essential to ensure even heat distribution across all radiators. One challenge identified is that the radiators do not have enough surface area to emit the required amount of heat effectively. Additionally, there is a potential issue with microzoning, particularly when Thermostatic Radiator Valves (TRVs) are used, as they may lead to inconsistent temperatures across different zones of the system.

Design

During SAP tests, system appeared under-designed in some rooms, due to long heat up rates or failure to achieve setpoint. Whereas in constant, it could generally achieve setpoint.

8.1.4.2 Discrete Heat

Summary

Discrete heat was tested withing eHome2, connected to a Vaillant monobloc ASHP, with COPs ranging between 2.3-2.9.

Occupant Comfort

In a constant heating pattern, the Living Room was underheated during the -5 °C test, with warmer temperatures observed around the perimeter of the room. Overall, the system exhibited generally low levels of hysteresis.

In a SAP heating pattern, there was significant underheating in all rooms during the -5 °C test. The Living Room, in particular, showed notable underheating in both the -5 °C and 5 °C tests. However, temperature control was generally good when the setpoint was achieved.

Responsiveness

Heat up rates were generally slow when compared to other systems.

Running Cost

Low running costs within eHome2 when compared to the IR panel heaters.
Greater SEEI when compared to IR heaters with eHome2.

Installation and Commissioning

Visually unintrusive design, and relatively easy install process. The system also has in built TRV to allow for a complete system installation, and having no external requirements for extra controls.

Design

Significant levels if underheating at -5 °C using the SAP heating profile suggests under design, possibly stemming from the heat output figure used by the heating designer. In the constant heating pattern at -5 °C, all rooms, with the exception of the Living Room, achieved setpoint temperature. The Kitchen/Diner utilised the larger 170 mm profile which suggests this may have been more appropriate for the Living Room as well, although this requires further clarification.

8.1.4.3 Under Floor Heating

Underfloor heating was tested in only the downstairs of TFH, with radiators installed for heating upstairs. The COP was measured between 1.2-3.7, depending on the ASHP used.

Occupant Comfort

The constant heating pattern resulted in a homogenous air temperature distribution with low levels of hysteresis.

In a SAP heating pattern, the temperature distribution was generally homogenous. However, the Living Room struggled to reach the setpoint. When the setpoint was achieved, the system demonstrated good temperature control.

Responsiveness

Slower heat up rates when compared to other systems tested in TFH. However, it should be noted that the temperature did not fall as much outside the heating periods.

Running Cost

Lower running costs when compared to tests using radiators only, and greater SEEI when compared to these same tests.

Installation and Commissioning

Low installation and up-front costs, with little commissioning required. The IR panels can be easily linked with smart systems for control.

The installation process of UHF can be more involved than that required traditional radiators. Space, access and power requirements also exist for the UFH manifold. However, in TFH this allows for controls to be added by systems such as the Honeywell system.

Design

It would appear the UFH systems were the most appropriately sized throughout the tests.

8.2 System observations

This section will examine some of the issues found by the research team, in terms of design, performance and other issues. It should be noted that these are only observations, and some basic observations, this will not be exhaustive, nor are the research team qualified to make design/installation decisions.

8.2.1 eHome2

8.2.1.1 Heat Pump Installation

- The property has been fitted with a Vaillant aroTHERM Plus 5kW Monoblock ASHP, in line with the initial specifications, with all protection zones observed.
- To safeguard against freezing, a glycol mixture, presumed to be an aqueous solution of monopropylene glycol, was utilized to protect the heat pump and external pipework. Upon testing, the concentration was found to be approximately 21%, offering protection down to approximately -7.8 °C. Even when tested at -20 °C, the solution only achieved a 'firm slush' state, indicating minimal risk of pipe or component failure. Notably, glycol has a lower Specific Heat Capacity (SHC) than water, roughly around 4009 J/kg.K (@45 °C), and possesses higher kinematic viscosity than water, necessitating additional electrical energy for medium transport.
- It was observed that there are additional labels affixed to the domestic hot water cylinder suggesting a mixture of other chemicals in the system, the effects of which remain unknown, it is not known what affects these will have, in particular with the glycol mixture, if any.
- The external primary pipework leading to the heat pump has been installed using copper and connected to the heat pump through flexible hoses, a method used to mitigate vibrations as recommended by the manufacturer. However, there are notable shortcomings in the insulation of the external pipework. The insulation application has been poorly installed, leaving sections of the pipe exposed and unsealed, allowing water ingress (Figure 167). Additionally, inadequate insulation coverage on the valves has resulted in parts of the brassware being exposed. The heat pump data cable (eBUS) has been installed using heat proof flex, which appears unsuitable for external usage.

8.2.1.2 Hydronic Separation and Zoning

- Contrary to the original design which included a buffer, no hydronic separation has been installed to the system, a 15 L volumiser has replaced the buffer presumably to add system volume.
- As well as the volumiser assisting with the defrost function by increasing system volume and available energy, an increased system volume would also help prevent excessive cycling of the heat pump. However, the volumiser is completely uninsulated and appears to be a repurposed solar thermal cooling station, this uninsulated body of liquid will ultimately become an unneeded emitter that will overheat its environment and increase heat loss (Figure 170)
- The property has been split into multiple micro zones as per the design specification, in practice this is causing very low flow rates often below the minimum specifications through the ASHP when zones are de-energised and resulting in increased cycling at times. This however we understand was put in place to allow for the researchers to create distinct zones in each room as required under SAP.
- The filling loop has been left in place, which is not good practice, this should be removed (Figure 169).

8.2.1.3 Thermaskirt emitters

- Thermaskirt appears to have been installed to the design specification.
- The ThermaSkirt system appears to be intermittently generating sound, potentially due to high velocity water at certain times passing through the control TRV valves or air in the system. This suggest alternatives such as open loop or manifold control may need to be considered as well as improvements around design and commissioning.

8.2.1.4 eHome2 Images

Figure 167. Poor insulation practice externally to the ASHP flow & return pipes

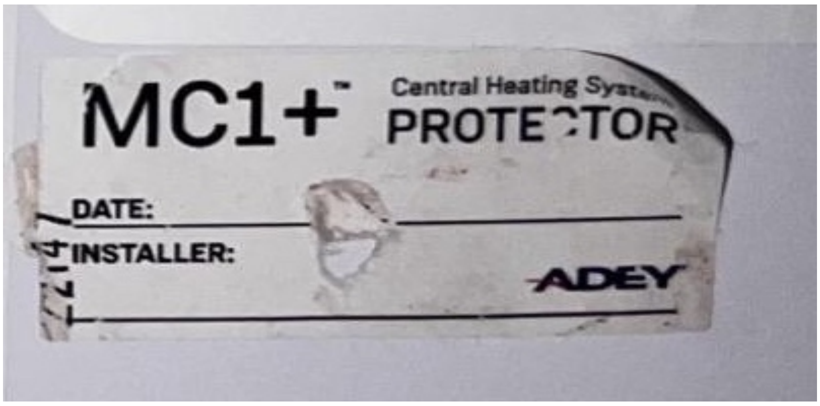


Figure 168. Labels showing the likelihood of various chemicals in the system as well as glycol.

Figure 169. Filling loop should be removed post installation to avoid any possible cross-contamination

Figure 170. Uninsulated volumizer/solar safety vessel

8.2.2 TFH

The indoor unit has been installed close to the external unit, in the loft space. The loft location can make the control interface difficult to access (Figure 171). Also, the Hydrotop unit is not possible to open without dismantling the unit (Figure 171).

Figure 171. Indoor and outdoor unit located in roof space

No Thermostatic Mixing Valve (TMV) protection has been fitted to the cylinder outlet to protect the occupier during any high-temperature sterilisation cycles, this will happen on a weekly basis, and if water is drawn at this point in time, then it could present a hazard (Figure 172).

Figure 172. Cylinder without TMV protection

A buffer vessel has been installed, which will decouple the ASHP internal hydronics with that of the property emitters (Figure 173). No detailed design principle or reasoning for this has been documented in the design package, and may affect the performance of the Panasonic ASHP. A DAB VS 65150-3 Evo fixed speed circulator distributes post-buffer energy around the emitters (Figure 173). This circulator does not comply with the 2013 Energy Related Products (ErP).

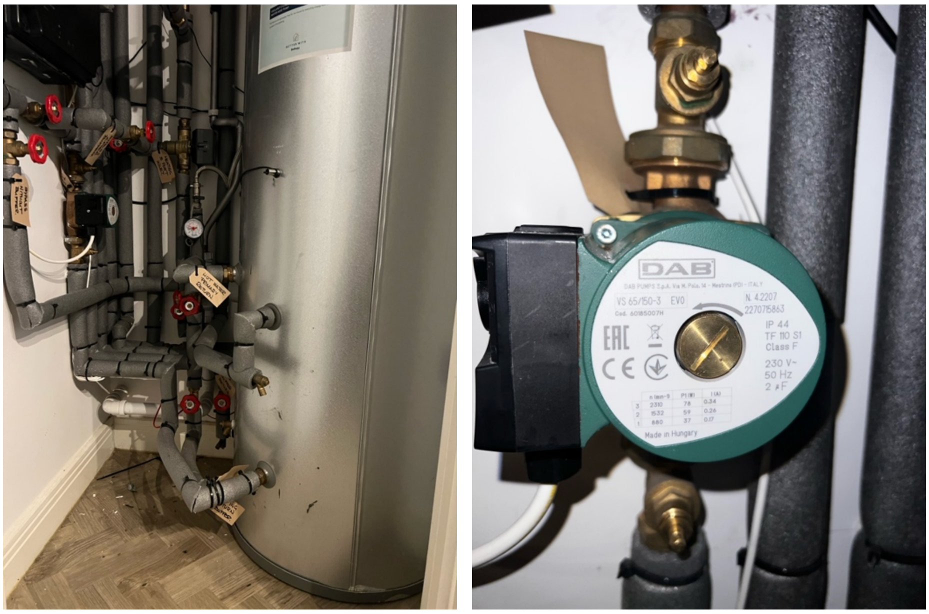


Figure 173. Buffer vessel and circulation pump

Further unnecessary hydronic and temperature-limiting components installed within the system are the UFH mixing valve (Figure 174) and additional circulation pump (Figure 174) which are fitted to the manifold. Again, no detailed design principle or reasoning for this has been documented in the design package; this configuration adds complications to the heating design when not required, brings additional parasitic energy consumption, inflates installation costs, and negatively impacts the performance of the Panasonic ASHP.

Figure 174. Additional circulation pump

A HydroTop containment assembly designed to facilitate the housing of the outdoor unit has been installed in the loft space, with the outdoor unit taking airflow over the evaporator from outside through ducting. Provisions to dispose of melted ice and water from the unit defrost cycles have been made by installing a waste pipe into the property wastewater system. This pipe remains unprotected from frost in some critical regions outside of the property thermal envelope. Also, it acts as a discharge pipe (Figure 175) for the pressure relief for the heating system; the acoustics of water running down the pipework above the sleeping areas during defrost cycles have yet to be tested but should be considered.


Figure 175. Waste pipe to dispose condensate located in the roof space

The unit is not influenced by the internal Honeywell Home thermostat, and consequently, the heat pump operates entirely independently from the dwelling. This does not comply with the current Building Regulations AD Part L 5.15 (MHCLG, 2023), which states that "*system controls* *should be wired so that when there is no demand for space heating or hot water, the heating appliance and pump are switched off*.

Water has been used as the transfer medium for both the Panasonic and Worcester Bosch heat pumps; this will carry some benefits attributing to the system efficiency due to the Specific Heat Capacity (SHC) and low viscosity of water as opposed to glycol but will also bring some inherent risks around freezing.

In the event of a system failure or power disruption, the Panasonic unit has a higher risk of frost damage under certain environmental conditions, due to its outdoor location. To help mitigate this risk, 2 no. Caleffi 108 series antifreeze valves (AFV) (Figure 176) have been installed close to the unit. If the water temperature within the pipework drops below 3 °C, the valves will open, allowing water to leave the system; this will attempt to empty the unit condenser enough to avoid frost damage; the heating system will need to be manually refilled and vented before further operation which can be a problem for less able occupiers. The manufacturer of the selected AFV requests that for reliable operation, the valves should be installed and left uninsulated; this does not comply with Building Regulations AD Part L Section 4.24 (MHCLG, 2023).

> *"Hot water and heating pipework. In a new system, all of the following new pipework should be insulated; A) Primary circulation pipes for heating circuits where they pass outside the heated living space, including where pipework passes into voids"*

The filling loop has been left in place, which is not good practice, this should be removed (Figure 176).

Figure 176. Left) Caleffi 108 series antifreeze valves. Right) Filling loop left in place

9. Summary

TFH

ASHP

- At 5 °C, in terms of SEEI, it was found that the most efficient setup was the Monobloc ASHP with radiators and underfloor heating in a constant heating pattern. When we consider a SAP heating pattern, the Monobloc ASHP with radiators was most efficient.
- At -5 °C, in terms of SEEI, the most efficient was Monobloc ASHP with radiators and underfloor heating in both the SAP and constant heating pattern.
- When we compare the Loft ASHP to the Monobloc, in terms of SEEI, the loft ASHP performed considerably worse; with Loft ASHP ranging from 0.44-0.48 K/kWh in constant heating, and 0.35-0.39 K/kWh in an SAP pattern.

- Loft ASHP tended to have the lowest COP, ranging between 1.0-1.4 across all tests. The monobloc system COP ranged from 1.1-3.6 across all tests. Chamber temperature and emitter type had little influence of the COP of the loft ASHP, this may result from its dependence on the backup heater.

- At -5 °C, heat up rates varied between 0.46-1.24 °C/hour, with the IR system had the fastest heat up rate of 1.25 °C/hour. At 5 °C, heat up rates varied between 0.03-0.97 °C/hour, with the fastest being Loft ASHP Rads. It should be noted that the 0.03 °C/hour figure results from little temperature drop outside of the heating period, which affected the calculation.

Monobloc ASHP

- At -5 °C
  - Rads + UFH
    - Constant. When using radiators and UFH, in a constant heating pattern there was a minor overshoot in the Living Room, and an overshoot of ~4 °C in the WC, generally low hysteresis. Setpoint achieved in all rooms.
    - SAP. When in an SAP pattern, there was an overshoot of 2 °C in the Living Room, with poor control. Kitchen and Hall had an overshoot in the evening. All rooms failed to hit setpoint in the morning period, and for a substantial time in the evening period.
  - When using radiators throughout the property with a SAP heating pattern, all rooms failed to hit their setpoints, with some rooms reaching as low as 10 °C in the heating off periods.
  - In a constant pattern, LR failed to achieve setpoint. WC overheated slightly. All other rooms were in the region of the setpoint.
  - In summary, at -5 °C chamber temperature, the monobloc with only radiators was not able to heat the property sufficiently when following a SAP heating pattern.

- At 5 °C
    - Rads + UFH
        - When using radiators and UFH, in a SAP heating pattern, the Living Room overshot the setpoint in both heating periods, as did the WC and Hall. With the other rooms generally achieving setpoint.
        - In a constant heating pattern, WC and Hall overshot by ~2 °C. All other zones were within ~1 °C of setpoint, with a low hysteresis.
    - Rads
        - When using rads only in constant heating pattern, Living Room overheated by ~1 °C. All other rooms were within ~1 °C of setpoint. All rooms had a low level of hysteresis.
        - When is SAP pattern, Living Room failed to achieve setpoint in both heating periods by ~1 °C. WC and Hall exceed the setpoint by ~1-2 °C. All other rooms achieved setpoint with ~1 °C.

Loft ASHP

- At -5 °C
    - The ASHP had to revert to the backup heater for a large proportion of the test, which could affect the COP.
    - Rads + UFH
        - During the Constant heating pattern test, the system had a low hysteresis. The Living Room achieved the setpoint temperature, alongside Bedroom 1 and 3, with a slight overshoot in the WC, Hall and Kitchen.
        - When following a SAP heating pattern, the Living Room failed to achieve setpoint in the morning period, and took five hours to achieve setpoint in the evening heating period. The Bathroom also failed to achieve setpoint in in the morning heating period and achieved setpoint only at the end of the evening heating period. WC, Kitchen and Hall all achieved setpoint in both heating periods. All other rooms failed to achieve setpoint in both heating periods. Outside of the heating periods, temperatures dropped to ~11 °C in some areas of the house.
    - Rads
        - During the SAP heating pattern, no rooms achieved setpoint temperature during the morning heating period. The Living Room failed to achieve setpoint in both the morning and evening heating periods. Only the WC, En-suite and Bathroom achieving setpoint during the evening heating period. Outside of the heating periods, temperatures dropped to ~11 °C in some areas of the house.
        - Under a constant heating pattern, the Living Room achieved setpoint temperature with low hysteresis. The WC overshot setpoint by only 1 °C. All other rooms achieved setpoint with a low hysteresis.

- At 5 °C
    - Rads + UFH
        - *Constant*. All rooms show low levels of hysteresis. Livingroom, Bedroom 3, Hall, WC and Landing all overheated between ~1.5-4.5 °C. All remain rooms achieved setpoint within ~0.5 °C.
        - *SAP*. Wide temperature distribution across the rooms (~7 °C). Control pattern difficult to understand. Living Room overshot the setpoint by ~2 °C in both heating periods. Bedroom 1, Bathroom and En-suite did not achieve setpoint in both heating periods. Bedroom 2 did not achieve setpoint during the morning heating period.
    - Rads
        - *Constant*. Living Room overshot the setpoint by ~1.2 °C. WC overheated, achieving ~21 °C with non-regular hysteresis. All other rooms were within ~1 °C of setpoint.
        - *SAP*. Living Room achieved setpoint in both morning and evening heating periods. WC overheated in both heating periods. Bedroom 3 did not achieve setpoint in either heating period.

IR

- The IR heating had a SEEI ranging from 0.39-0.44 K/kWh across both heating patterns and chamber temperatures, remaining relatively constant throughout all tests.
- At -5 °C, the WC and Bathroom achieved setpoint, all other rooms failed to achieve setpoint temperature, with heat distribution localised to where IR panels are located.
- At 5 °C, all rooms achieve setpoint temperature, with low hysteresis. Again, heat distribution localised to where IR panels are located.
- It should be noted that the WC overshot the setpoint temperature in both the -5 °C and 5 °C constant heating pattern tests.
- IR heating had the fastest heat up rate of all systems tested within TFH, with the exception of the 5 °C SAP test.

<u>eHome2</u>

Monobloc

Monobloc achieved the highest SEEI of the tests in eHome2, working better at the 5 °C chamber temperature than the -5 °C.

COP values ranged between 2.2-2.9 across all tests, with greater COPs achieved at 5 °C chamber temperature, and greatest value achieved during the 5 °C SAP test.

The IR heating system head the greatest heat up rates, ranging between 0.62-1.02 °C/hour. The Monobloc heated at rates of 0.38-0.69 °C/hour.

- At -5 °C
    - *Constant*. Livingroom underheated by ~3 °C. WC, Landing and Bedroom 2 overheated by ~1 °C. All other rooms were within ~0.5 °C of setpoint.
    - *SAP*. Living Room did not achieve setpoint, reaching a maximum of ~11 °C in the morning and ~12 °C in the evening heating periods. WC and Bathroom overshot the setpoint by ~1 °C in the evening heating period. All other rooms failed to achieve setpoint, with temperatures ranging between ~9-17 °C in the evening heating period.
- At 5 °C
    - *Constant*. Living Room overshot the setpoint by ~0.6 °C with little hysteresis. En-suite and WC overheated by ~1-2 °C. All other rooms achieved setpoint.
    - *SAP*. Living Room underheated, achieving ~11.6 °C in the morning, and ~ 19 °C in the evening. Bedroom 3 experienced a control anomaly, with no heat delivered after ~7pm. Bedroom 1 achieved setpoint at the end of the morning heating period, and after approx. four hours in the evening. Good control was achieved in the Kitchen. All other rooms overshot the setpoint.

IR

The IR system reaches is greatest SEEI at -5 °C chamber temperature, achieving 0.5 K/kWh in a SAP heating pattern. This is slightly reduced to 0.41 K/kWh at a 5 °C chamber temperature. In the constant heating mode, again, the efficiency is highest at -5 °C, reaching 0.39 K/kWh, reducing slightly to 0.36 K/kWh at 5 °C chamber temperature.

- At -5 °C
    - *Constant*. Under heating in the Living Room by ~ 2 °C. Bedroom 2 overheated by ~2 °C. All other rooms achieved setpoint within ~1 °C.
    - *SAP*. Living Room achieved a maximum temperature of ~12.7 °C in the morning, and ~14.6 °C in the evening. Both Bedroom 2 and Bathroom achieved their setpoint temperature, and WC achieved setpoint only at the end of the evening heating period. All other rooms failed to achieve setpoint, with temperatures ranging ~13.9—17.4 °C.
- At 5 °C
    - *Constant.* All rooms had low levels of hysteresis. En-suite and Bedroom 2 overshot the setpoint by ~ 1.5 °C. All other rooms achieved setpoint within ~1 °C.
    - *SAP.* Living Room failed to achieve setpoint by ~ 3 °C and ~1 °C respectively in the morning and evening heating periods. Kitchen failed to achieve setpoint in the morning heating period, and achieved setpoint in the evening within ~0.3 °C. Both Bedroom 2 and the Bathroom overshot the setpoint temperature. All other rooms achieved setpoint within ~2 °C.

9.1 Suggested Further Research

The main findings from this report suggest two shortcomings found in both homes; underheating in the extreme winter climate scenario, and some areas of missed opportunity around system efficiencies. The research team suggest the following further research to help address these shortcomings.

- **Effect of RH on ASHP Performance**
  - The chamber RH (~75-80%) throughout the ASHP testing, although typical in the UK, may have had an impact on the performance of the system, leading to more frequent defrost cycles. This may have had an impact on the system achieving internal setpoint temperatures. This cannot be confirmed within these results and would require further research.

- **TFH**
  - **Reconfigure buffer to volumizer** to examine possible changes in energy performance
  - **Remove surplus circulation pumps** to reduce parasitic load on the system, examine possible changes to system performance
  - **Experiment with different types of heating controls,** in particular with the loft mounted ASHP, which could significantly affect the energy performance of this system, which currently lacks sufficient control
  - **Optimal IR configuration** to examine how best to achieve homogenous temperature throughout rooms.
  - **Use of setback setpoints between SAP heating periods** to assess impact on ASHP heating provision and energy use

- **eHome2**
  - **Redesign and increase Thermaskirt emitter capacity** to increase heat output and reduce the risk of underheating
  - **Optimal IR configuration** to examine how best to achieve homogenous temperature throughout rooms.
  - **Insulate buffer** to examine possible changes in energy performance
  - **Use of setback setpoints between SAP heating periods** to assess impact on ASHP heating provision and energy use

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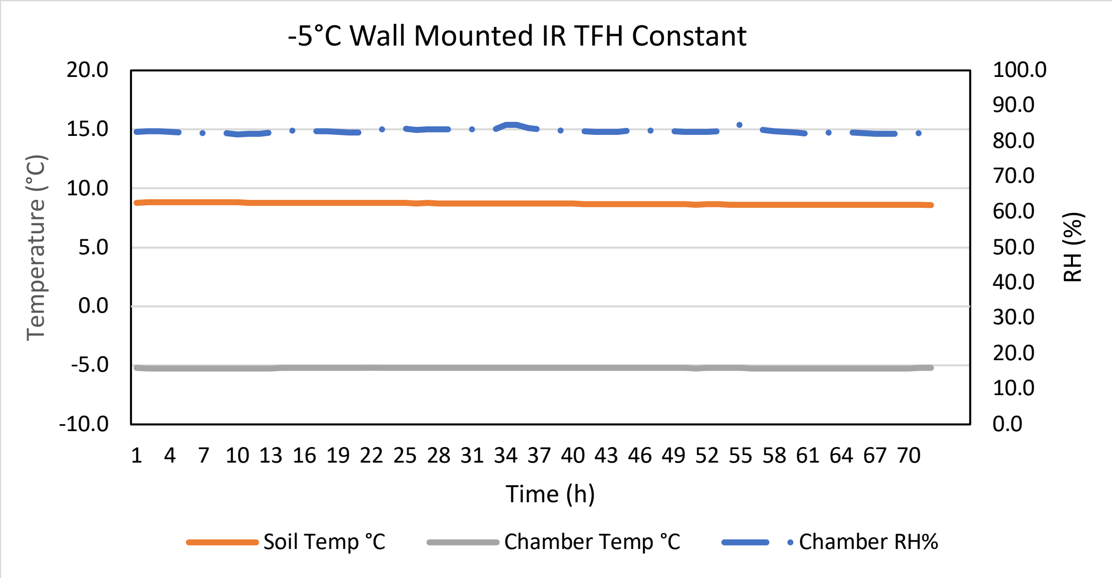
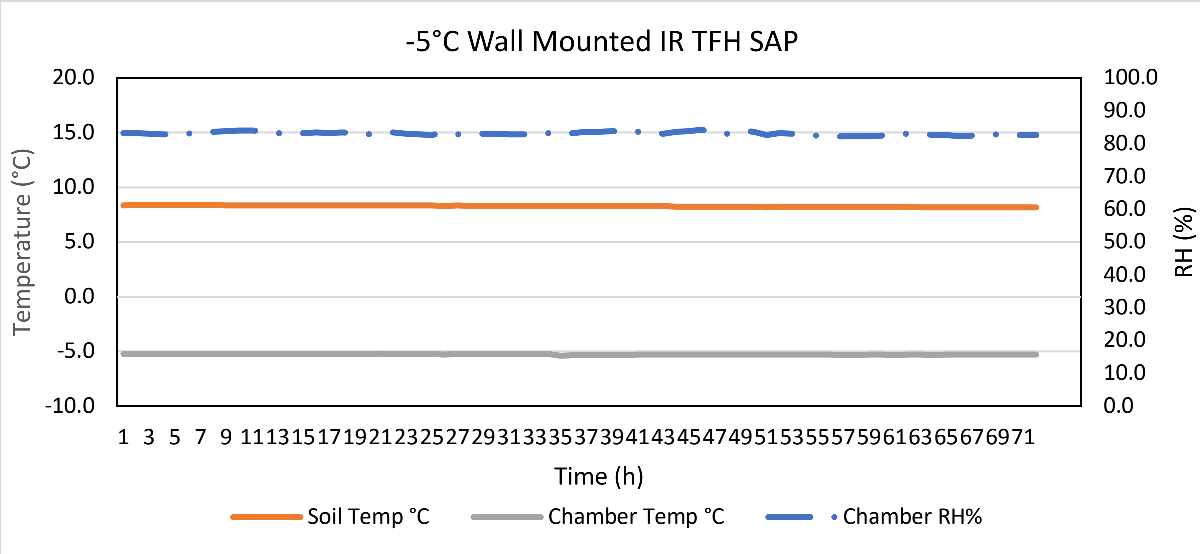
Appendix A – Chamber Climatic Conditions

-5°C Wall Mounted IR TFH Constant



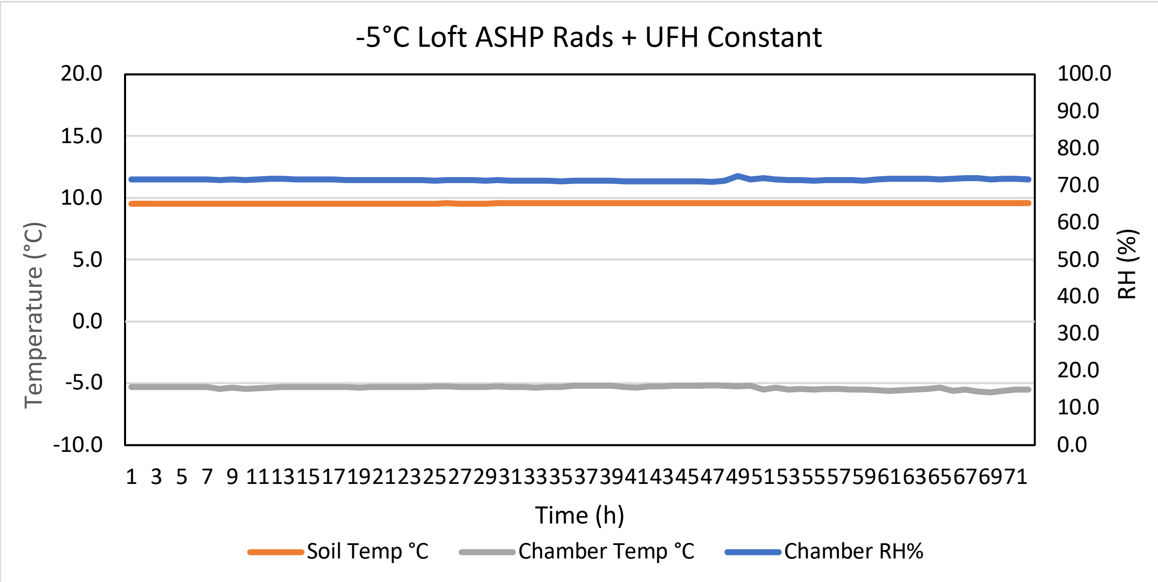
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	82.6	8.8	-5.2
2	83.2	8.7	-5.2
3	82.7	8.6	-5.2

-5°C Wall Mounted IR TFH SAP



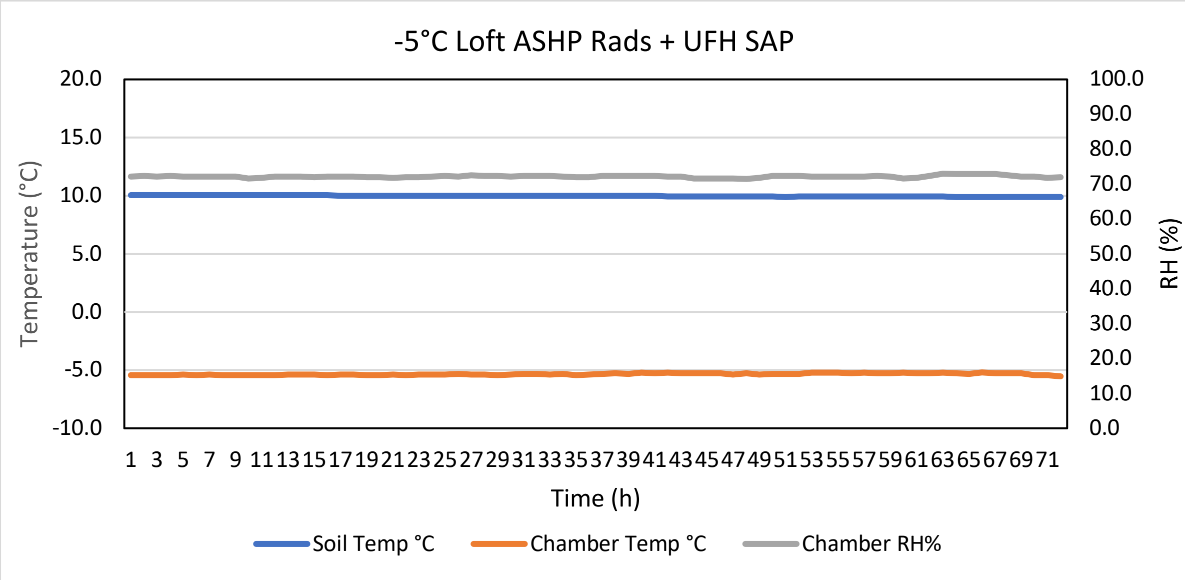
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	83.3	8.4	-5.2
2	83.2	8.3	-5.3
3	82.7	8.2	-5.3

-5°C Loft ASHP Rads + UFH Constant



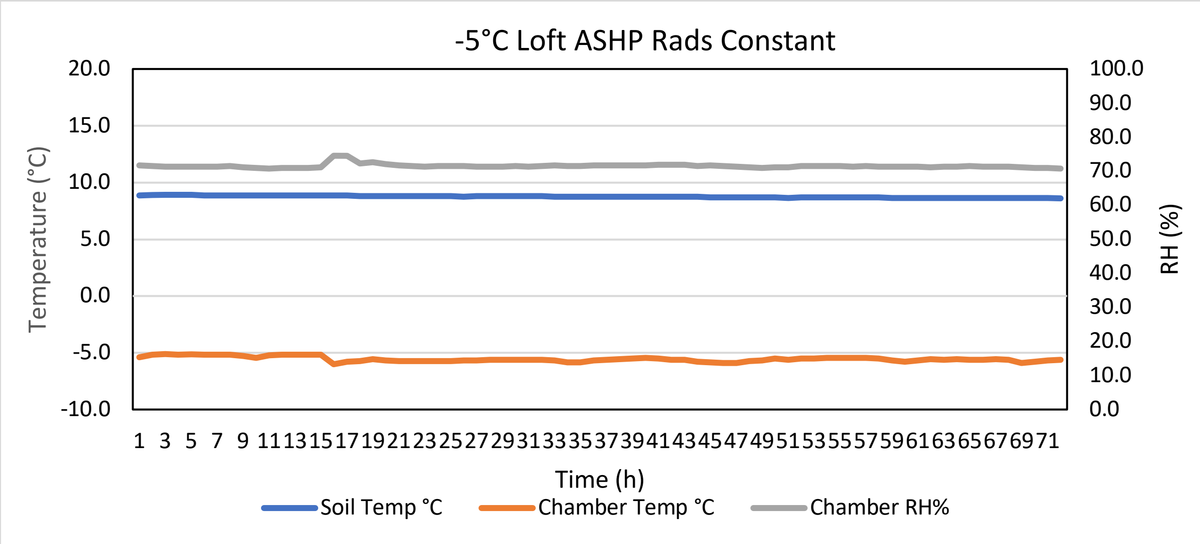
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	71.6	9.5	-5.3
2	71.3	9.6	-5.2
3	71.7	9.6	-5.5

-5°C Loft ASHP Rads + UFH SAP



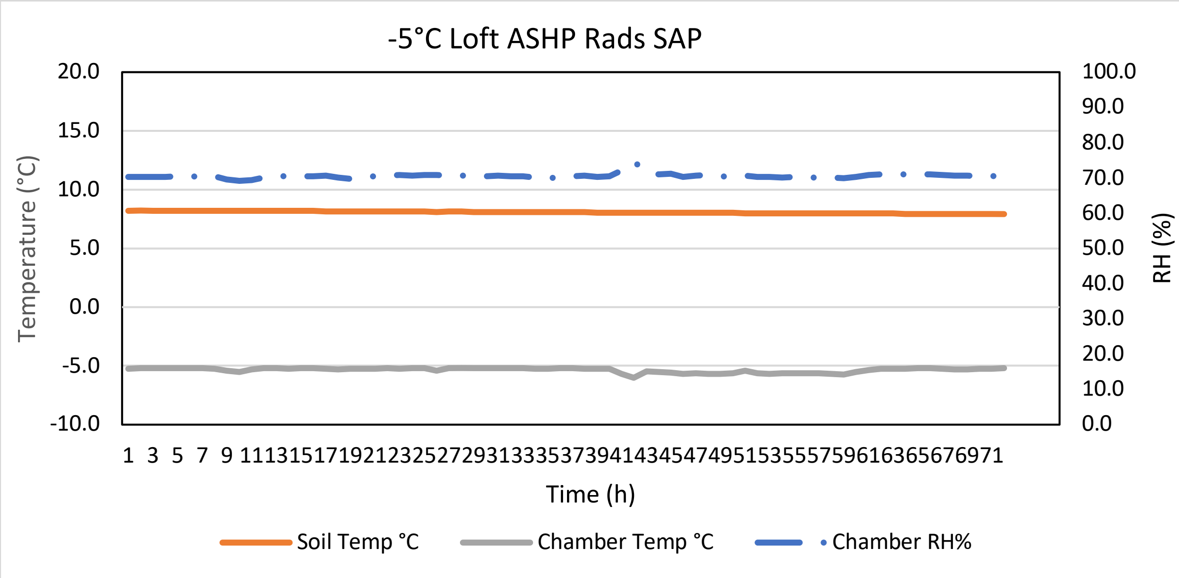
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	72.1	10.0	-5.4
2	72.1	10.0	-5.3
3	72.3	9.9	-5.3

-5°C Loft ASHP Rads Constant



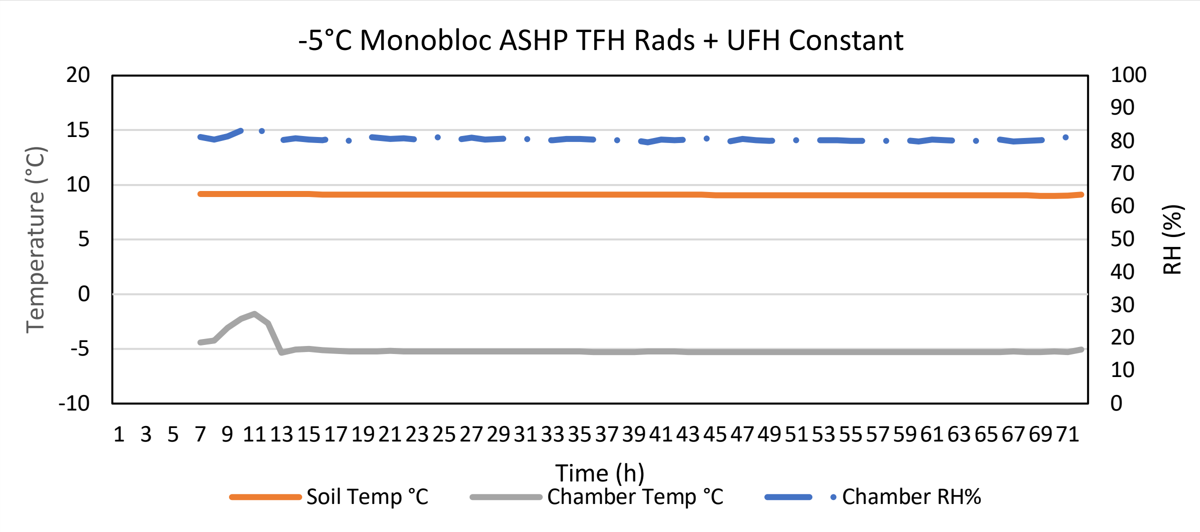
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	71.7	8.9	-5.4
2	71.6	8.8	-5.7
3	71.3	8.7	-5.6

-5°C Loft ASHP Rads SAP



24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	70.2	8.2	-5.2
2	70.8	8.1	-5.4
3	70.5	8.0	-5.4

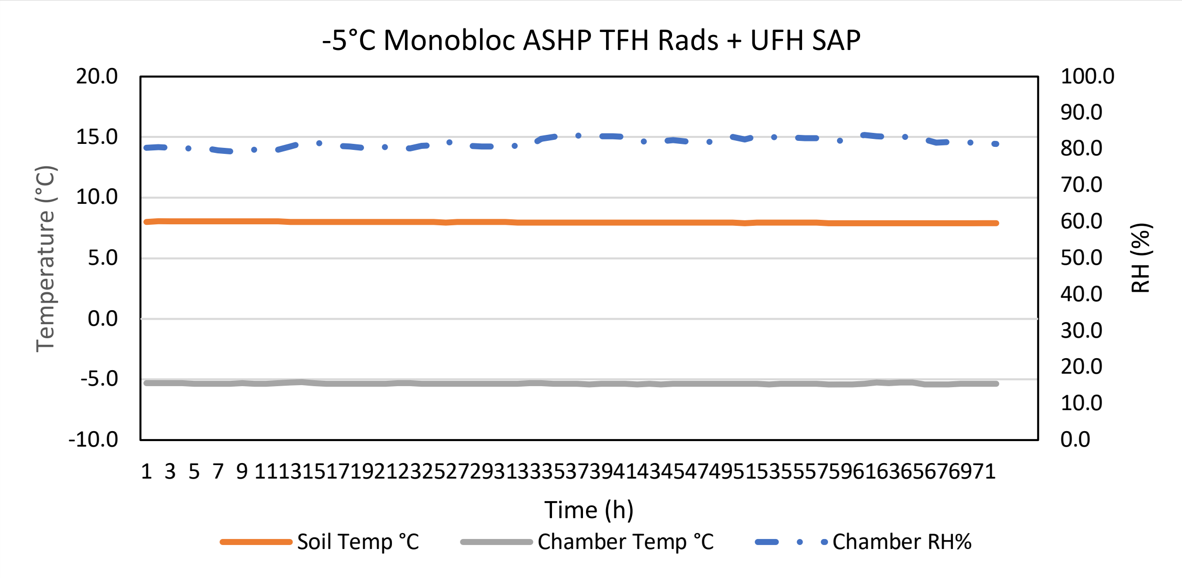
-5°C Monobloc ASHP TFH Rads + UFH Constant



24h Average			
Day	Chamber RH (%)	Soil Temperature (°C)	Chamber Temperature (°C)
1	81.2	9.1	-4.5
2	80.5	9.1	-5.3
3	80.3	9.0	-5.3

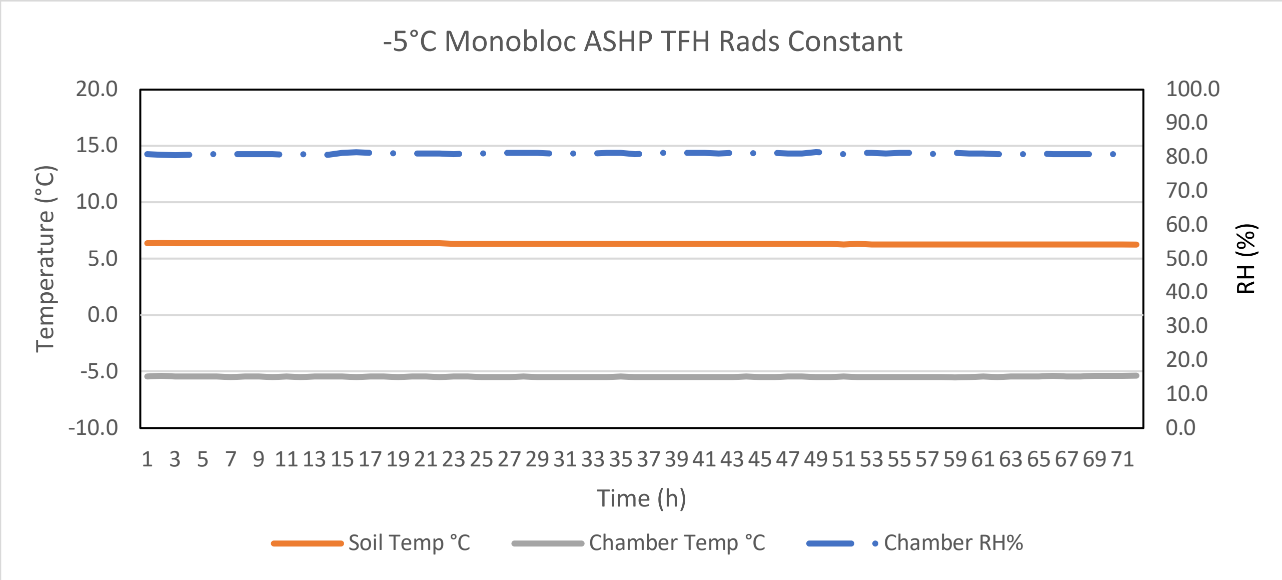
- Fluctuation in chamber temperature within the stabilisation period.

-5°C Monobloc ASHP TFH Rads + UFH SAP



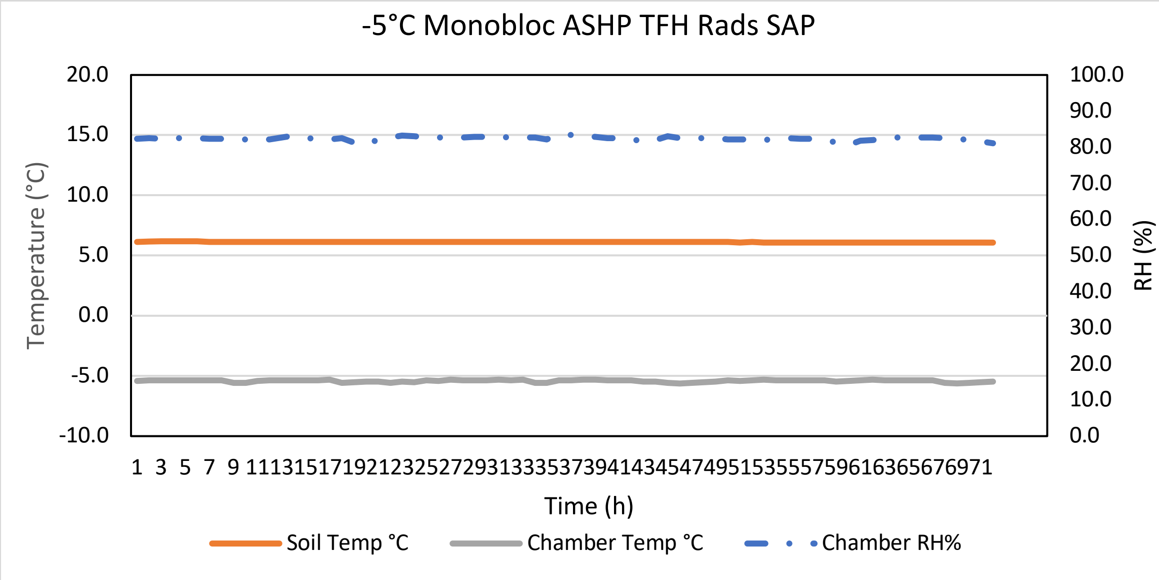
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	80.5	8.0	-5.3
2	82.2	8.0	-5.4
3	82.8	7.9	-5.4

-5°C Monobloc ASHP TFH Rads Constant



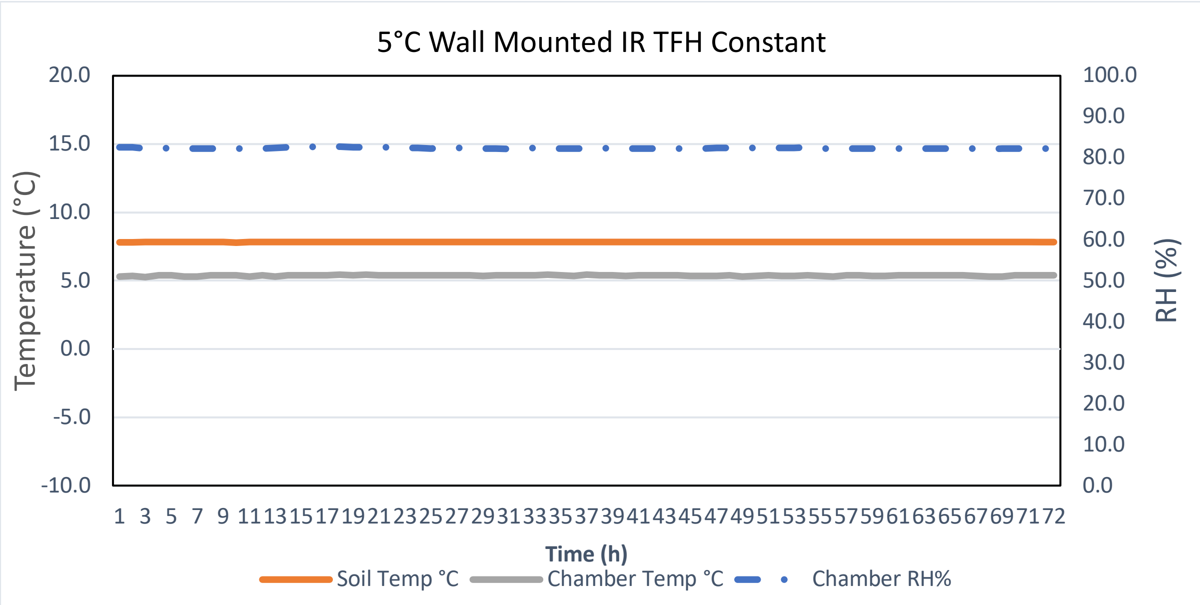
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	81.0	6.4	-5.4
2	81.2	6.3	-5.5
3	81.1	6.3	-5.4

-5°C Monobloc ASHP TFH Rads SAP



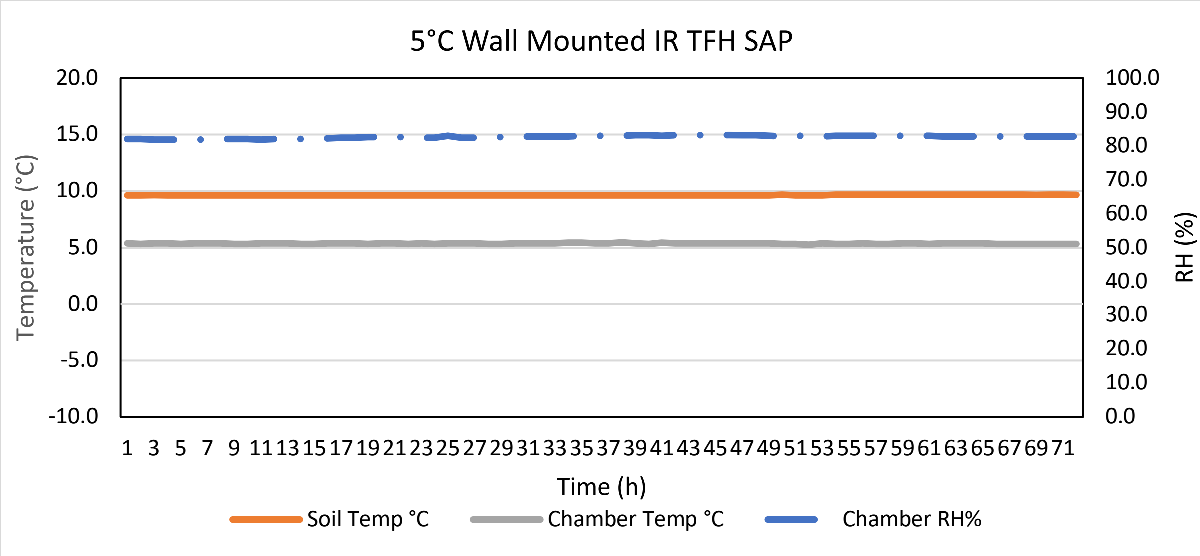
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	82.4	6.1	-5.4
2	82.6	6.1	-5.4
3	82.1	6.1	-5.4

5°C Wall Mounted IR TFH Constant



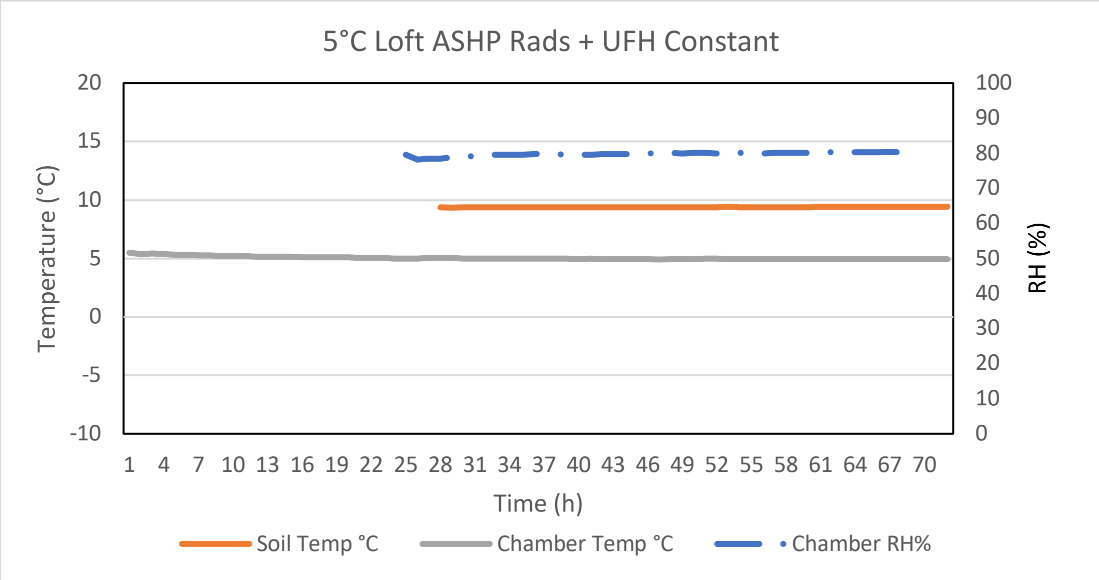
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	82.4	7.8	5.4
2	82.3	7.8	5.4
3	82.3	7.8	5.4

5°C Wall Mounted IR TFH SAP



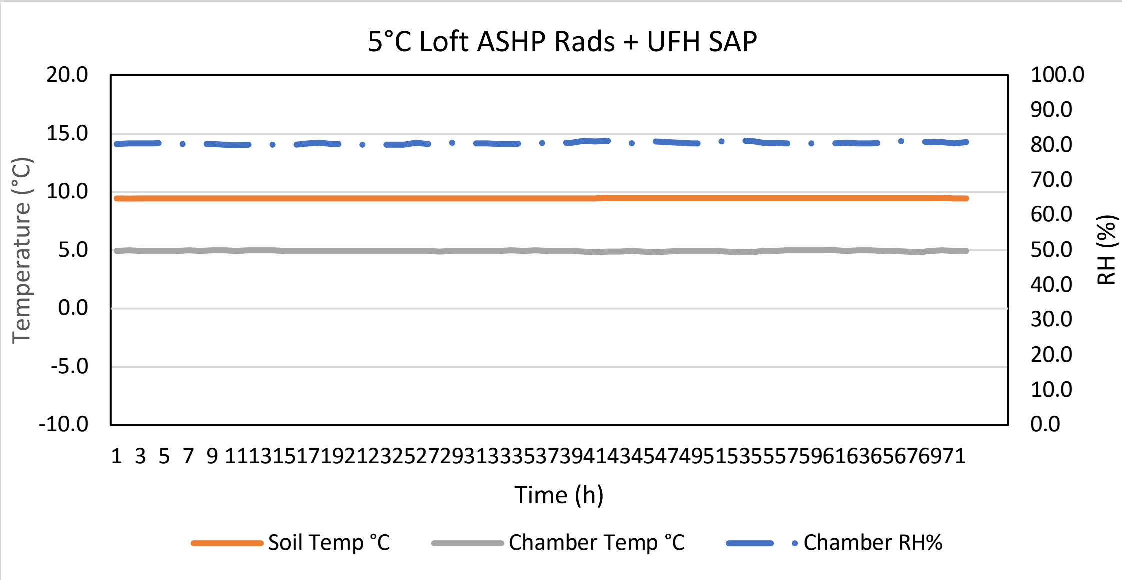
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	82.2	9.6	5.3
2	82.9	9.6	5.4
3	82.9	9.7	5.3

5°C Loft ASHP Rads + UFH Constant



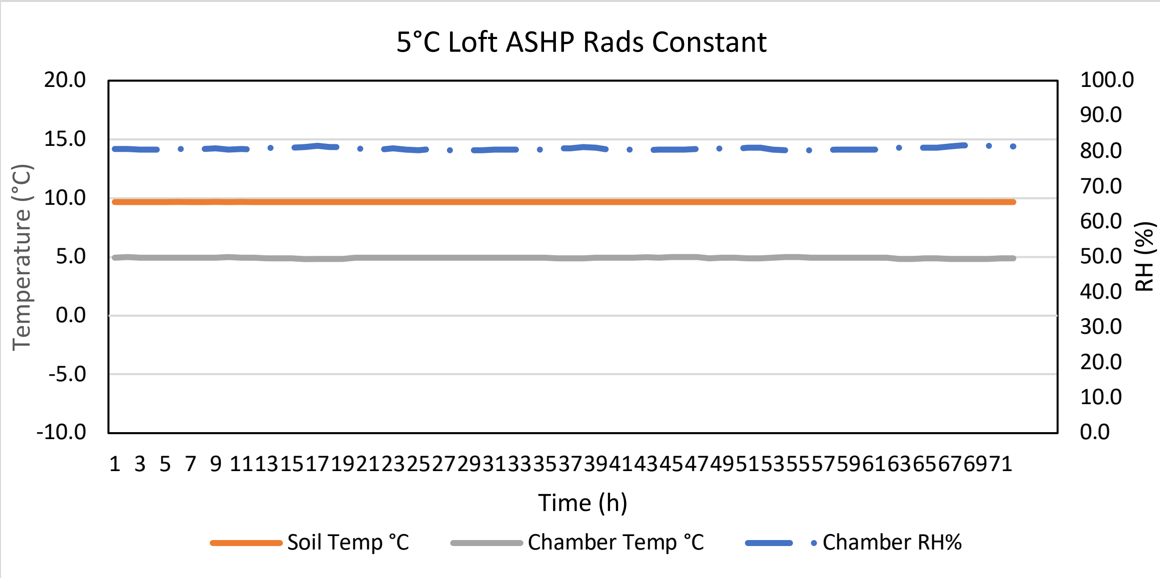
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	-	-	5.2
2	79.5	9.4	5.0
3	80.1	9.4	4.9

5°C Loft ASHP Rads + UFH SAP



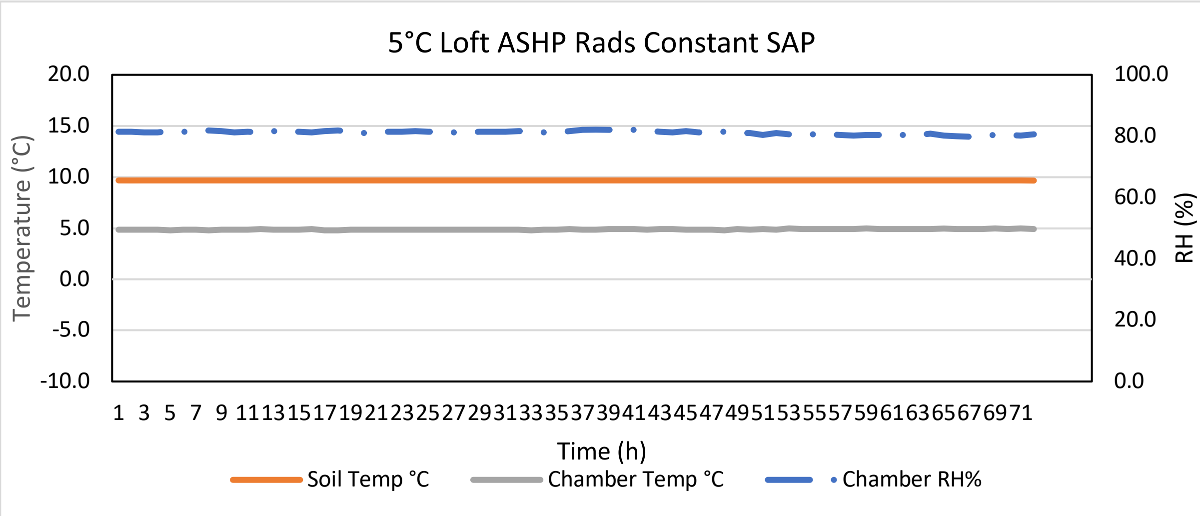
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	80.3	9.4	5.0
2	80.7	9.5	4.9
3	80.8	9.5	4.9

5°C Loft ASHP Rads Constant



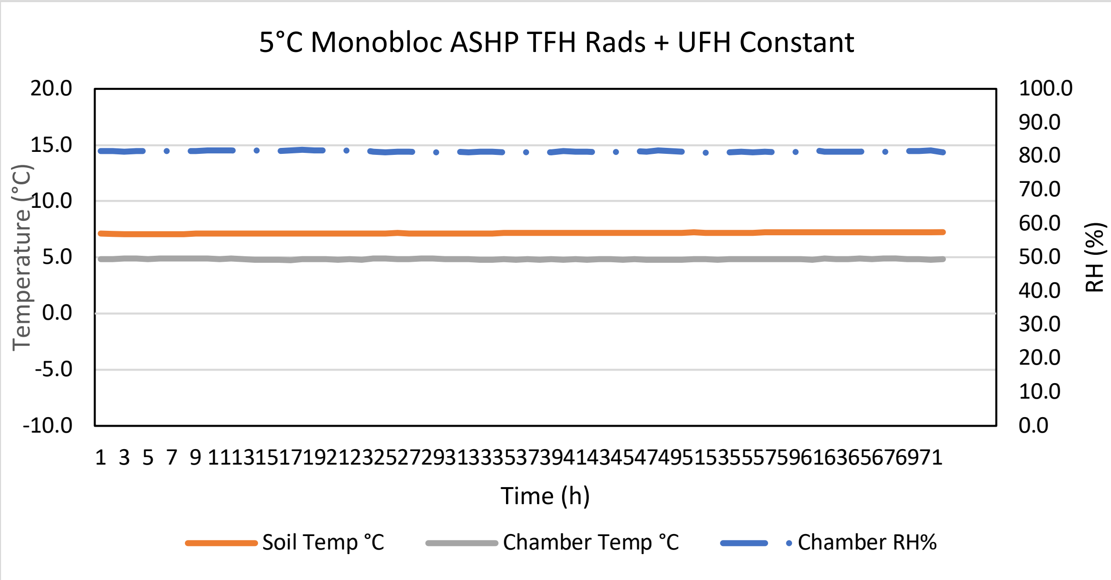
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	80.7	9.7	4.9
2	80.5	9.7	4.9
3	80.8	9.7	4.9

5°C Loft ASHP Rads SAP



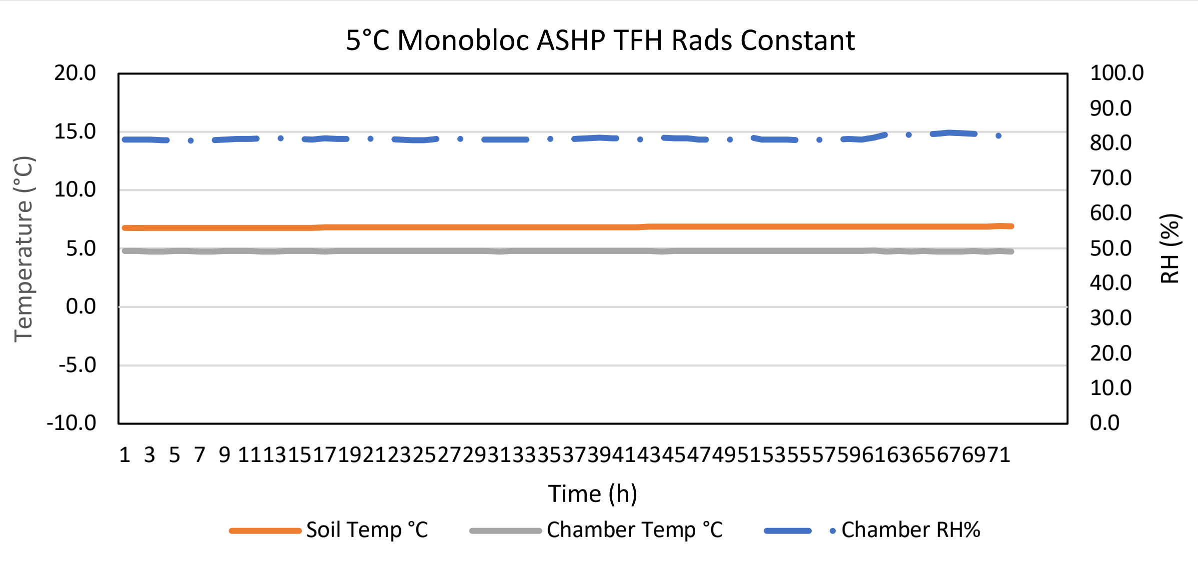
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	81.4	9.7	4.8
2	81.5	9.7	4.9
3	80.4	9.7	4.9

5°C Monobloc ASHP TFH Rads + UFH Constant



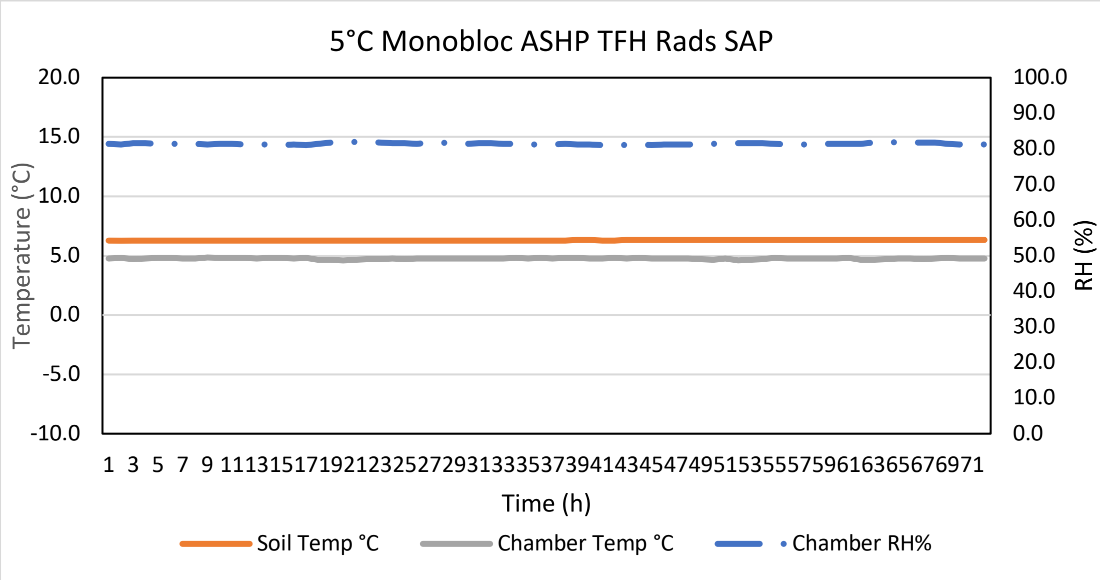
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	81.6	7.1	4.8
2	81.3	7.2	4.8
3	81.4	7.2	4.8

5°C Monobloc ASHP TFH Rads Constant



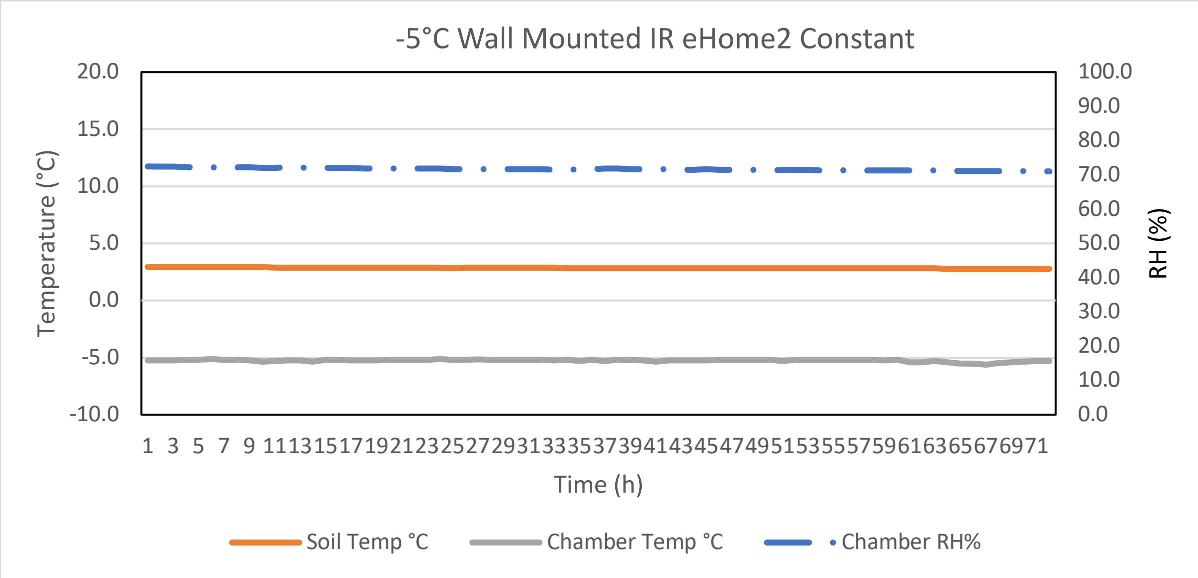
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	81.2	6.8	4.8
2	81.3	6.8	4.8
3	81.9	6.9	4.8

5°C Monobloc ASHP TFH Rads SAP



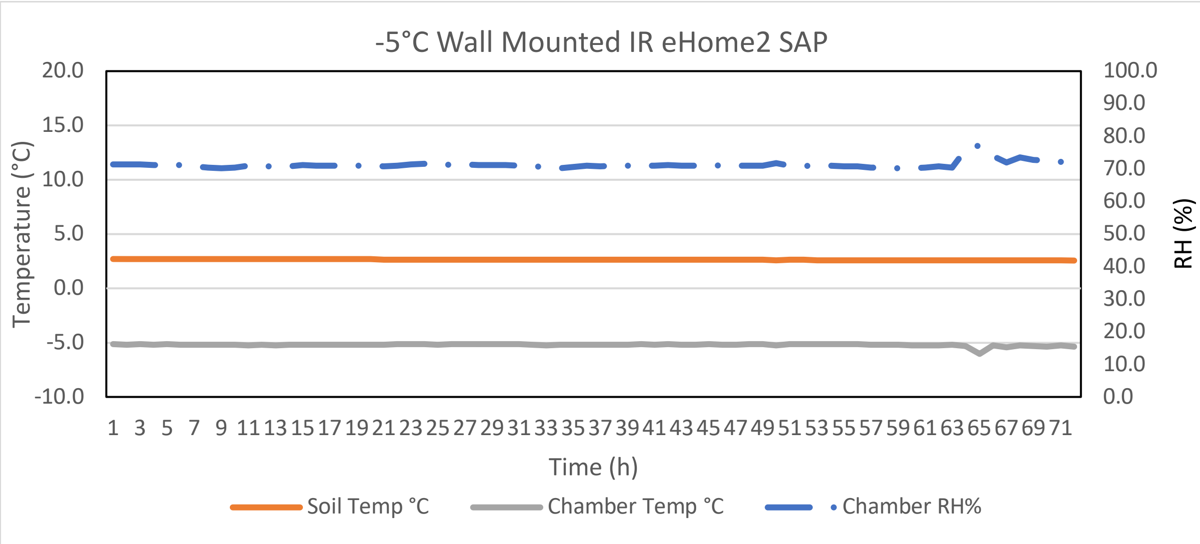
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	81.4	6.3	4.8
2	81.3	6.3	4.8
3	81.5	6.3	4.7

-5°C Wall Mounted IR eHome2 Constant



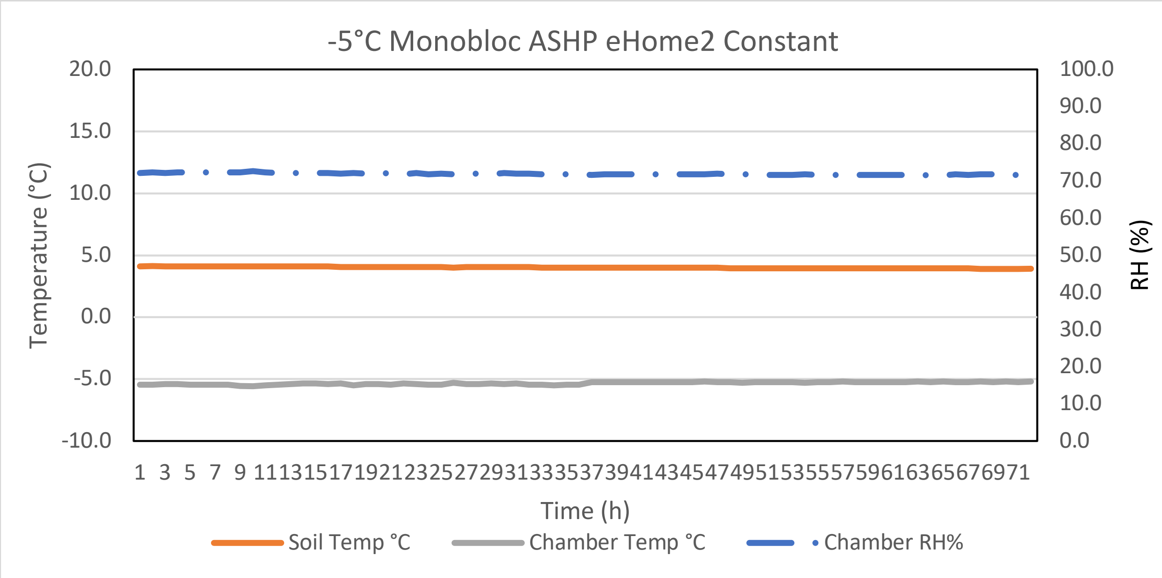
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	72.1	2.9	-5.2
2	71.6	2.8	-5.2
3	71.3	2.8	-5.3

-5°C Wall Mounted IR eHome2 SAP



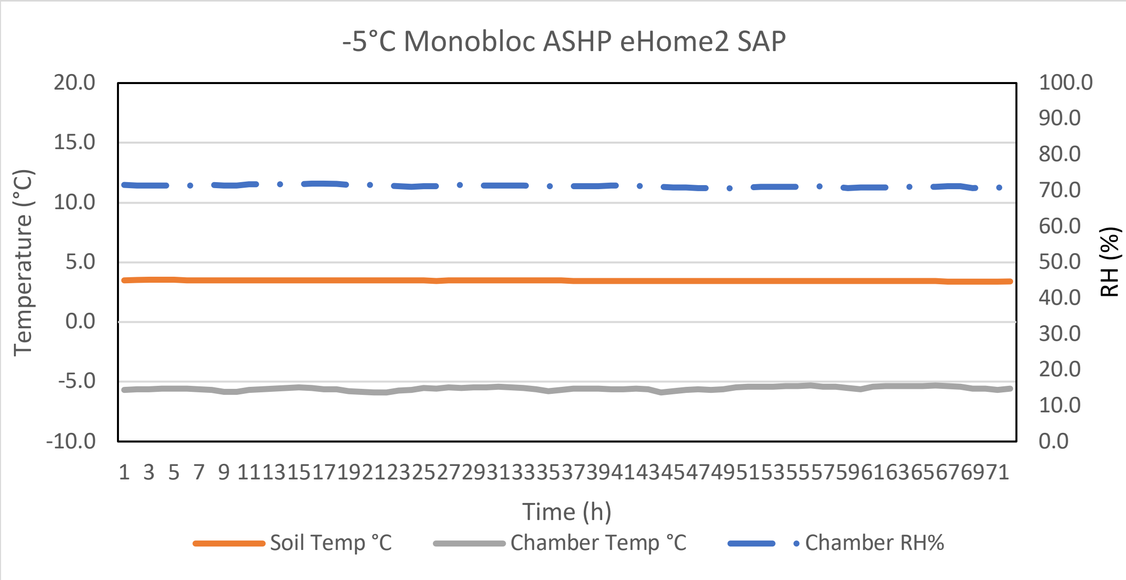
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	71.0	2.7	-5.2
2	71.0	2.6	-5.2
3	71.8	2.6	-5.3

-5°C Monobloc ASHP eHome2 Constant



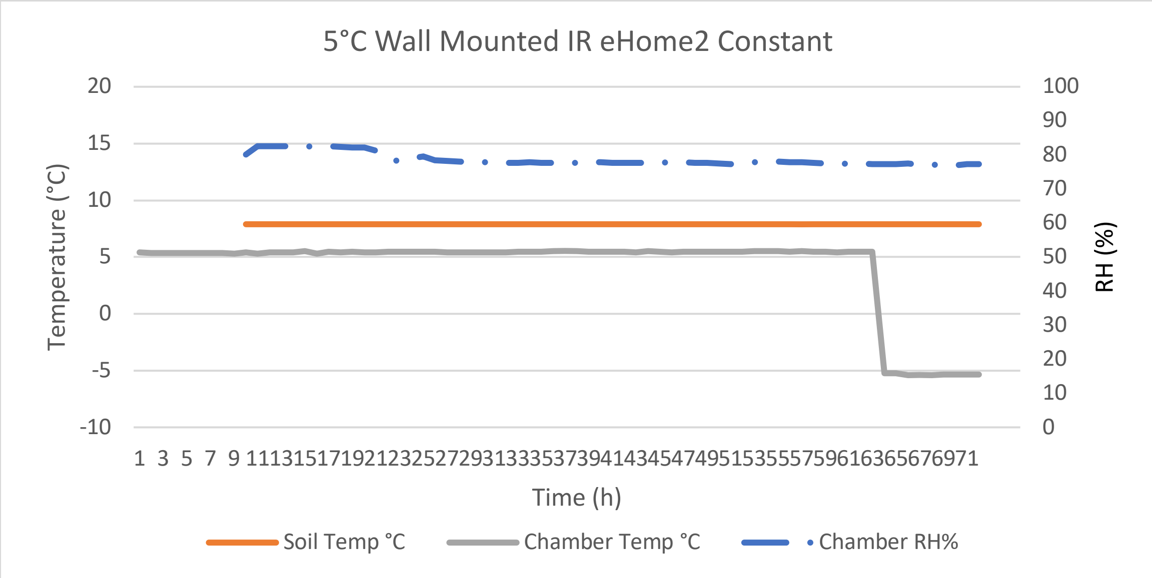
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	72.2	4.1	-5.4
2	71.8	4.0	-5.3
3	71.6	3.9	-5.2

-5°C Monobloc ASHP eHome2 SAP



24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	71.5	3.5	-5.7
2	71.2	3.5	-5.6
3	71.0	3.4	-5.4

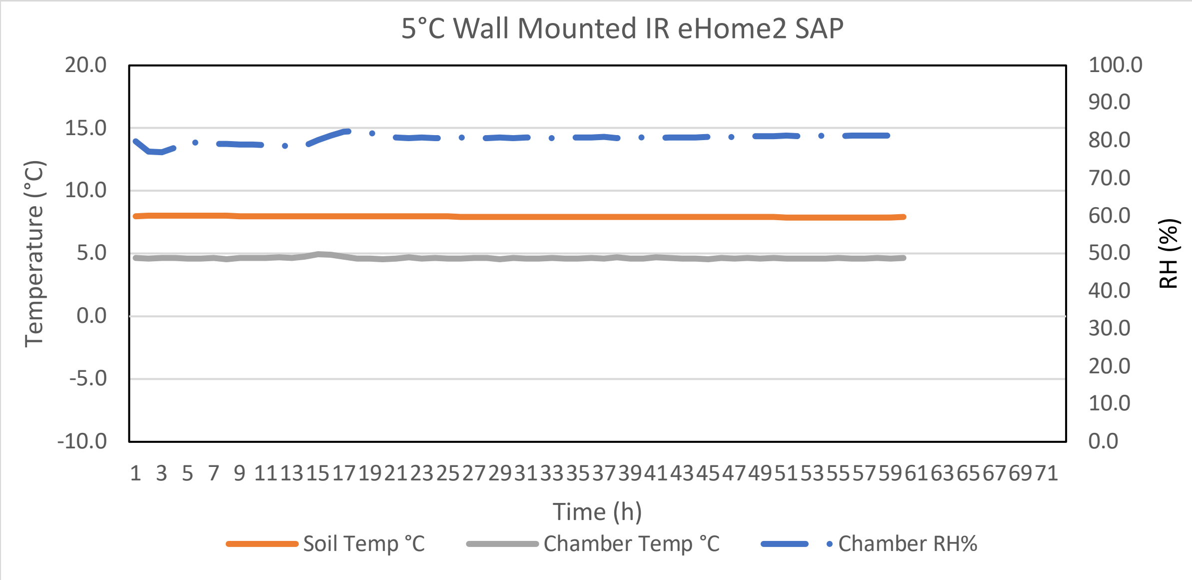
5°C Wall Mounted IR eHome2 Constant



24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	81.4	7.9	5.4
2	77.9	7.9	5.5
3	77.4	7.9	1.4

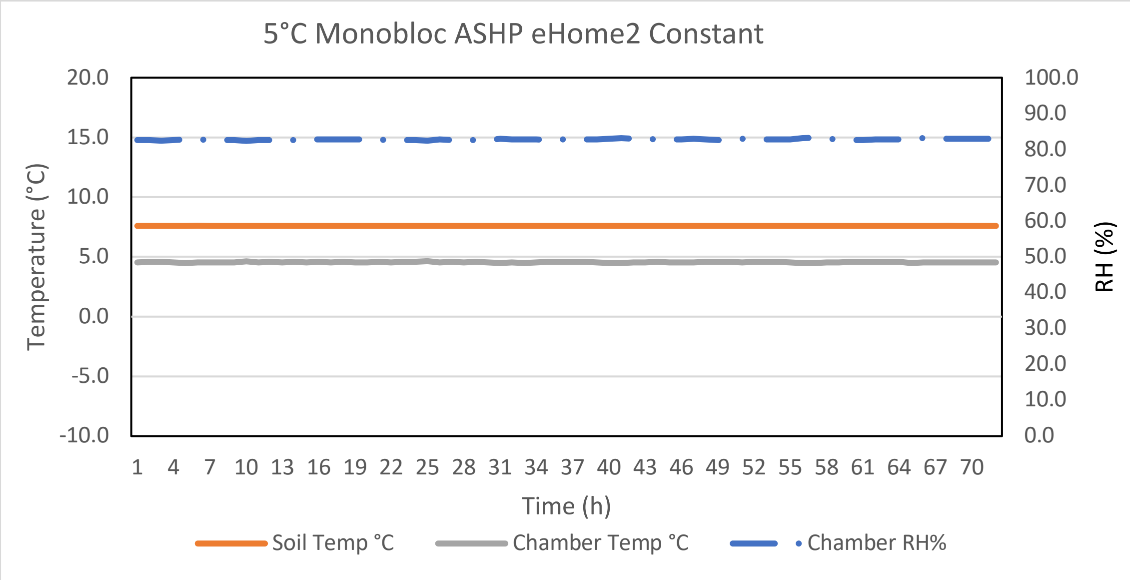
- Analysis conducted on Day 2

5°C Wall Mounted IR eHome2 SAP



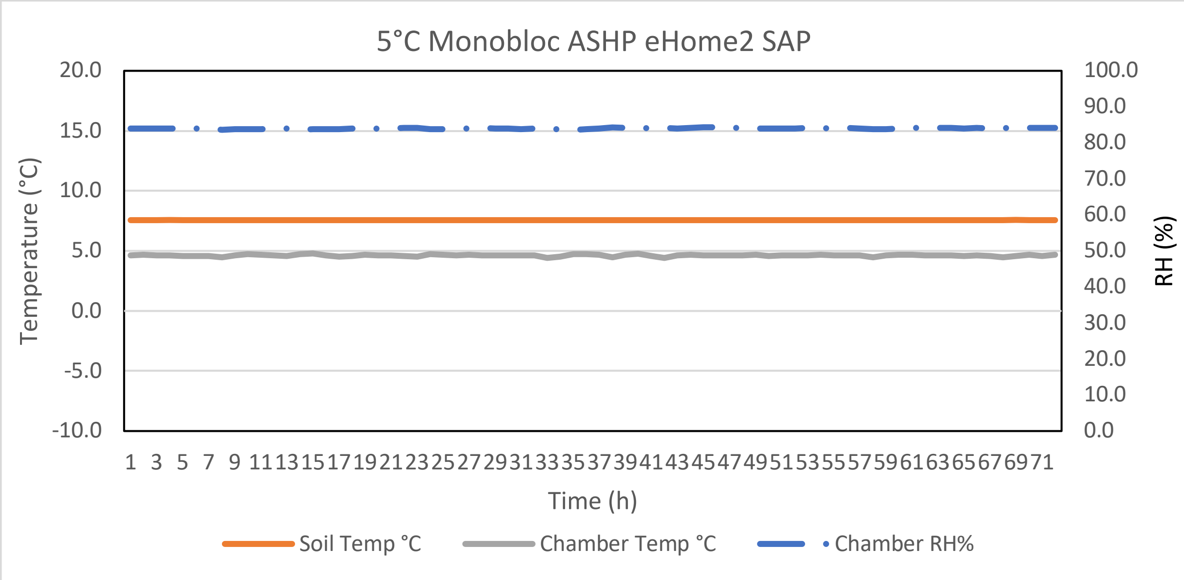
24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	79.8	8.0	4.7
2	80.9	7.9	4.6
3	81.2	7.9	4.6

5°C Monobloc ASHP eHome2 Constant



24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	82.7	7.6	4.6
2	82.8	7.6	4.6
3	82.9	7.6	4.6

5°C Monobloc ASHP eHome2 SAP



24h Average			
Day	**Chamber RH (%)**	**Soil Temperature (°C)**	**Chamber Temperature (°C)**
1	83.9	7.6	4.6
2	84.0	7.6	4.6
3	84.0	7.6	4.6

Appendix B – Monitoring equipment

The findings provided in this report are based on measurements obtained using the equipment listed in Table 69. Measurements were recorded at one-minute intervals by the Energy House's monitoring system.

Table 69: Measurement equipment used in THF heating system tests

Measurement	**Equipment**	**Uncertainty**
Electricity consumption	Siemens 7KT PAC1200 digital power meter	±1%
ASHP energy and power output	Sontex Superstatics 749 heat meter	±1%
ASHP flow rate	Sontex Superstatics 749 heat meter	±1%
ASHP flow and return temperature	Sontex Superstatics 749 heat meter	±0.3 °C
Internal shielded air temperature	Type-T thermocouples (calibrated to ± 0.1 °C)	± 0.1 °C
Mid-room shielded air temperatures	Campbell Scientific hygroVUE10 (20 to 60 °C)[2]	±0.1 °C
Chamber air temperatures	Campbell Scientific hygroVUE10 (–40 to 70 °C)[2]	±0.2 °C
Element surface temperatures	Type-T thermocouples (calibrated to ± 0.1 °C)	±0.1 °C
Relative humidity	Campbell Scientific HygroVUE10	±1.5%
Black globe temperature	Type-T thermocouple in 40 mm diameter globe	±0.1 °C

Table 70: Measurement equipment used in eHome2 heating system tests

Measurement	Equipment	Uncertainty
Electricity consumption	Siemens 7KT PAC1200 digital power meter	±1%
ASHP energy and power output	Sontex Superstatics 749 heat meter	±1%
ASHP flow rate	Sontex Superstatics 749 heat meter	±1%
ASHP flow and return temperature	Sontex Superstatics 749 heat meter	±0.3 °C
Internal shielded air temperature	Type-T thermocouples (calibrated to ± 0.1 °C)	±0.1 °C
Mid-room shielded air temperatures	Campbell Scientific hygroVUE10 (20 to 60 °C)[2]	±0.1 °C
Chamber air temperatures	Campbell Scientific hygroVUE10 (–40 to 70 °C)[2]	±0.2 °C
Element surface temperatures	Type-T thermocouples (calibrated to ± 0.1 °C)	±0.1 °C
Relative humidity	Campbell Scientific HygroVUE10	±1.5%
Black globe temperature	Type-T thermocouple in 40 mm diameter globe	±0.1 °C

Appendix C – Operative Temperature

Radiative temperature is a measure of the radiative heat in a given environment, following ASHRAE 55[3] and ISO 7730[4]. This can be influenced by the temperature of objects such as heat emitters and surfaces.

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

Where:
$\overline{T_r}$ = radiative temperature (°C)
T_{BG} = black globe temperature (°C)
T_a = air temperature (°C)
D = diameter of black globe sensor (mm)
v_{air} = air velocity (m/s)

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

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

Where:
T_{op} = Operative temperature (°C)

[3] ANSI/ASHRAE Standard (2020) 55 Thermal Environmental Conditions for Human Occupancy
[4] BS EN ISO 7730:2005 Ergonomics of the thermal environment.