BEAMA Air Source Heat Pump TRV Salford Energy House Test

Energy House Labs Technical Report

January 2026

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Executive summary

This report presents findings from the BEAMA Energy House Air Source Heat Pump (ASHP) Thermostatic Radiator Valve (TRV) Project undertaken at the University of Salford Energy House 1 test facility. The project was designed to assess the impact of TRVs on ASHP performance and inform future modelling of TRV use with ASHP systems.

Unlike gas central heating systems, TRVs are often omitted from ASHP installations based on concerns that they may reduce system efficiency and increase energy use. However, open-circuit design relies upon accurate sizing calculations and use of an appropriate weather compensation curve, neither of which can be guaranteed. Furthermore, open-circuit design limits occupant control and can lead to overheating in rooms with uncontrolled heat gains. Tests were therefore conducted to measure how trimming room temperatures using TRVs influences internal conditions, ASHP efficiency, and space heating energy consumption.

The Energy House, a Victorian solid wall end-terrace dwelling within an environmental chamber was equipped with an ASHP and radiators sized for a for a 45 °C flow temperature. Its heating circuit contained a volumiser and automatic bypass valve. Tests were performed under constant and diurnal external temperature profiles based on a typical UK winter day. The temperature of rooms accounting for around half of the internal volume of the Energy House was trimmed by 2–3 °C. The impact of both traditional and smart TRVs, volumiser integration, and differing heating patterns was tested.

The tests found that trimming internal temperatures with both traditional and smart TRVs reduced ASHP space heating energy consumption and did not significantly impact its coefficient of performance (COP). Reductions in energy consumption were proportional to reductions in space heating demand (internal to external temperature difference) achieved using TRVs. The trimming scenarios tested resulted in space heating energy savings of between 6-8%.

The findings suggest that TRVs can be used to provide occupants with greater internal temperature control and reduce ASHP space heating energy use, as is customary with gas central heating systems. Although, those with ASHP systems wishing to limit internal temperatures should initially reduce the flow temperature and programme setbacks, with TRVs used as a secondary measure. Using TRVs requires adequate volume within a system and flow rates to be maintained. Therefore, a volumiser and automatic bypass valve should be installed alongside an ASHP.

Contents

1 Introduction

This report provides findings from the BEAMA Energy House Air Source Heat Pump TRV Project undertaken by Energy House Labs at the University of Salford Energy House 1 test facility. The project was funded by BEAMA and was designed by Energy House Labs and Damon Hart-Davis.

The use of thermostatic radiator valves (TRVs) to provide microzoning is common practice with gas central heating systems. However, many air source heat pump (ASHP) systems are installed using the 'open circuit' (open loop) design principle in which TRVs are not fitted to radiators. The rationale for open circuit design is that TRVs may reduce system efficiency and increase space heating energy use. However, maintaining design temperatures in each zone requires accurate sizing calculations, correct system balancing, and the use of an appropriate weather compensation curve, none of which can be guaranteed in practice. Furthermore, concerns have been raised that open circuit design reduces the ability of occupants to reduce the temperature of zones to suit individual preferences and occupancy patterns and that it can result in overheating in rooms with high heat gains (e.g. solar).

To gain understanding of how TRVs impact ASHP performance, tests were conducted at the Salford Energy House under controlled conditions. TRVs were used to 'trim' the temperature of some zones below their design temperature and the impact on internal temperatures, ASHP efficiency, and ASHP energy use was measured. Additional test scenarios intended to inform future modelling of TRV use with ASHPs were included within the test programme.

2 Methodology

2.1 Test subject

2.1.1 The Salford Energy House

Testing was performed at the Energy House 1 test facility. It contains the Salford Energy House, a replica Victorian solid wall end-terrace house constructed within an environmental chamber. The Energy House was built using reclaimed materials and traditional construction methods and can be retrofitted to most fabric thermal performance standards. The chamber can replicate external air temperatures between -10 °C and +30 °C and can also simulate rainfall, wind, and solar radiation. The Energy House has a conventional hydronic central heating system with radiators in each room that can be served by a domestic gas condensing combination boiler and an ASHP. Its building automation control system enables simulation of occupant behaviour, such as window and door opening, lighting and appliance use, and domestic hot water (DHW) draw-offs. The Energy House shares a party wall with an adjoining building, referred to as Pemberton House. Environmental conditions in the chamber and Pemberton House can be controlled and repeated across multiple test periods. This makes it possible to measure the impact of changes to the Energy House's building fabric, heating provision, and occupancy behaviour with more speed and accuracy than houses in the field.

2.1.2 Fabric thermal performance

Table 1 and Appendix E provide details of the Energy House fabric. The configuration of the Energy House's thermal elements for the test can be considered representative of most English solid wall dwellings, 88% of which have uninsulated external walls and 87% have full double glazing. 61% have less than 200 mm or more of loft insulation, and 39% have 200 mm or more of loft insulation[1]. The 270 mm loft insulation depth is intended to represent homes that have been subject to low-cost fabric energy efficiency improvements through schemes such as the Energy Company Obligation (ECO). The SAP rating of 67 is in good agreement with the average SAP rating in England of 66[2]. The air permeability value of 12.7 $m^3.h^{-1}.m^{-2}$ @ 50 Pa is comparable with UK average[3] of 11.5 $m^3.h^{-1}.m^{-2}$ @ 50 Pa.

Table 1: Configuration of the Energy House thermal elements during the test programme.

Thermal element	Construction
External walls	225 mm solid wall with 12.5 mm wet plaster
Roof	Cold roof with 270 mm insulation at ceiling level
Ground floor	Uninsulated suspended timber (carpeted in living room)
Windows	‘E’ rated double glazing units in PVCu frames
Doors	‘E’ rated PVCu doors (rear half glazed)
Party wall	Solid wall with plaster finish on both sides

2.2 Space heating system

2.2.1 Heating system sizing

The system was sized by the Energy House Labs research team. The calculation used an external design temperature of -3 °C, which is mid-range for UK heat load calculations. An internal design temperature of 21 °C was used for all rooms to allow for temperature trimming within comfortable ranges, to reduce heat load calculation uncertainty, and simplify modelling. A design temperature of 21 °C was selected for Pemberton House[4] to reflect test conditions simulating an occupied neighbour.

Previous work at the Energy House has shown that the use of DHDG/MCS assumed fabric performance values results in significant system oversizing. To reduce the impact of oversizing it was decided to size the ASHP and radiators based on an informed heat load calculation using measured U-values and ventilation rates[5]. The heat loads calculated using both assumed and informed fabric performance values are given in Table 2. Neither calculation includes an additional 15% for intermittent heating, as most test scenarios used a constant heating pattern.

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[1] English housing data from Department for Levelling Up, Housing and Communities (2021) *English housing survey 2020 to 2021: Headline report*. London: Department for Levelling Up, Housing and Communities. Available at: gov.uk/government/statistics/english-housing-survey-2020-to-2021-headline-report

[2] English housing data from Department for Levelling Up, Housing and Communities (2021) *English housing survey 2020 to 2021: Headline report*. London: Department for Levelling Up, Housing and Communities. Available at: gov.uk/government/statistics/english-housing-survey-2020-to-2021-headline-report

[3] Stephen, BRE Report 359, Airtightness in UK dwellings: BRE’s test results and their significance, Building Research Establishment, Watford, (1998)

[4] DHDG/MCS uses a design temperature of 10 °C for adjoining dwellings.

[5] Fabric thermal performance measured during DEEP Project in 2021 (https://assets.publishing.service.gov.uk/media/6717be32e319b91ef09e3857/5.01_DEEP_Energy_House_Fabric.pdf).

Vaillant provided an aroTHERM plus monobloc ASHP for the project. Based on the informed heat load calculation, the 5 kW model was selected for the test[6].

The 5 kW Vaillant aroTHERM plus ASHP targets a flow rate of 0.86 m^3/h during normal space heating operation, opposed to a specific ΔT (e.g. 5 °C) as is observed in some heat pump units. The ASHP target flow rate was apportioned according to the relative heat loss of each zone to provide the target flow rate for each radiator (Table 2).

Table 2: Energy House Labs heat load calculation and target flow rate for each zone.

Zone	Assumed heat load (W)	Informed heat load (W)	Informed heat load (%)	Target flow rate (m^3/h)
Living room	1541	951	27	0.231
Kitchen	1508	849	24	0.206
Stairs	239	103	3	0.025
Bedroom 1	1204	812	23	0.197
Bedroom 2	794	580	16	0.141
Bathroom	366	253	7	0.061
Total	**5653**	**3547**	**100**	**0.86**

Based on the informed heat load calculation and a flow rate of 0.86 m^3/h, a ΔT of 3.55 °C would be expected across the system at the external design temperature of -3 °C.

2.2.2 Radiators

A 45 °C design flow temperature was chosen as it enabled the existing living room radiator to be retained. Moreover, a flow temperature below 45 °C would have caused practical difficulties installing radiators. The details of the installed radiators are below (Table 3).

Table 3: Installed radiators and calculated outputs.

Radiator	Type	Height (mm)	Length (mm)	Connections	Output (W)	Demand met (%)
Living room	K2 Custom	500	1800	TBOE	970	102
Kitchen	K2	600	1600	BOE	927	109
Stairs	K1	450	600	BOE	152	148
Bedroom 1	K2	450	1800	BOE	825	102
Bedroom 2	K2	600	1000	BOE	579	100
Bathroom	K1	450	1000	BOE	253	100
Total	-	-	-	-	**3706**	**104**

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[6] The 7 kW Vaillant aroTHERM plus would have been required if based on DHDG/MCS assumptions.

An oversized radiator was installed in the kitchen, as there was no appropriately sized radiator readily available. The 1600 mm radiator was selected as the 1400 mm version would have been undersized. The reason for the significant oversizing of the stairs radiator was a miscalculation in the planning stage. However, this zone represents only 3% of the total heat load. Overall, the total installed radiator capacity was 4% greater than the informed heat load.

2.2.3 Radiator valves

TRVs were fitted to the flow side of each radiator. Two types of TRV were selected by BEAMA:

1. Traditional TRV – Danfoss RAS-C[2].
2. Smart TRV – Schneider Electric Drayton Wiser TRVs, room thermostats, and hub. The room thermostats were used with the TRVs, as this reduced issues caused by the microclimates at the location of TRVs. The hub was wired to the ASHP controller.

Time constraints meant that it was not possible to perform the baseline tests without any TRVs fitted, thus replicating an open circuit installation. Traditional TRVs were left in their fully open position when no trimming was required.

Firepower Flow Regulating Valves (FRV) were fitted to the return side of each radiator in place of the lockshields supplied with the TRVs. FRV valves were used to assist with the balancing process.

2.2.4 Air source heat pump

The Vaillant aroTHERM plus 5 kW R290 monobloc ASHP (Figure 1) was located by the gable wall of the Energy House. Minimum clearances were provided and an air circulation fan situated on the rear wall of the chamber was used as a precautionary measure to avoid recirculation of exhaust air into the supply.

Figure 1: Vaillant aroTHERM plus ASHP installed for the test.

A Vaillant uniSTOR pre-plumbed, unvented DHW cylinder was installed so that the system would reflect a typical ASHP installation, and the manufacturer supplied, Honeywell 3-port valve was used in the installation. However, the time required to achieve DHW production repeatability meant that it was not possible to include DHW production and draw-offs in the test programme.

An automatic bypass valve was present on the heating circuit below the bedroom 1 radiator to provide flow through the system when TRVs are closed. The manufacturer's datasheet states that the ASHP can provide flow rates between 0.4 m^3/h to 0.86 m^3/h. During the commissioning process, it was found that ASHP provided flow through the circuit at a rate of 0.27 m^3/h with all radiator valves closed, though no heat output from the ASHP was measured. Flow to radiators was gradually increased and the ASHP provided heat output once the flow rate was above the minimum threshold of 0.4 m^3/h. Previous tests with a Samsung Monobloc ASHP found that the unit would fault and flow would cease once below the minimum flow rate, and the unit would not automatically resume when flow through radiators was restored. The Samsung ASHP then required intervention and the fault to be manually cleared by resetting the controller before the heating operation would resume. Therefore, ASHPs, such as the Vaillant aroTHERM plus, are more suited to systems where TRV use could potentially result in flow rates below the ASHP minimum flow rate.

A 25 litre volumiser was installed in a configuration which enabled it to be isolated and bypassed. This enabled the impact of the volumiser to be assessed under some scenarios.

No changes were made to the existing heating circuit pipework. A schematic of the heating circuit can be found in Appendix H.

2.2.5 System balancing

System balancing was performed by the Energy House Labs research team. The chamber temperature was maintained at a constant temperature of 4.5 °C during the balancing process. This temperature was used in the tests, and it also allowed the accuracy of the weather compensation curve to be assessed.

The FRVs were set to the desired flow rates based on the radiator sizing calculation in Table 4[7]. The flow rates achieved by the FRVs were in reasonable agreement with the flow meter measurements for most radiators. The markings on the valves also assisted with adjusting flow rates later in the balancing process. This suggests that FRVs can provide a rapid and reasonably accurate method of achieving system flow rates.

Flow meter measurements were then used to achieve the calculated flow rates through each radiator. The air temperatures throughout the house were not homogeneous once the system had stabilised. Most notably, the living room was too cold and the kitchen too hot. The flow rates of the radiators were adjusted until temperatures in the Energy House varied by <0.5 °C. The revised flow rates are given in Table 4.

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[7] The minor differences between the target flow rates in Table 2 and the calculated flow rates in Table 4 are due to rounding.

Table 4: System balancing calculated and measured radiator outputs and flow rates.

Radiator	Calculated heat loss under test conditions (W)	Measured radiator output (W)	Calculated flow rate (m^3/h)	Measured flow rate (m^3/h)	Measured ΔT (°C)
Living room	627	651	0.23	0.374	1.5
Kitchen	569	582	0.206	0.046	10.9
Stairs	53	54	0.025	0.003	15.6
Bedroom 1	555	562	0.197	0.269	1.8
Bedroom 2	412	351	0.140	0.048	6.3
Bathroom	165	195	0.061	0.084	2
Sum	**2380**	**2396**	**0.859**	**0.824**	-

The flow rates required to create a homogenous internal temperature were significantly different to the calculated flow rates. The power output of each radiator was close to the calculated heat loss for their respective room, except for bedroom 2 and the bathroom. Adjustments to the flow rates through these radiators would be expected to compensate for this discrepancy. Flow rate modifications would also be expected for the kitchen and the stairs due to the oversized radiators. The additional flow through the living room and bedroom may partially be explained by pipework losses, as they are the final radiators on each circuit. Notably, the living room pipework is outside of the thermal envelope. Discrepancies may also exist between the stated and actual output of radiators. The calculation assumed a ΔT of 2.4 °C across the system and radiators at 4.5 °C external temperature. However, the adjustments resulted in differing ΔTs across the radiators. The flow rate of 0.824 m^3/h after balancing was 4% lower than the anticipated flow rate of 0.86 m^3/h.

2.3 Test conditions

2.3.1 Internal environment

The ASHP controller was programmed to use only weather compensation (no room influence) to control the flow temperature and, therefore, the internal air temperature. The 0.75 weather compensation curve[8] setting was selected for the test as it closely aligns with system design temperatures (21 °C internal, -3 °C external, 45 °C flow).

A constant heating pattern was used in the main body of tests. The SAP heating periods of 07:00-09:00 and 16:00-23:00 were used in tests with a setback heating pattern (Appendix B). Two methods of setback between heating periods were tested.

1. The ASHP controller was programmed with a 2 °C setback.
2. Smart TRVs were on all radiators programmed with a 2 °C setback. This scenario was intended to provide an extreme case of TRV intervention.

Room temperature trimming was performed in the kitchen, bedroom 2, and bathroom which are located on the rear (south) elevation of the Energy House (Figure 2). These rooms represent 43% of the total volume of the Energy House and 47% of its heat loss (based on the informed heat load calculation).

Figure 2: Energy House floor plan showing zones subject to temperature trimming.

A target reduction in room temperature of 2-3 °C in south facing rooms was chosen for the tests. This would result in no rooms being maintained below the Public Health England minimum recommended indoor temperature of 18 °C[9].

Three methods of room temperature trimming were used in the main body of tests:

1. **Lockshields valves** – The (FRV) lockshields were used to restrict flow through radiators. There was insufficient time to adjust lockshields so that the target reduction was achieved in all rooms.
2. **Traditional TRVs** – The TRVs were set to achieve similar temperatures to those maintained by the lockshields.
3. **Smart TRVs** – The room thermostats paired with each TRV were set to similar mid-room temperatures to those maintained by the lockshields and traditional TRVs.

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[8] Heating curve in the myVAILLANT app.

[9] Wookey, R., Bone, A., Carmichael, C. and Crossley, A. (2014). Minimum home temperature thresholds for health in winter – A systematic literature review. Public Health England.

Reducing the temperature in the south facing rooms results in heat transfer from the adjoining stairs zone. To compensate, the flow to the stairs radiator was increased during tests with lockshield and traditional TRV trimming. Increasing the output of the stairs radiator was considered a preferable first course of action to increasing ASHP flow temperature, as it is less likely to impact efficiency. Though it must be noted that the stairs radiator was able to significantly increase output as it was oversized. There was concern that increasing the flow through the stairs radiator may mask the impact of increased resistance resulting from trimming. The flow rate was therefore reduced to near the baseline rate prior to the smart TRV test (test 11). Although this modification reduces the robustness of comparing traditional and smart TRVs, it allowed two trimming scenarios to be tested (with and without mitigation for increased heat transfer between zones).

2.3.2 External (chamber) environment

Tests were performed under two scenarios with the chamber HVAC system programmed to provide the average UK external air temperature during the meteorological winter (December to February).

1. **Constant** – Based on the average UK winter temperature of 4.5 °C obtained from Table U1 of SAP10.
2. **Diurnal** – The diurnal temperature was selected for the main phase of testing. It is based on the mean hourly dry bulb (air) temperature throughout winter for Leeds using Chartered Institution of Building Services Engineers (CIBSE) Test Reference Year (TRY) data, which is based on UK Meteorological Office data. The climate in Leeds can be considered typical of the UK for heat pump performance modelling purposes[10]. The 24-hour mean temperature for the diurnal temperature pattern shown in Figure 3 is 4.5 °C.

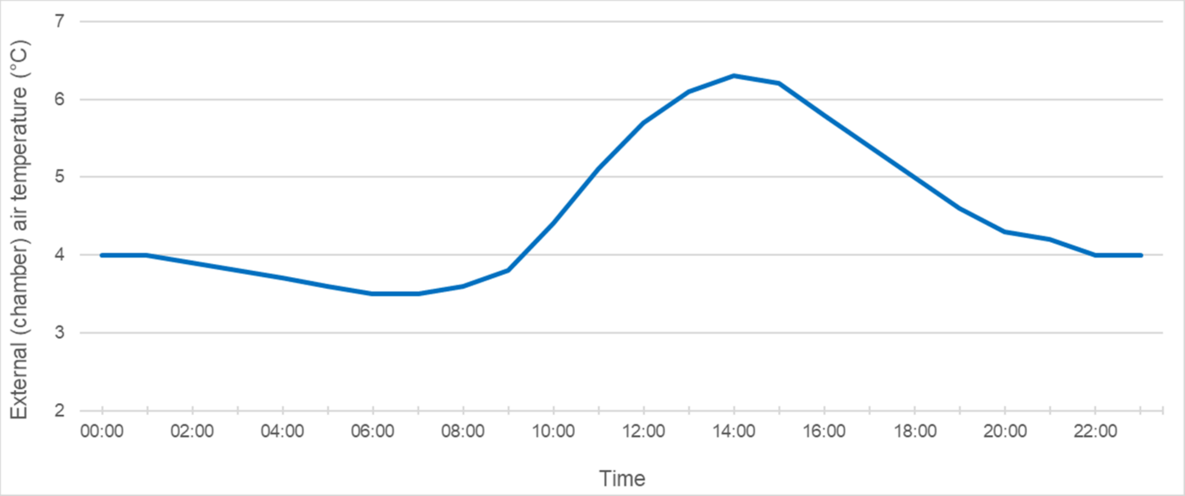

Figure 3: Diurnal external temperature pattern.

The rationale for using constant and dynamic external scenarios was to provide insight into the impact of external temperature variation on internal temperature control using pure weather compensation control. Additionally, it was to inform whether future modelling of various building archetypes and heating scenarios can be performed using a constant external temperature, thus reducing the complexity associated with external conditions.

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[10] https://tools.bregroup.com/heatpumpefficiency/dwelling-heat-loss

To reduce heat transfer between dwellings, zones in Pemberton House were maintained at the temperature of adjoining rooms in the Energy House. This involved changing the setpoint of the PID controlled electric resistance heaters depending on test conditions.

Relative humidity in the chamber was between 80% and 85% throughout the test programme.

2.4 Test duration

To minimise thermal mass effects resulting from charging and discharging of the building fabric, each test was a minimum of 72 hours in duration. The final 24-hour period for each test was the reporting period. The stabilisation period prior to the reporting period allowed the Energy House to reach a state of dynamic equilibrium, thus ensuring repeatability.

2.5 Measurement equipment

The findings provided in this report are based on measurements obtained from the Energy House monitoring system using the equipment listed in Table 5.

Table 5: Measurement equipment used during the test programme.

Measurement	Equipment	Uncertainty
ASHP electricity consumption	SPC SDM120 power meter	±1%
ASHP & radiator energy & power output	Zenner Zelsius C5 heat meter	±2 % (typical)
ASHP & radiator flow & return temps.	PT-100 RTD (Zenner Zelsius C5)	±0.3 °C
Mid-room and chamber air temp.	Campbell Scientific HygroVUE10	±0.1 °C

ASHP electricity consumption provided in the report is for the entire system. Therefore, the efficiency values provided in this report are COP_{H4}.

ASHP COP_{H4} was calculated using the following equation:

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

2.6 Tests performed

The test programme, shown in Table 6, was designed to measure the impact of TRVs on ASHP performance and provide information for modelling purposes.

Table 6: Test programme.

Test no.	External pattern	Volumiser	Trimming	Internal pattern	Stairs temp. mitigation
1	Constant	No	n/a	Constant	No
2	Constant	Yes	n/a	Constant	No
3	Diurnal	Yes	n/a	Constant	No
4	Diurnal	No	n/a	Constant	No
5	Diurnal	Yes	Lockshield	Constant	Yes
6	Constant	Yes	Lockshield	Constant	Yes
7	Constant	Yes	Trad. TRV	Constant	Yes
8	Diurnal	Yes	Trad. TRV	Constant	Yes
9	Diurnal	Yes	Trad. TRV	SAP with setback (ASHP)	Yes
10	Diurnal	Yes	n/a	SAP with setback (ASHP)	Yes
11	Diurnal	Yes	Smart TRV	Constant	No
12	Diurnal	Yes	Smart TRV	SAP with setback (Smart TRV)	No

The test groups are shown in Table 7. The main body of the report contains findings from the test group measuring the impact of trimming on the diurnal external temperature. The results from other test groups can be found in Appendix A to Appendix D.

Table 7: Test groups.

Test group	Tests	Baseline test	Results
Impact of trimming (diurnal external temperature)	**3,5,8,11**	**3**	**Section 3**
Impact of trimming (constant external temperature)	2,6,7	2	Appendix A
Impact of setback between heating periods (no trimming)	3,10	3	Appendix B1
Impact of trimming with setback heating pattern	9,10,12	10	Appendix B2
Impact of volumiser (diurnal external)	3,4	4	Appendix C1
Impact of volumiser (constant external)	1,2	1	Appendix C2
Impact of diurnal external temperature (no volumiser)	1,4	1	Appendix D1
Impact of diurnal external temperature (volumiser & TRVs)	7,8	7	Appendix D2

3 Results

3.1 Internal temperatures

Figure 4 shows the internal air temperatures during each 24-hour reporting period. 24-hour mean air temperatures are provided in Table 8.

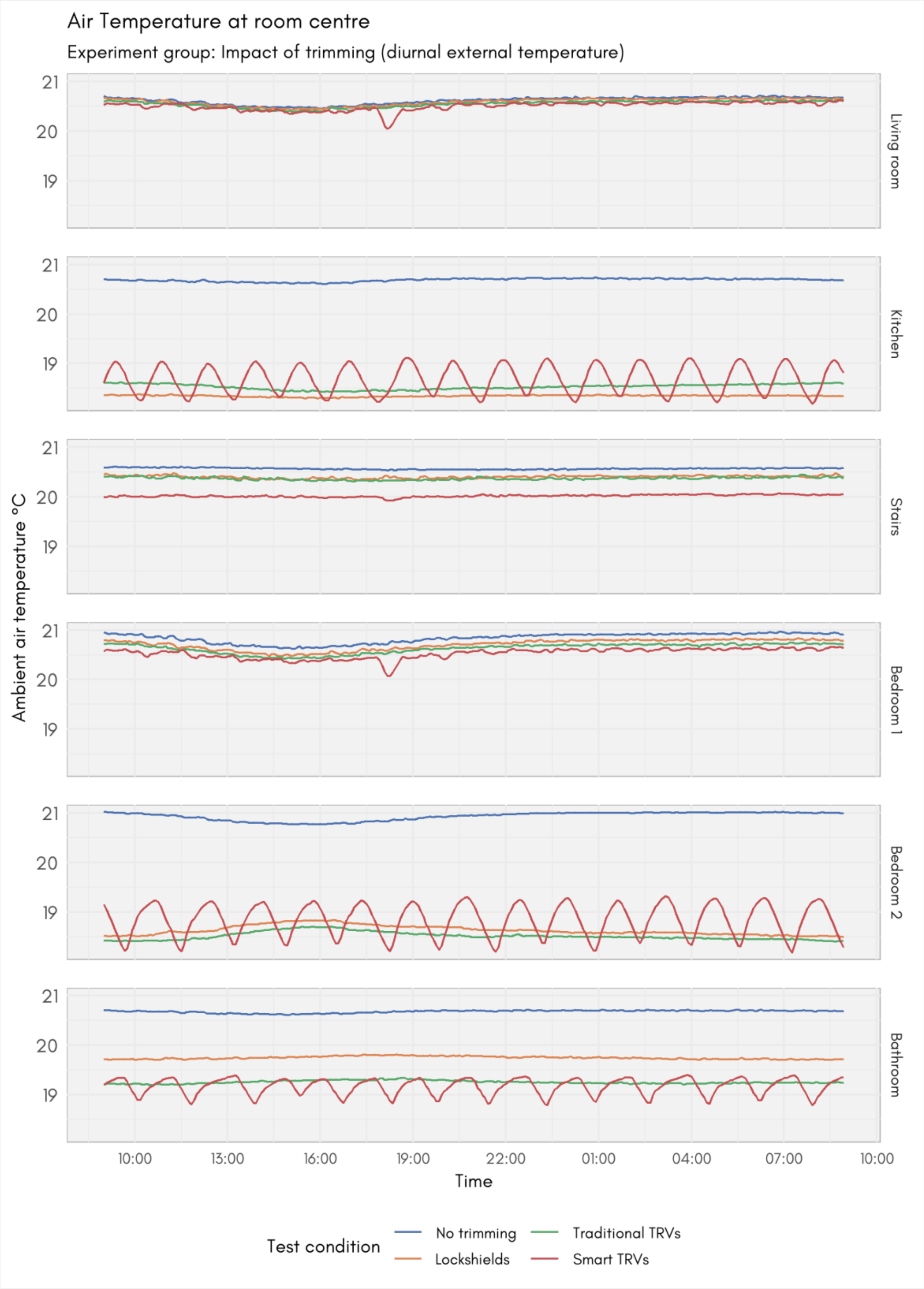

Figure 4: Impact of trimming with diurnal external temperature – Internal air temperatures.

Table 8: Impact of trimming with diurnal external temperature – 24-hour mean internal air temperatures. Change from no trimming baseline shown in parenthesis. Italics denotes room that were subject to trimming.

Test	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
No trimming	20.6 ±0.1	20.8 ±0.1	20.6 ±0.1	20.7 ±0.1	20.9 ±0.1	20.7 ±0.1
Lockshields	20.6 ±0.1 (-0.0 ±0.1)	20.7 ±0.1 (-0.1 ±0.1)	20.4 ±0.1 (-0.2 ±0.1)	18.3 ±0.1 (-2.3 ±0.1)	18.6 ±0.1 (-2.3 ±0.1)	19.7 ±0.1 (-0.9 ±0.1)
Traditional TRVs	20.5 ±0.1 (-0.1 ±0.1)	20.6 ±0.1 (-0.2 ±0.1)	20.4 ±0.1 (-0.2 ±0.1)	18.5 ±0.1 (-2.2 ±0.1)	18.5 ±0.1 (-2.4 ±0.1)	19.3 ±0.1 (-1.4 ±0.1)
Smart TRVs	20.5 ±0.1 (-0.1 ±0.1)	20.5 ±0.1 (-0.3 ±0.1)	20.0 ±0.1 (-0.6 ±0.1)	18.7 ±0.1 (-2.0 ±0.1)	18.8 ±0.1 (-2.1 ±0.1)	19.2 ±0.1 (-1.5 ±0.1)

In the baseline test (no trimming), all rooms were within 0.4 °C of the 21 °C internal design temperature. Temperature fluctuations during the 24-hour period were the result of the diurnal external temperature and weather compensation control (refer to Appendix D).

Trimming reduced the kitchen and bedroom 2 temperatures by between 2 °C and 2.4 °C. The reductions in temperature in each of these rooms was reasonably consistent for all three trimming methods. The bathroom temperature was reduced by between 0.9 °C and 1.5 °C. Both the traditional and smart TRVs produced similar temperature reductions.

The traditional TRVs provided a relatively constant air temperature and demonstrated similar behaviour to lockshield trimming. The smart TRVs maintained setpoint with a hysteresis of <±0.5 °C.

Trimming resulted in no significant change in living room temperature from the baseline test. The temperature in bedroom 1 reduced by 0.2 °C and 0.3 °C in the traditional and smart TRV tests, respectively. Trimming caused a decrease in the stairs temperature as the radiator output became insufficient to account for heat transfer to the adjoining rooms, which were the subject of trimming. The mitigation measure of increasing flow through the stairs radiator (refer to Section 2.3.1) in the lockshield and traditional TRV tests meant that this zone was only 0.2 °C cooler than the baseline test. In the smart TRV test, the lower flow rate through the stairs radiator meant that this zone was 0.6 °C cooler than the baseline test.

The drop in internal temperatures measured around 18:00 in the smart TRV test was the result of the heat pump cycling (refer to Section 0).

It is interesting to note that the bedroom 2 temperature decreased in the afternoon due to the diurnal external temperature pattern in the baseline test but increased during the afternoon in the lockshield and traditional TRV tests.

3.2 Heat pump cycling

Figure 5 shows active heating periods during each 24-hour reporting period. Table 9 summarises the cycling behaviour of the ASHP during each 24-hour reporting period.

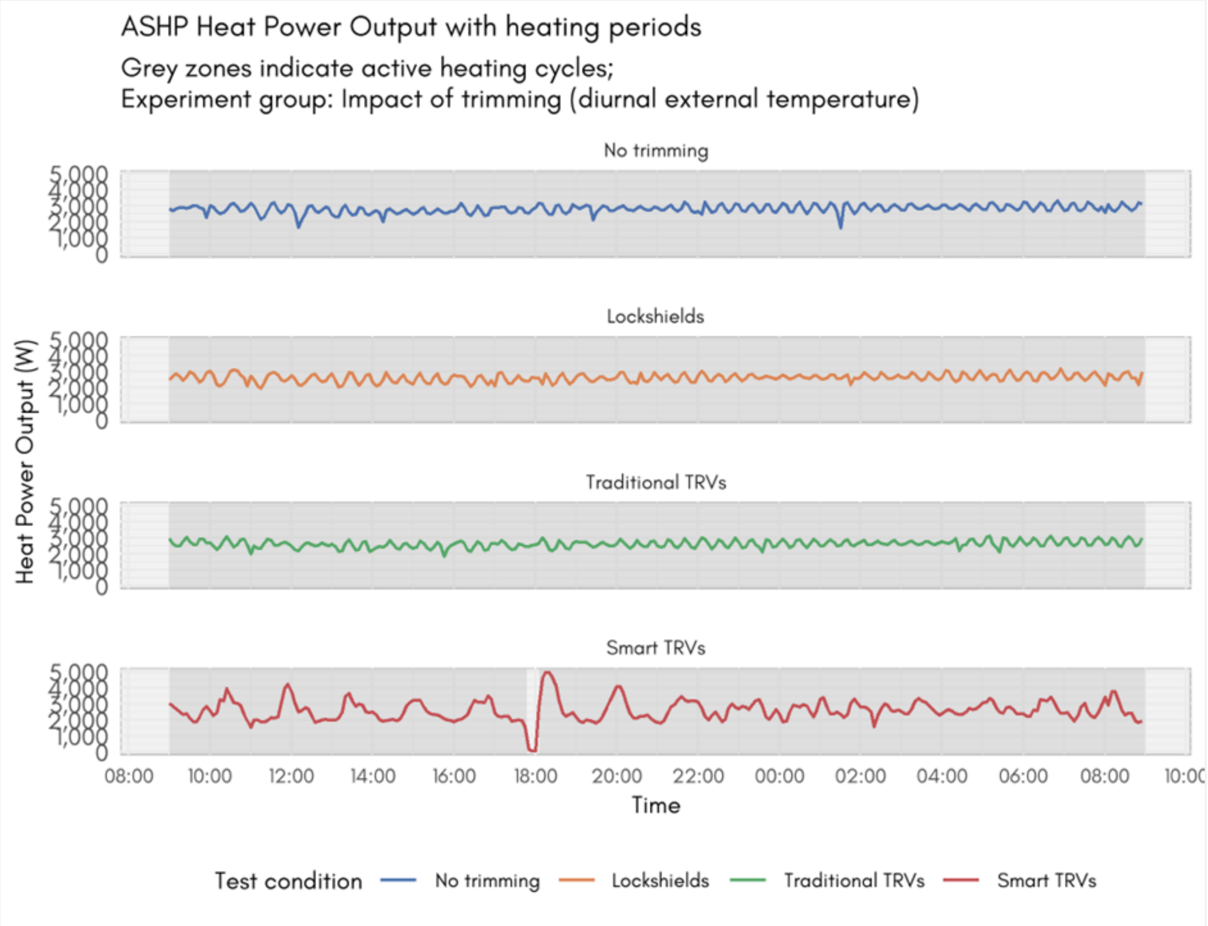

Figure 5: Impact of trimming with diurnal external temperature – Heat pump cycles.

Table 9: Impact of trimming with diurnal external temperature – Heat pump cycles.

Test	% Time On	Cycle #	Cycle Duration	Mean Power (W)	Median Power (W)	Max Power (W)
No trimming	100%	1	24h 0m	2,816	2,820	3,300
Lockshields	100%	1	24h 0m	2,622	2,600	3,180
Traditional TRVs	100%	1	24h 0m	2,613	2,600	3,100
Smart TRVs	99%	1	8h 45m	2,488	2,340	4,200
		2	14h 55m	2,666	2,590	4,960

The ASHP was in constant operation throughout all tests except for the smart TRV test as the heat demand was above the minimum output of ASHP. During the smart TRV test, no heat output was measured from the ASHP for a period of ~20 minutes at around 18:00. The ΔT across the ASHP during this period indicates a defrost cycle (refer to Section 3.4).

3.3 Flow rates

Figure 6 shows the flow rates though the ASHP unit and the radiators during each 24-hour reporting period. Mean flow rates are provided in Table 10.

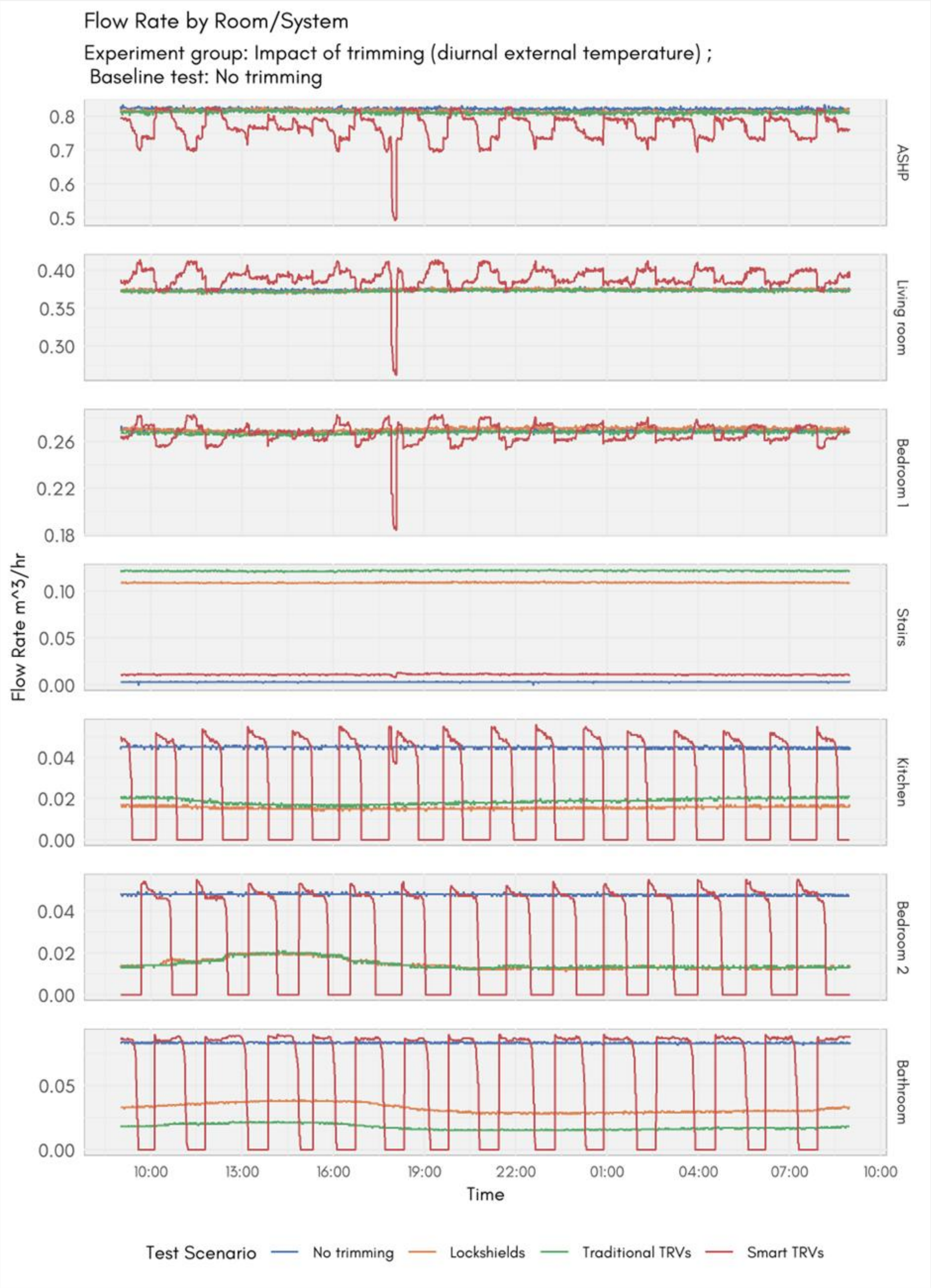

Figure 6: Impact of trimming with diurnal external temperature – Flow rates.

Table 10: Impact of trimming with diurnal external temperature – Mean flow rates during periods of flow >0 m^3/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	ASHP Flow (m^3/h)	Living room Flow (m^3/h)	Bedroom 1 Flow (m^3/h)	Stairs Flow (m^3/h)	*Kitchen Flow (m^3/h)*	*Bedroom 2 Flow (m^3/h)*	*Bathroom Flow (m^3/h)*
No trimming	0.822 ±0.017	0.374 ±0.008	0.269 ±0.005	0.003 ±<0.001	0.045 ±0.001	0.048 ±0.001	0.083 ±0.002
Lockshields	0.815 ±0.017 (-0.007 ±0.024)	0.374 ±0.008 (0 ±0.011)	0.27 ±0.006 (+0.002 ±0.008)	0.109 ±0.002 (+0.106 ±0.002)	0.016 ±<0.001 (-0.029 ±0.001)	0.014 ±<0.001 (-0.033 ±0.001)	0.032 ±0.001 (-0.051 ±0.002)
Traditional TRVs	0.811 ±0.017 (-0.01 ±0.024)	0.373 ±0.008 (-0.001 ±0.011)	0.268 ±0.005 (-0.001 ±0.008)	0.122 ±0.003 (+0.119 ±0.003)	0.019 ±<0.001 (-0.026 ±0.001)	0.015 ±<0.001 (-0.033 ±0.001)	0.018 ±<0.001 (-0.066 ±0.002)
Smart TRVs	0.767 ±0.016 (-0.055 ±0.023)	0.39 ±0.008 (+0.016 ±0.011)	0.267 ±0.005 (-0.002 ±0.008)	0.011 ±<0.001 (+0.008 ±<0.001)	0.048 ±0.001 (+0.003 ±0.001)	0.047 ±0.001 (-0.001 ±0.002)	0.082 ±0.002 (-0.002 ±0.003)

Trimming with traditional TRVs resulted in similar flow rates and behaviour to trimming with lockshields. Flow rates were relatively stable and variation observed across the 24-hour period appears to be linked to the diurnal external temperature pattern, as rates were more stable with a constant external temperature (refer to Appendix D). Lockshield and traditional TRV trimming had minimal impact on the flow rate through the ASHP and the radiators that were not subject to trimming. This could be due to deliberately increasing the flow rate through the stairs radiator to compensate for heat transfer between rooms (refer to Section 2.3.1).

Smart TRVs demonstrated distinct on/off behaviour to maintain the setpoint. Their digital behaviour contrasts with the analogue behaviour exhibited by the traditional TRVs. Flow rates through trimmed radiators were in close agreement with baseline values during periods when the smart TRVs were open. The on/off behaviour of smart TRVs had an impact on the flow rate through non-trimmed radiators. The flow rate through non-trimmed radiators was approx. 10% greater when the smart TRVs were closed than when they were open. The flow rate through the ASHP reduced when all smart TRVs were closed. The higher flow rate through the stairs radiator was attributed to the difficulty faced by the research team in matching baseline flow rates prior to the smart TRV test. Although the scale in Figure 6 makes flow rate variation difficult to identify, similar behaviour to the other non-trimmed radiators was identified.

The differing impact on flow rates through the ASHP and radiators that were not subject to trimming is partially due to the flow rate through the stairs radiator not being deliberately increased in the smart TRV test. By not providing additional flow through the stairs radiator, the additional resistance caused by TRV operation increased the flow rate through the non-trimmed radiators and reduced the flow rate through the ASHP. If the flow through the stairs radiator had not been adjusted in the lockshield and traditional TRV tests, it is likely that flow through the non-trimmed radiators would have increased and flow through the ASHP would also have reduced. Though the change in flow rates would have been lower, as flow through the radiators subject to trimming would have been at a constant rate.

Table 10 provides the flow rates through the ASHP and each radiator are the mean of periods with flow rate > 0 m^3/h. As the flow rates were effectively constant during the tests with no trimming, lockshield trimming, and traditional TRVs, the total for all radiators is within the uncertainty of the ASHP flow rate measurement. In the smart TRV test, the flow rate through the radiators in rooms subject to trimming was zero for a significant proportion of time, so the flow rates given Table 10 are greater than the mean across the 24-hour test period. This explains why the sum of the flow rate through each radiator in this test is greater than the flow through the ASHP unit.

3.4 ASHP and radiator ΔT

ASHP flow and return temperatures during each 24-hour reporting period are shown in Figure 7. The ΔT across the ASHP and each radiator during each 24-hour reporting period is shown in Figure 8. The 24-hour mean ΔT across the ASHP and each radiator is provided in Table 11.

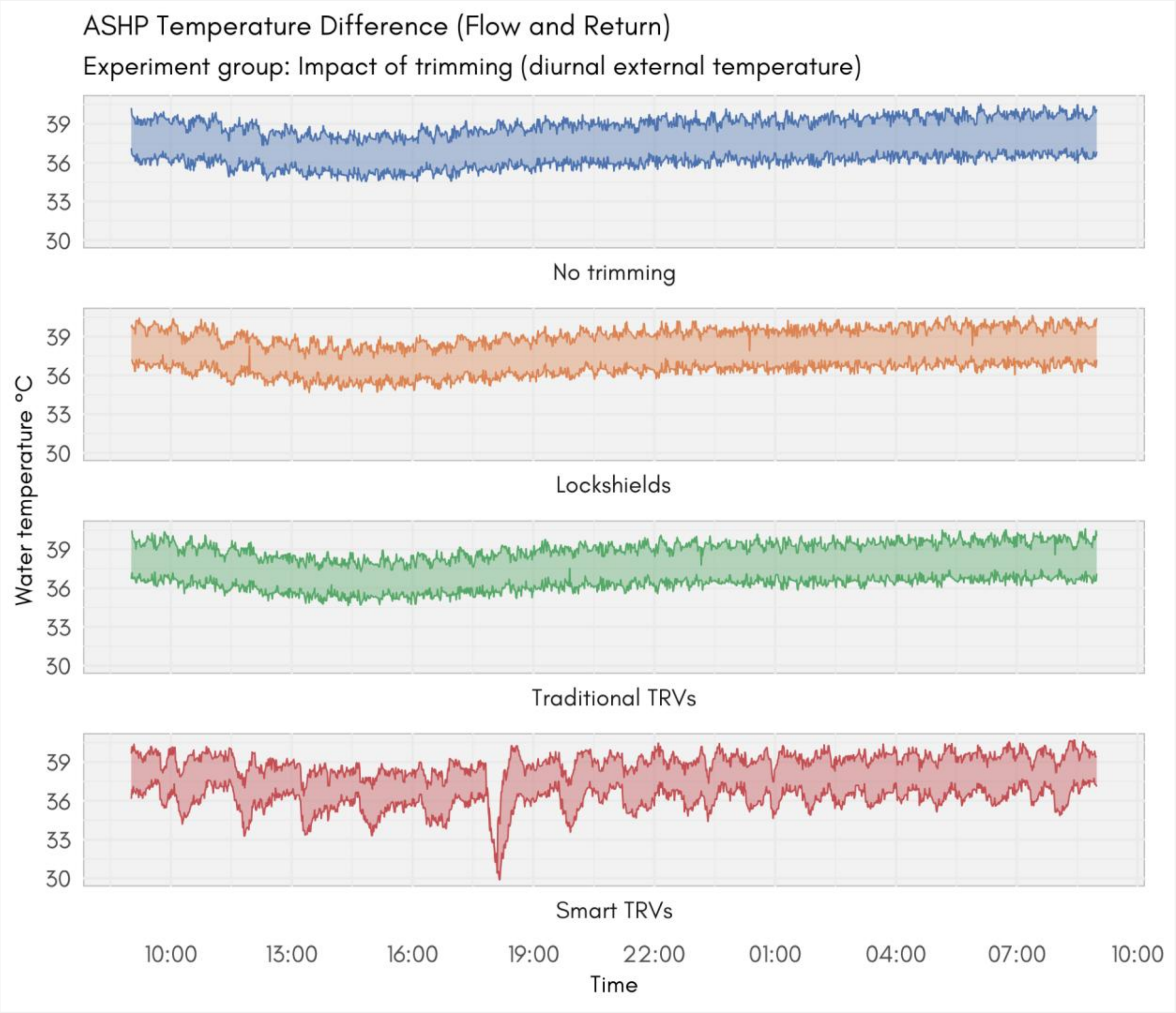

Figure 7: Impact of trimming with diurnal external temperature – ASHP flow and return temperatures.

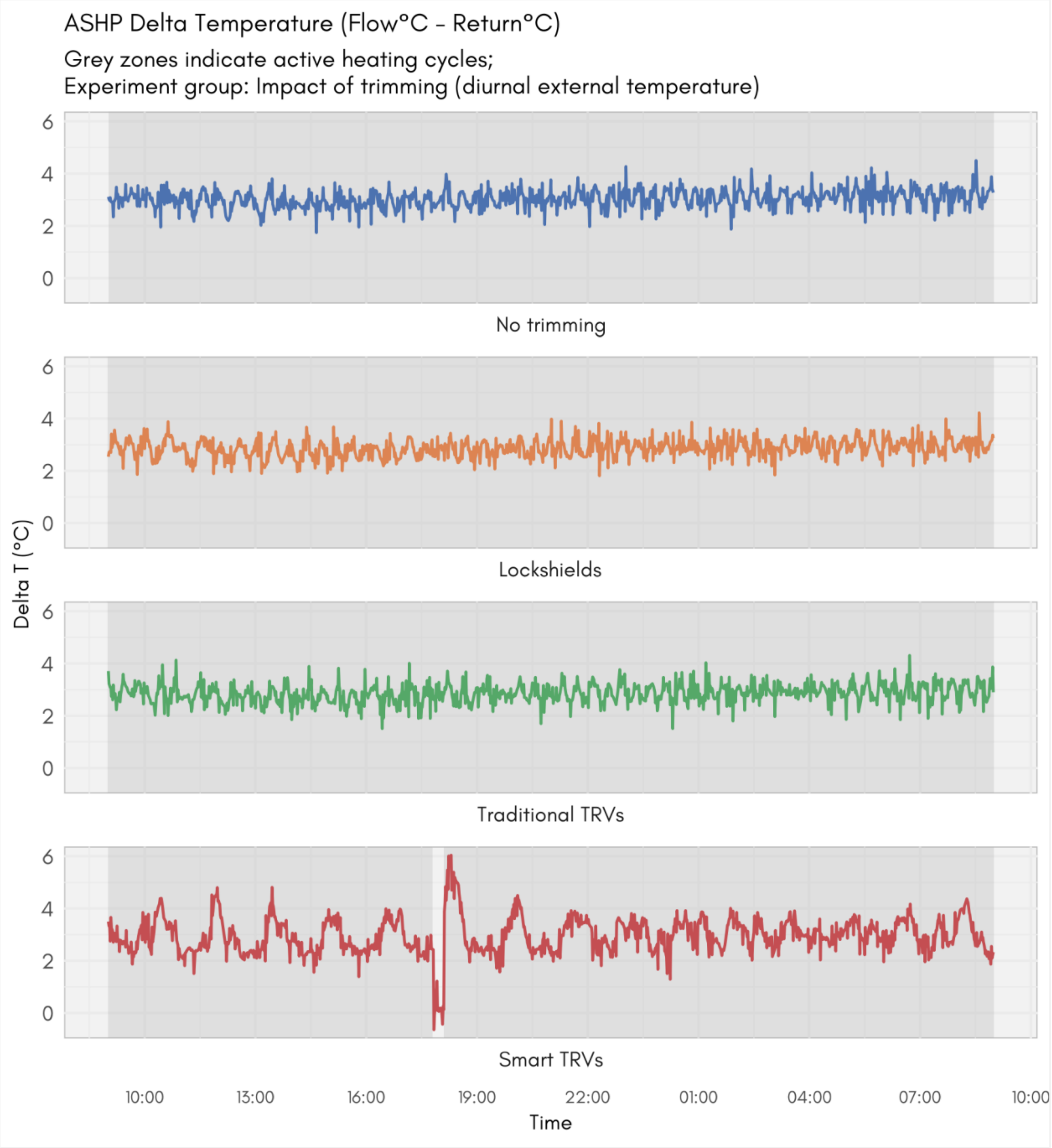

Figure 8: Impact of trimming with diurnal external temperature – ASHP ΔT.

Table 11: Impact of trimming with diurnal external temperature – Mean ASHP and radiator ΔT during periods of flow >0 m³/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP**	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
No trimming	3.1 ±0.6	1.3 ±0.5	1.7 ±0.6	15.9 ±1	11 ±0.8	6.5 ±0.7	1.9 ±0.6
Lockshields	2.9 ±0.6 (-0.2 ±0.8) (-6 ±27.1%)	1.4 ±0.5 (0.1 ±0.8) (9.8 ±58.7%)	1.8 ±0.6 (0 ±0.8) (1 ±44.7%)	1.3 ±0.5 (-14.6 ±1.1) (-91.9 ±9%)	18.2 ±1 (7.2 ±1.3) (65.2 ±13.1%)	14.2 ±0.9 (7.7 ±1.2) (117 ±21.6%)	5.1 ±0.7 (3.2 ±0.9) (169.2 ±67.5%)
Traditional TRVs	2.9 ±0.6 (-0.2 ±0.8) (-7.3 ±27%)	1.3 ±0.5 (0 ±0.8) (-3.8 ±58.2%)	1.8 ±0.6 (0 ±0.8) (2.8 ±44.7%)	1.2 ±0.5 (-14.7 ±1.1) (-92.5 ±9%)	16.7 ±1 (5.7 ±1.3) (52.3 ±12.5%)	14.1 ±0.9 (7.5 ±1.2) (115.1 ±21.5%)	8 ±0.7 (6.2 ±0.9) (326.8 ±108.2%)
Smart TRVs	2.9 ±0.6 (-0.2 ±0.8) (-5.3 ±27.1%)	1.2 ±0.5 (-0.1 ±0.8) (-6.2 ±58.2%)	1.8 ±0.6 (0.1 ±0.8) (4 ±44.8%)	9.5 ±0.8 (-6.4 ±1.3) (-40.5 ±8.3%)	14.5 ±0.9 (3.6 ±1.3) (32.3 ±11.6%)	9.2 ±0.8 (2.7 ±1) (41.1 ±16.5%)	2.6 ±0.6 (0.7 ±0.8) (39 ±44.1%)

None of the trimming scenarios caused a significant change in 24-hour mean ΔT across the system or the living room and bedroom 1 radiators from the baseline test. There was a significant increase in mean ΔT across the radiators which were subject to trimming in the lockshield and traditional TRV tests due to a reduction in flow rate. In the smart TRV test, the increases in mean ΔT were lower and not significant for the bathroom radiator. The increases in mean ΔT in this test may be due to on/off behaviour rather than reduced flow rates[11].

The ΔT throughout the 24-hour periods was relatively stable in the lockshield and traditional TRV tests compared with the smart TRV test. This difference can be attributed to flow rate behaviour (refer to Section 3.3).

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[11] During off periods the water within the radiators cools while flow continues within the heating circuit. When a smart TRV opens a large ΔT is initially measured across the radiator.

3.5 Power output

Figure 9 shows the power output from the ASHP the radiators during each 24-hour reporting period. Mean power outputs are provided in Table 12.

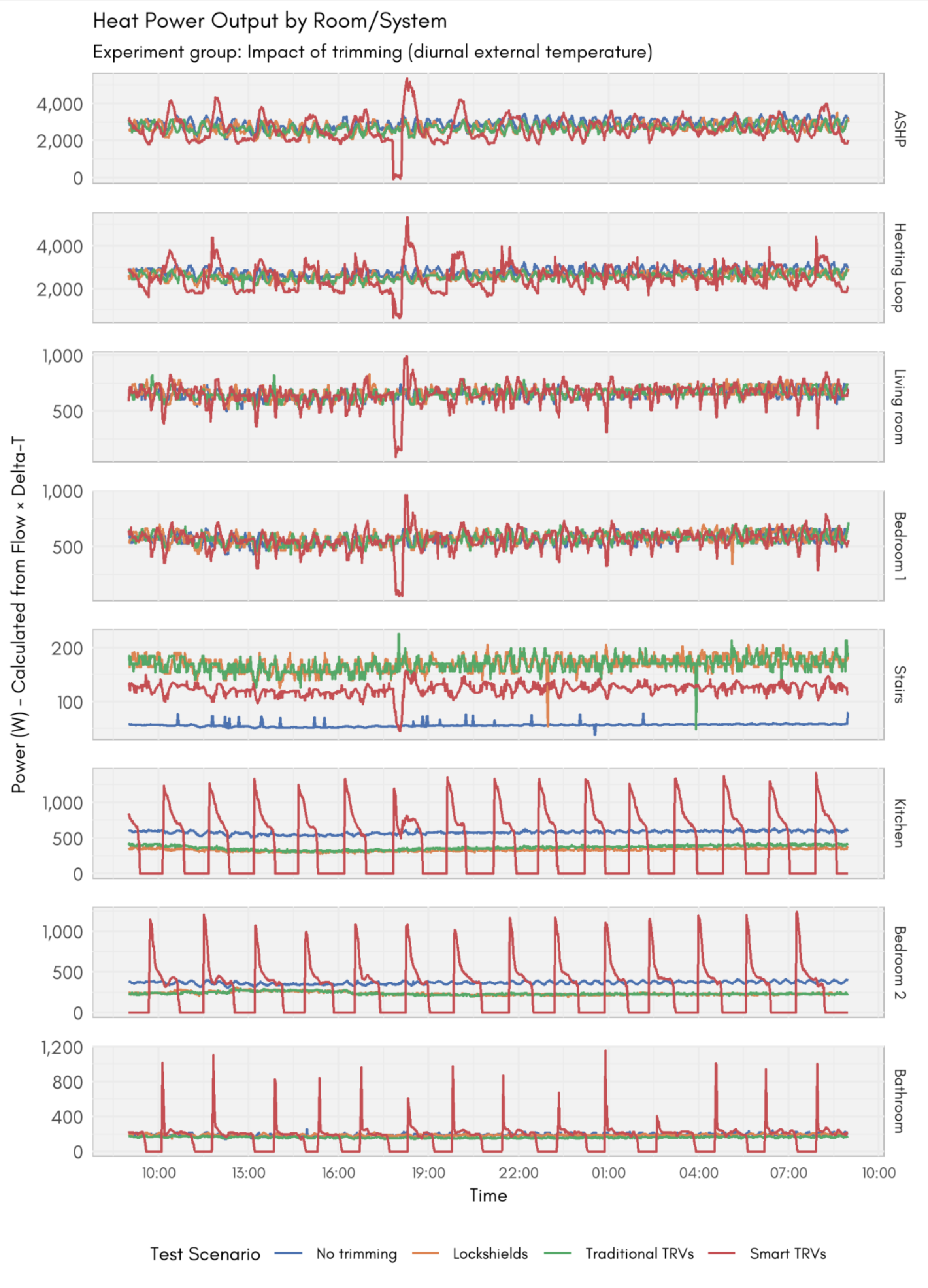

Figure 9: Impact of trimming with diurnal external temperature – ASHP and radiator power output.

Table 12: Impact of trimming with diurnal external temperature – Mean ASHP and radiator power output during periods of flow >0 m^3/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP (W)**	**Living room (W)**	**Bedroom 1 (W)**	**Stairs (W)**	***Kitchen (W)***	***Bedroom 2 (W)***	***Bathroom (W)***
No trimming	2817 ±200	569 ±235	511 ±51	57 ±4	527 ±23	304 ±15	129 ±12
Lockshields	2622 ±193 (-195 ±278) (-6.9 ±10%)	625 ±237 (+56 ±333) (+9.8 ±59%)	516 ±51 (+5 ±72) (+0.9 ±14%)	165 ±69 (+108 ±69) (+191 ±123%)	299 ±13 (-229 ±27) (-43 ±5%)	200 ±9 (-104 ±18) (-34 ±6%)	120 ±7 (-9 ±14) (-7 ±11%)
Traditional TRVs	2615 ±193 (-202 ±278) (-7.2 ±10%)	546 ±234 (-23 ±331) (-4.1 ±58%)	516 ±50 (+5 ±71) (+0.9 ±14%)	168 ±76 (+112 ±76) (+197.3 ±135%)	327 ±14 (-200 ±27) (-38 ±5%)	201 ±9 (-103 ±18) (-34 ±6%)	100 ±5 (-30 ±13) (-23 ±11%)
Smart TRVs	2574 ±190 (-243 ±276) (-8.6 ±10%)	560 ±245 (-9 ±340) (-1.6 ±60%)	511 ±49 (0 ±71) (-0.1 ±14%)	122 ±11 (+65 ±12) (+115 ±22%)	780 ±32 (+252 ±39) (+48 ±8%)	466 ±21 (+162 ±26) (+53 ±9%)	207 ±16 (+77 ±20) (+60 ±17%)

Trimming radiators with lockshields and traditional TRVs reduced their power output by between 7% and 43%. Power output from trimmed radiators in the smart TRV test was greater, however, each radiator was off for significant periods. The spike in power output when smart TRVs open is due to water cooling in the radiator during off periods, which gives a high ΔT when flow is restored[12].

Increasing flow through the stairs radiator in the lockshields and traditional TRV tests increased its output to more than the calculated 142 W required to compensate for the additional heat transfer to the trimmed zones, although a temperature reduction of 0.2 °C was measured.

When smart TRVs were not allowing flow, the power output of non-trimmed radiators increased and *vice versa*. The on/off behaviour meant that mean outputs across the 24-hour period aligned with the baseline values, except for the stairs radiator, where higher power output can be explained by modifications made to the system (refer to Section 3.3).

The sum of radiator power outputs was below that of the ASHP in each test. This can be attributed to pipework losses, which could explain some of the issues experienced during the balancing process (refer to Section 2.2.5).

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[12] Power output is calculated using heat meter flow rate and ΔT.

3.6 ASHP energy and coefficient of performance (COP)

Table 13 provides the ASHP electricity consumption, heat output, and COP_{H4} for each 24-hour reporting period.

Table 13: Impact of trimming with diurnal external temperature – ASHP energy and COP. Change from no trimming baseline shown in parenthesis.

Test	**ASHP electricity consumption (kWh)**	**ASHP heat output (kWh)**	**COP_{H4}**
No trimming	19.1 ±0.2	67.6 ±1	3.54 ±0.06
Lockshields	18.0 ±0.2 (-1.1 ±0.3 -5.9 ±1.4%)	62.9 ±1 (-4.7 ±1.4 -6.9 ±2.1%)	3.50 ±0.06 (-0.04 ±0.09 -1.0 ±2.5%)
Traditional TRVs	17.8 ±0.2 (-1.3 ±0.3 -6.7 ±1.4%)	62.7 ±1 (-4.9 ±1.4 -7.2 ±2.1%)	3.52 ±0.06 (-0.02 ±0.09 -0.5 ±2.5%)
Smart TRVs	17.6 ±0.2 (-1.5 ±0.3 -7.8 ±1.4%)	61.7 ±0.9 (-5.9 ±1.3 -8.7 ±2%)	3.50 ±0.06 (-0.03 ±0.09 -0.9 ±2.5%)

Trimming internal temperatures resulted in no significant change in COP in any scenario. Space heating energy use reductions of between 6% and 8% were measured. Figure 10 shows that reductions in energy use were proportional to reductions in the whole house internal to external ΔT.

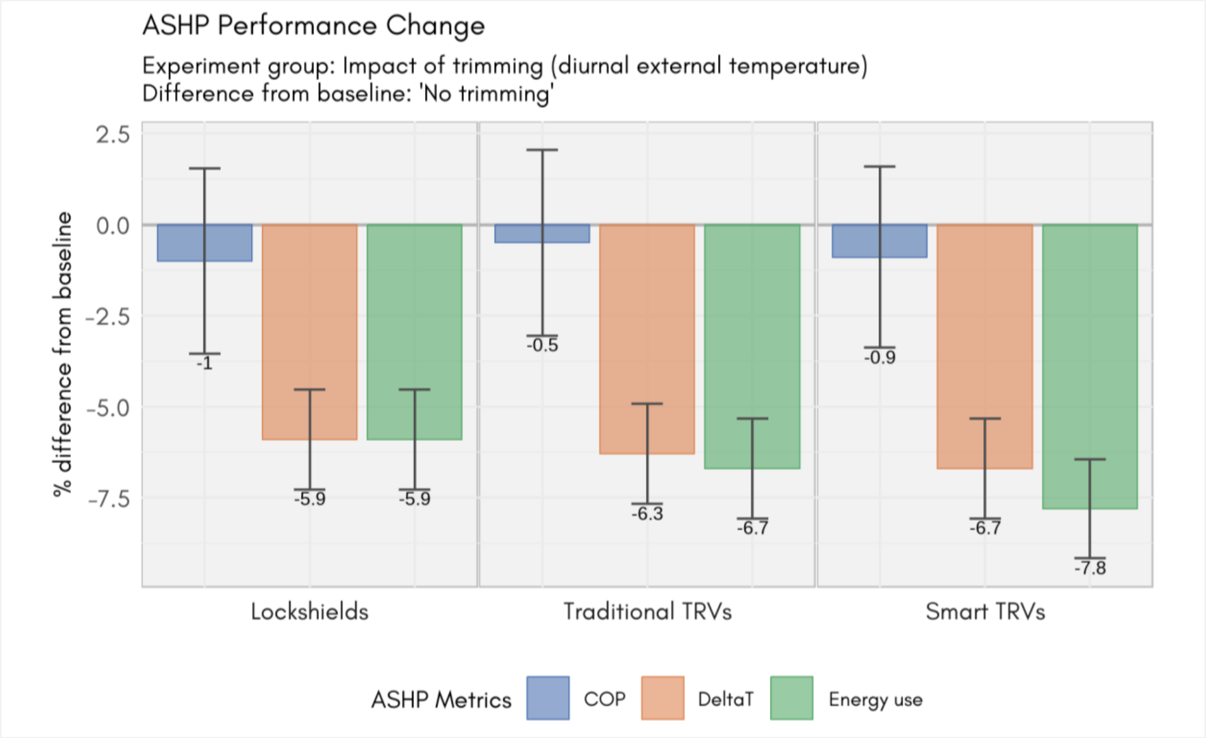


Figure 10: Impact of trimming with diurnal external temperature – Percentage change in COP, whole house internal to external ΔT, and space heating energy use.

4 Summary

Trimming internal temperatures with TRVs reduced ASHP space heating energy consumption by 6-8% and had no impact the efficiency of the ASHP. Percentage reductions in energy use were in line with the percentage reductions in the whole house internal to external temperature difference achieved using TRVs.

Traditional and smart TRVs exhibited differing characteristics, with traditional TRVs exhibiting analogue behaviour and smart TRVs exhibiting digital behaviour. The variation in flow rates caused by smart TRV on/off behaviour did not impact ASHP efficiency.

TRV use was also found to result in a reduction in the air temperatures of adjoining zones, though this unintended consequence of TRV use also applies to gas central heating systems. Maintaining a zone is below its design temperature means that radiators in adjoining zones must increase their output to compensate for the additional heat transfer within a dwelling. The tests found that TRV use increased the flow rate through other radiators on the system. This could result in additional power output elsewhere in the dwelling, which may reduce the impact of increased heat transfer between zones. Manually increasing the flow rate through radiators in the zone most directly impacted by trimming elsewhere in the dwelling could provide more effective and targeted mitigation. Though in some instances, emitter capacity in adjoining zones may be insufficient to maintain design temperature, and ASHP flow temperature may need to be increased, which would have an impact on system efficiency. Modelling may provide insight as to how TRV use redistributes radiator flow rates and heat output throughout a dwelling.

Trimming internal temperatures with traditional TRVs had a similar impact on system behaviour as trimming with lockshield valves. Although traditional TRVs are not a substitute for accurately sizing and balancing a system, they may provide occupants with a simple method to mitigate the impact of oversized radiators or those with too high a flow rate.

People with ASHP systems should be made aware that TRVs should be used as a secondary measure to reduce internal temperatures. To ensure the most efficient ASHP operation, the initial course of action should be to reduce the flow temperature until the worst performing room reaches a comfortable temperature. TRVs should then be used to trim temperatures in other rooms.

The headline finding may not be applicable to all occupancy behaviours, heating circuits and ASHPs. The use of more aggressive trimming scenarios should be assessed. This could include use of very low TRV settings on some radiators to simulate unused rooms. Such work should include exploring mitigation measures to compensate for increased heat transfer within dwellings. The radiators subject to trimming comprised a relatively low proportion of the total flow rate through the system. Trimming of radiators with a high proportion of flow rate requires further examination. Further investigation is also required to understand how TRV trimming impacts ASHPs with differing characteristics regarding minimum flow rates. Modelling of test data could provide further insight and could be used to target further research.

Appendix A – Impact of trimming (constant temperature)

Internal temperatures

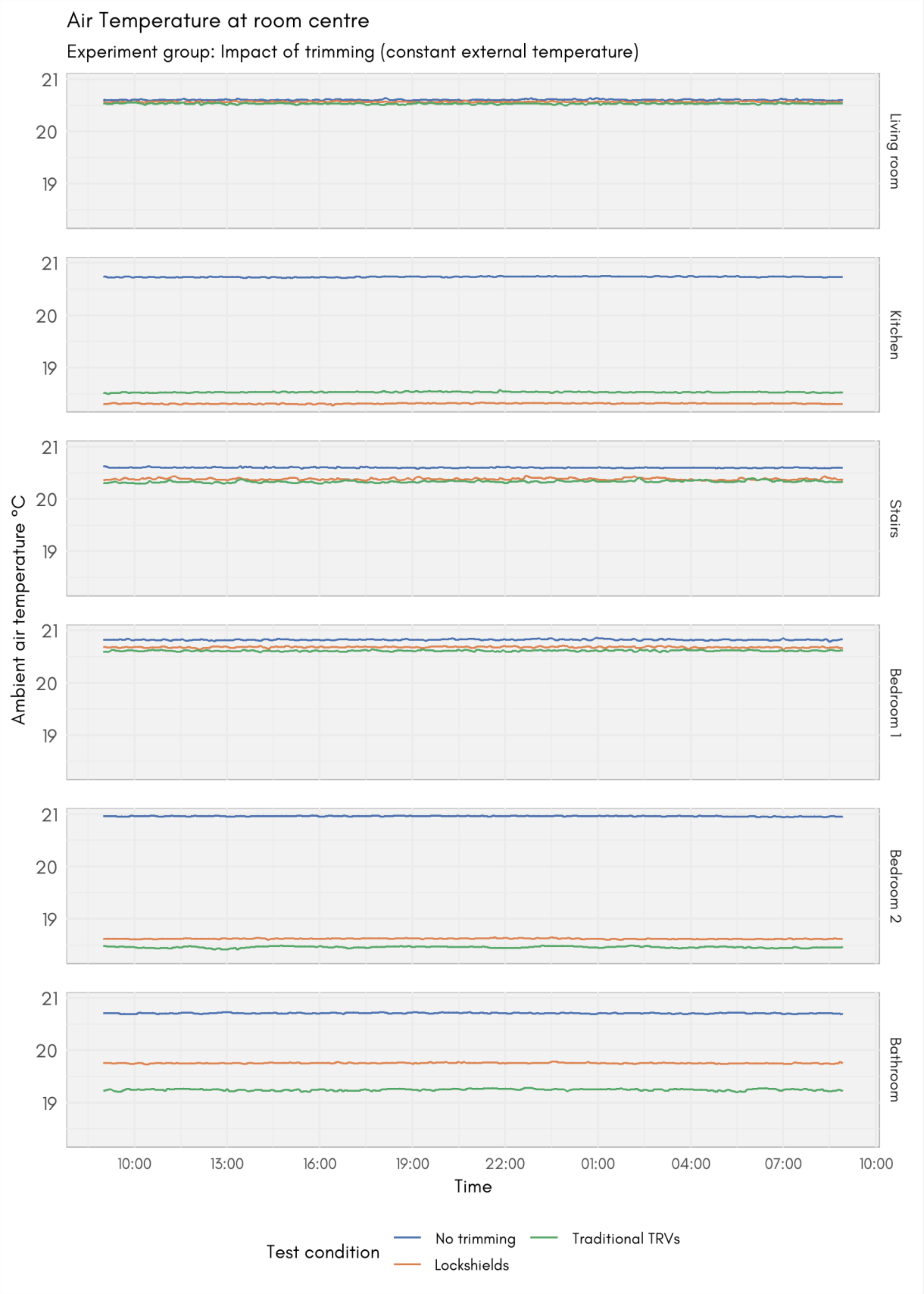


Figure A.1: Impact of trimming with constant external temperature – Internal air temperatures.

Table A.1: Impact of trimming with constant external temperature – 24-hour mean internal air temperatures. Change from no trimming baseline shown in parenthesis. Italics denotes rooms that were subject to trimming.

Test	Living room	Stairs	Bedroom 1	*Kitchen*	*Bedroom 2*	*Bathroom*
No trimming	20.6 ±0.1	20.6 ±0.1	20.8 ±0.1	20.7 ±0.1	21.0 ±0.1	20.7 ±0.1
Lockshields	20.6 ±0.1 (-0.0 ±0.1)	20.4 ±0.1 (-0.2 ±0.1)	20.7 ±0.1 (-0.1 ±0.1)	18.3 ±0.1 (-2.4 ±0.1)	18.6 ±0.1 (-2.3 ±0.1)	19.8 ±0.1 (-1.0 ±0.1)
Traditional TRVs	20.5 ±0.1 (-0.1 ±0.1)	20.3 ±0.1 (-0.3 ±0.1)	20.6 ±0.1 (-0.2 ±0.1)	18.5 ±0.1 (-2.2 ±0.1)	18.5 ±0.1 (-2.5 ±0.1)	19.2 ±0.1 (-1.5 ±0.1)

Heat pump cycling

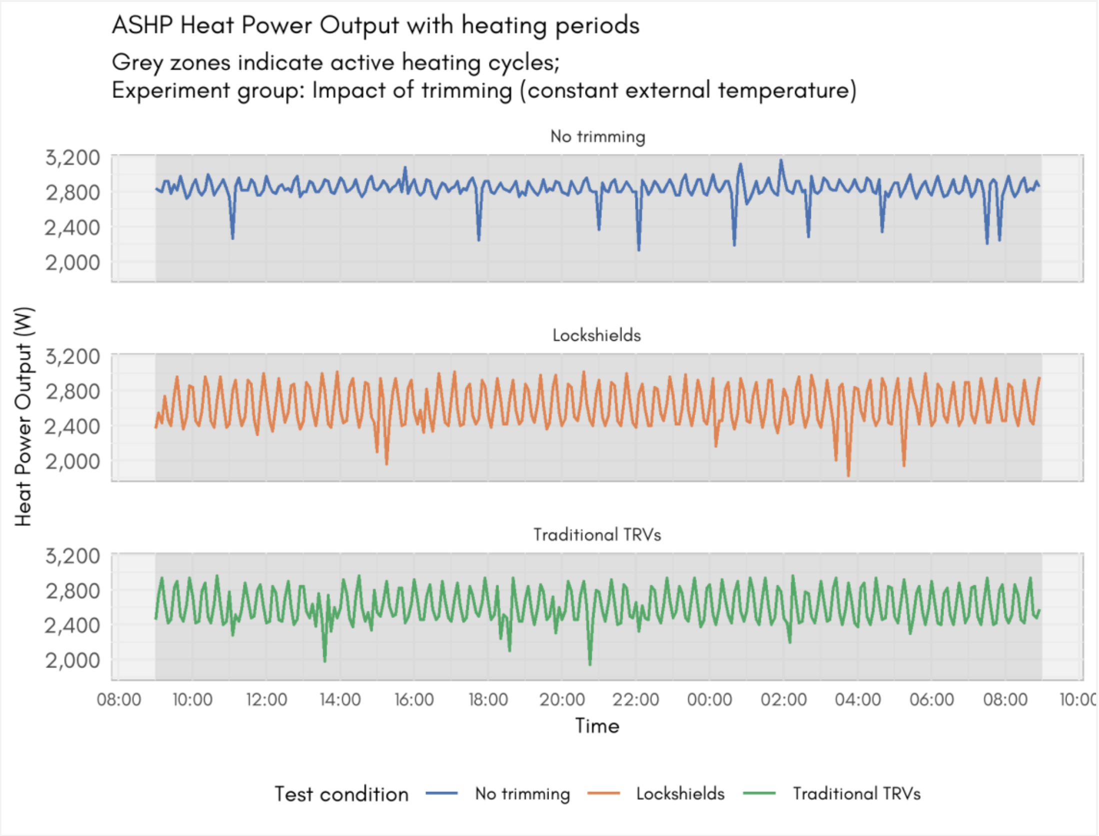


Figure A.2: Impact of trimming with constant external temperature – Heat pump cycles.

Table A.2: Impact of trimming with constant external temperature – Heat pump cycles.

Test	% Time On	Cycle #	Cycle Duration	Mean Power (W)	Median Power (W)	Max Power (W)
No trimming	100%	1	24h 0m	2,834	2,840	3,160
Lockshields	100%	1	24h 0m	2,628	2,600	3,020
Traditional TRVs	100%	1	24h 0m	2,614	2,600	2,960

Flow rates

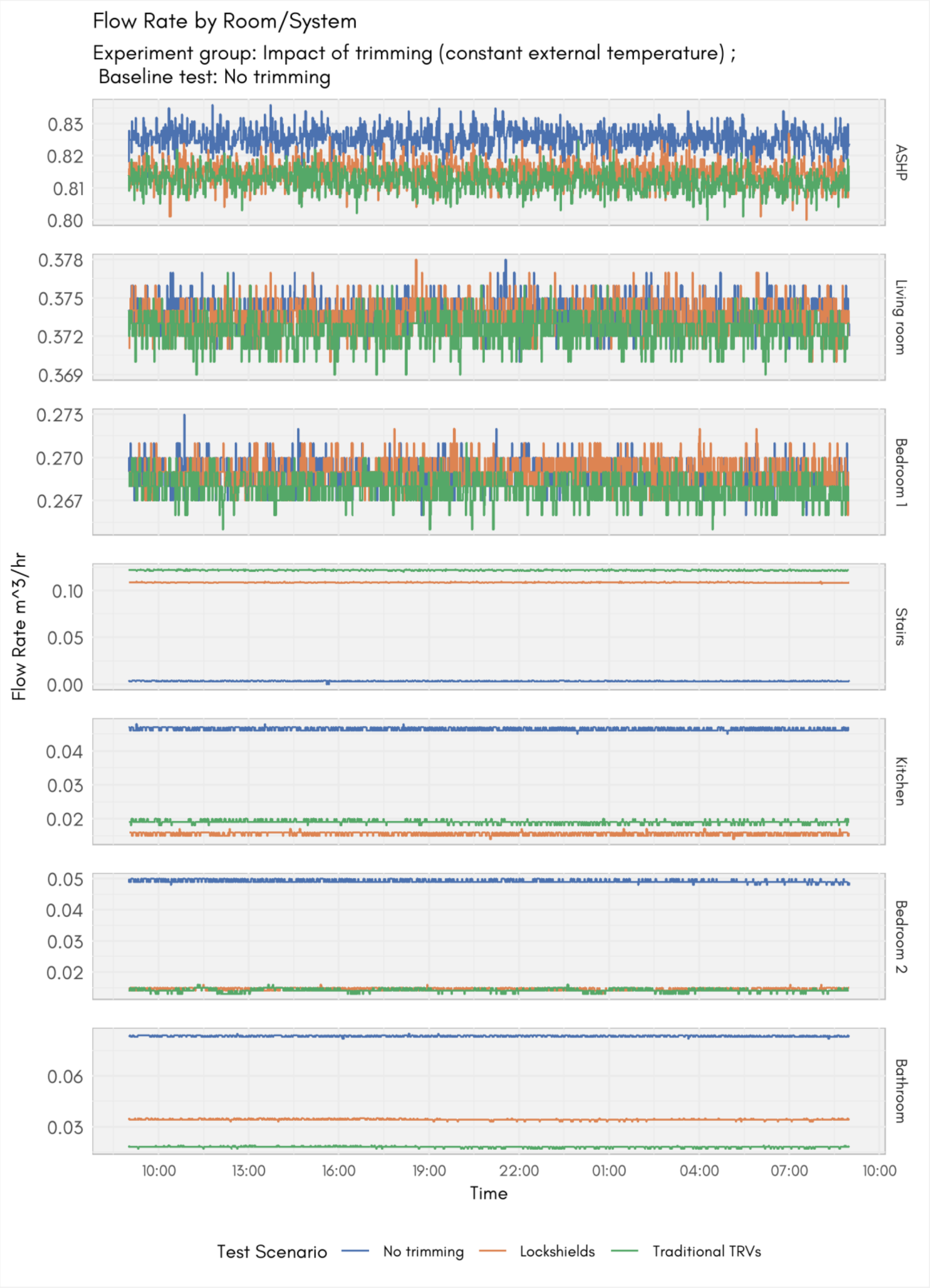


Figure A.3: Impact of trimming with constant external temperature – Flow rates.

Table A.3: Impact of trimming with constant external temperature – Mean flow rates during periods of flow >0 m³/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP Flow (m³/hr)**	**Living room Flow (m³/hr)**	**Bedroom 1 Flow (m³/hr)**	**Stairs Flow (m³/hr)**	***Kitchen Flow (m³/hr)***	***Bedroom 2 Flow (m³/hr)***	***Bathroom Flow (m³/hr)***
No trimming	0.826 ±0.017	0.374 ±0.008	0.269 ±0.005	0.003 ±<0.001	0.046 ±0.001	0.049 ±0.001	0.084 ±0.002
Lockshields	0.815 ±0.017 (-0.011 ±0.024)	0.374 ±0.008 (0 ±0.011)	0.269 ±0.006 (+0 ±0.008)	0.109 ±0.002 (+0.105 ±0.002)	0.016 ±<0.001 (-0.031 ±0.001)	0.015 ±<0.001 (-0.035 ±0.001)	0.034 ±0.001 (-0.049 ±0.002)
Traditional TRVs	0.812 ±0.017 (-0.013 ±0.024)	0.372 ±0.008 (-0.001 ±0.011)	0.268 ±0.005 (-0.001 ±0.008)	0.122 ±0.003 (+0.118 ±0.003)	0.019 ±0.001 (-0.027 ±0.001)	0.014 ±<0.001 (-0.035 ±0.001)	0.018 ±<0.001 (-0.066 ±0.002)

ASHP and radiator ΔT

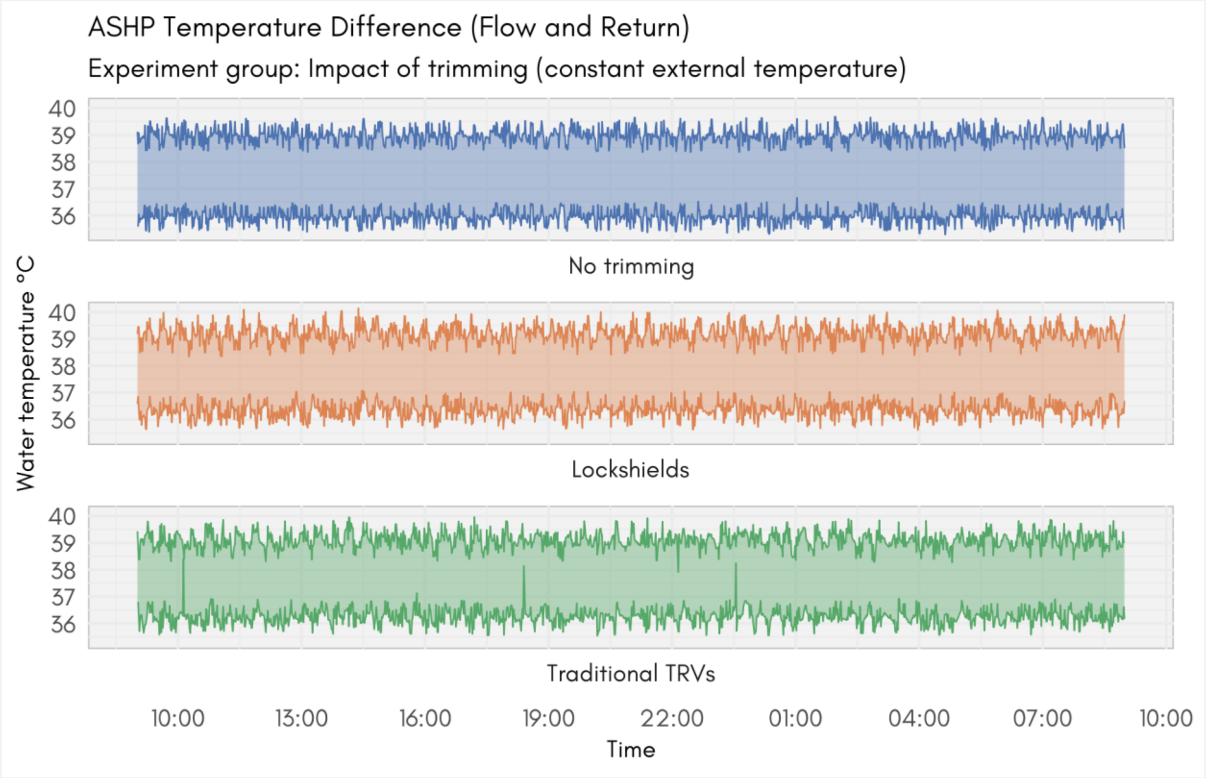


Figure A.4: Impact of trimming with constant external temperature – ASHP flow and return temperatures.

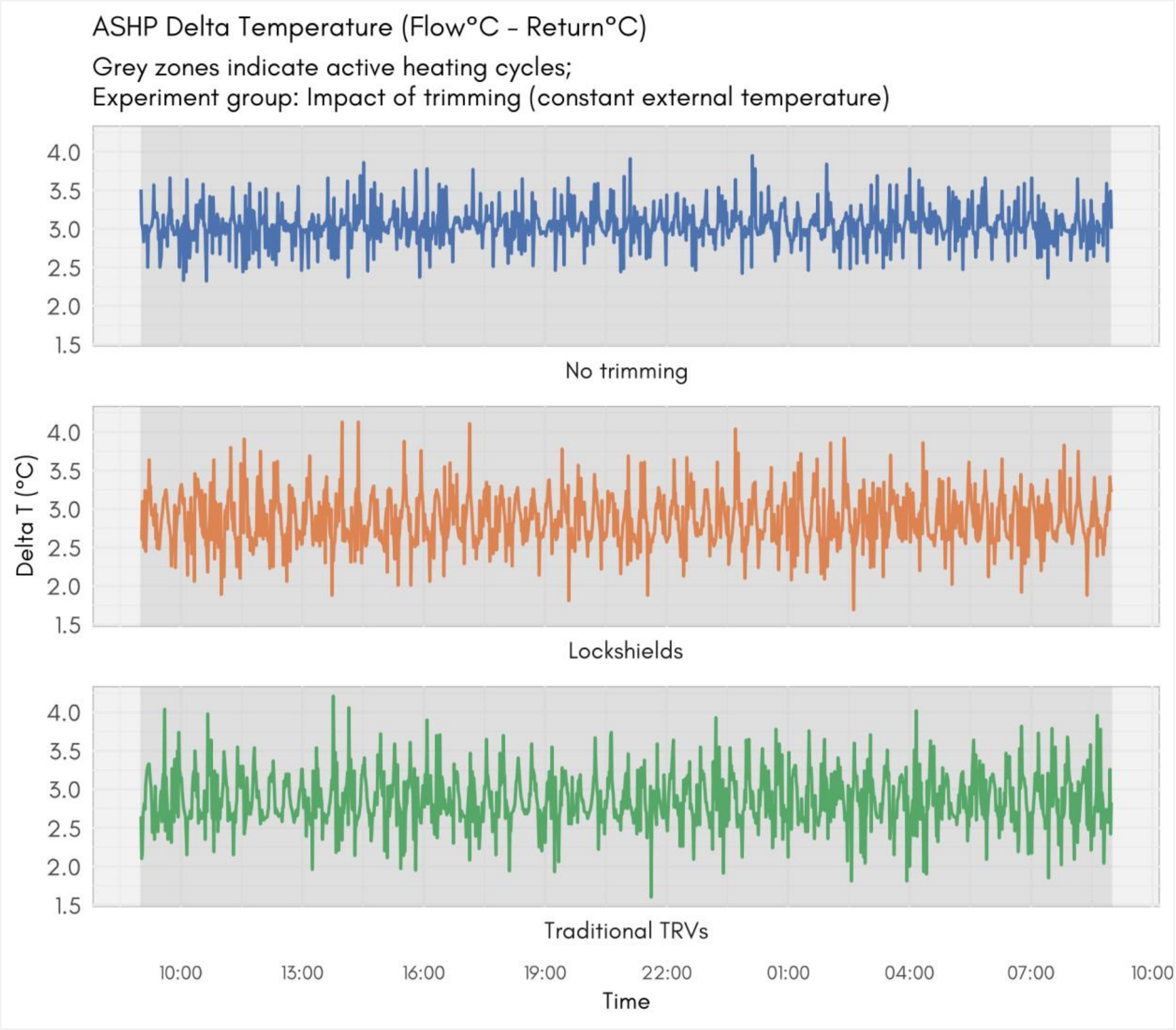


Figure A.5: Impact of trimming with constant external temperature – ASHP ΔT.

Table A.4: Impact of trimming with constant external temperature – Mean ASHP and radiator ΔT during periods of flow >0 m³/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP**	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
No trimming	3 ±0.6	1.5 ±0.5	1.8 ±0.6	15.5 ±1	10.8 ±0.8	6.4 ±0.7	1.9 ±0.6
Lockshields	2.8 ±0.6 (-0.2 ±0.8) (-7.2 ±27.4%)	1.4 ±0.5 (-0.1 ±0.8) (-8.4 ±51.4%)	1.8 ±0.6 (0 ±0.8) (-1.9 ±43.7%)	1.3 ±0.5 (-14.2 ±1.1) (-91.5 ±9.1%)	18.2 ±1 (7.4 ±1.3) (69 ±13.4%)	14.1 ±0.9 (7.7 ±1.2) (119.2 ±22%)	4.8 ±0.6 (2.8 ±0.9) (146.7 ±60.9%)
Traditional TRVs	2.8 ±0.6 (-0.3 ±0.8) (-8.4 ±27.4%)	1.3 ±0.5 (-0.2 ±0.8) (-12.5 ±51.4%)	1.8 ±0.6 (0.1 ±0.8) (2.8 ±43.8%)	1.2 ±0.5 (-14.3 ±1.1) (-92.4 ±9.1%)	16.8 ±1 (6 ±1.3) (56.2 ±12.8%)	14.2 ±0.9 (7.8 ±1.2) (120.4 ±22.1%)	7.8 ±0.7 (5.9 ±0.9) (303.2 ±99.4%)

Power output

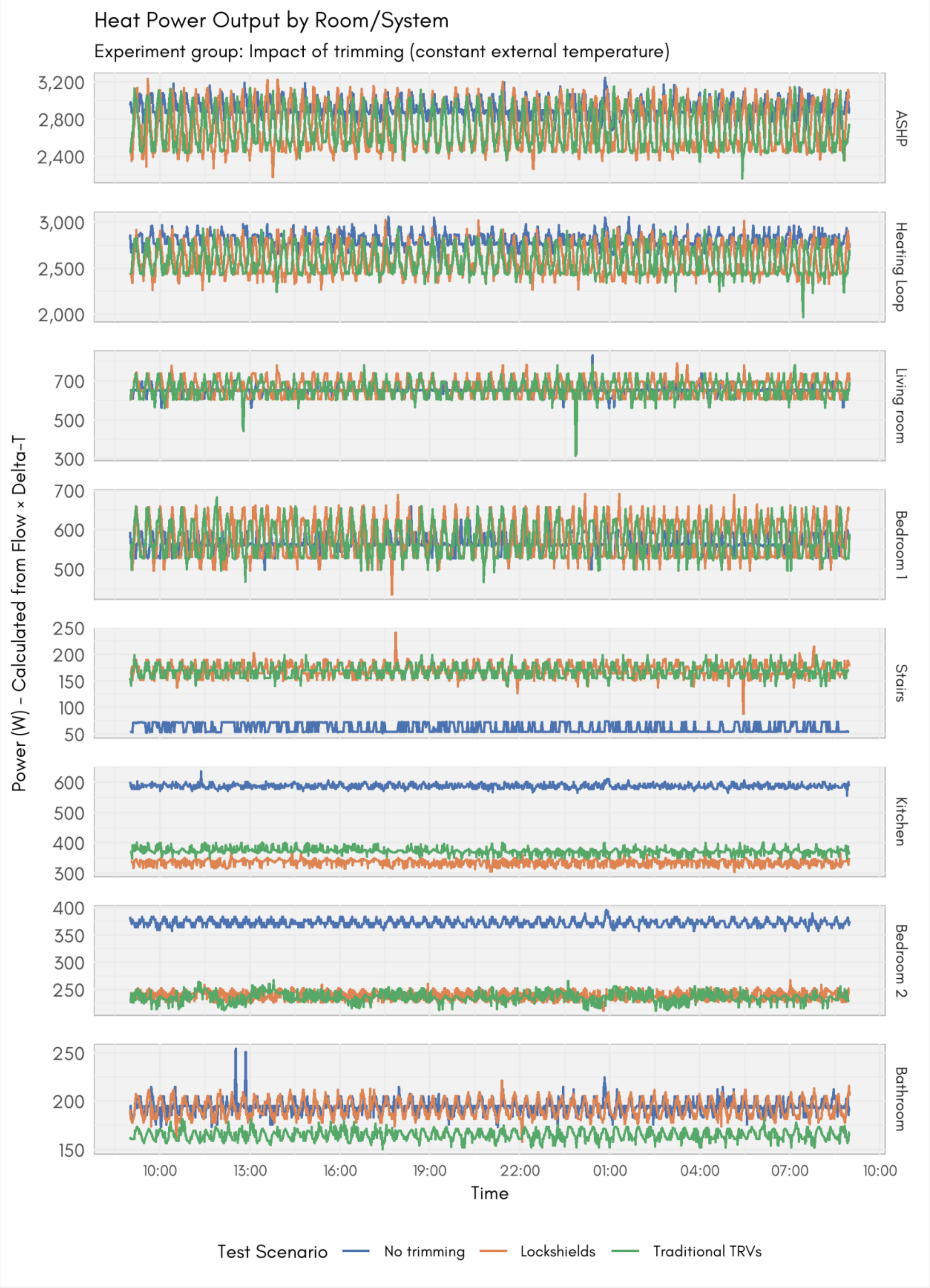


Figure A.6: Impact of trimming with constant external temperature – ASHP and radiator power output.

Table A.5: Impact of trimming constant external temperature – Mean ASHP and radiator power output during periods of flow >0 m^3/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP (W)**	**Heating Loop (W)**	**Living room (W)**	**Bedroom 1 (W)**	**Stairs (W)**	***Kitchen (W)***	***Bedroom 2 (W)***	***Bathroom (W)***
No trimming	2834 ±199	2723 ±200	650 ±237	500 ±49	62 ±5	509 ±22	299 ±15	116 ±11
Lockshields	2627 ±193 (-208 ±277) (-7.3 ±10%)	2509 ±184 (-214 ±272) (-7.8 ±10%)	595 ±235 (-55 ±334) (-8.4 ±51%)	525 ±52 (+25 ±71) (+5 ±14%)	166 ±68 (+105 ±69) (+170.3 ±112%)	300 ±13 (-209 ±26) (-41.1 ±5%)	200 ±9 (-99 ±18) (-33.2 ±6%)	129 ±8 (+13 ±13) (+11.4 ±11%)
Traditional TRVs	2614 ±193 (-220 ±278) (-7.8 ±10%)	2502 ±188 (-221 ±275) (-8.1 ±10%)	567 ±234 (-84 ±333) (-12.9 ±51%)	524 ±50 (+24 ±70) (+4.8 ±14%)	166 ±76 (+105 ±76) (+170.4 ±124%)	302 ±13 (-207 ±26) (-40.6 ±5%)	198 ±9 (-100 ±18) (-33.6 ±6%)	99 ±5 (-17 ±12) (-14.3 ±10%)

ASHP energy and COP

Table A.6: Impact of trimming with constant external temperature – ASHP energy and COP. Change from no trimming baseline shown in parenthesis.

Test	**Electrical Energy In (kWh)**	**Heat Energy Out (kWh)**	**COP$_{H4}$**
No trimming	19.0 ±0.2	68.0 ±1	3.57 ±0.06
Lockshields	18.0 ±0.2 (-1.1 ±0.3 -5.6 ±1.4%)	63.0 ±1 (-5.0 ±1.4 -7.3 ±2.1%)	3.51 ±0.06 (-0.06 ±0.09 -1.8 ±2.5%)
Traditional TRVs	17.9 ±0.2 (-1.2 ±0.3 -6.1 ±1.4%)	62.8 ±1 (-5.2 ±1.4 -7.7 ±2%)	3.51 ±0.06 (-0.06 ±0.09 -1.7 ±2.5%)

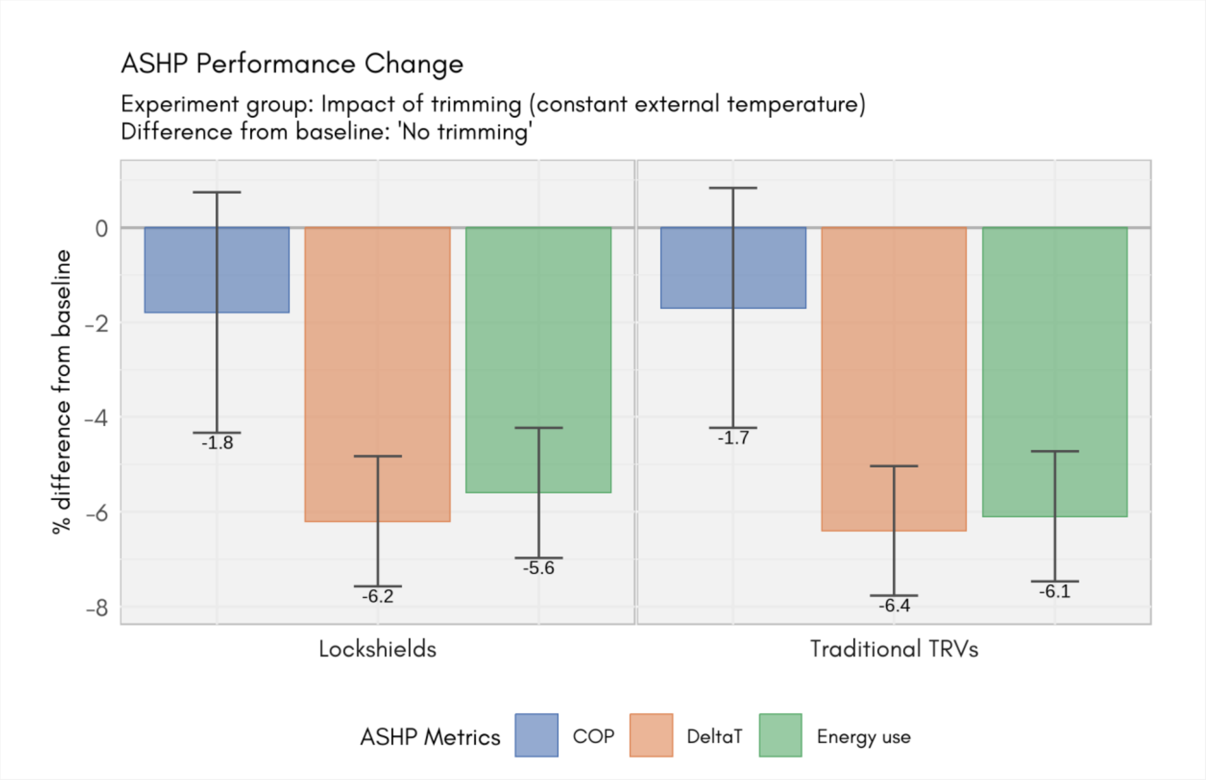


Figure A.7: Impact of trimming with constant external temperature – Percentage change in COP, whole house internal to external ΔT, and space heating energy use.

Summary

Internal temperatures over each 24 hour period with a constant external temperature were more stable than those experienced with a diurnal temperature pattern, though this difference was not related to trimming (refer to Appendix D). Otherwise, there was no notable difference in system behaviour from that observed with a diurnal temperature pattern (refer to the main body of the report).

Appendix B – Setback temperature pattern

B1 – Impact of setback between heating periods

Internal temperatures

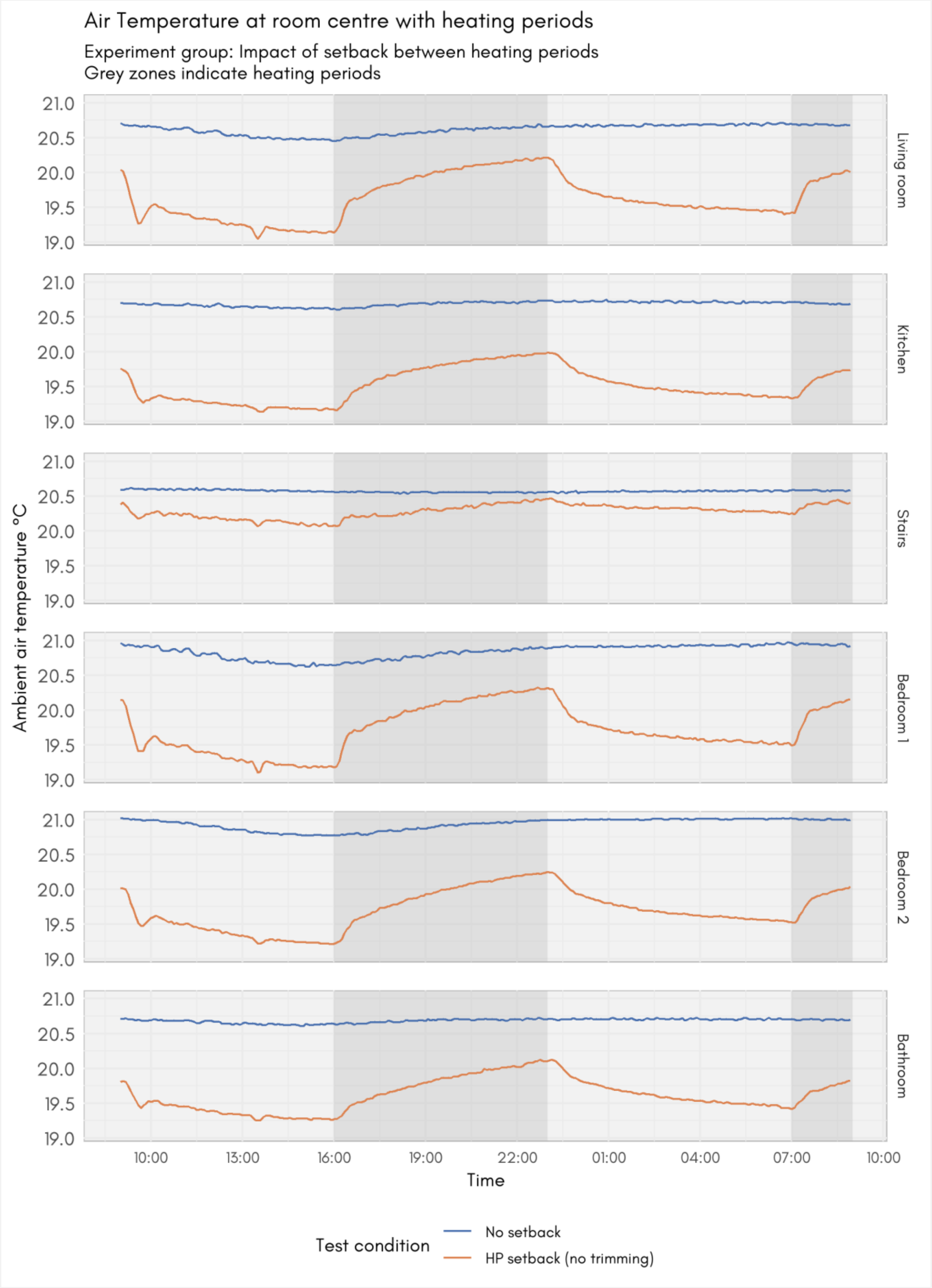


Figure B1.1: Impact of setback between heating periods - Internal air temperatures

Table B1.1: Impact of setback between heating periods – 24-hour mean internal air temperatures. Change from no setback baseline shown in parenthesis.

Test	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
No setback	20.6 ±0.1	20.8 ±0.1	20.6 ±0.1	20.7 ±0.1	20.9 ±0.1	20.7 ±0.1
HP setback (no trimming)	19.6 ±0.1 (-1.0 ±0.1)	19.7 ±0.1 (-1.1 ±0.1)	20.3 ±0.1 (-0.3 ±0.1)	19.5 ±0.1 (-1.2 ±0.1)	19.7 ±0.1 (-1.2 ±0.1)	19.6 ±0.1 (-1.1 ±0.1)

Table B1.2: Impact of setback between heating periods - Mean internal air temperatures, heating periods only. Change from no setback baseline shown in parenthesis.

Test	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
No setback	20.6 ±0.1	20.8 ±0.1	20.6 ±0.1	20.7 ±0.1	20.9 ±0.1	20.7 ±0.1
HP setback (no trimming)	19.9 ±0.1 (-0.7 ±0.1)	20.0 ±0.1 (-0.8 ±0.1)	20.3 ±0.1 (-0.2 ±0.1)	19.7 ±0.1 (-1.0 ±0.1)	19.9 ±0.1 (-1.0 ±0.1)	19.8 ±0.1 (-0.9 ±0.1)

Heat pump cycling

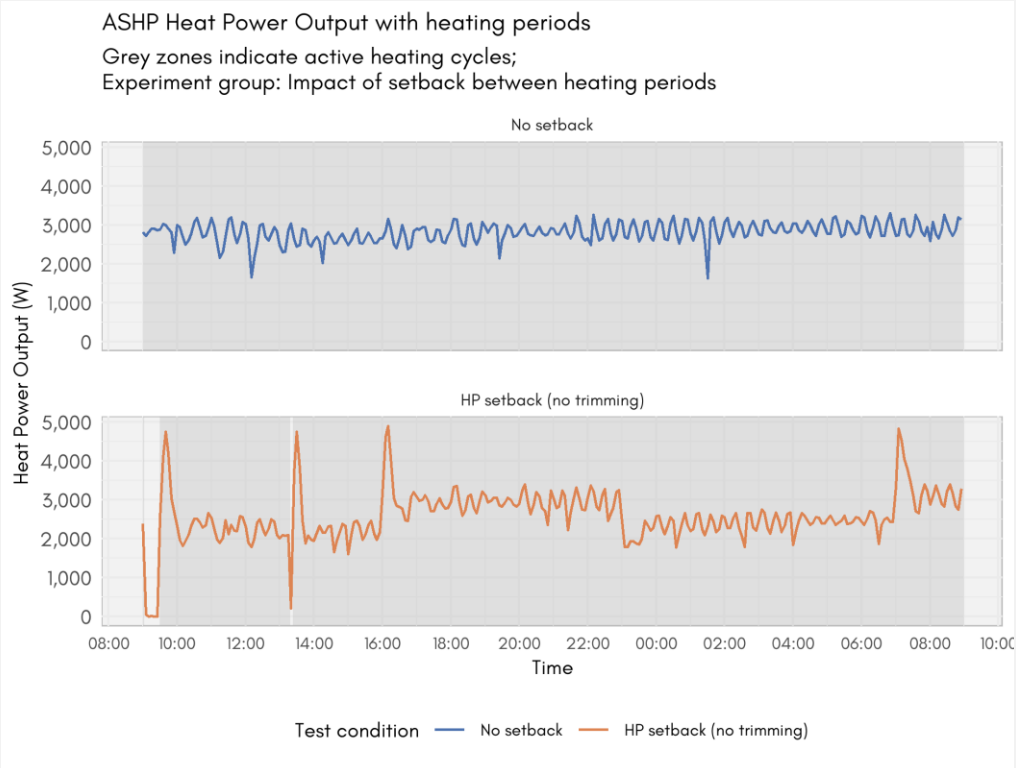


Figure B1.2: Impact of setback between heating periods – Heat pump cycles

Table B1.3: Impact of setback between heating periods – Heat pump cycles

Test	% Time On	Cycle #	Cycle Duration	Mean Power (W)	Median Power (W)	Max Power (W)
No setback	100%	1	24h 0m	2,816	2,820	3,300
HP setback (no trimming)	98%	1	3h 50m	2,407	2,310	4,760
		2	19h 35m	2,690	2,640	4,900

Flow rates

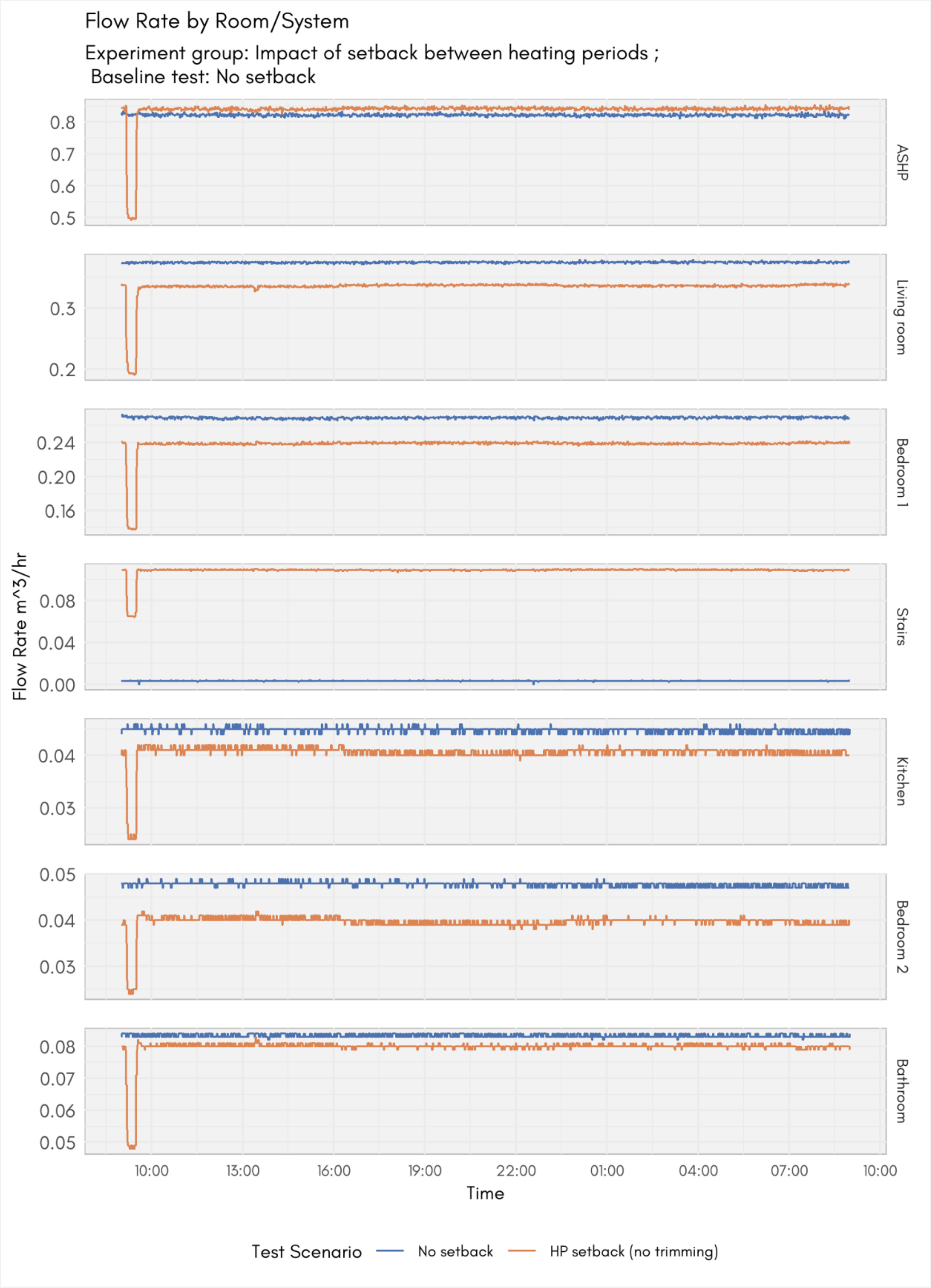


Figure B1.3: Impact of setback between heating periods - Flow rates

Table B1.4: Impact of setback between heating periods – Mean flow rates during periods of flow >0 m3/h. Change from no setback baseline shown in parenthesis.

Test	ASHP Flow (m³/hr)	Living room Flow (m³/hr)	Bedroom 1 Flow (m³/hr)	Stairs Flow (m³/hr)	Kitchen Flow (m³/hr)	Bedroom 2 Flow (m³/hr)	Bathroom Flow (m³/hr)
No setback	0.822 ±0.017	0.374 ±0.008	0.269 ±0.005	0.003 ±<0.001	0.045 ±0.001	0.048 ±0.001	0.083 ±0.002
HP setback (no trimming)	0.837 ±0.017 (+0.015 ±0.024)	0.334 ±0.007 (-0.04 ±0.01)	0.238 ±0.005 (-0.031 ±0.007)	0.109 ±0.002 (+0.106 ±0.002)	0.041 ±0.001 (-0.004 ±0.001)	0.04 ±0.001 (-0.008 ±0.001)	0.08 ±0.002 (-0.004 ±0.002)

ASHP and radiator ΔT

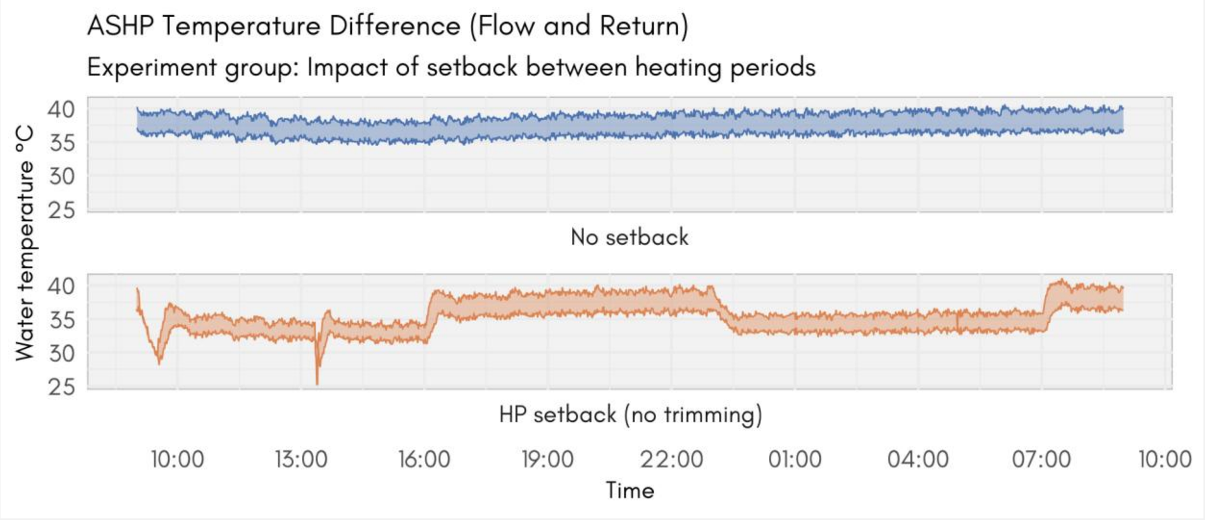


Figure B1.4: Impact of setback between heating periods – ASHP flow and return temperatures.

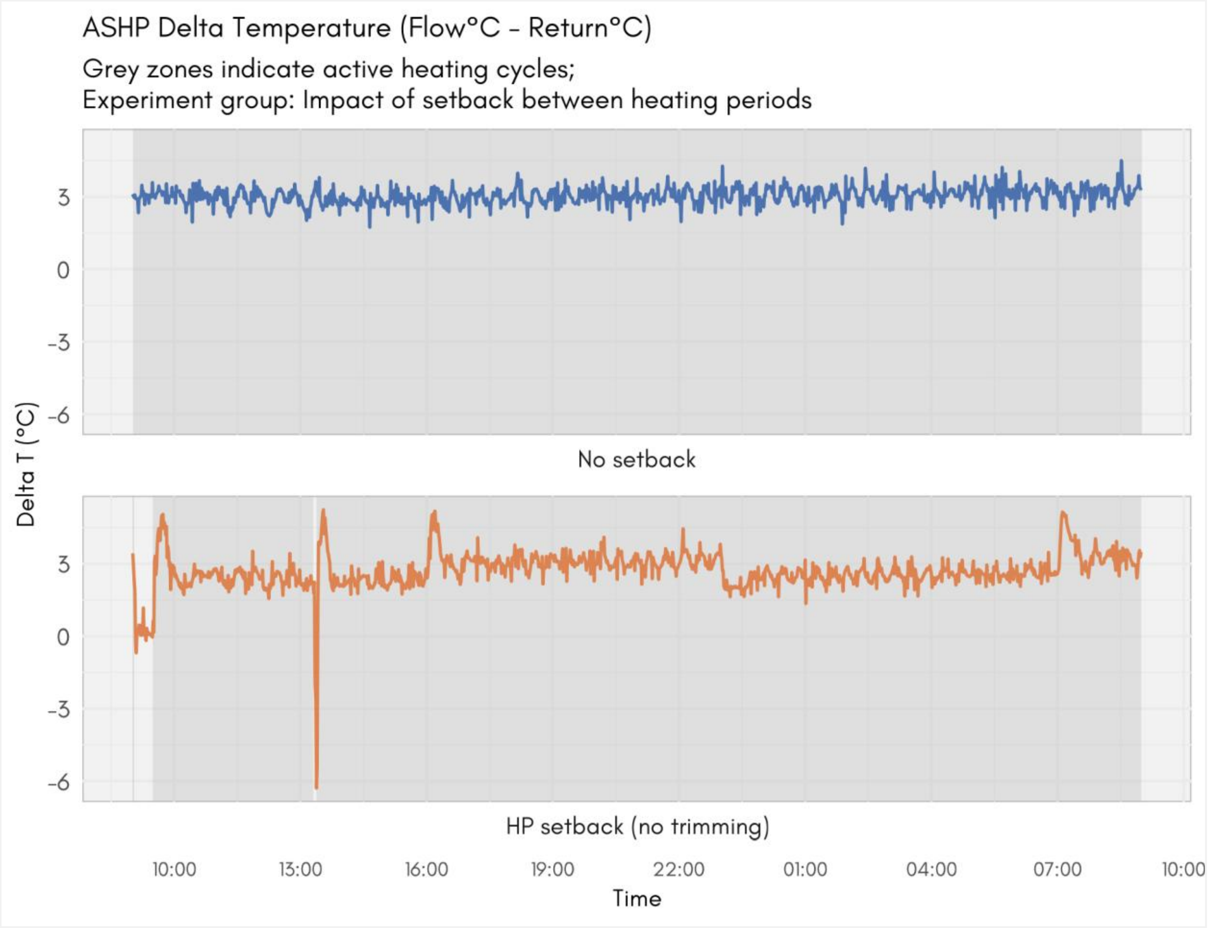


Figure B1.5: Impact of setback between heating periods - ASHP ΔT.

Table B1.5: Impact of setback between heating periods - Mean ASHP and radiator ΔT during periods of flow >0 m^3/h. Change from no setback baseline shown in parenthesis.

Test	ASHP	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
No setback	3 ±0.6	1.3 ±0.5	1.7 ±0.6	15.9 ±1	11 ±0.8	6.5 ±0.7	1.9 ±0.6
HP setback (no trimming)	2.6 ±0.6 (-0.4 ±0.8) (-14.6 ±27.8%)	1.4 ±0.5 (0.1 ±0.8) (10 ±58.7%)	1.8 ±0.6 (0 ±0.8) (2 ±44.7%)	1.1 ±0.5 (-14.9 ±1.1) (-93.3 ±9%)	10.7 ±0.8 (-0.3 ±1.2) (-2.4 ±10.6%)	6.9 ±0.7 (0.4 ±1) (6 ±15.2%)	1.8 ±0.6 (-0.1 ±0.8) (-5.9 ±41.6%)

Power output

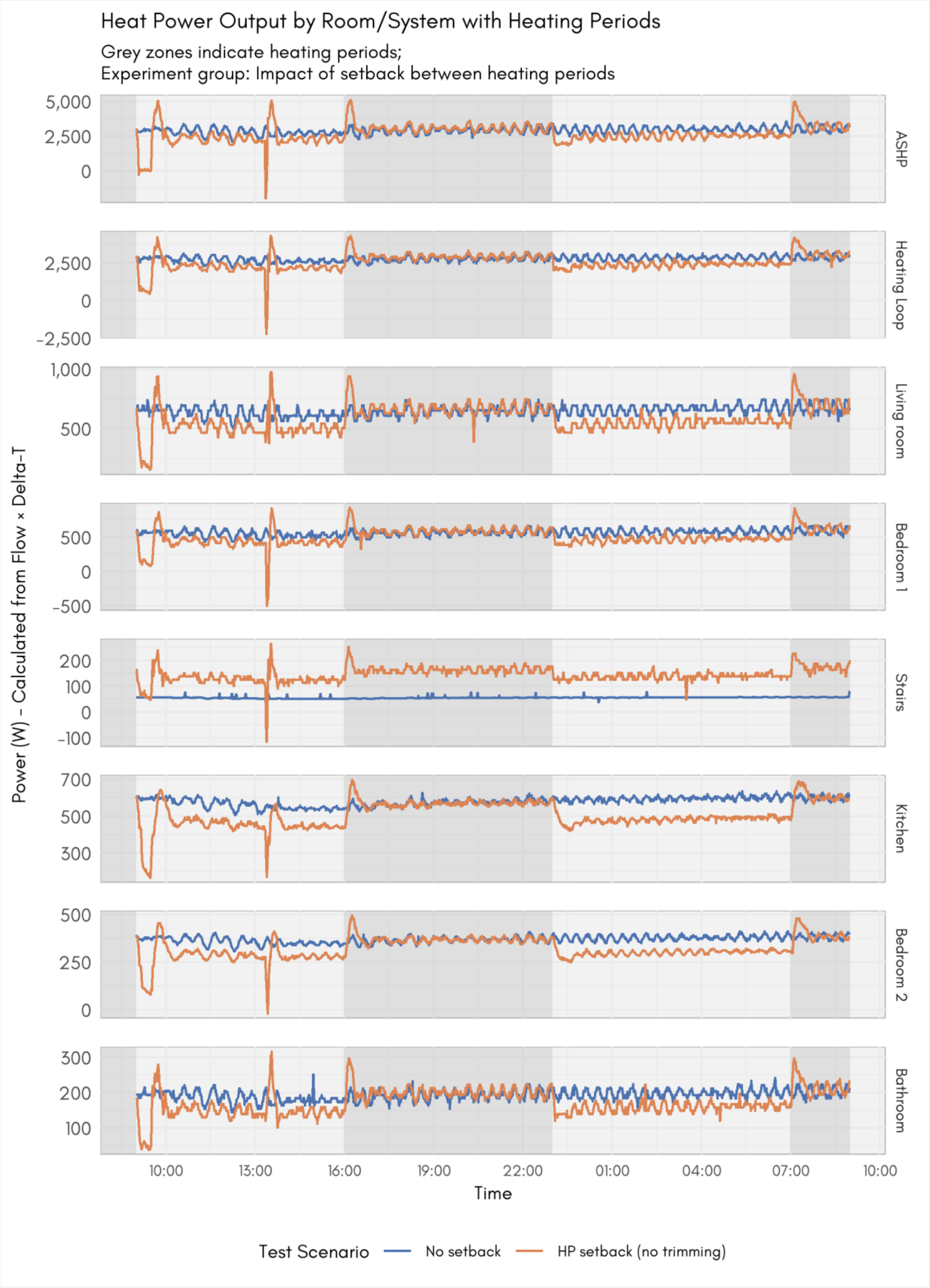


Figure B1.6: Impact of setback between heating periods - ASHP and radiator power output.

Table B1.6: Impact of setback between heating periods – Mean ASHP and radiator power output during periods of flow >0 m³/h. Change from no setback baseline shown in parenthesis.

Test	**ASHP (W)**	**Heating Loop (W)**	**Living room (W)**	**Bedroom 1 (W)**	**Stairs (W)**	**Kitchen (W)**	**Bedroom 2 (W)**	**Bathroom (W)**
No setback	2817 ±200	2698 ±195	569 ±235	511 ±51	57 ±4	527 ±23	304 ±15	129 ±12
HP setback (no trimming)	2587 ±201 (-230 ±284) (-8.2 ±10%)	2471 ±192 (-226 ±273) (-8.4 ±10%)	561 ±212 (-8 ±317) (-1.4 ±56%)	449 ±44 (-62 ±67) (-12.2 ±13%)	135 ±67 (+79 ±67) (+138.8 ±120%)	448 ±20 (-80 ±30) (-15.1 ±6%)	269 ±14 (-34 ±21) (-11.3 ±7%)	120 ±12 (-10 ±17) (-7.5 ±13%)

ASHP energy and COP

Table B1.7: Impact of setback between heating periods – ASHP energy and COP. Change from no setback baseline shown in parenthesis.

Test	**Electrical Energy In (kWh)**	**Heat Energy Out (kWh)**	**COP_{H4}**
No setback	19.1 ±0.2	67.6 ±1	3.54 ±0.06
HP setback (no trimming)	17.3 ±0.2 (-1.8 ±0.3 -9.5 ±1.4%)	62.0 ±0.9 (-5.6 ±1.4 -8.3 ±2%)	3.58 ±0.06 (+0.05 ±0.09 +1.3 ±2.5%)

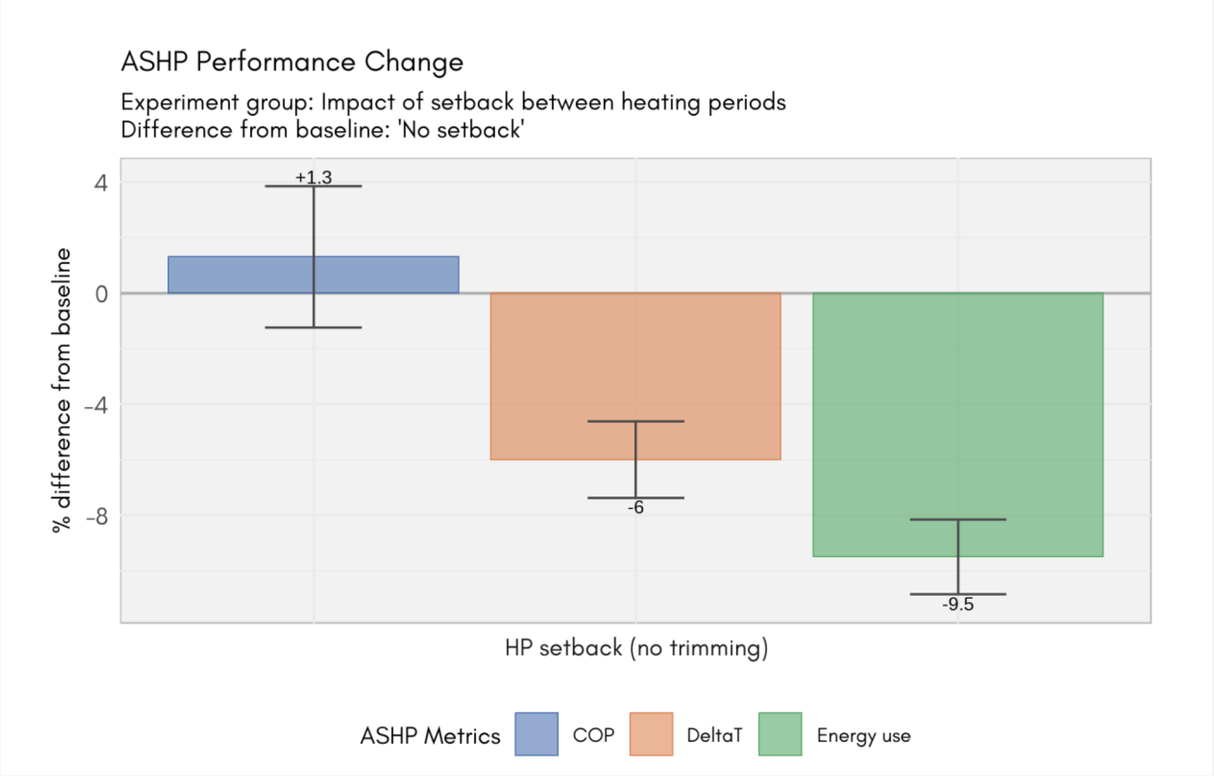


Figure B1.7: Impact of setback between heating periods – Percentage change in COP, whole house internal to external ΔT, and space heating energy use.

Summary (Appendix B1)

Programming the heat pump with a setback setpoint between heating periods also reduced the internal temperature outside of the setback periods. This was due to a combination of using weather compensation control without any room influence and the close alignment between the weather compensation curve and the heat loss of the Energy House. Therefore, the ASHP flow temperature is only sufficient to maintain the setpoint rather than increase the setpoint. This shows that some room compensation is required for setback heating patterns in situations where the weather compensation curve closely aligns with fabric thermal performance.

Although the setback significantly reduced energy use, the reduction in heating period temperatures means that it is not robust to compare energy use with tests in which setpoints were achieved during heating periods, as occupants would experience notably lower temperatures. The setback heating test with no trimming does, however, provide a baseline to assess TRV use with a setback heating pattern (Appendix B2.). Despite the ASHP producing a lower flow temperature during the 15 hours with a setback setpoint, there was no significant change in COP across the 24-hour period.

B2 – Setback tests

Internal temperature

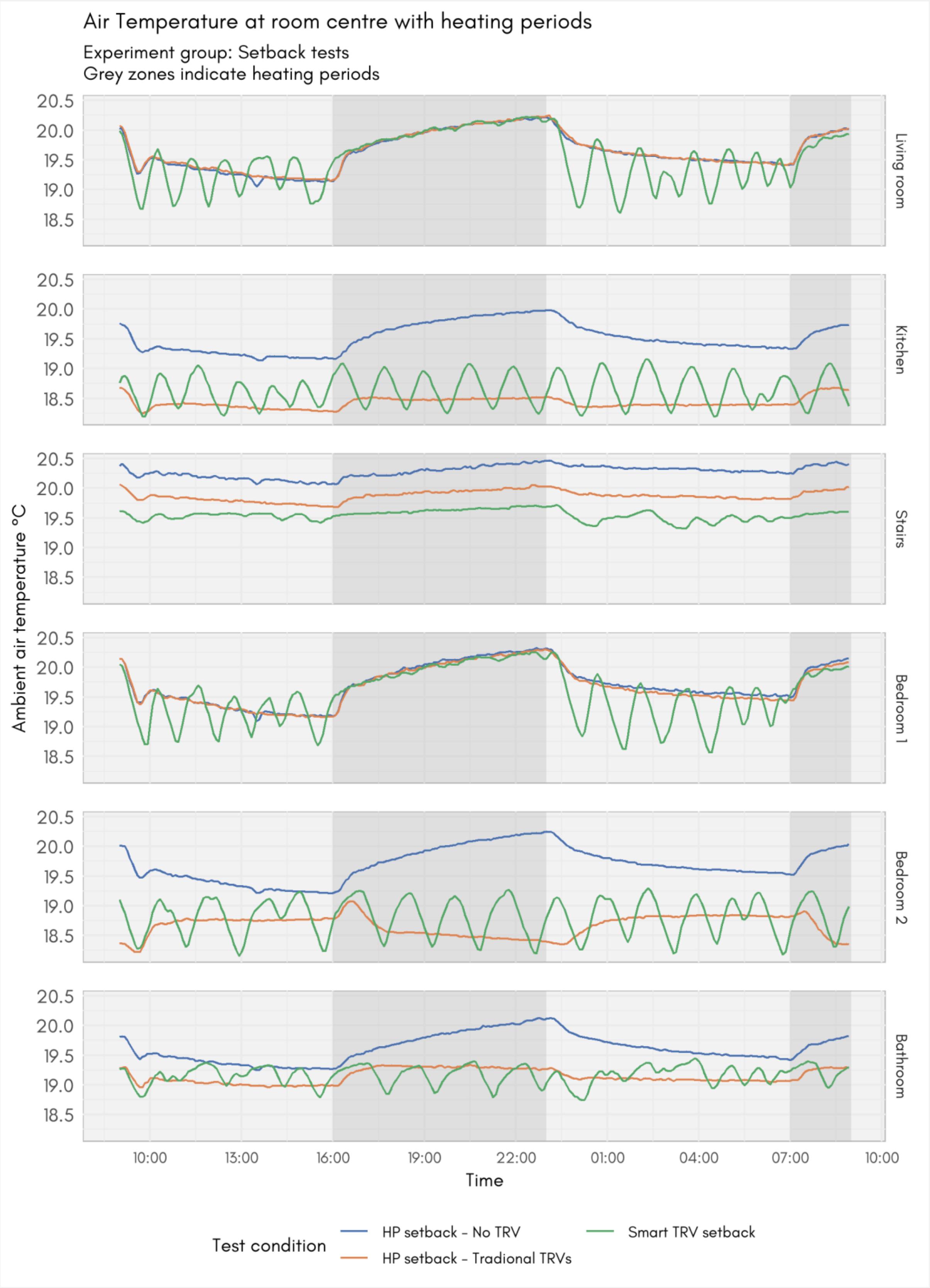


Figure B2.1: Setback tests – Internal air temperatures

Table B2.1: Setback tests – 24-hour mean internal air temperatures. Change from no TRV baseline shown in parenthesis. Italics denotes rooms that were subject to trimming.

Test	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
HP setback - No TRV	19.6 ±0.1	19.7 ±0.1	20.3 ±0.1	19.5 ±0.1	19.7 ±0.1	19.6 ±0.1
HP setback - Traditional TRVs	19.7 ±0.1 (+0.0 ±0.1)	19.7 ±0.1 (-0.0 ±0.1)	19.9 ±0.1 (-0.4 ±0.1)	18.4 ±0.1 (-1.1 ±0.1)	18.7 ±0.1 (-1.0 ±0.1)	19.1 ±0.1 (-0.5 ±0.1)
Smart TRV setback	19.5 ±0.1 (-0.1 ±0.1)	19.5 ±0.1 (-0.2 ±0.1)	19.5 ±0.1 (-0.7 ±0.1)	18.6 ±0.1 (-0.9 ±0.1)	18.8 ±0.1 (-0.9 ±0.1)	19.2 ±0.1 (-0.5 ±0.1)

Table B2.2: Setback tests temperature – Mean internal air temperatures during heating periods. Change from no TRV baseline shown in parenthesis. Italics denotes rooms that were subject to trimming.

Test	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
HP setback - No TRV	19.9 ±0.1	20.0 ±0.1	20.3 ±0.1	19.7 ±0.1	19.9 ±0.1	19.8 ±0.1
HP setback - Traditional TRVs	19.9 ±0.1 (+0.0 ±0.1)	20.0 ±0.1 (-0.0 ±0.1)	19.9 ±0.1 (-0.4 ±0.1)	18.5 ±0.1 (-1.2 ±0.1)	18.6 ±0.1 (-1.3 ±0.1)	19.3 ±0.1 (-0.5 ±0.1)
Smart TRV setback	19.9 ±0.1 (-0.0 ±0.1)	20.0 ±0.1 (-0.0 ±0.1)	19.6 ±0.1 (-0.7 ±0.1)	18.7 ±0.1 (-1.0 ±0.1)	18.8 ±0.1 (-1.1 ±0.1)	19.2 ±0.1 (-0.6 ±0.1)

Heat pump cycling

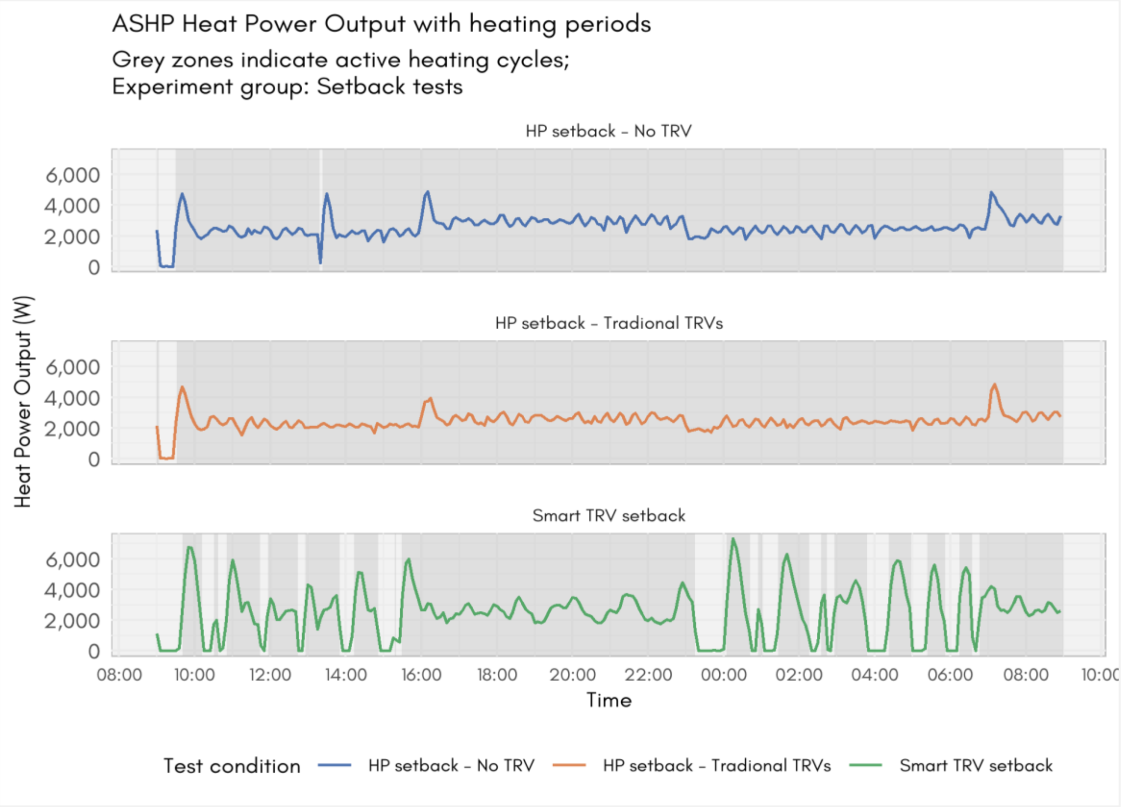


Figure B2.2: Setback tests – Heat pump cycles

Table B2.3: Setback tests – Heat pump cycles

Test	% Time On	Cycle #	Cycle Duration	Mean Power (W)	Median Power (W)	Max Power (W)
HP setback - No TRV	98%	1	3h 50m	2,407	2,310	4,760
		2	19h 35m	2,690	2,640	4,900
HP setback - Traditional TRVs	98.1%	1	23h 30m	2,481	2,420	4,880
Smart TRV setback	74.3%	1	0h 30m	5,063	5,400	6,780
		2	0h 5m	2,020	2,020	2,020
		3	0h 55m	3,429	3,140	5,920
		4	0h 45m	2,596	2,600	3,400
		5	0h 55m	2,906	2,840	4,300
		6	0h 40m	3,450	3,290	5,120
		7	7h 45m	2,762	2,600	5,980
		8	0h 35m	4,515	4,720	7,320
		9	0h 5m	2,230	2,230	2,700
		10	0h 50m	3,738	3,790	6,320
		11	0h 10m	3,390	3,390	3,640
		12	0h 50m	3,532	3,500	4,600
		13	0h 35m	4,674	4,760	5,880
		14	0h 30m	3,851	3,838	5,625
		15	0h 20m	4,720	5,000	5,420
		16	2h 15m	2,985	2,720	4,220

Flow rates

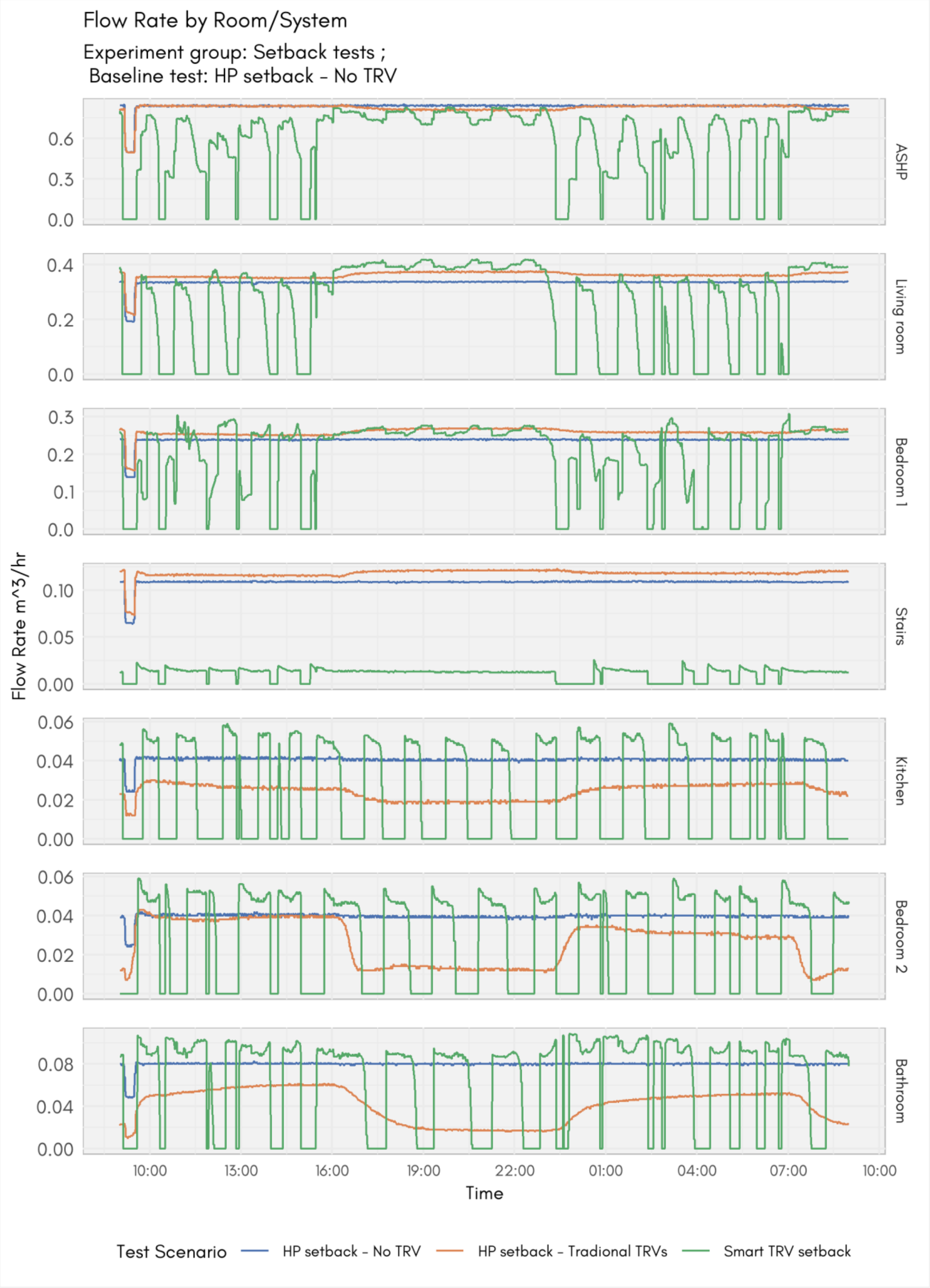


Figure B2.3: Setback tests – Flow rates.

Table B2.4: Setback tests – Mean flow rates during periods of flow >0 m3/h. Change from no setback baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	ASHP Flow (m^3/hr)	Living room Flow (m^3/hr)	Bedroom 1 Flow (m^3/hr)	Stairs Flow (m^3/hr)	*Kitchen Flow (m^3/hr)*	*Bedroom 2 Flow (m^3/hr)*	*Bathroom Flow (m^3/hr)*
HP setback - No TRV	0.837 ±0.017	0.334 ±0.007	0.238 ±0.005	0.109 ±0.002	0.041 ±0.001	0.04 ±0.001	0.08 ±0.002
HP setback - Traditional TRVs	0.826 ±0.017 (-0.011 ±0.025)	0.361 ±0.007 (+0.027 ±0.01)	0.259 ±0.005 (+0.021 ±0.007)	0.118 ±0.002 (+0.009 ±0.003)	0.024 ±0.001 (-0.016 ±0.001)	0.026 ±0.001 (-0.013 ±0.001)	0.041 ±0.001 (-0.039 ±0.002)
Smart TRV setback	0.676 ±0.014 (-0.161 ±0.022)	0.342 ±0.007 (+0.008 ±0.01)	0.232 ±0.005 (-0.006 ±0.007)	0.014 ±<0.001 (-0.095 ±0.002)	0.049 ±0.001 (+0.009 ±0.001)	0.048 ±0.001 (+0.009 ±0.001)	0.091 ±0.002 (+0.011 ±0.003)

ASHP and radiator ΔT

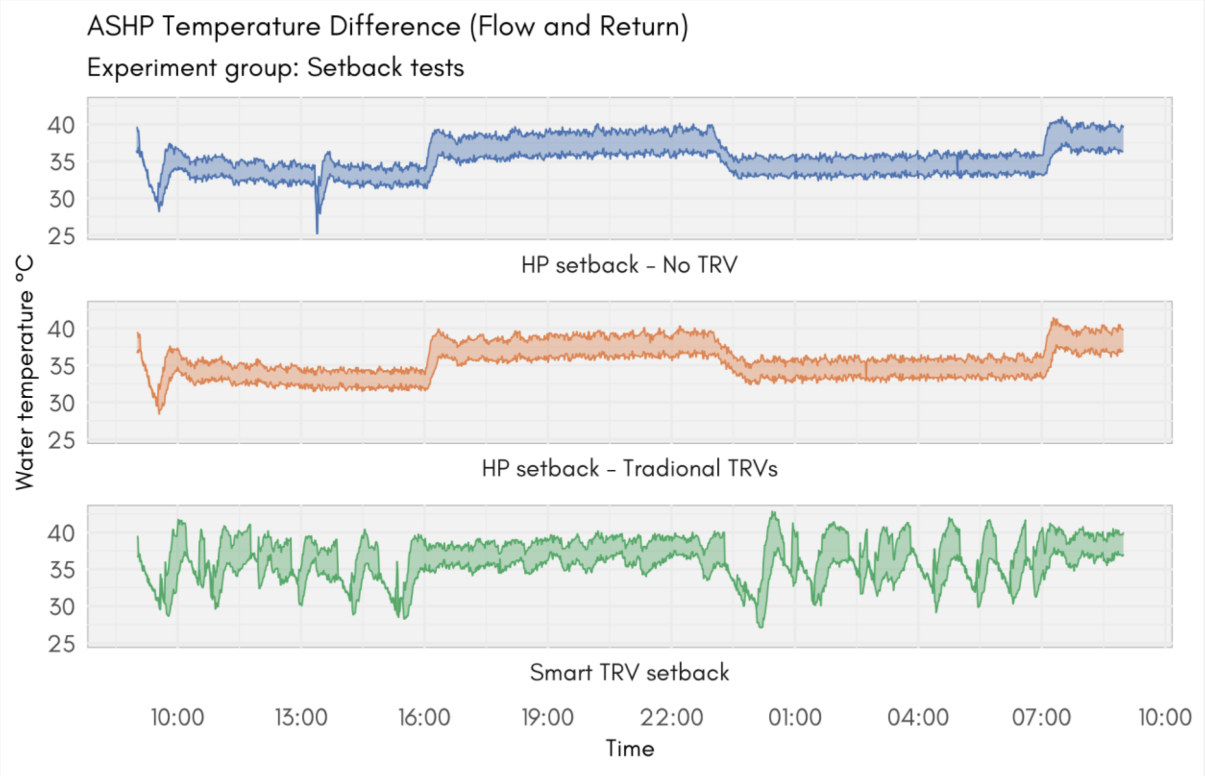


Figure B2.4: Setback tests – ASHP flow and return temperatures.

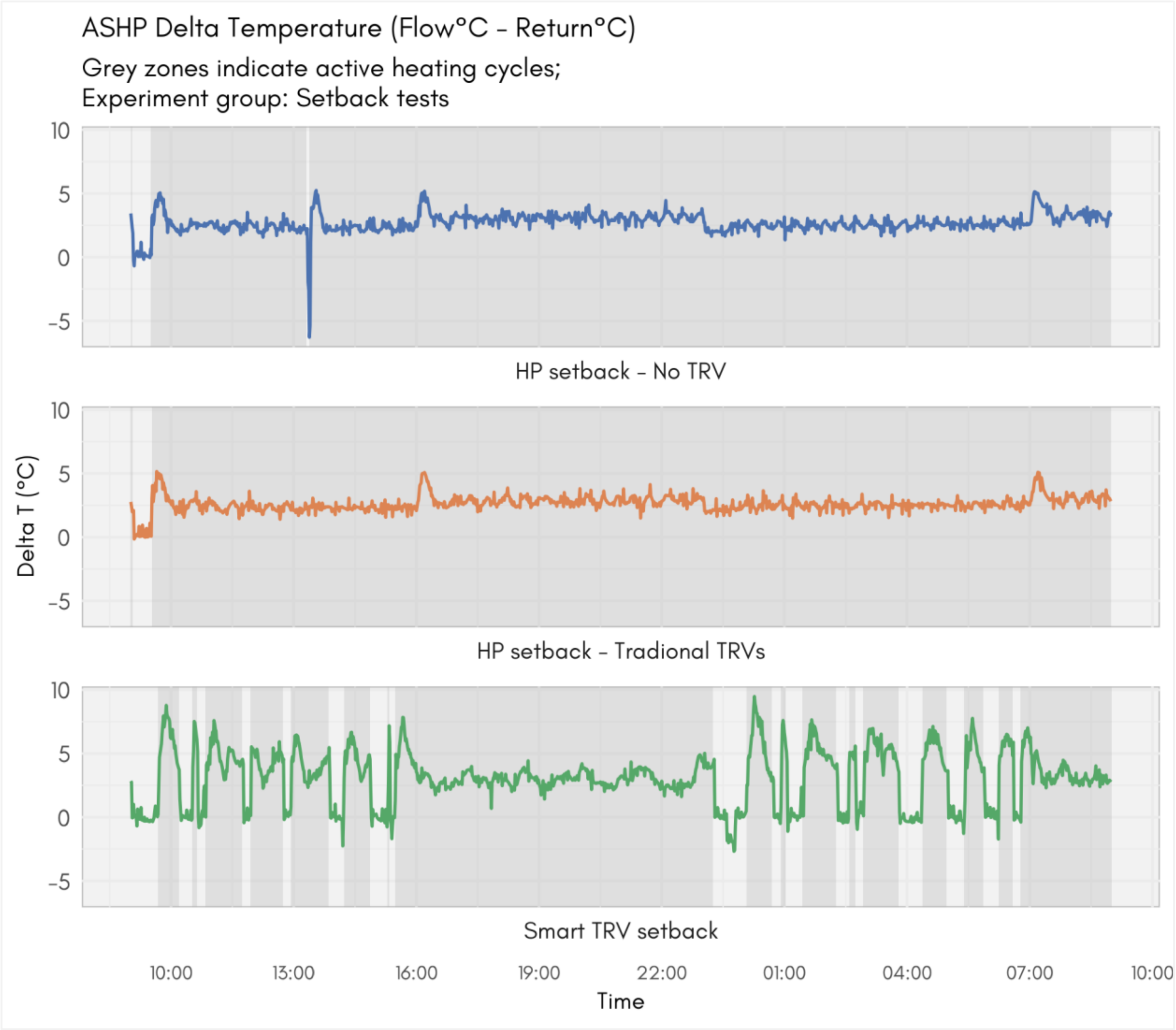


Figure B2.5: Setback tests – ASHP ΔT.

Table B2.5: Setback tests – Mean ASHP and radiator ΔT during periods of flow >0 m³/h. Change from no TRV baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP**	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
HP setback - No TRV	2.6 ±0.6	1.4 ±0.5	1.8 ±0.6	1.1 ±0.5	10.7 ±0.8	6.9 ±0.7	1.8 ±0.6
HP setback - Traditional TRVs	2.5 ±0.6 (0 ±0.8) (-1.8 ±31.9%)	1.4 ±0.5 (0 ±0.8) (-2.1 ±53.4%)	1.6 ±0.5 (-0.1 ±0.8) (-7.8 ±43.8%)	1 ±0.5 (0 ±0.8) (-3.4 ±70.4%)	14 ±0.9 (3.3 ±1.2) (30.6 ±11.7%)	10.1 ±0.8 (3.2 ±1.1) (46.2 ±16.1%)	4.3 ±0.6 (2.5 ±0.8) (139.6 ±64.2%)
Smart TRV setback	3.4 ±0.6 (0.9 ±0.8) (35.1 ±33.7%)	1.9 ±0.6 (0.4 ±0.8) (31.1 ±55.3%)	1.8 ±0.6 (0 ±0.8) (2.7 ±43.9%)	8.7 ±0.8 (7.6 ±0.9) (710.2 ±364.1%)	14.4 ±0.9 (3.6 ±1.2) (33.9 ±11.9%)	9 ±0.8 (2.1 ±1) (30.2 ±15.4%)	2.2 ±0.6 (0.4 ±0.8) (24.4 ±45.3%)

Power output

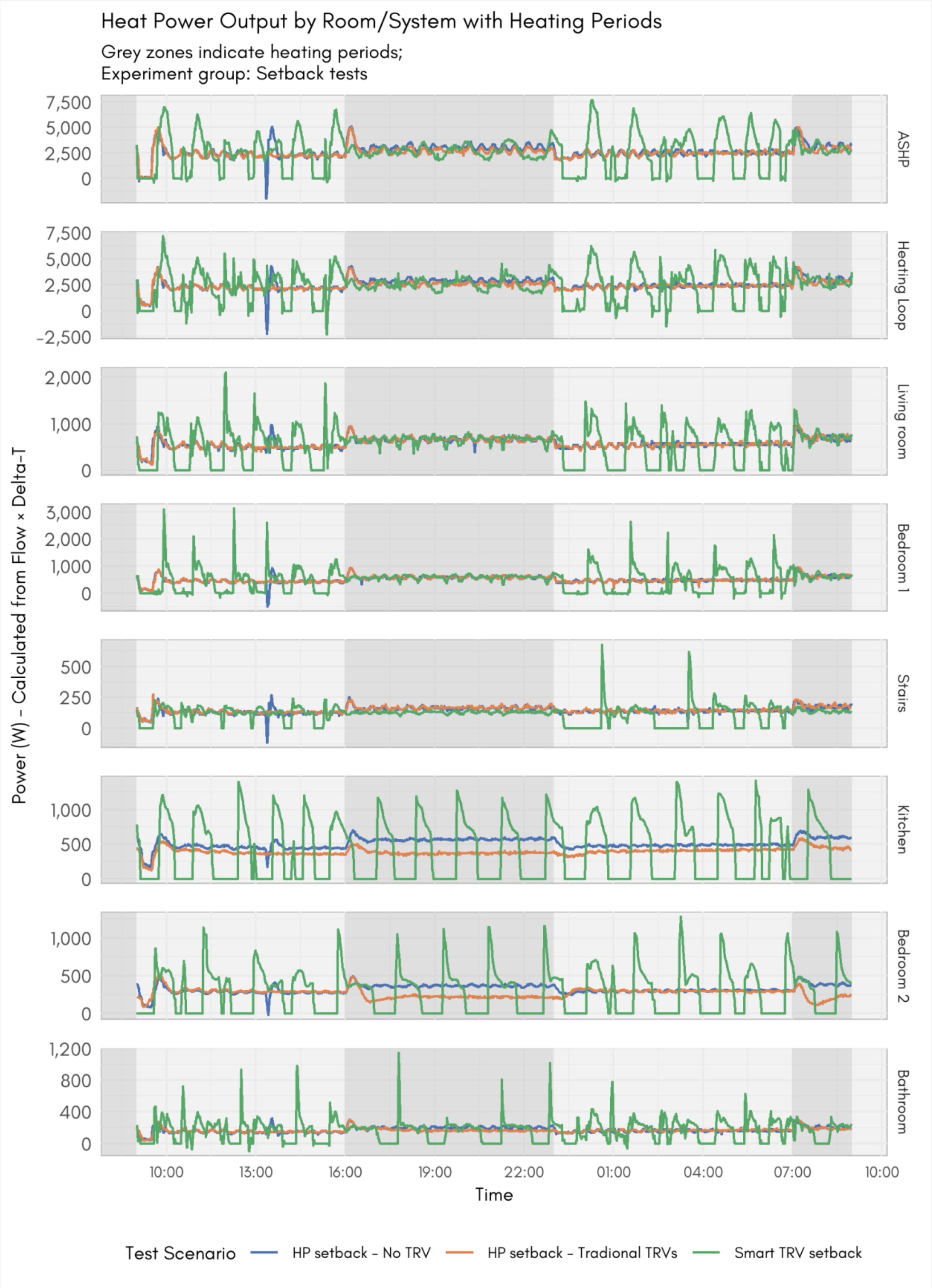


Figure B2.6: Setback tests – ASHP and radiator power output.

Table B2.6: Setback tests – Mean ASHP and radiator power output during periods of flow >0 m^3/h. Change from no TRV baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP (W)**	**Heating Loop (W)**	**Living room (W)**	**Bedroom 1 (W)**	**Stairs (W)**	***Kitchen (W)***	***Bedroom 2 (W)***	***Bathroom (W)***
HP setback - No TRV	2587 ±201	2471 ±192	561 ±212	449 ±44	135 ±67	448 ±20	269 ±14	120 ±12
HP setback - Traditional TRVs	2436 ±192 (-151 ±278) (-5.8 ±11%)	2333 ±185 (-138 ±267) (-5.6 ±11%)	597 ±230 (+36 ±313) (+6.4 ±56%)	452 ±47 (+2 ±64) (+0.5 ±14%)	142 ±73 (+7 ±99) (+5.2 ±74%)	345 ±15 (-103 ±25) (-23.1 ±6%)	222 ±10 (-47 ±17) (-17.5 ±6%)	105 ±6 (-15 ±13) (-12.6 ±11%)
Smart TRV setback	2830 ±186 (+243 ±274) (+9.4 ±11%)	2684 ±179 (+213 ±262) (+8.6 ±11%)	691 ±204 (+130 ±295) (+23.1 ±53%)	530 ±51 (+81 ±67) (+18.1 ±15%)	142 ±13 (+7 ±69) (+5.4 ±51%)	796 ±32 (+348 ±38) (+77.7 ±9%)	468 ±21 (+199 ±25) (+73.8 ±10%)	197 ±17 (+77 ±21) (+64.2 ±18%)

ASHP energy and COP

Table B2.7: Setback tests – ASHP energy and COP. Change from no TRV baseline shown in parenthesis.

Test	**Electrical Energy In (kWh)**	**Heat Energy Out (kWh)**	**COP_{H4}**
HP setback - No TRV	17.3 ±0.2	62.0 ±0.9	3.58 ±0.06
HP setback - Traditional TRVs	16.2 ±0.2 (-1.1 ±0.2 -6.1 ±1.4%)	58.4 ±0.9 (-3.5 ±1.3 -5.7 ±2.1%)	3.60 ±0.07 (+0.01 ±0.09 +0.4 ±2.6%)
Smart TRV setback	17.1 ±0.2 (-0.1 ±0.2 -0.8 ±1.4%)	58.7 ±0.7 (-3.3 ±1.1 -5.3 ±1.8%)	3.42 ±0.05 (-0.16 ±0.08 -4.5 ±2.3%)

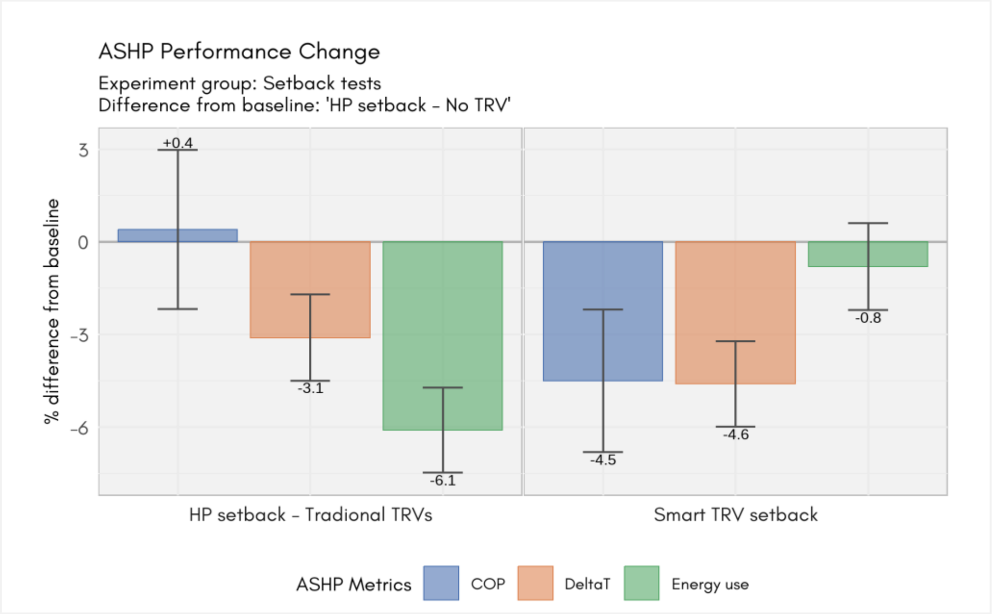


Figure B2.7: Setback tests – Percentage change in COP, whole house internal to external ΔT, and space heating energy use.

Summary (Appendix B2)

Traditional TRVs provided similar conditions in non-trimmed rooms as the baseline test. In rooms subject to trimming, there was a relatively low reduction in temperature during setback periods. Flow rate measurements suggest that the TRVs were trimming the internal temperature of the bathroom and kitchen during setback periods. During heating periods, the flow temperature increased, which resulted in the TRVs further restricting flow, which in turn increased the flow rate through non-trimmed radiators. However, the temperature of bedroom 2 cooled during the heating periods. Trimming did not impact the COP and significantly reduced space heating energy use. In this instance, the percentage reduction in energy use was greater than the percentage reduction in ΔT.

Using smart TRVs on all radiators to provide a setback between heating periods significantly increased heat pump cycling. All cycling occurred during the setback periods. This was due to the flow temperature being greater than required for the setback temperature, as the heat pump was not programmed to reduce the flow temperature during these periods. The longest shutdown was after the evening heating period, when all rooms were above the setback temperature, so no TRVs were calling for heat. The 5% reduction in COP was the only significant reduction measured in the entire test programme. The reduction in COP meant no savings in energy use were made, though there was also no increase from the baseline test. This demonstrates that whole house setback periods should be programmed using the heat pump controller, rather than smart TRVs on all radiators. It is worth considering that occupants in this scenario may have gained some comfort benefits without increasing ASHP energy use. Had smart TRVs been used for purely trimming purposes alongside programming the ASHP to provide setback, then cycling would have been reduced. Findings from the other tests suggest that had the heat pump followed a setback pattern, energy use and COP may have been similar to the use of traditional TRVs.

The behaviour during setback periods also demonstrates the importance of ensuring weather compensation curves are not set too high, as this could result in unnecessary TRV intervention, which in extreme cases may reduce flow rates below minimum levels and increase cycling, which could have an impact on ASHP efficiency.

Appendix C – Impact of volumiser

C1 – Constant external temperature

Internal temperature

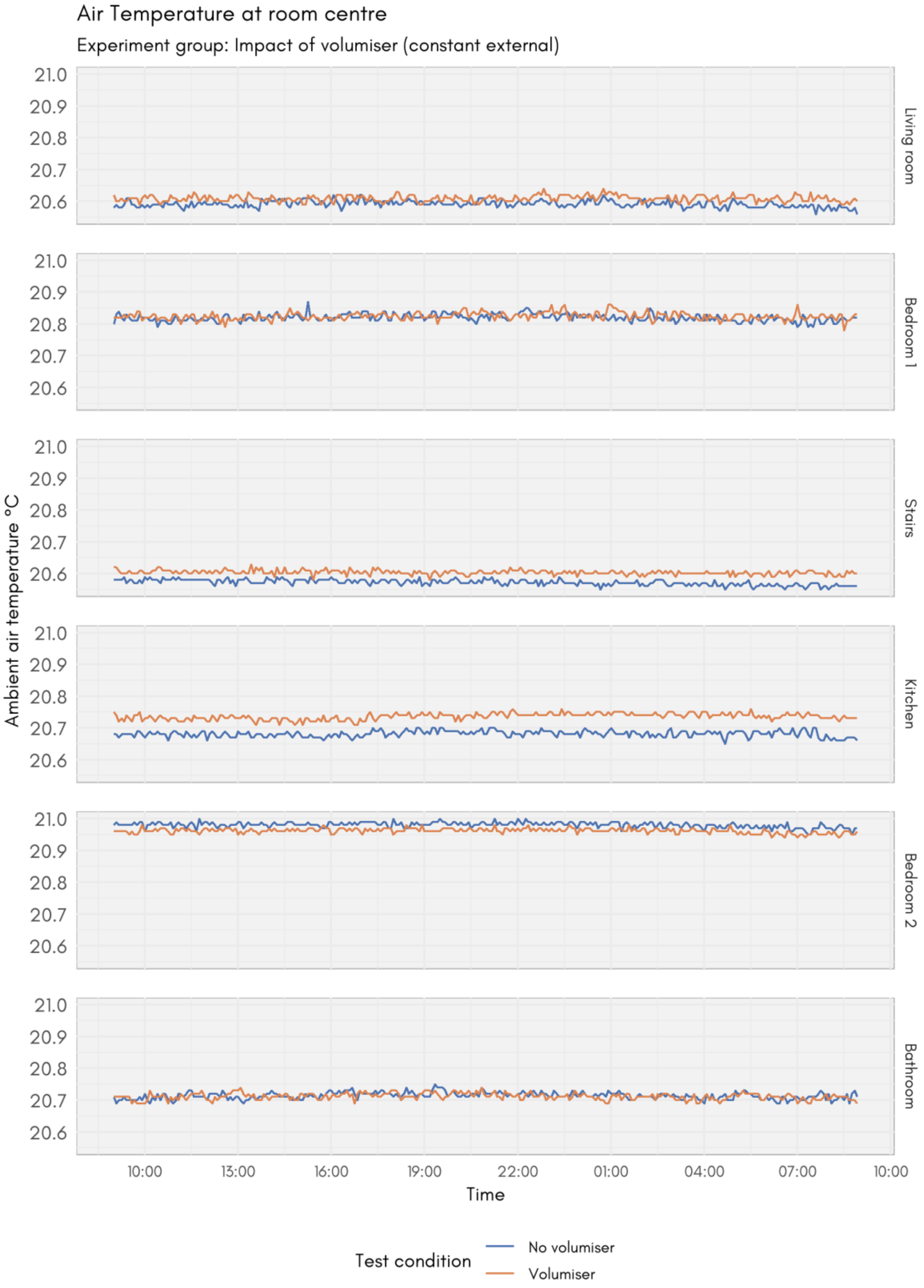


Figure C1.1: Impact of volumiser (constant external) – Internal air temperature

Table C1.1: Impact of volumiser (constant external) – 24-hour mean internal air temperatures. Change from no volumiser baseline shown in parenthesis.

Test	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
No volumiser	20.6 ±0.1	20.8 ±0.1	20.6 ±0.1	20.7 ±0.1	21.0 ±0.1	20.7 ±0.1
Volumiser	20.6 ±0.1 (+0.0 ±0.1)	20.8 ±0.1 (+0.0 ±0.1)	20.6 ±0.1 (+0.0 ±0.1)	20.7 ±0.1 (+0.1 ±0.1)	21.0 ±0.1 (-0.0 ±0.1)	20.7 ±0.1 (-0.0 ±0.1)

Heat pump cycling

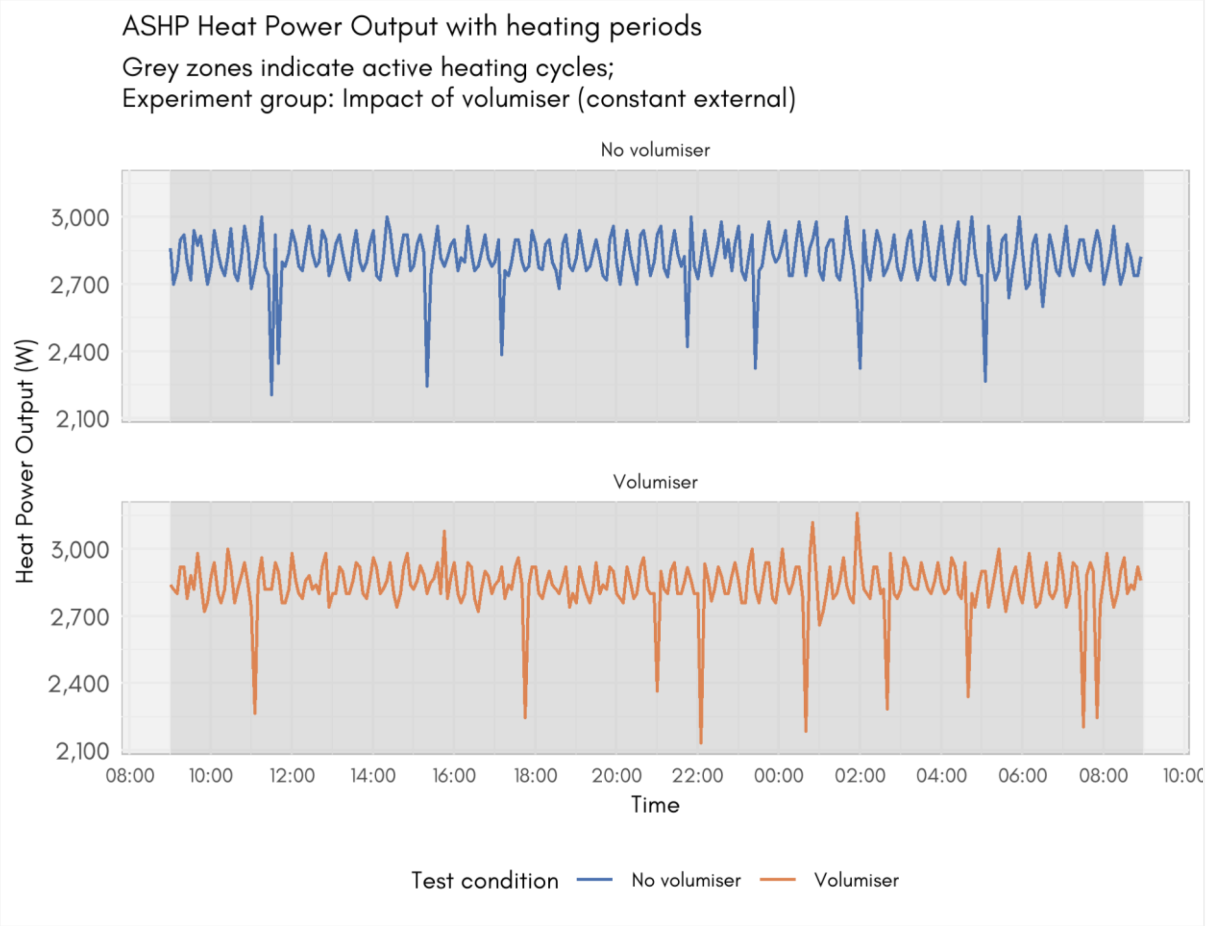


Figure C1.2: Impact of volumiser (constant external temperature) – Heat pump cycles

Table C1.2: Impact of volumiser (constant external temperature) – Heat pump cycles

Test	% Time On	Cycle #	Cycle Duration	Mean Power (W)	Median Power (W)	Max Power (W)
No volumiser	100%	1	24h 0m	2,814	2,820	3,000
Volumiser	100%	1	24h 0m	2,834	2,840	3,160

Flow rates

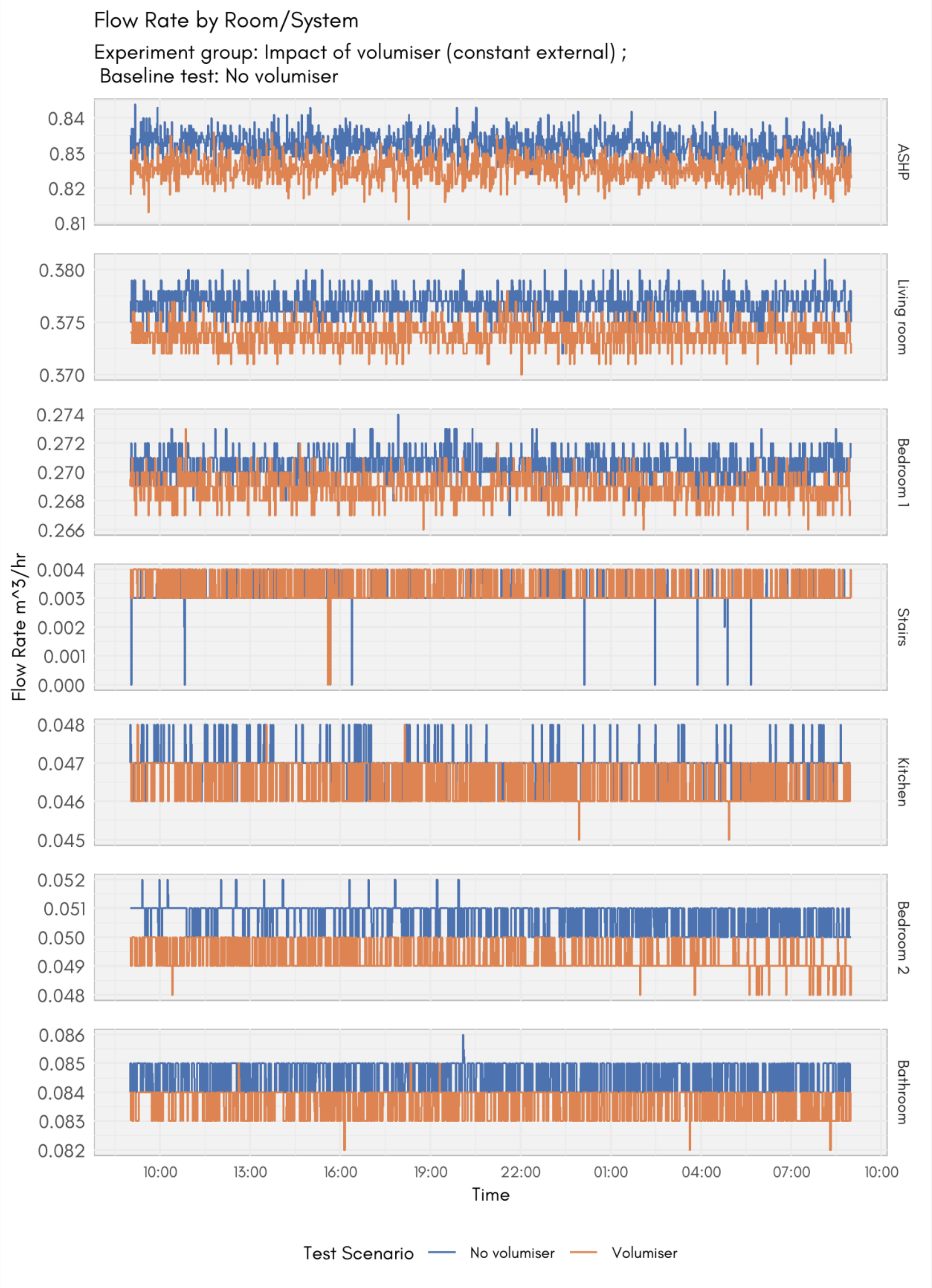


Figure C1.3: Impact of volumiser (constant external temperature) – Flow rates.

Table C1.3: Impact of volumiser (constant external temperature) – Mean flow rates during periods of flow >0 m3/h. Change from no volumiser baseline shown in parenthesis.

Test	**ASHP Flow (m³/hr)**	**Living room Flow (m³/hr)**	**Bedroom 1 Flow (m³/hr)**	**Stairs Flow (m³/hr)**	**Kitchen Flow (m³/hr)**	**Bedroom 2 Flow (m³/hr)**	**Bathroom Flow (m³/hr)**
No volumiser	0.832 ±0.017	0.377 ±0.008	0.27 ±0.006	0.003 ±<0.001	0.047 ±0.001	0.051 ±0.001	0.085 ±0.002
Volumiser	0.826 ±0.017 (-0.007 ±0.024)	0.374 ±0.008 (-0.003 ±0.011)	0.269 ±0.005 (-0.002 ±0.008)	0.003 ±<0.001 (+0 ±<0.001)	0.046 ±0.001 (-0.001 ±0.001)	0.049 ±0.001 (-0.001 ±0.002)	0.084 ±0.002 (-0.001 ±0.003)

ASHP and radiator ΔT

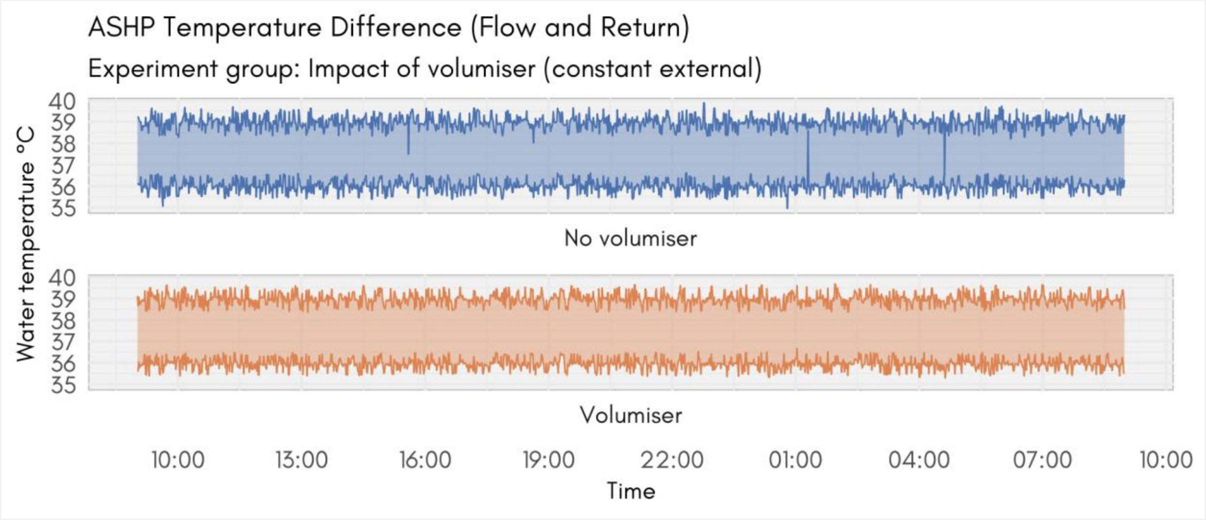


Figure C1.4: Impact of volumiser (constant external temperature) – ASHP flow and return temperatures.

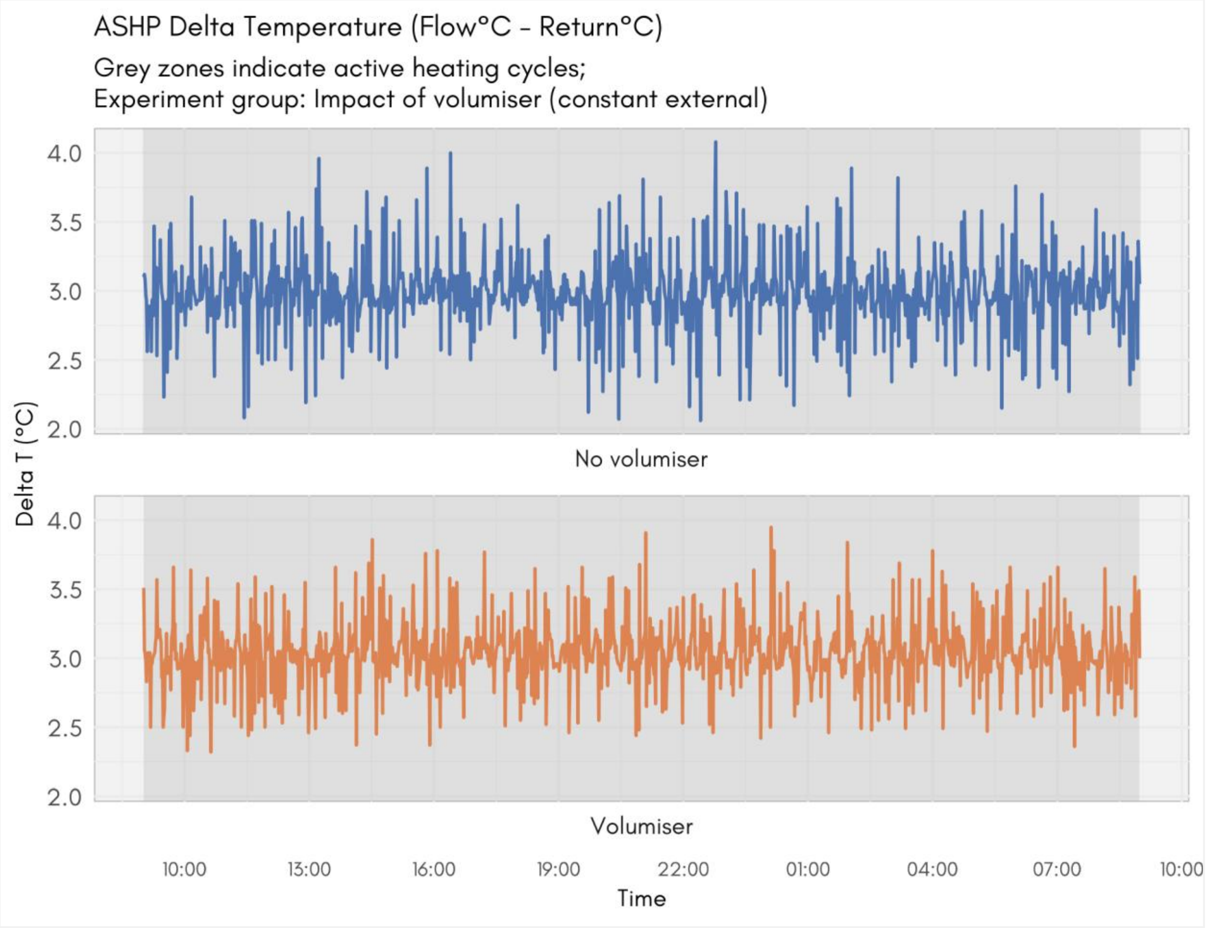


Figure C1.5: Impact of volumiser (constant external temperature – ASHP ΔT.

Table C1.4: Impact of volumiser (constant external temperature) – Mean ASHP and radiator ΔT during periods of flow >0 m³/h. Change from no volumiser baseline shown in parenthesis.

Test	ASHP	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
No volumiser	3 ±0.6	1.4 ±0.5	1.6 ±0.5	15.8 ±1	10.5 ±0.8	6.3 ±0.7	1.9 ±0.6
Volumiser	3 ±0.6 (0 ±0.8) (0.8 ±27.8%)	1.5 ±0.5 (0.1 ±0.8) (5.7 ±54.4%)	1.8 ±0.6 (0.2 ±0.8) (9.6 ±47.8%)	15.5 ±1 (-0.2 ±1.4) (-1.5 ±8.7%)	10.8 ±0.8 (0.3 ±1.2) (2.7 ±11%)	6.4 ±0.7 (0.2 ±1) (2.5 ±15.5%)	1.9 ±0.6 (0.1 ±0.8) (2.8 ±41.8%)

Power output

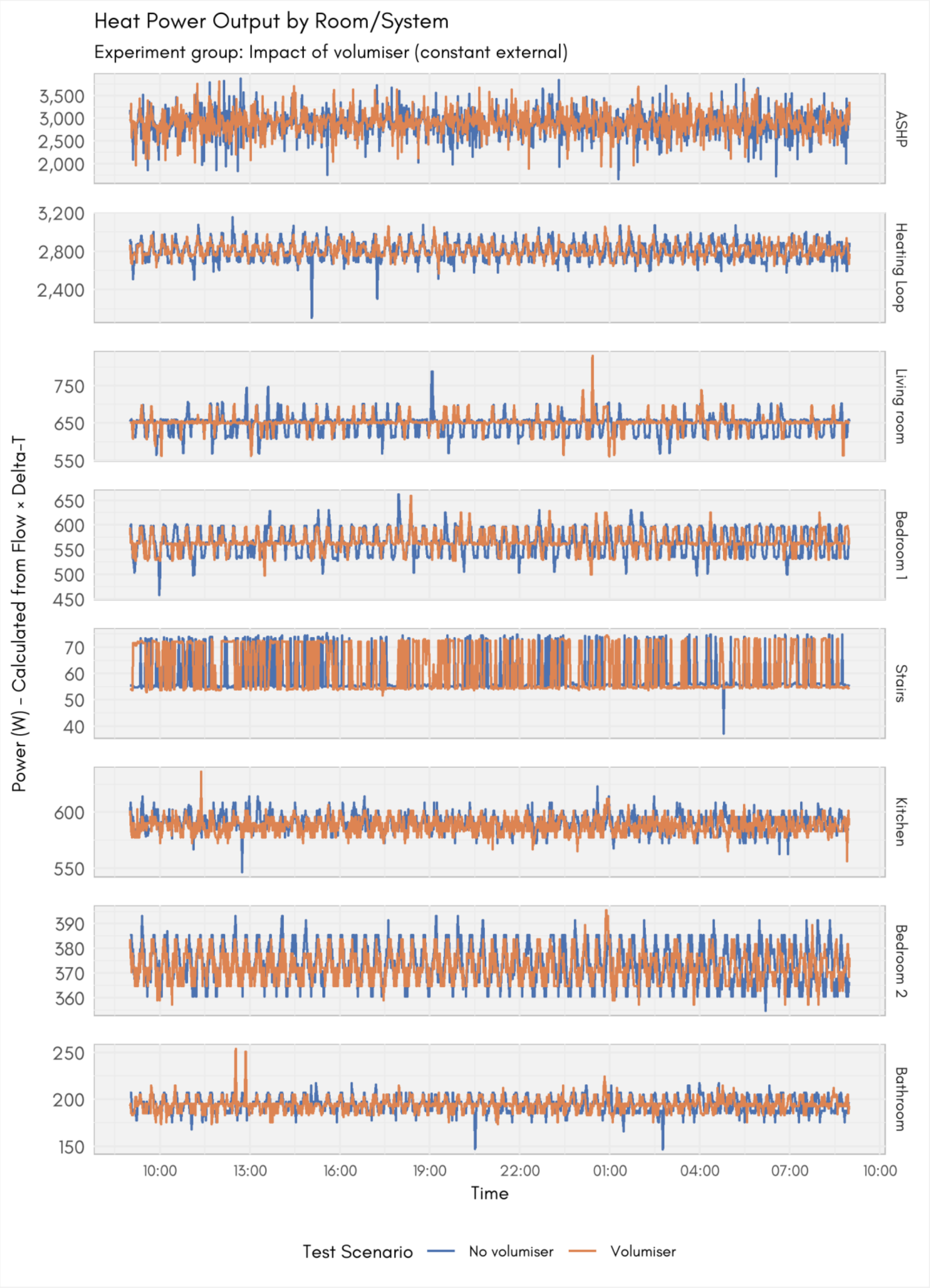


Figure C1.6: Impact of volumiser (constant external temperature) – ASHP and radiator power output.

Table C1.5: Impact of volumiser (constant external temperature) – Mean ASHP and radiator power output during periods of flow >0 m³/h. Change from no volumiser baseline shown in parenthesis.

Test	ASHP (W)	Heating Loop (W)	Living room (W)	Bedroom 1 (W)	Stairs (W)	Kitchen (W)	Bedroom 2 (W)	Bathroom (W)
No volumiser	2814 ±202	2716 ±199	620 ±238	501 ±52	57 ±5	520 ±23	299 ±15	124 ±12
Volumiser	2834 ±199 (+20 ±284) (+0.7 ±10%)	2723 ±200 (+7 ±282) (+0.2 ±10%)	650 ±237 (+30 ±336) (+4.8 ±54%)	500 ±49 (-1 ±71) (-0.2 ±14%)	62 ±5 (+4 ±7) (+7.3 ±12%)	509 ±22 (-10 ±32) (-2 ±6%)	299 ±15 (-1 ±22) (-0.2 ±7%)	116 ±11 (-8 ±16) (-6.6 ±13%)

ASHP energy and COP

Table C1.6: Impact of volumiser (constant external temperature) – ASHP energy and COP. Change from no volumiser baseline shown in parenthesis.

Test	Electrical Energy In (kWh)	Heat Energy Out (kWh)	COP_{H4}
No volumiser	19.0 ±0.2	67.4 ±1	3.55 ±0.06
Volumiser	19.0 ±0.2 (+0.1 ±0.3 +0.3 ±1.4%)	68.0 ±1 (+0.6 ±1.4 +0.8 ±2.1%)	3.57 ±0.06 (+0.02 ±0.09 +0.5 ±2.5%)

C2 – Diurnal external temperature

Internal temperatures

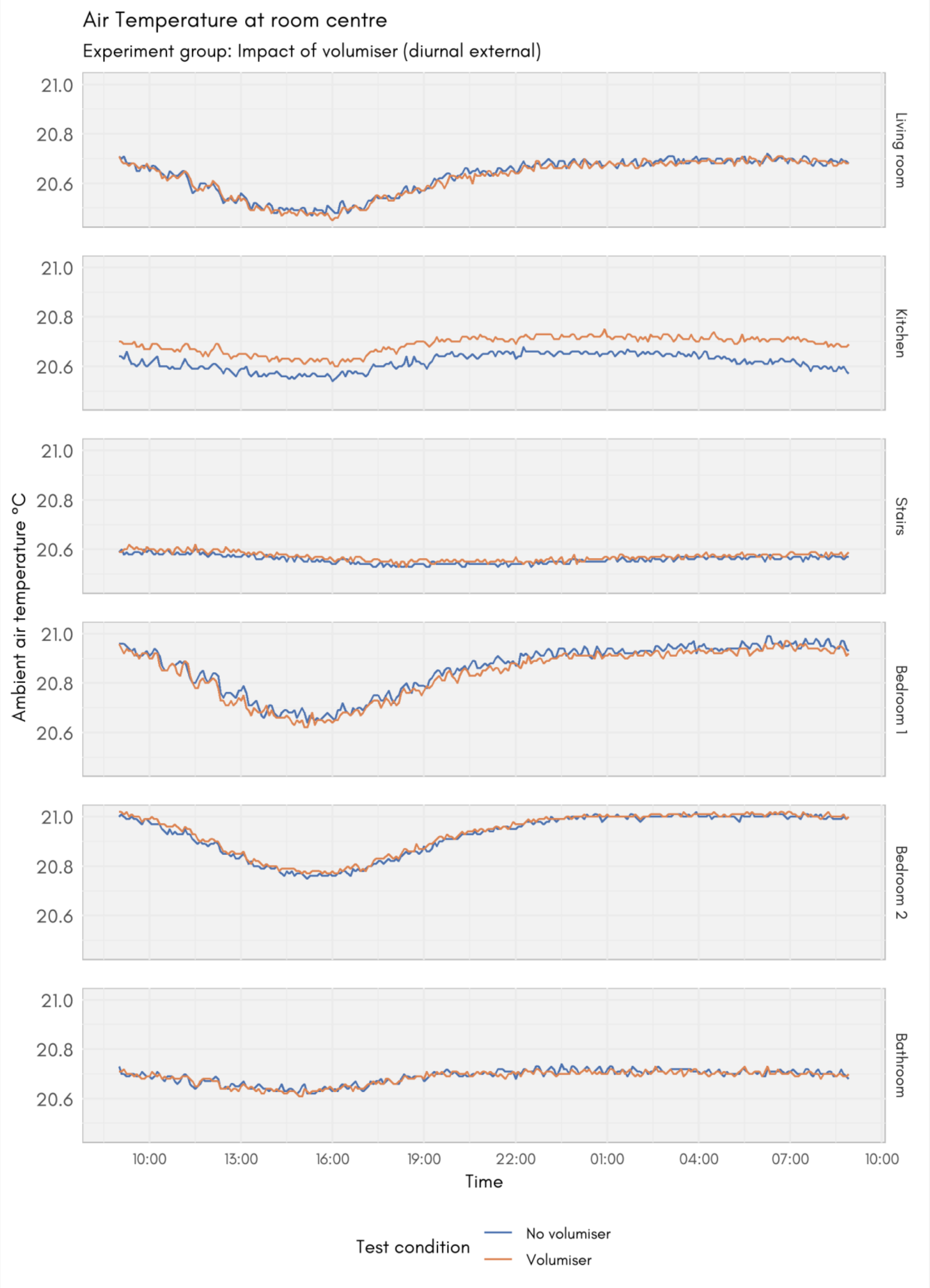


Figure C2.1: Impact of volumiser (diurnal external temperature) – Internal air temperatures

Table C2.1: Impact of volumiser (diurnal external temperature) – 24-hour mean internal air temperatures. Change from no volumiser baseline shown in parenthesis.

Test	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
No volumiser	20.6 ±0.1	20.9 ±0.1	20.6 ±0.1	20.6 ±0.1	20.9 ±0.1	20.7 ±0.1
Volumiser	20.6 ±0.1 (-0.0 ±0.1)	20.8 ±0.1 (-0.0 ±0.1)	20.6 ±0.1 (+0.0 ±0.1)	20.7 ±0.1 (+0.1 ±0.1)	20.9 ±0.1 (+0.0 ±0.1)	20.7 ±0.1 (-0.0 ±0.1)

Heat pump cycling

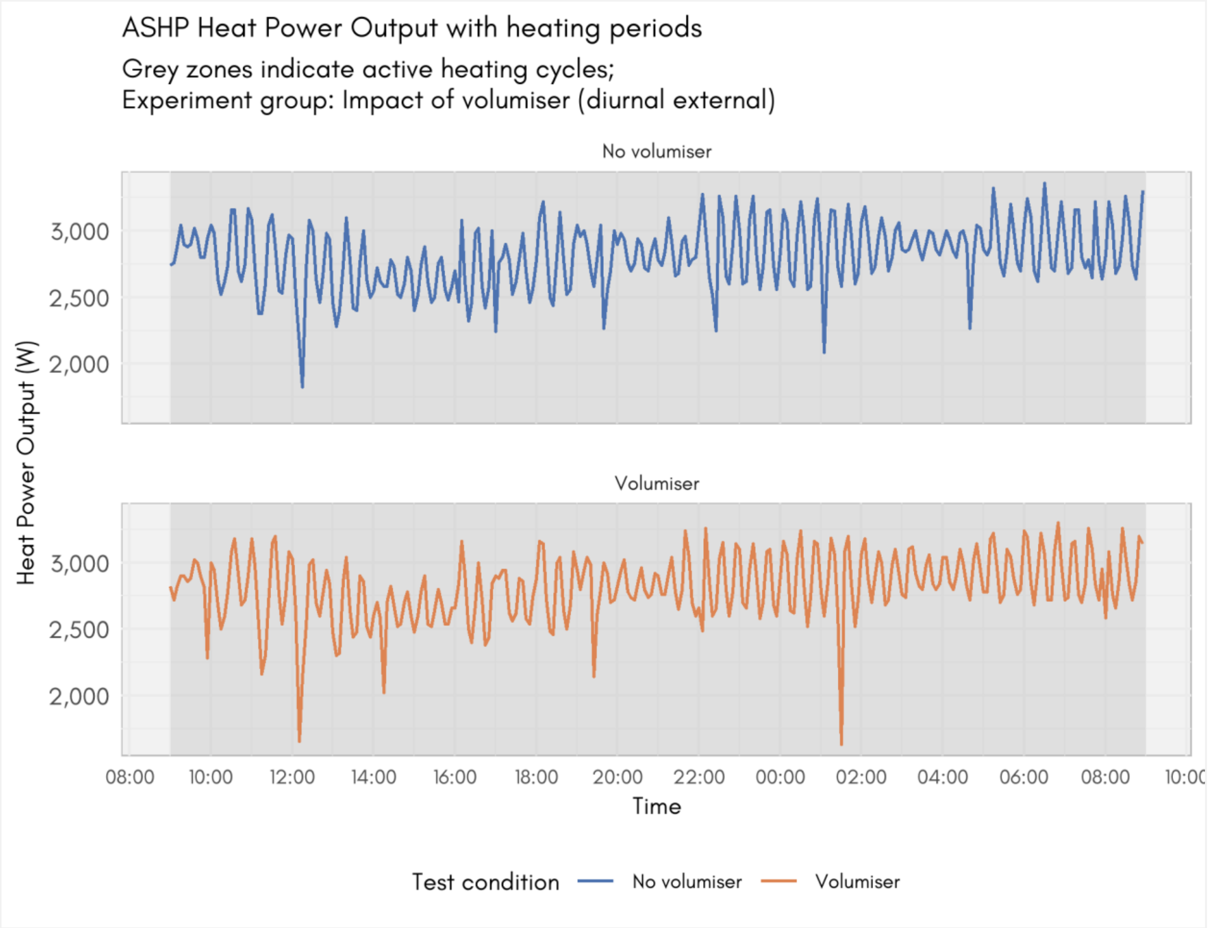


Figure C2.2: Impact of volumiser (diurnal external temperature) – Heat pump cycles

Table C2.2: Impact of volumiser (diurnal external temperature) – Heat pump cycles

Test	% Time On	Cycle #	Cycle Duration	Mean Power (W)	Median Power (W)	Max Power (W)
No volumiser	100%	1	24h 0m	2,812	2,800	3,360
Volumiser	100%	1	24h 0m	2,816	2,820	3,300

Flow rates

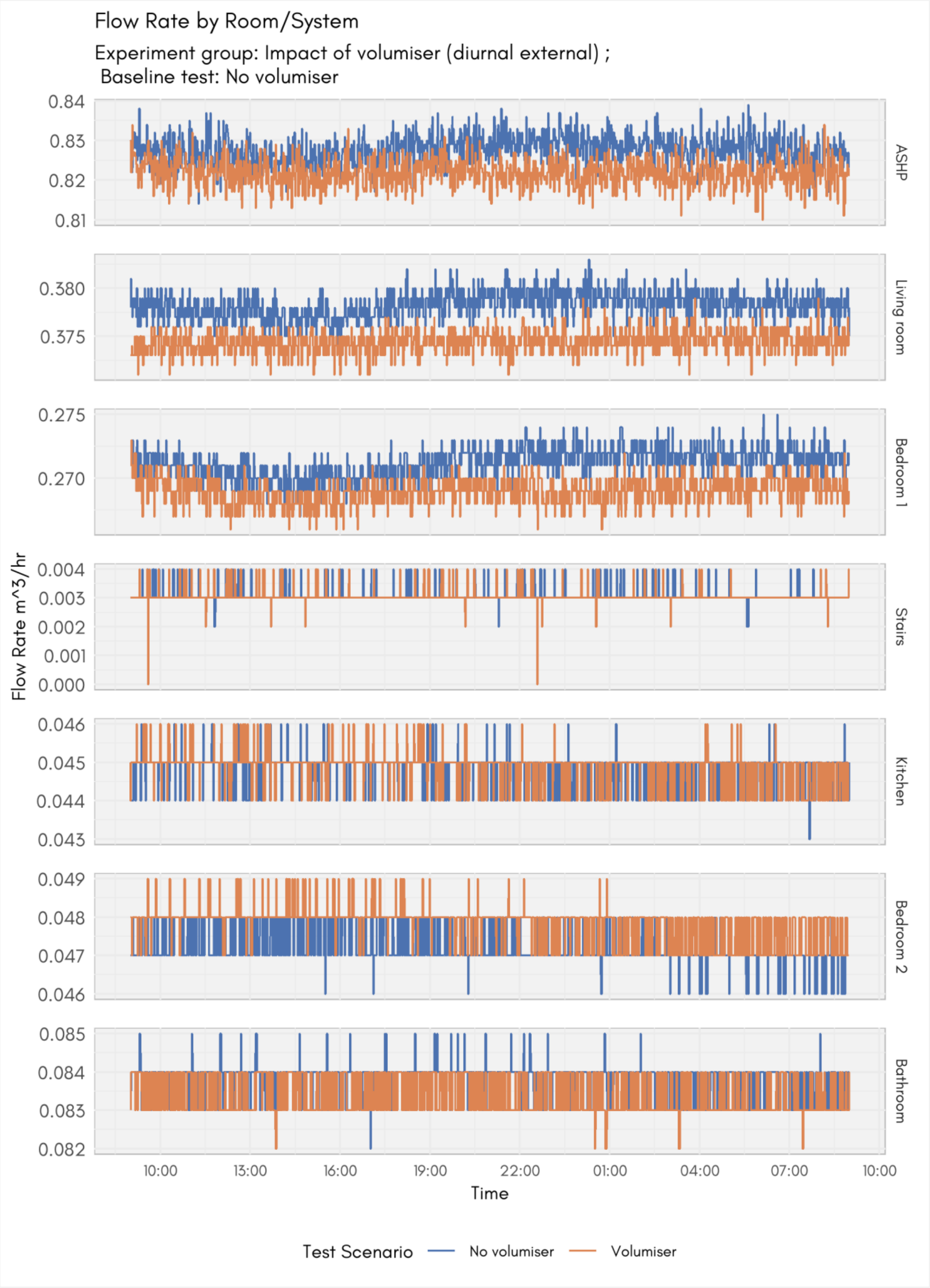


Figure C2.3: Impact of volumiser (diurnal external temperature) – Flow rates.

Table C2.3: Impact of volumiser (diurnal external temperature) – Mean flow rates during periods of flow >0 m3/h. Change from no volumiser baseline shown in parenthesis.

Test	ASHP Flow (m^3/hr)	Living room Flow (m^3/hr)	Bedroom 1 Flow (m^3/hr)	Stairs Flow (m^3/hr)	Kitchen Flow (m^3/hr)	Bedroom 2 Flow (m^3/hr)	Bathroom Flow (m^3/hr)
No volumiser	0.828 ±0.017	0.378 ±0.008	0.271 ±0.006	0.003 ±<0.001	0.045 ±0.001	0.047 ±0.001	0.084 ±0.002
Volumiser	0.822 ±0.017 (-0.006 ±0.024)	0.374 ±0.008 (-0.004 ±0.011)	0.269 ±0.005 (-0.002 ±0.008)	0.003 ±<0.001 (0 ±<0.001)	0.045 ±0.001 (+0 ±0.001)	0.048 ±0.001 (+0.001 ±0.002)	0.083 ±0.002 (0 ±0.003)

ASHP and radiator ΔT

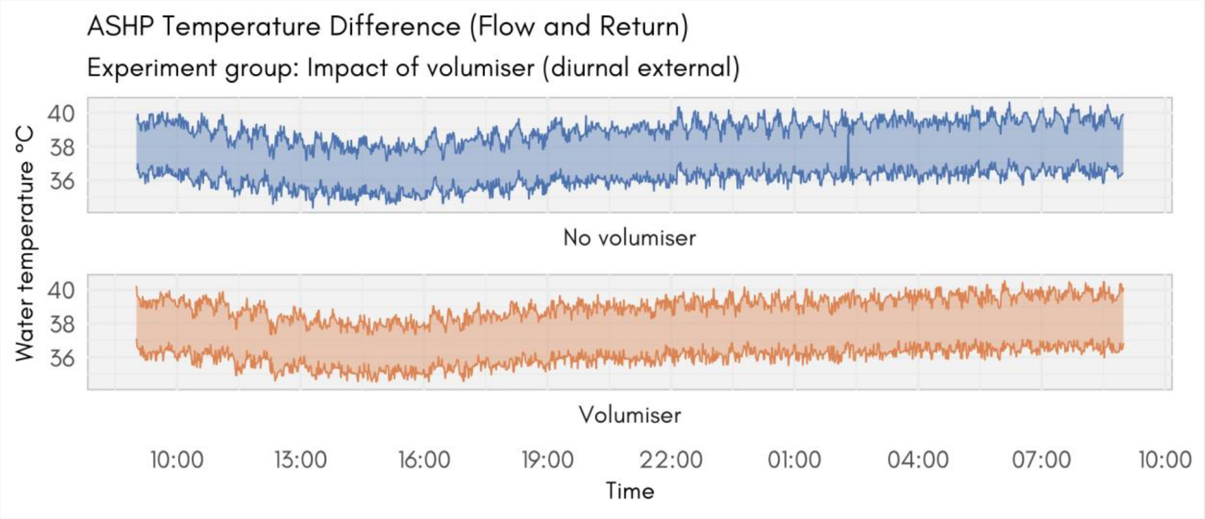


Figure C2.4: Impact of volumiser (diurnal external temperature) – ASHP flow and return temperatures.

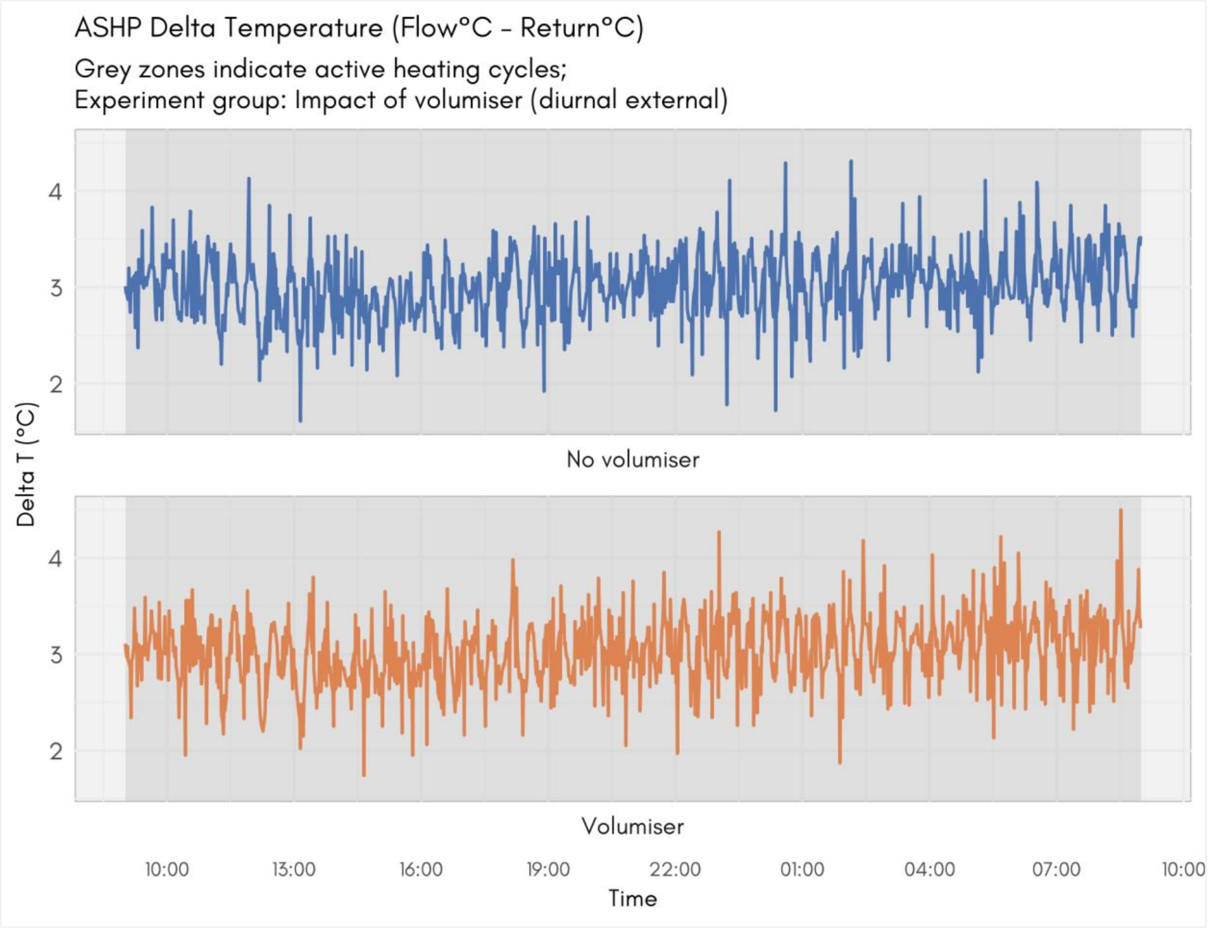


Figure C2.5: Impact of volumiser (diurnal external temperature) – ASHP ΔT.

Table C2.4: Impact of volumiser (diurnal external temperature) – Mean ASHP and radiator ΔT during periods of flow >0 m³/h. Change from no volumiser baseline shown in parenthesis.

Test	ASHP	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
No volumiser	3 ±0.6	1.4 ±0.5	1.8 ±0.6	16 ±1	11 ±0.8	6.7 ±0.7	1.9 ±0.6
Volumiser	3 ±0.6 (0 ±0.8) (-0.2 ±27.9%)	1.3 ±0.5 (-0.1 ±0.8) (-6.3 ±54.8%)	1.7 ±0.6 (0 ±0.8) (-1.8 ±43.9%)	15.9 ±1 (0 ±1.4) (-0.3 ±8.7%)	11 ±0.8 (0 ±1.2) (-0.3 ±10.7%)	6.5 ±0.7 (-0.1 ±1) (-2 ±14.8%)	1.9 ±0.6 (-0.1 ±0.8) (-3.1 ±40.5%)

Power output

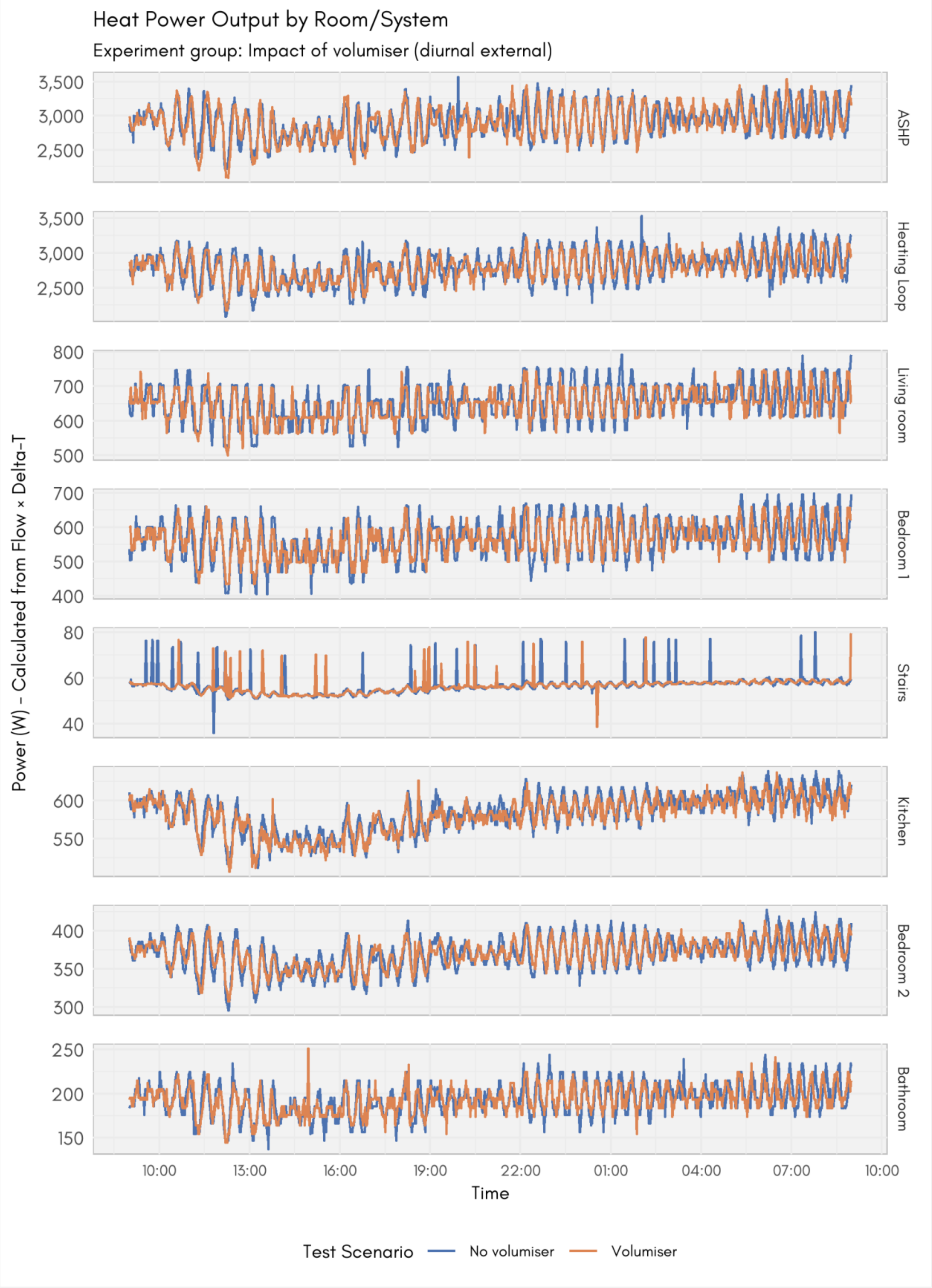


Figure C2.6 Impact of volumiser (diurnal external temperature) – ASHP and radiator power output.

Table C2.5: Impact of volumiser (diurnal external temperature) – Mean ASHP and radiator power output during periods of flow >0 m³/h. Change from no volumiser baseline shown in parenthesis.

Test	ASHP (W)	Heating Loop (W)	Living room (W)	Bedroom 1 (W)	Stairs (W)	Kitchen (W)	Bedroom 2 (W)	Bathroom (W)
No volumiser	2813 ±200	2719 ±199	615 ±239	510 ±50	57 ±5	534 ±23	309 ±16	134 ±12
Volumiser	2817 ±200 (+4 ±283) (+0.1 ±10%)	2698 ±195 (-21 ±278) (-0.8 ±10%)	569 ±235 (-45 ±335) (-7.4 ±55%)	511 ±51 (+2 ±71) (+0.3 ±14%)	57 ±4 (-1 ±6) (-0.9 ±11%)	527 ±23 (-6 ±33) (-1.2 ±6%)	304 ±15 (-5 ±22) (-1.6 ±7%)	129 ±12 (-5 ±18) (-3.5 ±13%)

ASHP energy and COP

Table C2.6: Impact of volumiser (diurnal external temperature) – ASHP energy and COP. Change from no volumiser baseline shown in parenthesis.

Test	Electrical Energy In (kWh)	Heat Energy Out (kWh)	COP_{H4}
No volumiser	19.2 ±0.2	67.4 ±1	3.51 ±0.06
Volumiser	19.1 ±0.2 (-0.1 ±0.3 -0.5 ±1.4%)	67.6 ±1 (+0.1 ±1.4 +0.2 ±2.1%)	3.54 ±0.06 (+0.03 ±0.09 +0.7 ±2.5%)

Summary (Appendix C1 & C2)

The use of the volumiser without trimming had no significant impact of system behaviour with either a constant or diurnal external temperature pattern.

At the end of the test programme, overnight tests were performed with a constant external temperature, in which the impact of the volumiser with traditional TRVs was tested. The tests found that the volumiser had no impact on ASHP COP. Though it must be noted that the test duration was insufficient to demonstrate repeatability.

Appendix D – Impact of diurnal external temperature

D1 - No Volumiser

Internal temperatures

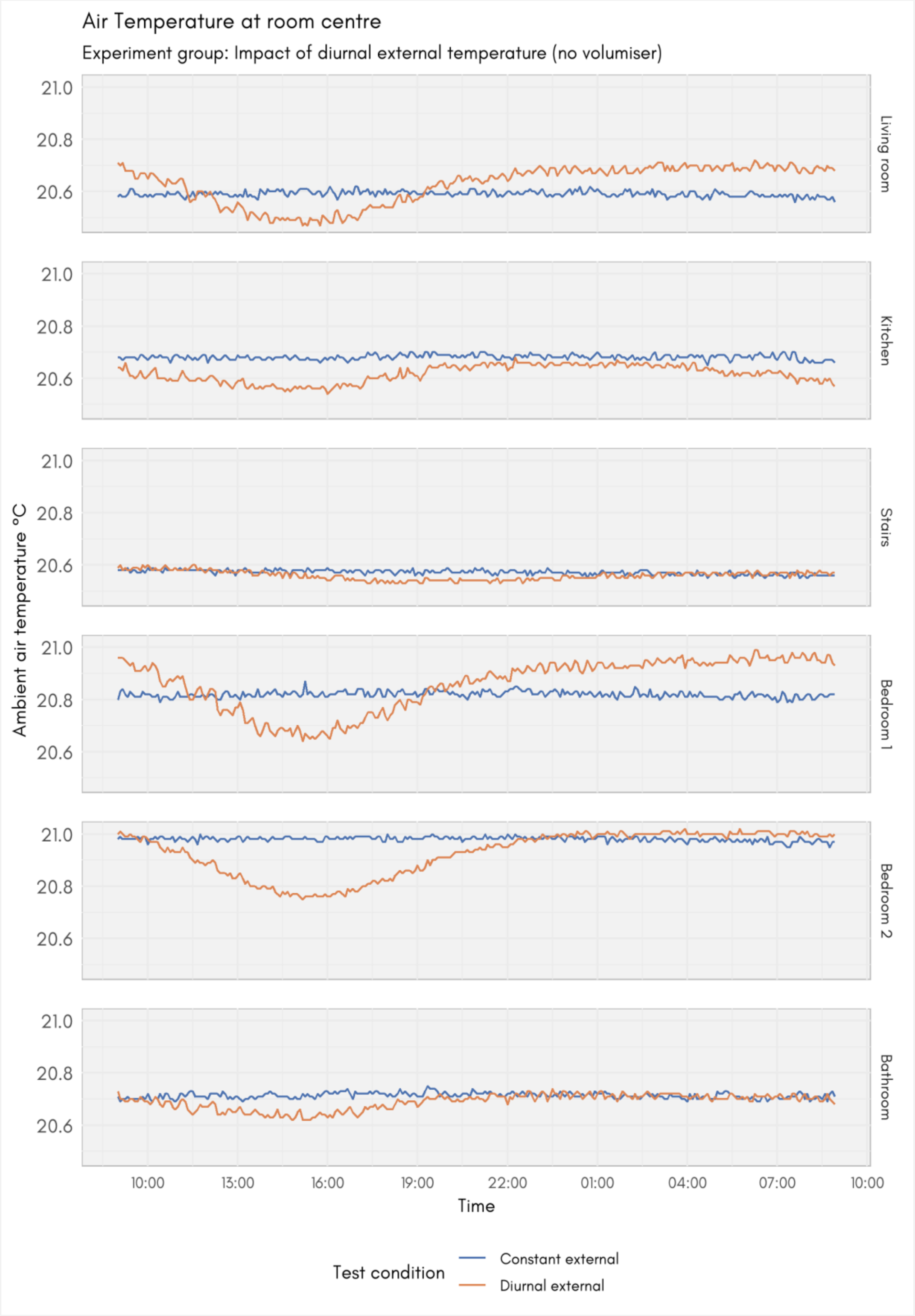


Figure D1.1: Impact of diurnal external temperature (no volumiser) – Internal air temperatures

Table D1.1: Impact of diurnal external temperature (no volumiser) – 24-hour mean internal air temperatures. Change from constant external baseline shown in parenthesis.

Test	Living room	Bedroom 1	Stairs	Kitchen	Bedroom 2	Bathroom
Constant external	20.6 ±0.1	20.8 ±0.1	20.6 ±0.1	20.7 ±0.1	21.0 ±0.1	20.7 ±0.1
Diurnal external	20.6 ±0.1 (+0.0 ±0.1)	20.9 ±0.1 (+0.0 ±0.1)	20.6 ±0.1 (-0.0 ±0.1)	20.6 ±0.1 (-0.1 ±0.1)	20.9 ±0.1 (-0.1 ±0.1)	20.7 ±0.1 (-0.0 ±0.1)

Heat pump cycling

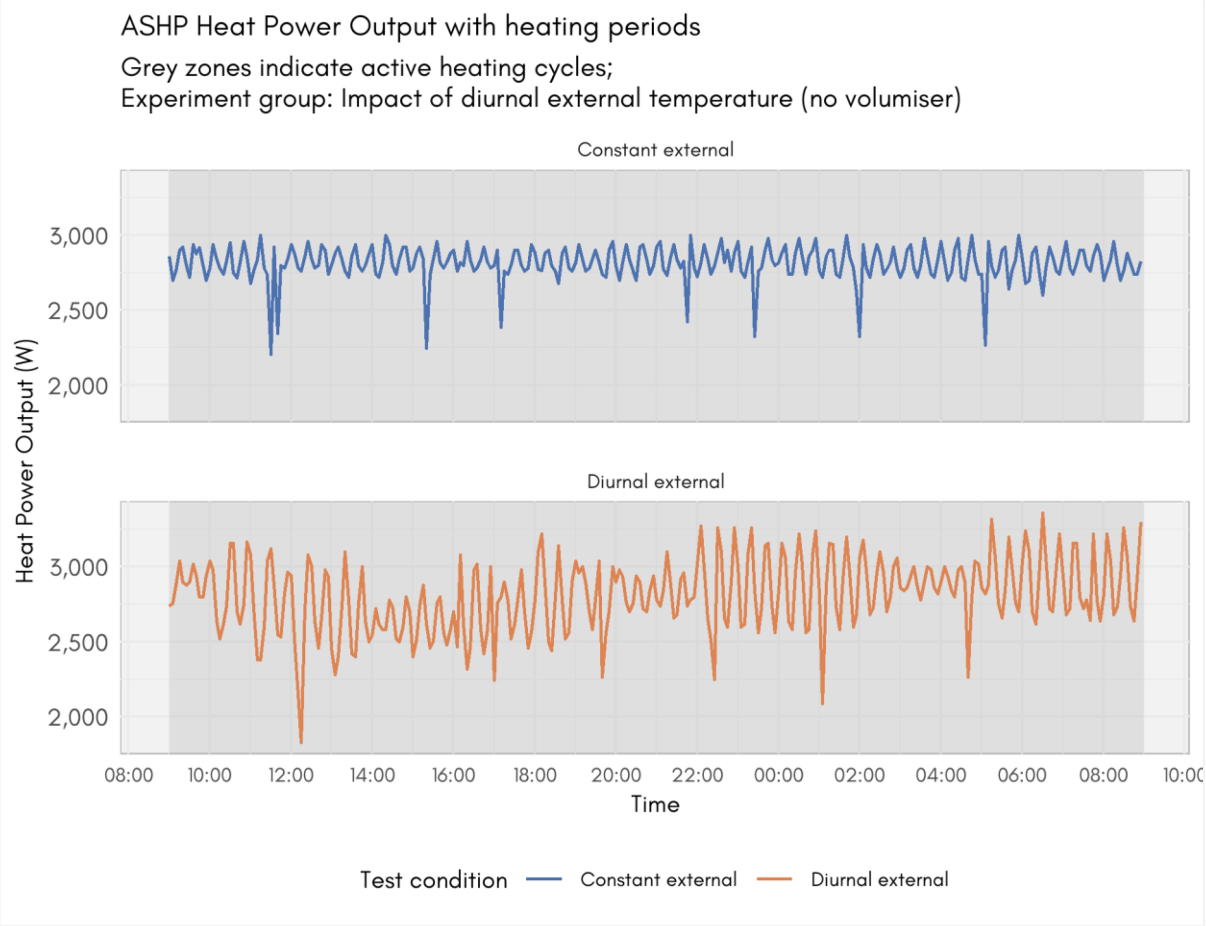


Figure D1.2: Impact of diurnal external temperature (no volumiser) – Heat pump cycles

Table D1.2: Impact of diurnal external temperature (no volumiser) – Heat pump cycles

Test	% Time On	Cycle #	Cycle Duration	Mean Power (W)	Median Power (W)	Max Power (W)
Constant external	100%	1	24h 0m	2,814	2,820	3,000
Diurnal external	100%	1	24h 0m	2,812	2,800	3,360

Flow rates

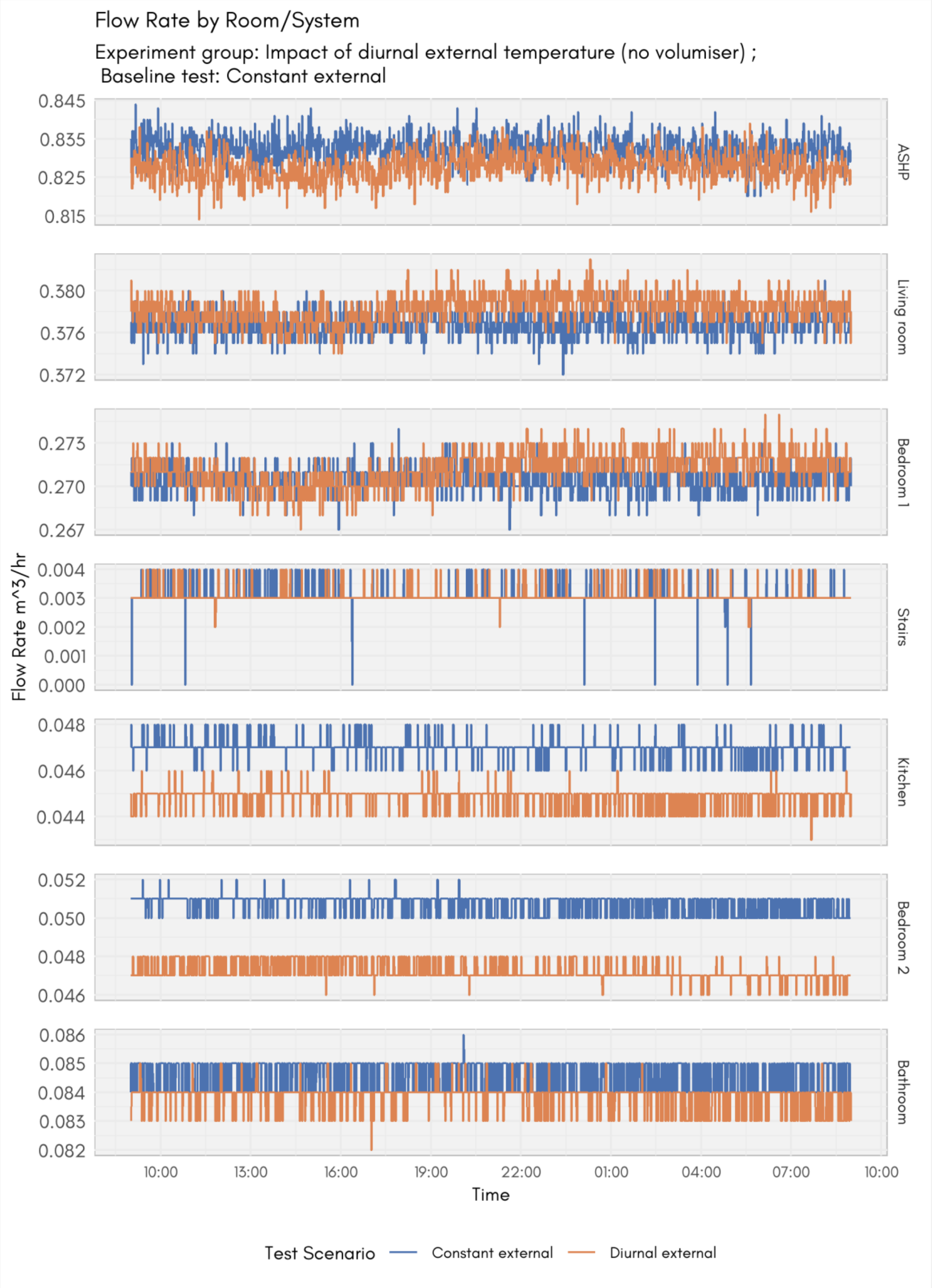


Figure D1.3: Impact of diurnal external temperature (no volumiser) – Flow rates.

Table D1.3: Impact of diurnal external temperature (no volumiser) – Mean flow rates during periods of flow >0 m3/h. Change from constant external temperature baseline shown in parenthesis.

Test	**ASHP Flow (m^3/hr)**	**Living room Flow (m^3/hr)**	**Bedroom 1 Flow (m^3/hr)**	**Stairs Flow (m^3/hr)**	**Kitchen Flow (m^3/hr)**	**Bedroom 2 Flow (m^3/hr)**	**Bathroom Flow (m^3/hr)**
Constant external	0.832 ±0.017	0.377 ±0.008	0.27 ±0.006	0.003 ±<0.001	0.047 ±0.001	0.051 ±0.001	0.085 ±0.002
Diurnal external	0.828 ±0.017 (-0.005 ±0.024)	0.378 ±0.008 (+0.002 ±0.011)	0.271 ±0.006 (+0.001 ±0.008)	0.003 ±<0.001 (0 ±<0.001)	0.045 ±0.001 (-0.002 ±0.001)	0.047 ±0.001 (-0.003 ±0.002)	0.084 ±0.002 (-0.001 ±0.003)

ASHP and radiator ΔT

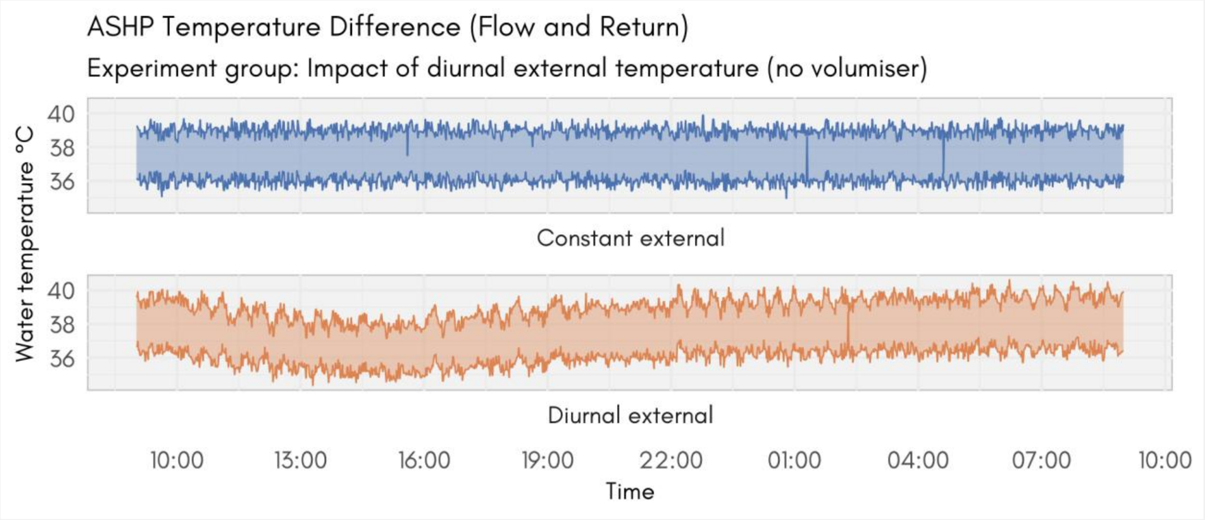


Figure D1.4: Impact of diurnal external temperature (no volumiser) – ASHP flow and return temperatures.

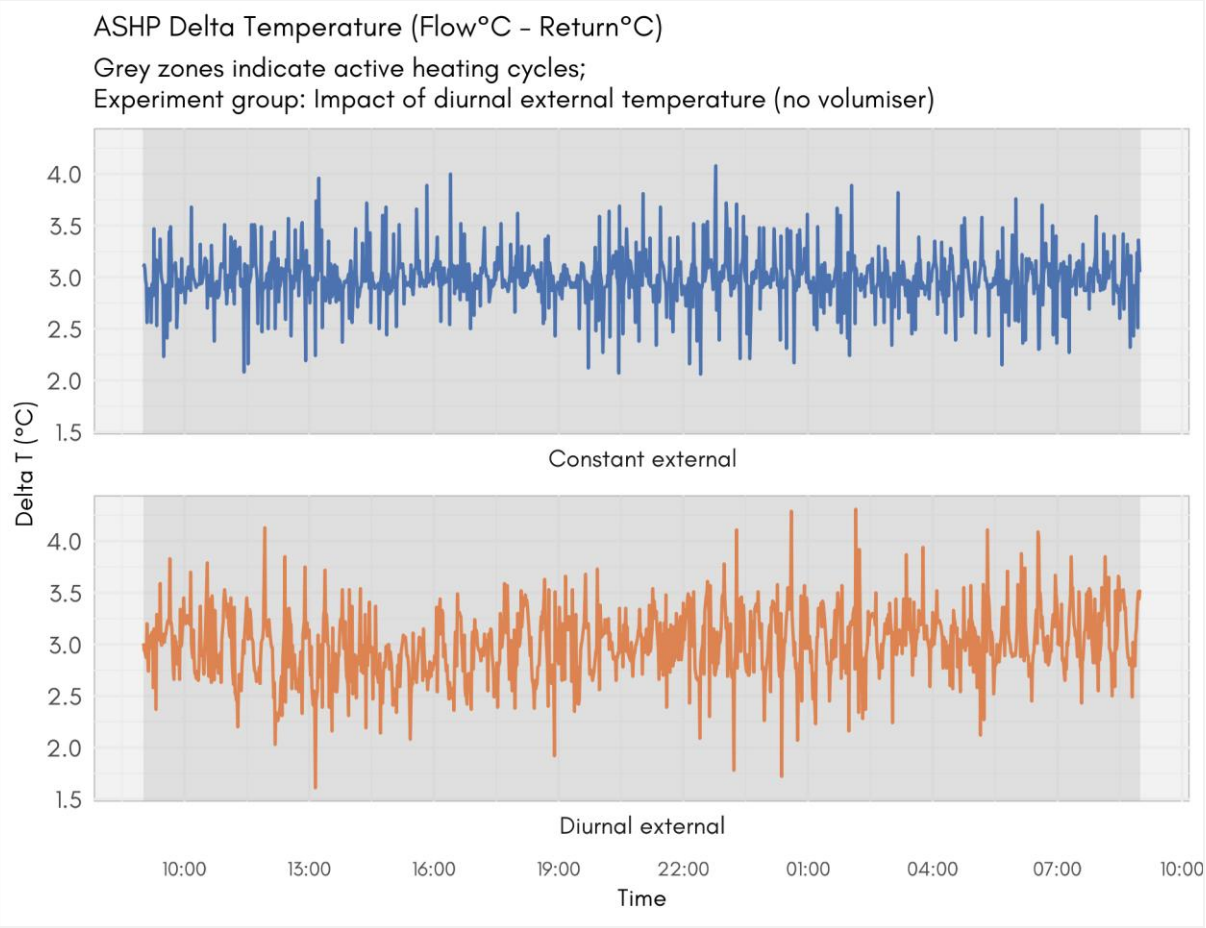


Figure D1.5: Impact of diurnal external temperature (no volumiser) – ASHP ΔT.

Table D1.4: Impact of diurnal external temperature (no volumiser) – Mean ASHP and radiator ΔT during periods of flow >0 m³/h. Change from constant external temperature baseline shown in parenthesis.

Test	**ASHP**	**Living room**	**Bedroom 1**	**Stairs**	**Kitchen**	**Bedroom 2**	**Bathroom**
Constant external	2.9 ±0.6	1.4 ±0.5	1.6 ±0.5	15.8 ±1	10.5 ±0.8	6.3 ±0.7	1.9 ±0.6
Diurnal external	3 ±0.6 (0.1 ±0.8) (1.7 ±28.3%)	1.4 ±0.5 (0 ±0.8) (-1.4 ±54.2%)	1.8 ±0.6 (0.1 ±0.8) (9 ±47.8%)	16 ±1 (0.2 ±1.4) (1.4 ±8.8%)	11 ±0.8 (0.5 ±1.2) (5.1 ±11.1%)	6.7 ±0.7 (0.4 ±1) (6.1 ±15.6%)	1.9 ±0.6 (0.1 ±0.8) (3.2 ±41.8%)

Power output

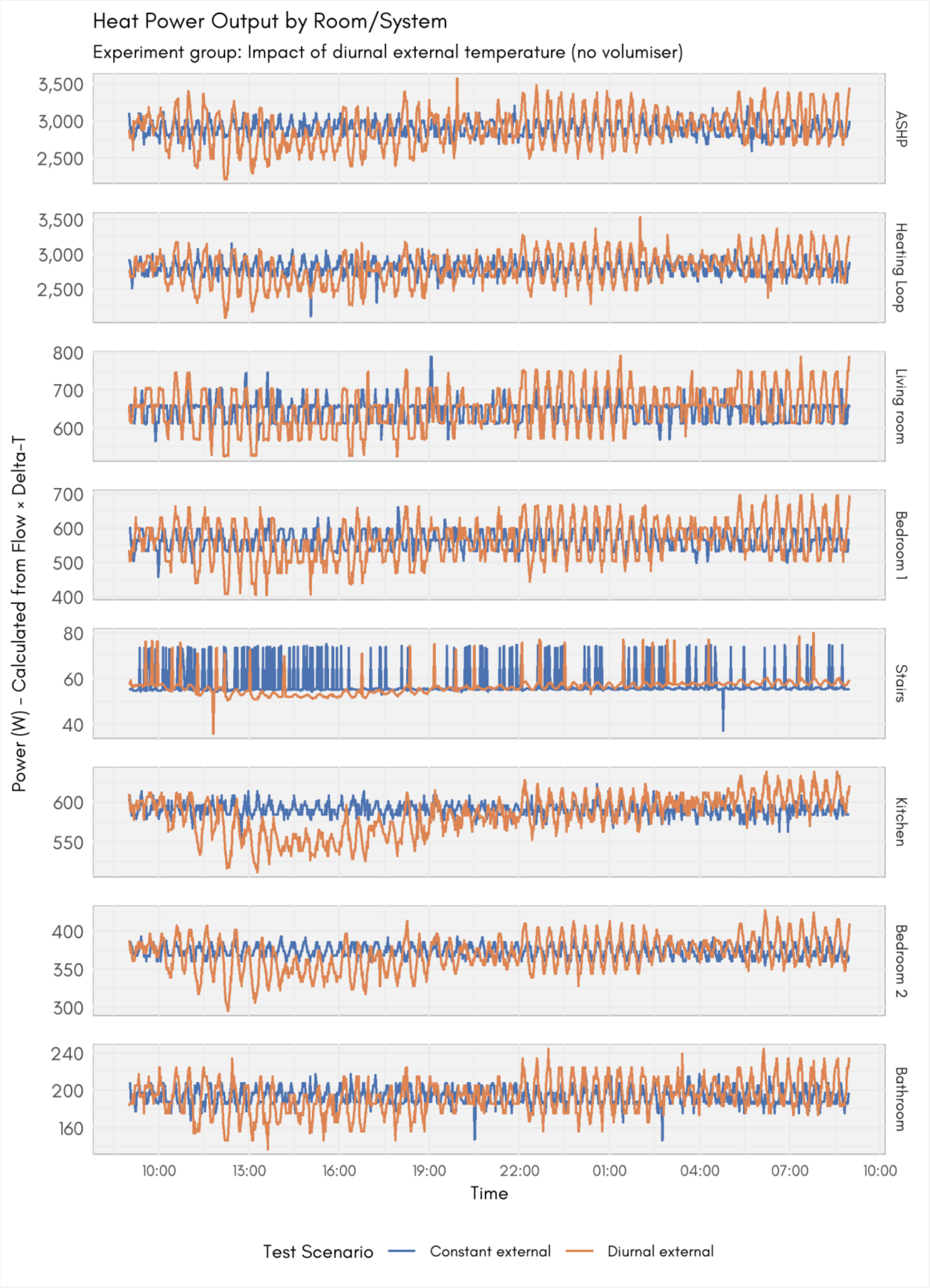


Figure D1.6: Impact of diurnal external temperature (no volumiser) – ASHP and radiator power output.

Table D1.5: Impact of diurnal external temperature (no volumiser) – Mean ASHP and radiator power output during periods of flow >0 m^3/h. Change from constant external temperature baseline shown in parenthesis.

Test	ASHP (W)	Heating Loop (W)	Living room (W)	Bedroom 1 (W)	Stairs (W)	Kitchen (W)	Bedroom 2 (W)	Bathroom (W)
Constant external	2814 ±202	2716 ±199	620 ±238	501 ±52	57 ±5	520 ±23	299 ±15	124 ±12
Diurnal external	2813 ±200 (-1 ±284) (-0.1 ±10%)	2719 ±199 (+3 ±281) (+0.1 ±10%)	615 ±239 (-6 ±337) (-1 ±54%)	510 ±50 (+9 ±72) (+1.7 ±14%)	57 ±5 (0 ±6) (-0.5 ±11%)	534 ±23 (+14 ±33) (+2.7 ±6%)	309 ±16 (+9 ±22) (+3.1 ±7%)	134 ±12 (+10 ±17) (+8 ±14%)

ASHP energy and COP

Table D1.6: Impact of diurnal external temperature (no volumiser) – ASHP energy and COP. Change from constant external temperature baseline shown in parenthesis.

Test	Electrical Energy In (kWh)	Heat Energy Out (kWh)	COP_{H4}
Constant external	19.0 ±0.2	67.4 ±1	3.55 ±0.06
Diurnal external	19.2 ±0.2 (+0.2 ±0.3 +1.2 ±1.4%)	67.4 ±1 (-0.0 ±1.4 -0.0 ±2.1%)	3.51 ±0.06 (-0.04 ±0.09 -1.2 ±2.5%)

D2 – With volumiser and TRVs

Internal temperatures

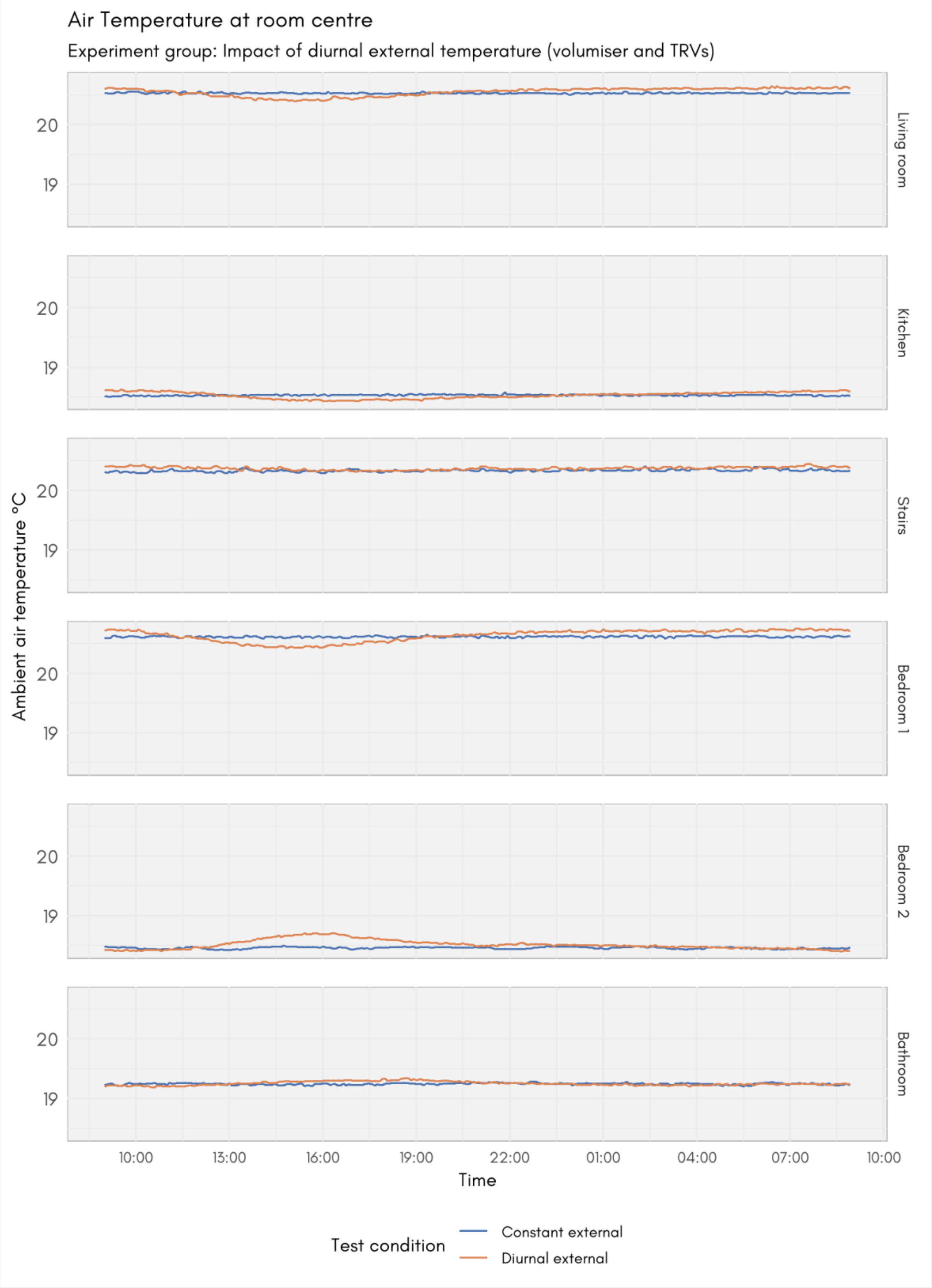


Figure D2.1: Impact of diurnal external temperature (with volumiser and TRVs) – Internal air temperatures

Table D2.1: Impact of diurnal external temperature (with volumiser and TRVs) – 24-hour mean internal air temperatures. Change from constant external temperature baseline shown in parenthesis. Italics denotes rooms that were subject to trimming.

Test	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
Constant external	20.5 ±0.1	20.6 ±0.1	20.3 ±0.1	18.5 ±0.1	18.5 ±0.1	19.2 ±0.1
Diurnal external	20.5 ±0.1 (+0.0 ±0.1)	20.6 ±0.1 (+0.0 ±0.1)	20.4 ±0.1 (+0.0 ±0.1)	18.5 ±0.1 (-0.0 ±0.1)	18.5 ±0.1 (+0.1 ±0.1)	19.3 ±0.1 (+0.0 ±0.1)

Heat pump cycling

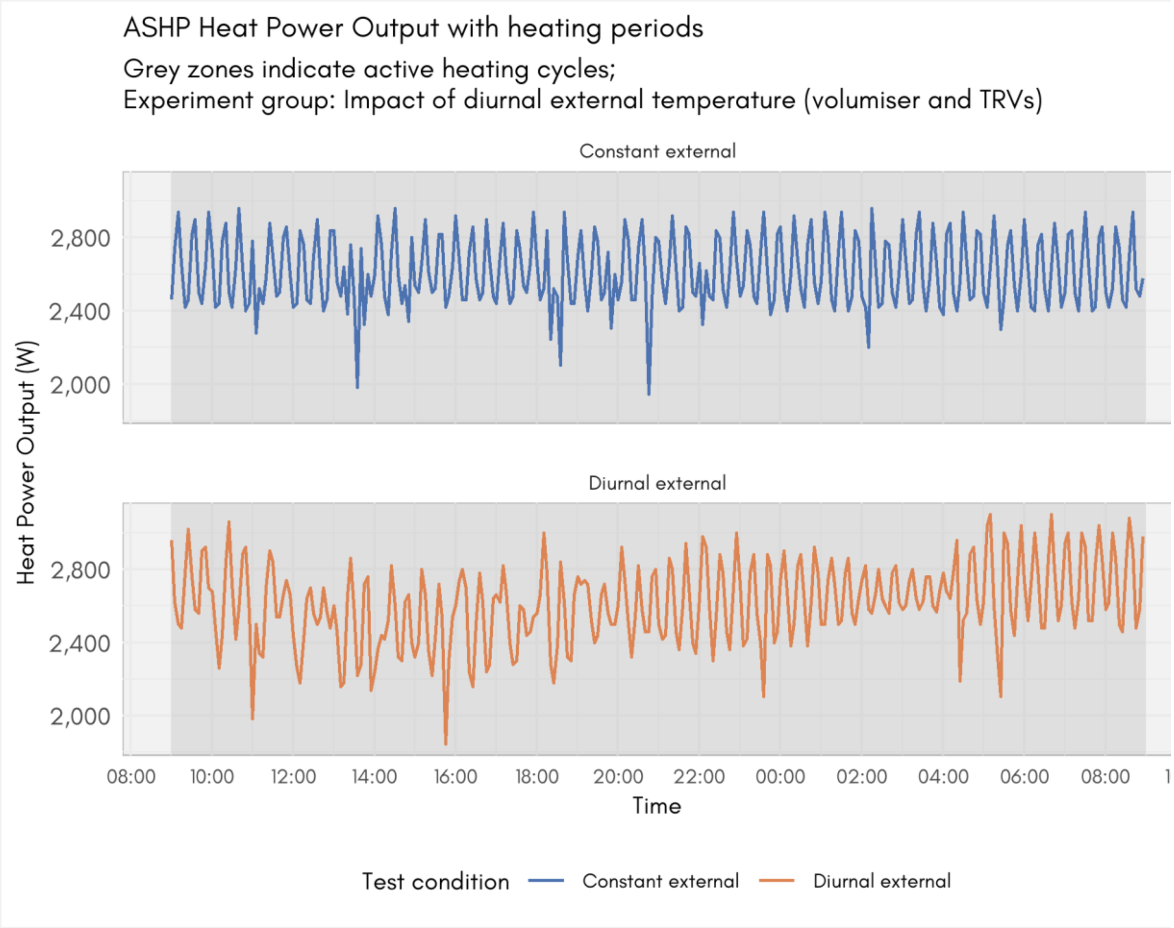


Figure D2.2: Impact of diurnal external temperature (with volumiser and TRVs) – Heat pump cycles

Table D2.2: Impact of diurnal external temperature (with volumiser and TRVs) – Heat pump cycles

Test	**% Time On**	**Cycle #**	**Cycle Duration**	**Mean Power (W)**	**Median Power (W)**	**Max Power (W)**
Constant external	100%	1	24h 0m	2,614	2,600	2,960
Diurnal external	100%	1	24h 0m	2,613	2,600	3,100

Flow rates

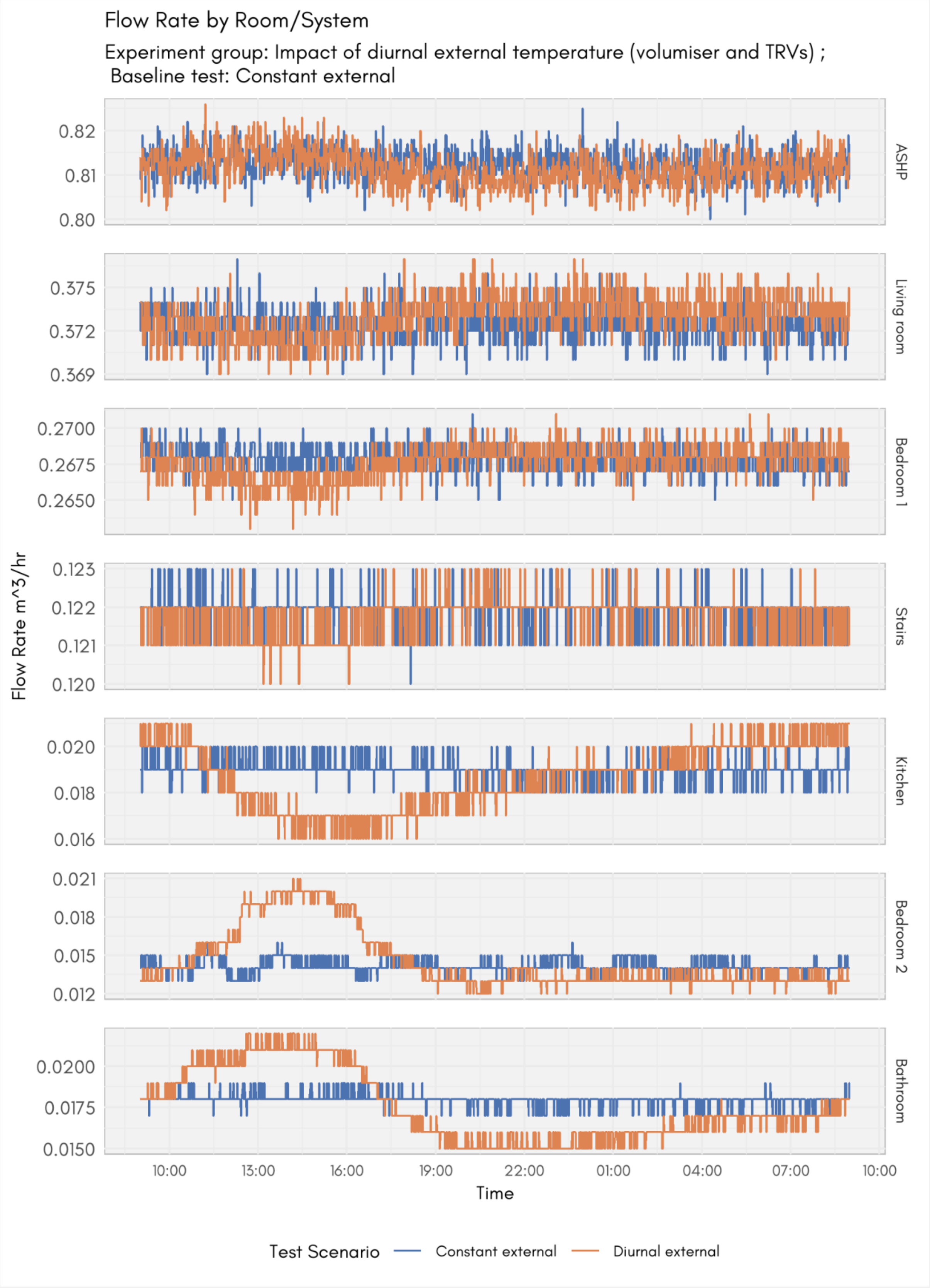


Figure D2.3: Impact of diurnal external temperature (with volumiser and TRVs) – Flow rates.

Table D2.3: Impact of diurnal external temperature (with volumiser and TRVs) – Mean flow rates during periods of flow >0 m3/h. Change from no setback baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP Flow (m^3/hr)**	**Living room Flow (m^3/hr)**	**Bedroom 1 Flow (m^3/hr)**	**Stairs Flow (m^3/hr)**	***Kitchen Flow (m^3/hr)***	***Bedroom 2 Flow (m^3/hr)***	***Bathroom Flow (m^3/hr)***
Constant external	0.812 ±0.017	0.372 ±0.008	0.268 ±0.005	0.122 ±0.003	0.019 ±0.001	0.014 ±<0.001	0.018 ±<0.001
Diurnal external	0.811 ±0.017 (-0.001 ±0.024)	0.373 ±0.008 (+0 ±0.011)	0.268 ±0.005 (0 ±0.008)	0.122 ±0.003 (0 ±0.004)	0.019 ±<0.001 (0 ±0.001)	0.015 ±<0.001 (+0 ±0.001)	0.018 ±<0.001 (0 ±0.001)

ASHP and radiator ΔT

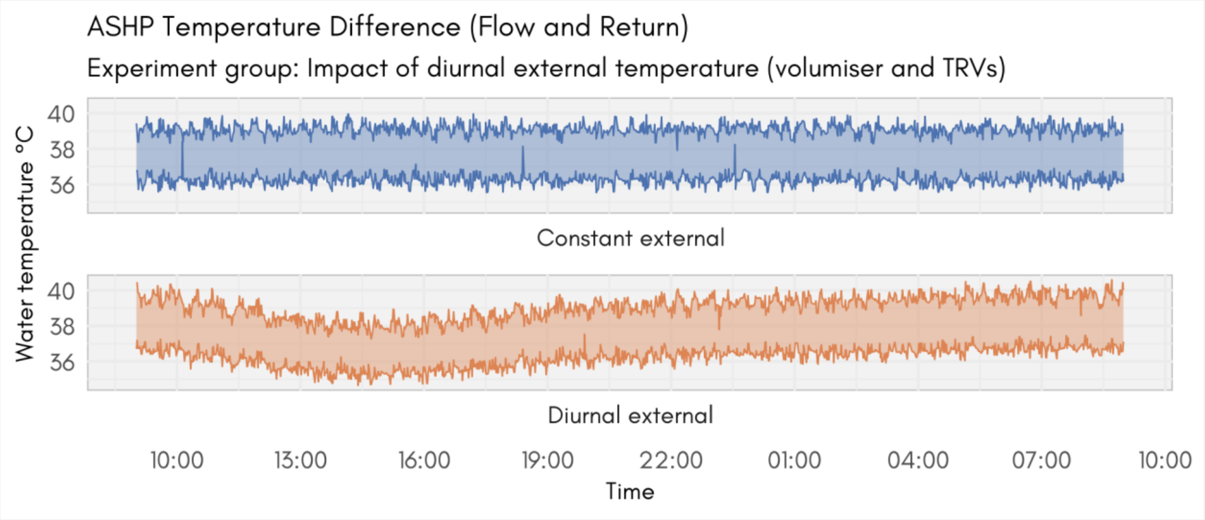


Figure D2.4: Impact of diurnal external temperature (with volumiser and TRVs) – ASHP flow and return temperatures.

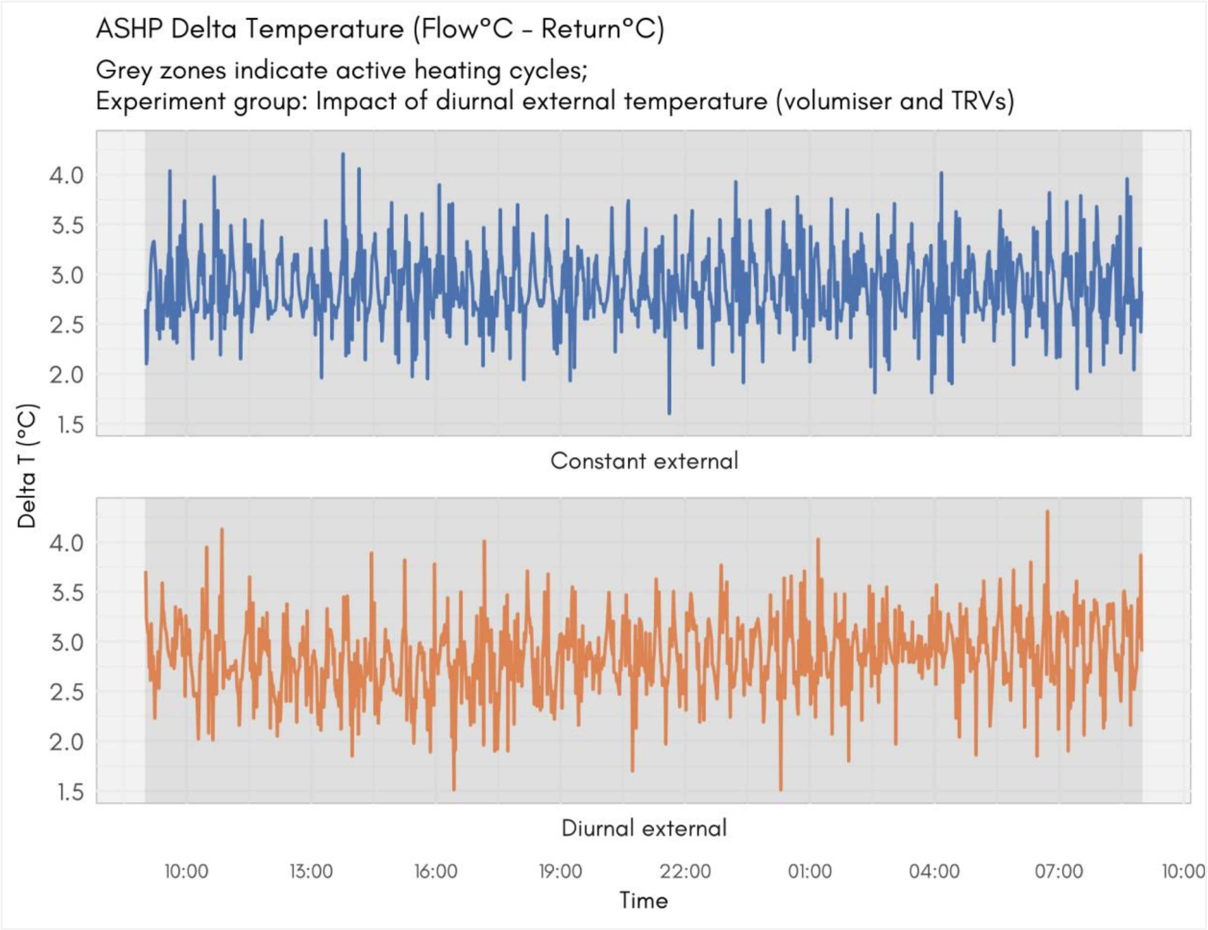


Figure D2.5: Impact of diurnal external temperature (with volumiser and TRVs) – ASHP ΔT.

Table D2.4: Impact of diurnal external temperature (with volumiser and TRVs) – Mean ASHP and radiator ΔT during periods of flow >0 m³/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP**	**Living room**	**Bedroom 1**	**Stairs**	***Kitchen***	***Bedroom 2***	***Bathroom***
Constant external	2.8 ±0.6	1.3 ±0.5	1.8 ±0.6	1.2 ±0.5	16.8 ±1	14.2 ±0.9	7.8 ±0.7
Diurnal external	2.8 ±0.6 (0 ±0.8) (0.1 ±29.7%)	1.3 ±0.5 (0 ±0.8) (-3.8 ±58.2%)	1.8 ±0.6 (0 ±0.8) (-2.3 ±42.6%)	1.2 ±0.5 (0 ±0.8) (1.1 ±64.5%)	16.7 ±1 (-0.1 ±1.4) (-0.5 ±8.4%)	14.1 ±0.9 (-0.1 ±1.3) (-1 ±9.2%)	8 ±0.7 (0.2 ±1) (3 ±13.4%)

Power output

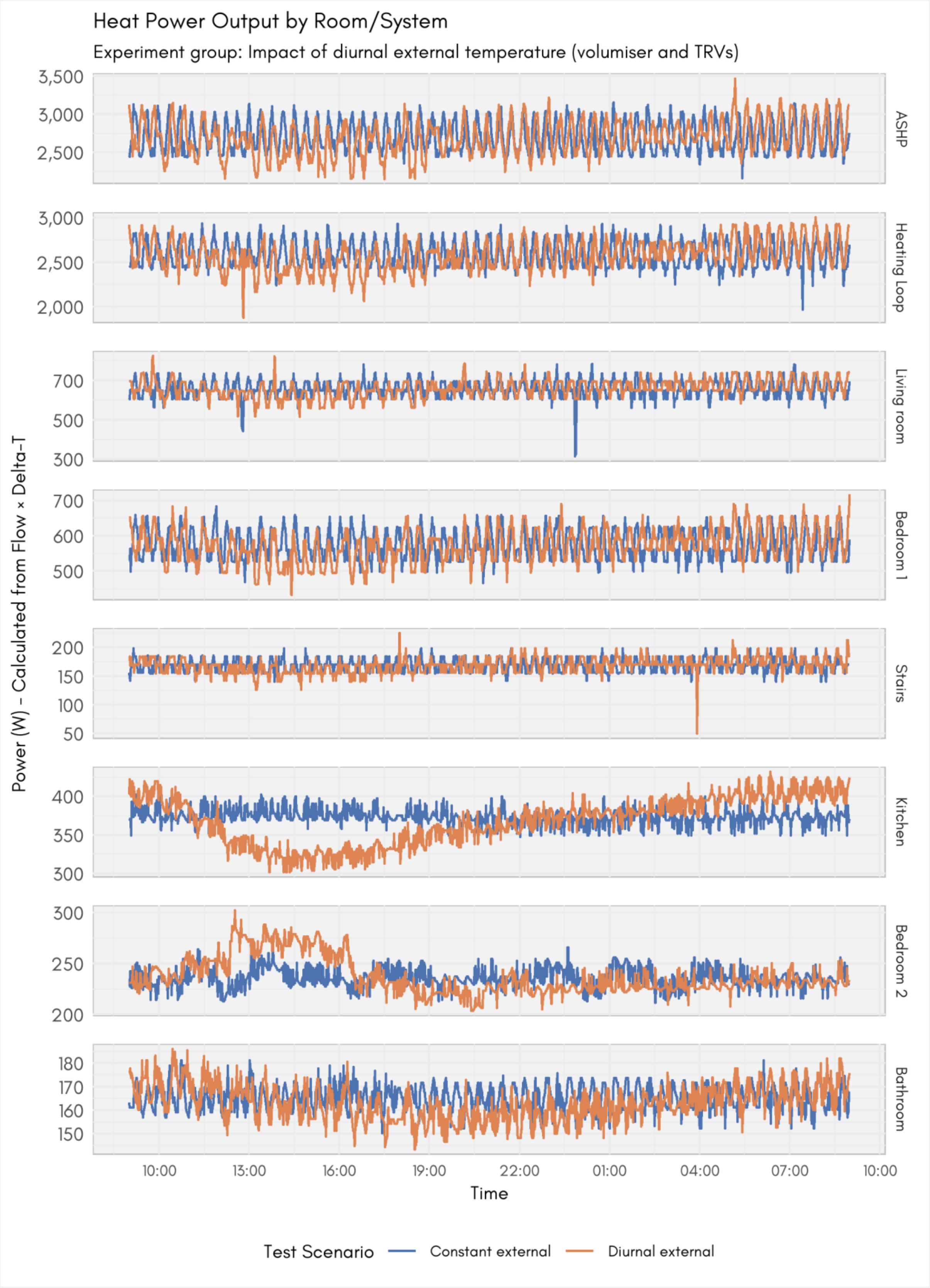


Figure D2.6: Impact of diurnal external temperature (with volumiser and TRVs) – ASHP and radiator power output.

Table D2.5: Impact of diurnal external temperature (with volumiser and TRVs) – Mean ASHP and radiator power output during periods of flow >0 m^3/h. Change from no trimming baseline shown in parenthesis. Italics denotes radiators that were subject to trimming.

Test	**ASHP (W)**	**Heating Loop (W)**	**Living room (W)**	**Bedroom 1 (W)**	**Stairs (W)**	***Kitchen (W)***	***Bedroom 2 (W)***	***Bathroom (W)***
Constant external	2614 ±193	2502 ±188	567 ±234	524 ±50	166 ±76	302 ±13	198 ±9	99 ±5
Diurnal external	2615 ±193 (+1 ±274) (+0 ±10%)	2492 ±187 (-10 ±266) (-0.4 ±11%)	546 ±234 (-21 ±330) (-3.7 ±58%)	516 ±50 (-8 ±71) (-1.5 ±14%)	168 ±76 (+2 ±107) (+1 ±65%)	327 ±14 (+25 ±19) (+8.2 ±6%)	201 ±9 (+2 ±13) (+1.2 ±7%)	100 ±5 (+0 ±7) (+0.1 ±7%)

ASHP energy and COP

Table D2.6: Impact of diurnal external temperature (with volumiser and TRVs) – ASHP energy and COP. Change from Constant external temperature baseline shown in parenthesis.

Test	**Electrical Energy In (kWh)**	**Heat Energy Out (kWh)**	**COP_{H4}**
Constant external	17.9 ±0.2	62.8 ±1	3.51 ±0.06
Diurnal external	17.8 ±0.2 (-0.1 ±0.3 -0.3 ±1.4%)	62.7 ±1 (-0.1 ±1.4 -0.1 ±2.2%)	3.52 ±0.06 (+0.01 ±0.09 +0.2 ±2.6%)

Summary (Appendix D1 & D2)

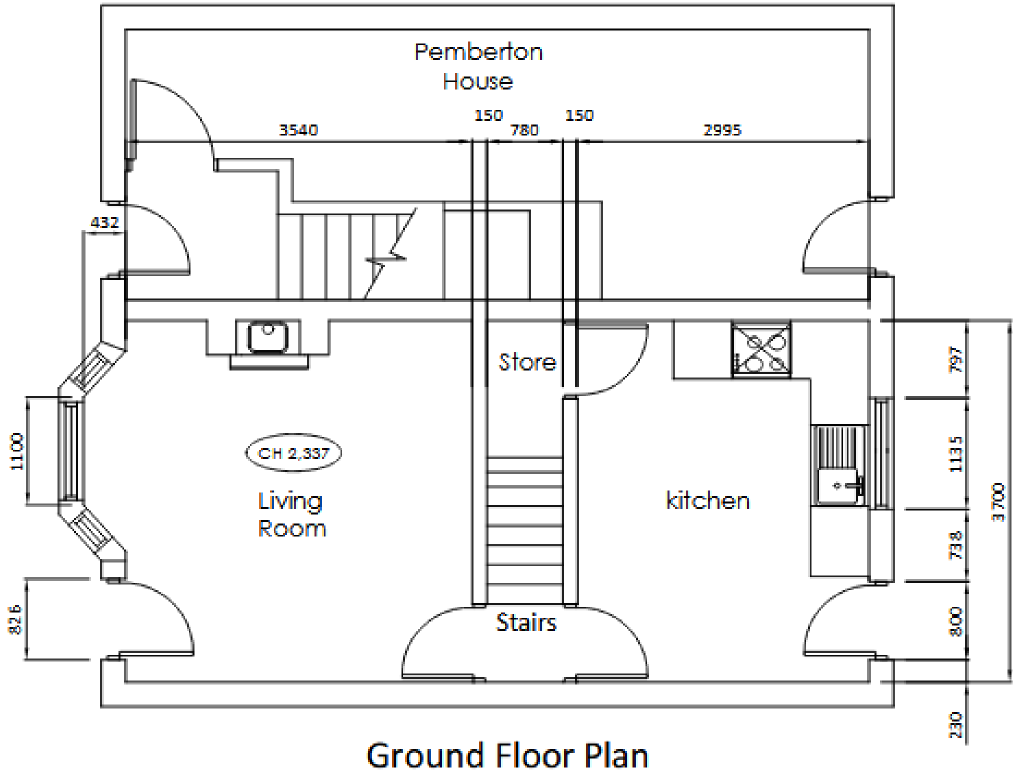
Changing from a constant to a diurnal external temperature pattern had no measurable impact on COP or energy use. The primary difference observed was a reduction in internal temperature stability. The typical room temperature variation from the constant test was <±0.2 °C. However, there was no significant change in the 24-hour mean internal temperature of any room. Reduced stability can be attributed to a combination of weather compensation control, modifying the flow temperature and thermal inertia of the building fabric. Weather compensation responds to changes in external temperature at a faster rate than the building fabric, this results in a misalignment between heat input and heat loss.

Appendix E – Energy House construction details

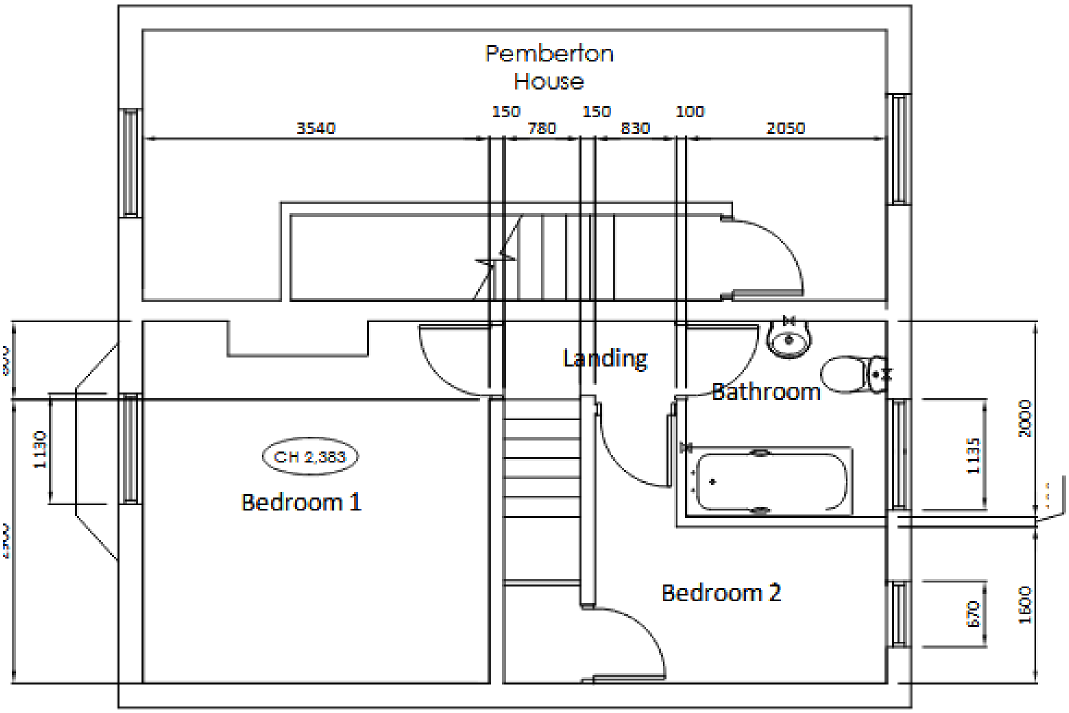
Table A1. Salford Energy House construction details during test programme

Thermal element	Construction
External walls	Solid wall – 222.5 mm brick arranged in English bond (5 courses) with 9 mm lime mortar and 10.5 mm British Gypsum Thistle hardwall plaster with a 2 mm Thistle Multi-Finish final coat. The ground and intermediate floor joists are built-in to the gable wall.
Roof	Purlin and rafter cold roof structure with 270 mm insulation at ceiling level. 100 mm mineral wool insulation (λ 0.044 W/mK) between 100x50 mm ceiling joists. 170 mm mineral wool (λ 0.044 W/mK) above and perpendicular to joists. Ceiling joists run parallel to the gable wall at 400 mm centres above lath (6 mm) and plaster (17 mm) ceiling
Ground floor	Suspended timber ground floor above a ventilated underfloor void (20 mm depth). 150x22 mm floorboards fixed to 200x50 mm floor joists at 400 mm centres. Floor joists run between the gable and party wall with joists ends built into masonry walls.
Windows	'E' rated double glazing units in PVCu frames.
Doors	Front – 'E' rated PVCu Rear – 'E' rated half glazed PVCu.
Party wall	Solid wall – as external walls but with plaster finish on both sides.

Appendix F – Energy House floor plans

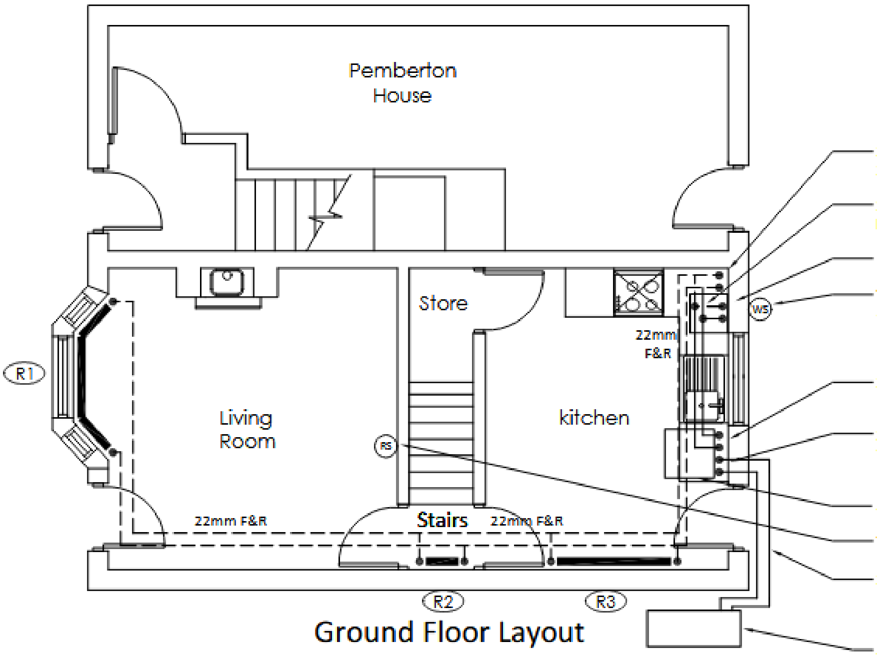


Ground Floor Plan



First Floor Plan

Appendix G – Energy House heating services layout



22mm Ø heating F&R rise to above & 22mm Ø heating F&R drop to floor void.

22mm Ø heating F&R drop to common heating header beneath boiler.

Gas fired combination boiler.

Typical location of weather compensation sensor.

28mm Ø ASHP F&R drop to 22mmØ F& R common heating header.

28mm Ø ASHP F&R rise to enter the property to internal module.

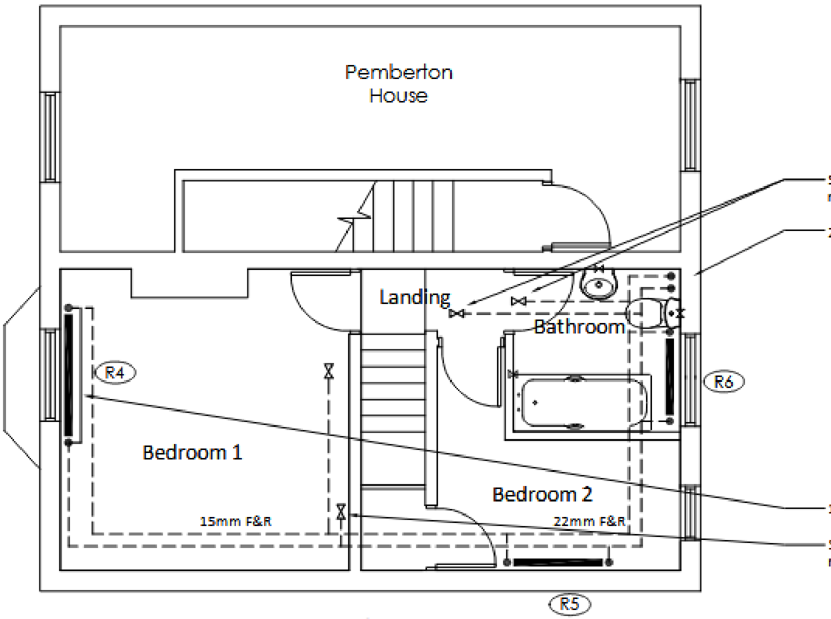
ASHP indoor plant.

Typical location of heating controller.

28mm Ø ASHP F&R pipework at low level.

Air Source Heat Pump (ASHP).

Ground Floor Layout



Spare pipework connections for additional radiators

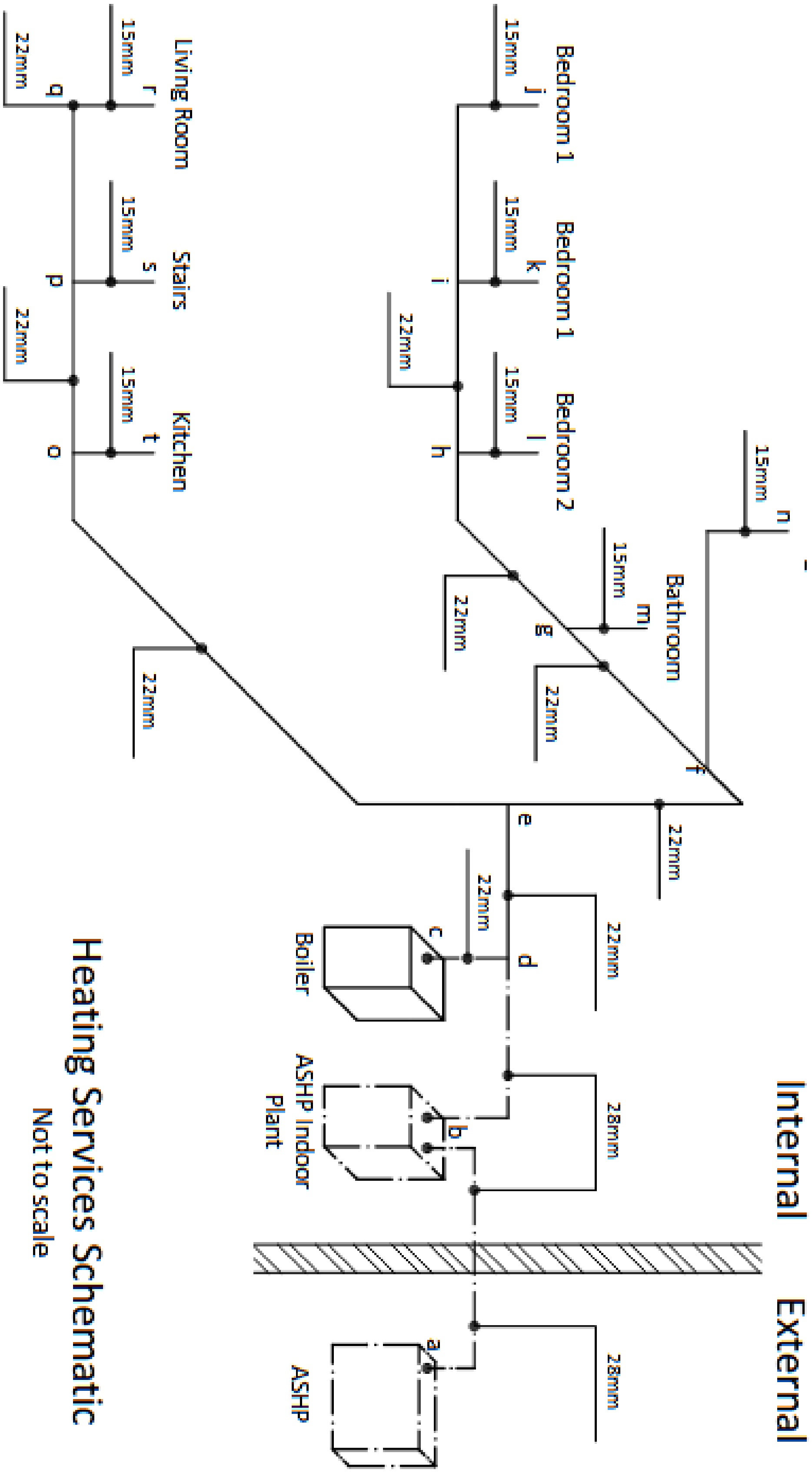
22mm Ø heating F&R rise from below.

15mm Ø radiator bypass beneath Radiator R4.

Spare pipework connections for additional radiators.

First Floor Layout

Appendix H – Energy House heating services schematic



Heating Services Schematic

Not to scale