Understanding the effects of reducing boiler flow temperatures

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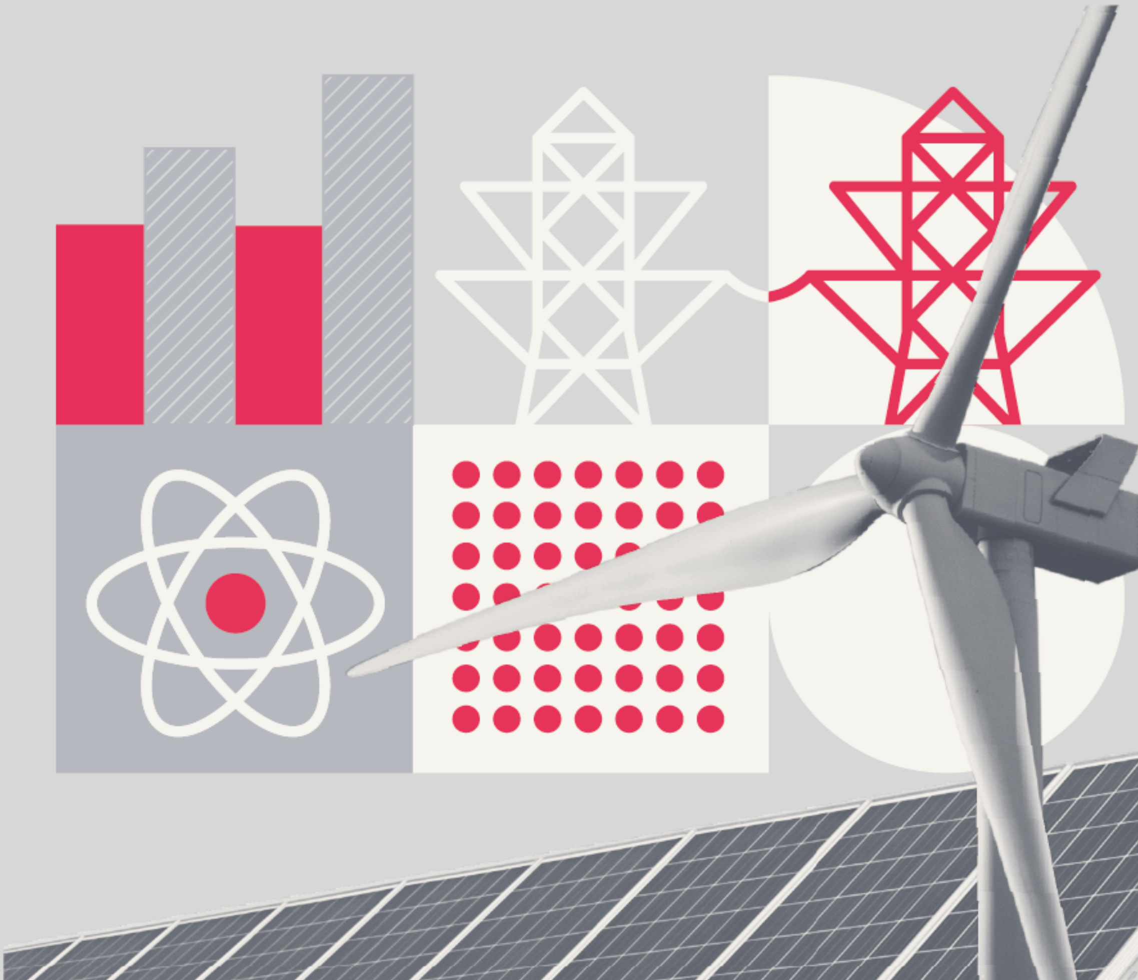

A report prepared by Energy Systems Catapult on behalf of Nesta

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Energy Systems Catapult supports innovators in unleashing opportunities from the transition to a clean, intelligent energy system.

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1. Introduction

Nesta is interested in understanding the effects of reducing the flow temperature of heating systems, specifically seeking to understand the effects on energy use and cost, warm-up times and comfort.

Anecdotal evidence gathered by Nesta in advance of the project suggested that combi-condensing boilers have their flow temperature set high (70-80°C). As a result, the heating system return temperature remains high, and the boiler does not enter its most efficient condensing mode that it would if return temperatures were cooler. Nesta wanted to gather further evidence to evaluate the hypothesis that reducing the boiler's flow temperature would reduce the heating system's return temperature sufficiently for the boiler to enter its most efficient condensing mode and thus reduce gas use, whilst also maintaining comfort levels for householders.

To evaluate this hypothesis, Nesta commissioned Energy Systems Catapult (ESC) to undertake detailed dynamic modelling simulations. ESC has developed its own domestic energy modelling tool, Home Energy Dynamics (HED), that accurately predicts the performance of domestic heating systems.

This report is presented in seven further chapters. Chapter two summarises the simulation choices made by Nesta for the project. Chapter three shows the efficacy of HED and presents results from validating against tests undertaken at the Salford Energy House. Chapters four and five present results from the simulations, showing changes in gas use for different flow temperatures, with chapter six presenting how reducing flow temperature affects comfort. Chapter seven provides additional details for some simulations, providing visual data to show the boiler's operations and resulting gas use and comfort. Chapter eight concludes the findings from the project.

2. Method

Nesta identified their preferences for the simulations that would be run in HED and the variations that need to be evaluated, namely the dwelling archetype (built form, age), occupancy details, simulation time-periods and flow temperatures.

ESC has a library of dwelling archetype 'house models' that were available for Nesta to select from and that are based on detailed surveys of domestic dwellings in the UK. The house models describe the physical characteristics of the dwelling, such as its construction method, geometry and layout, and detailed information on its heating system.

Nesta also selected from a library of occupancy profiles that ESC has developed through its Living Lab[1]. These occupancy profiles describe the make-up of the household with regards to ages and number of people, as well as their preferences for heating their home, identifying the rooms they would like to be heated, the times of day they would like heat and the temperatures they desire.

Simulations are run using real weather data for a specific location and for specific times of the year, according to Nesta's choices. Finally, Nesta selected the boiler flow temperatures they wanted to evaluate.

2.1. Simulation choices

The following sections detail the choices that Nesta made for the simulations. It should be noted that modelling and the running of simulations is an inherently uncertain activity and the results presented in this report may not match experiences in the real world.

2.1.1. HOUSE MODELS

Nesta selected five house models from ESC's library:

- A **pre-1919 mid-terrace dwelling** – it accounts for a large proportion of the English housing stock (10.8%), is typically poorly insulated but has two party walls. Two bedrooms.
- A **1919-1944 semi-detached dwelling** – it accounts for a reasonably large proportion of the English housing stock (7.7%), was built with cavity walls but some remain uninsulated, was built without loft insulation and some remain uninsulated. It has a single party wall. Three bedrooms.
- A **1945-1964 semi-detached dwelling** – it accounts for a reasonably large proportion of the English housing stock (7.8%), was built with cavity walls but some remain uninsulated, was built without loft insulation and some remain uninsulated. It has a single party wall. Three bedrooms.
- A **1965-1980 flat** – it accounts for a reasonably large proportion of the English housing stock (5%), was built with cavity walls but some remain uninsulated. It is smaller so it is likely to have a different occupancy profile to other archetypes. One bedroom.
- A **1981-2002 detached dwelling** – it accounts for a reasonably large proportion of the English housing stock (5.4%), was built with insulated cavity walls and loft, and is large so it can accommodate a variety of occupancy profiles. Five bedrooms.

ESC's house models are based on real dwellings. This means each archetype has unique radiator sizes, pipework routing, house orientation and window sizes.

Further details of the house models can be found in Appendix 1 – House Models.

2.1.2. Occupancy profiles

Nesta selected the following household types:

- Couple with single child – two adults at work during the day, school-age child
- One person over 60 years of age — one adult at home all day, retired
- Couple with children, family of four – two adults at work during the day, two school-age children

The following preferences for heating the house were chosen:

- 'Toasty cruisers', who tend to prefer warmer temperatures – setpoints of 22°C in living areas (lounge, kitchen, dining room, study) and 20°C in bedrooms and circulation zones.

[1] https://es.catapult.org.uk/tools-and-labs/living-lab/

- ‘Cool conservers’, who tend to prefer cooler temperatures – setpoints of 20°C in living areas (lounge, kitchen, dining room, study) and 18°C in bedrooms and circulation zones.
- Standard assessment procedure (SAP) temperature profiles – setpoints of 21°C in living areas (lounge, kitchen, dining room, study) and 18°C in bedrooms and circulation zones.

In addition, Nesta wanted to understand the effects of using ‘setback temperatures’ (a minimum temperature that householders do not want their house to drop below outside of the times when heat is required, for example, overnight). Setback temperatures of 15°C, 16°C and 17°C were selected.

The household types and heating preferences combine to determine how the heating system is used (for example, which rooms are heated to which temperatures at which times of the day). The total hours of heating are summarised in Table 1. Further details of the occupancy profiles can be found in Appendix 2 – Occupancy Profiles.

Table 1: weekly hours of heating per occupancy profile[2]

Household type	Toasty cruiser	Cool conserver	SAP
Couple with single child	76	66	77
One person over 60	112	86	77
Couple with children, family of four	76	66	77

2.1.3. Simulation periods and weather

Nesta chose to run simulations over the course of two weeks in deep winter, two weeks in spring and full annual simulations. ‘Typical’ weather data for Manchester was selected (see Appendix 3 – Weather Profiles). In all simulations, the time interval in HED was set to 600 seconds (10 minutes).

2.1.4. Flow temperatures

Nesta selected the following flow temperatures to be simulated: 80°C, 70°C, 60°C, 55°C, 50°C and 45°C

2.1.5. Other

In all simulations, a Worcester Bosch Greenstar 24i Junior gas combi-condensing boiler was modelled.

The 1919-1944 semi-detached house was modelled with cavity wall and loft insulation, and without both insulation types. The house model with insulation has 60mm of blown wall insulation in the wall cavity and 250mm of mineral wool in the loft. The house without insulation has neither.

2.2. Summary of choices

Nesta’s aforementioned choices are summarised in Table 2. In addition to the simulations chosen by Nesta, ESC simulated each scenario for a full year and made comparisons between 80°C, 60°C and 45°C flow temperatures.

[2] HED calculates additional ‘warm-up’ time according to the weather conditions and how quickly the house responds to being heated

Table 2: summary of simulation characteristics

House archetype	Insulation changes	Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Time periods
Pre-1919 mid-terrace dwelling (70m²)	N/A	Couple with single child	Cool conserver	80, 70, 60, 55, 50, 45	N/A	Winter and spring
		Couple with single child	Cool conserver		15, 16, 17 in living areas	Winter
		One person over 60	Toasty cruiser		N/A	Winter and spring
		One person over 60	Toasty cruiser		17 in living areas	Winter
		One person over 60	Toasty cruiser but only heats living room, keeps radiators off in other rooms		N/A	Winter and spring
		One person over 60	Toasty cruiser but only heats living room, keeps radiators off in other rooms		17 in living areas	Winter
1919-1944 semi-detached dwelling (104m²)	N/A	Couple with children, family of four	Cool conserver	80, 70, 60, 55, 50,45	N/A	Winter and spring
	N/A	Couple with children, family of four	Cool conserver		15 in living areas	Winter
	No loft or wall insulation	Couple with children, family of four	Cool conserver		N/A	Winter and spring
	N/A	One person over 60	Toasty cruiser		N/A	Winter and spring
	N/A	One person over 60	Toasty cruiser		17 in living areas	Winter
	No loft or wall insulation	One person over 60	Toasty cruiser		N/A	Winter and spring
1945-1964 semi-detached dwelling (67m²)	N/A	Couple with children, family of four	Toasty cruiser	80, 70, 60, 55, 50, 45	N/A	Winter and spring
		Couple with children, family of four	Cool conserver		N/A	
		One person over 60	Toasty cruiser		N/A	
		One person over 60	Cool conserver		N/A	
1965-1980 flat (41m²)	N/A	Couple with single child	Cool conserver	80, 70, 60, 55, 50, 45	N/A	Winter and spring
		Couple with single child	Cool conserver		15 in living areas	Winter
		One person over 60	Toasty cruiser		N/A	Winter and spring
		One person over 60	Toasty cruiser		17 in living areas	Winter
		Couple with single child	Cool conserver – but half the hours (33h a week)		N/A	Winter and spring
		Couple with single child	Cool conserver – but half the hours (33h a week)		15 in living areas	Winter
1981-2002 detached dwelling (149m²)	N/A	Couple with children, family of four	Cool conserver	80, 70, 60, 55, 50, 45	N/A	Winter and spring
		Couple with children, family of four	Cool conserver		15 in living areas	Winter
		One person over 60	Toasty cruiser		N/A	Winter and spring
		One person over 60	Toasty cruiser		17 in living areas	Winter

3. Validation of HED

To validate the efficacy of HED to predict real-world performance, ESC undertook simulations of the Salford Energy House. The Salford Energy House is a unique research and testing laboratory and comprises an early 20th century two-bedroom end-terraced house within an environmental chamber, allowing an accurate and rapid assessment of energy-efficient measures such as reducing flow temperature in a controlled environment.

The Salford Energy House ran a number of tests reducing boiler flow temperature on behalf of Nesta, with results made available to ESC in order to validate findings from HED. The characteristics of these tests are summarised in Table 3.

Table 3: summary of tests run in Salford Energy House

House Archetype	Insulation changes	Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Time periods
Salford Energy House ($54m^2$)	N/A	SAP	07:00-0900 and 16:00-23:00. 21°C in the living room, 22°C in the bathroom, 18°C elsewhere.	80, 70, 60, 55, 50	N/A	Winter day
				55	17	Winter day
				70, 55	N/A	Spring day

Each of Salford Energy House's tests were run for a three-day period, allowing two days for the house to reach equilibrium and a final day of running a test and collecting data. Data was collected at 60-second intervals. A small number of differences remain between how the Salford Energy House tests were run and how ESC simulations were run:

- The Salford Energy House has a single thermostat in the living room that controls the boiler on/off and thermostatic radiator valves (TRVs) in other rooms, whereas ESC's HED calculates the thermal mass of air in each room reaching the setpoint before switching the boiler on/off. Both have a 1°C hysteresis.
- The Salford Energy House's tests did not simulate the house benefiting from solar gains, whereas ESC's HED does include solar gains.

All other test characteristics (for example, the internal temperature of the adjoining terrace property) were set up to match the Salford Energy House[3].

3.1. Results

The following graphs[4] (Figure 1) show measured gas use in the Salford Energy House and simulated gas use in ESC's HED, at different flow temperatures. Each graph shows a single day's worth of data (24 hours at 60-second intervals = 1,440 data points) for a given flow temperature, from the hours of 06:00 to 06:00. In each graph, the orange line depicts Salford Energy House data and the blue line depicts ESC's HED simulation data. The validations were completed 'blind', for example, ESC ran simulations of the Salford Energy House without having Salford Energy House results. The initial set of simulations were used, and no further simulations were carried out, as may have been required in a calibration exercise.

Salford Energy House tests do not include a 'warm-up period' whereby the heating comes on earlier than the heating profile settings in order to ensure the house is at the desired setpoint at the start of the heating period. ESC's validation also does not include a warm-up period for the validation simulations (in order to match Salford Energy House results) but does for the remainder of the simulations in this report.

[3] The characteristics of the Salford Energy House and their tests are described in a [2022 Nesta report]
[4] The graphs are shown to indicate the general trends and ability of HED to predict Salford Energy House, not to be read in detail, hence their smaller size.

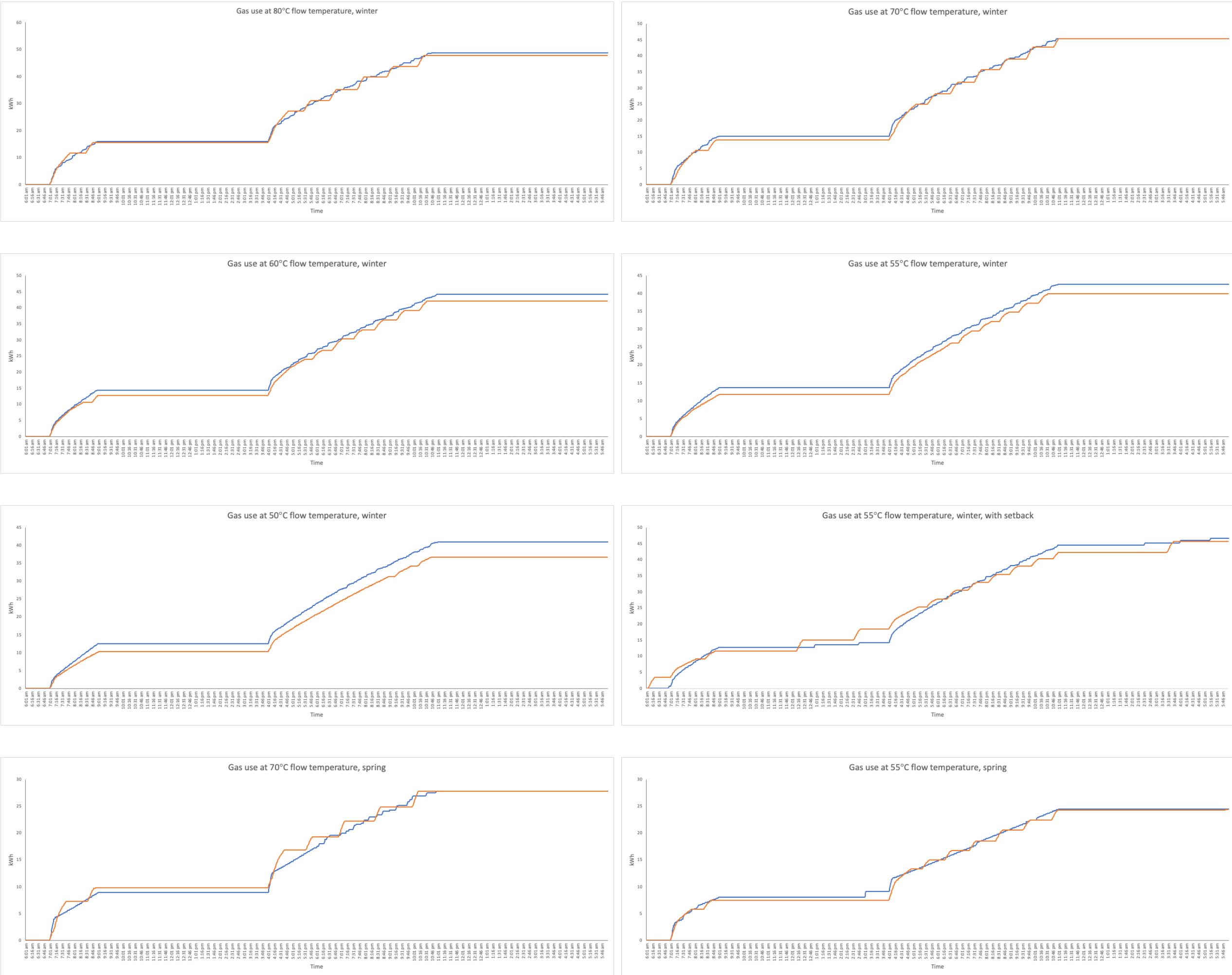


Figure 1: graphs showing efficacy of HED to predict gas use in Salford Energy House

In each graph there is a difference between predicted (ESC's HED) and actual (Salford Energy House) energy use, which is summarised in Table 4. Differences are often small (three differences are <1%, two are at 2%) but one difference is 10%, and in two other cases the differences are around 5%. The larger differences are shown at lower flow temperatures in the winter simulations. An approximate 10% difference in predicted versus actual energy consumption is particularly high for Home Energy Dynamics. A justification for the higher differences at lower flow temperatures is the aforementioned difference in the way that the Salford Energy House's boiler is controlled (single thermostat in the living room) compared to the way that ESC's HED controls the boiler, by requiring all rooms to meet the desired temperature. At lower flow temperatures, rooms are harder to heat, meaning it is more likely that the boiler will work continuously during heating periods, rather than cycling on/off as a setpoint is reached or temperature drops. The Salford Energy House thermostat also has an 'anticipator' that predicts when the heating setpoint will be met, and so shuts off the heating system in advance in order to prevent 'overshooting'. This functionality is not included in ESC's modelling of the Salford Energy House and can therefore also partially explain the small discrepancy between the two sets of results.

Table 4: summary of differences between actual and predicted energy use

Flow (°C)	Season	Setback (°C)	Gas use (kWh)		Difference (kWh)	Difference (%)
			Salford Energy House	ESC's HED		
80	Winter	N/A	47.82	48.80	0.98	2.00
70	Winter	N/A	45.37	45.42	0.05	0.12
60	Winter	N/A	42.04	44.18	2.14	4.84
55	Winter	N/A	39.93	42.57	2.64	6.19
50	Winter	N/A	36.76	40.93	4.17	10.18
55	Winter	17	45.72	46.62	0.91	1.94
70	Spring	N/A	27.81	27.77	(0.04)	(0.15)
55	Spring	N/A	24.32	24.48	0.16	0.67

3.2. Additional simulations of Salford Energy House

In addition to simulations to validate the efficacy of HED to predict real-world performance, ESC undertook further simulations of the Salford Energy House[5]. These simulations are to understand effects if changes are made to how the heating system is used, congruent with scenarios with other house models. These simulations repeat the validation simulations but for two-week winter and spring periods, add a 17°C setback and increase heating periods by 30 and 60 minutes in both the morning and afternoon heating periods to simulate longer warm-up periods. The details of these additional simulations are shown in Table 5.

Table 5: additional simulations of the Salford Energy House

House archetype	Insulation changes	Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Time periods
Salford Energy House	N/A	SAP	07:00-09:00 and 16:00-23:00. 21°C in the living room, 22°C in the bathroom, 18°C elsewhere.	80, 70, 60, 55, 50, 45	N/A	Winter
						Spring
					17°C	Winter
						Spring
			06.00-09:00 and 15:30-23:00. 21°C in the living room, 22°C in the bathroom, 18°C elsewhere.	80, 70, 60, 55, 50, 45	N/A	Winter
						Spring
			06:00-09:00 and 15:00-23:00. 21°C in the living room, 22°C in the bathroom, 18°C elsewhere.	80, 70, 60, 55, 50, 45	N/A	Winter
						Spring

In total, 264 simulations were run in HED according to Nesta's choices in Table 2, with an additional 96 full-year simulations and 48 simulations of the Salford Energy House (Table 5) making 408 simulations in total.

[5] It was not possible to do further validations of the Salford Energy House with these simulations, as their tests were only run for three days, two of which were getting the house to reach an equilibrium.

4. Gas use: full-year simulations

A central aspect of Nesta's objectives is to assess the annual reductions in gas use that can be realised by reducing from an 80°C flow temperature to a 60°C flow temperature. Results are shown per house model, showing total annual gas use – *for space heating only* – and proportion gas use reduction from reducing flow temperature compared to a 'baseline' flow temperature of 80°C. Also shown are savings that can be made by reducing flow temperature further to 45°C.

4.1. Annual results – summary

A number of conclusions can be made from the annual simulations results that are described in sections 4.2 to 4.7:

- Modest savings can be made by reducing boiler flow temperature from 80°C to 60°C. Across all 32 scenarios, the mean annual saving that can be expected from reducing from 80°C to 60°C is 2.7%. Reducing from 80°C to 45°C increases the mean annual saving to 9.3%.
- Thirteen scenarios with higher gas use (>9,000kWh at 80°C) show greater savings; the mean annual saving that can be expected from reducing from 80°C to 60°C is 4.2%. Reducing from 80°C to 45°C increases the mean annual saving to 12.5%.
- Six scenarios with even higher gas use (>12,000kWh at 80°C) show greater savings; the mean annual saving that can be expected reducing from 80°C to 60°C is 7.4%. Reducing from 80°C to 45°C increases the mean annual saving to 19.0%.
- Using a setback temperature has a negligible effect on total annual gas use and does not materially affect the savings that can be achieved from reducing flow temperatures.
- In the scenarios where a single living room (with staircase) is heated, gas use reductions of approximately 10% are found (comparing the same flow temperature across scenarios). Reducing the number of hours for which the heating is on by half and increasing warm-up times by 30 or 60 minutes has a negligible effect on gas use (between scenarios). However, this is due to heating setpoints being met and the heating system switching off for the remainder of the heating period, regardless of how long the heating period is.
- The occupancy profile 'one person over 60' has a single, long (all-day) heating period, compared to other occupancy profiles that have two shorter heating periods (morning and evening). This occupancy profile tends to have higher gas use but smaller reductions in gas use from reducing flow temperature, when compared to other occupancy profiles for the same house model. A single heating period means that the boiler's flow temperature is not given the opportunity to cool down to ambient temperature (other than overnight), as it does when a long period elapses between heating periods (for example, daytime). Heating from an ambient temperature is when the boiler is working at its most efficient rate.
- The gas use reductions for the scenario whereby heating hours are halved are greater than for the same occupancy profile but with 'full' heating periods. However, the reduction in gas use is negligible when employing this heating strategy.
- There are only two scenarios for which annual gas use increases at lower flow temperatures for the Salford Energy House with an extended warm-up period, for example, scenarios where the heating is on for longer at a lower flow temperature.

4.2. Pre-1919 mid-terrace dwelling (EPC ~C/D – 70m^2)

Results in Table 6 show annual savings of around 2-3% of gas use from reducing flow temperature from 80°C to 60°C, increasing to around 3-5% when reducing to 45°C. The exception is the final scenario whereby the living room radiator is the only radiator in use, with all other rooms unheated.

This heating strategy reduces annual gas use by around 10%, but between the flow temperatures savings are small (<1% from 80°C to 60°C). This is further explained in section 7.1.

Table 6: simulated annual gas use for pre-1919 mid-terrace dwelling

Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Annual gas use (kWh)	Reduction vs 80°C (%)
Couple with single child	Cool conserver	80	N/A	7,085.0	X
		60		6,916.0	2.4
		45		6,702.7	5.4
		80	15	7,130.3	X
		60		6,959.9	2.4
		45		6,773.2	5.0
		80	16	7,210.7	X
		60		7,036.6	2.4
		45		6,900.0	4.3
		80	17	7,363.1	X
		60		7,207.5	2.1
		45		7,114.7	3.4
One person over 60	Toasty cruiser	80	N/A	9,533.0	X
		60		9,277.6	2.7
		45		9,136.6	4.2
		80	17	9,852.7	X
		60		9,619.2	2.4
		45		9,493.0	3.7
One person over 60	Toasty cruiser but only heats living room, keeps radiators off in other rooms	80	N/A	8,619.4	X
		60		8,542.2	0.9
		45		8,399.3	2.6
		80	17	8,642.1	X
		60		8,574.9	0.8
		45		8,497.2	1.7

4.3. 1919-1944 SEMI-DETACHED DWELLING (EPC ~C/D, E/F – 104M^2)

For this house type, results in Table 7 vary according to the occupancy profile and heating pattern. The 'couple with children, family of four – cool conserver' profile uses less gas and proportionately saves more compared to 'one person over 60 – toasty cruiser'. The house simulated without insulation consequentially uses a lot more gas, but reductions in gas use are higher as flow temperatures are reduced. The scenarios with a setback use less gas than without.

Table 7: Simulated annual gas use for 1919-1944 semi-detached dwelling

Occupancy profile	Heating pattern	Insulation changes	Flow (°C)	Setback (°C)	Annual gas use (kWh)	Reduction vs 80°C (%)
Couple with children; family of four	Cool conserver	N/A	80	N/A	9,167.0	X
			60		9,050.6	1.3
			45		8,351.5	8.9
		N/A	80	15	8,853.8	X
			60		8,609.6	2.8
			45		7,929.0	10.4
		No loft or wall insulation	80	N/A	16,781.2	X
			60		15,284.7	8.9
			45		12,480.1	25.6
One person over 60	Toasty cruiser	N/A	80	N/A	11,056.3	X
			60		11,026.5	0.3
			45		10,381.9	6.1
		N/A	80	17	11,033.5	X
			60		11,009.3	0.2
			45		10,370.0	6.0
		No loft or wall insulation	80	N/A	21,342.0	X
			60		19,472.9	8.8
			45		15,753.8	26.2

4.4. 1945-1964 SEMI-DETACHED DWELLING (EPC ~E – 67M²)

Results in Table 8 show savings for this house model are greater than they are for the previous two house models, with gas use reducing by approximately 4-5% when reducing from 80°C to 60°C for the 'couple with children, family of four', and approximately 13-16% when reducing to 45°C. Savings are not as high for the 'one person over 60' occupancy profile (80°C to 60°C, approximately 1-2%; 80°C to 45°C, approximately 8%).

Table 8: simulated annual gas use for 1945-1964 semi-detached dwelling

Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Annual gas use (kWh)	Reduction vs 80°C (%)
Couple with children, family of four	Toasty cruiser	80	N/A	10,714.3	X
		60		10,219.6	4.6
		45		9,031.4	15.7
	Cool conserver	80	N/A	8,927.1	X
		60		8,574.4	4.0
		45		7,691.7	13.8
One person over 60	Toasty cruiser	80	N/A	10,373.5	X
		60		10,183.2	1.8
		45		9,490.4	8.5
	Cool conserver	80	N/A	9,849.6	X
		60		9,688.7	1.6
		45		9,069.7	7.9

4.5. 1965-1980 FLAT (EPC ~E – 41M²)

Results in Table 9 show total gas use is lower, and savings are also not as pronounced as for other house models (80°C to 60°C approximately 1%). The heating strategy of reducing the number of hours that the flat is heated reduces gas use and increases savings from reducing flow temperature (80°C to 60°C, approximately 2-3%; 80°C to 45°C, approximately 11-14%). Switching from a strategy of heating for the full number of hours to heating for half the hours reduces gas use, but not significantly; this is further examined in section 7.4.

Table 9: simulated annual gas use for 1965-1980 flat

Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Annual gas use (kWh)	Reduction vs 80°C (%)
Couple with single child	Cool conserver	80	N/A	6,152.1	X
		60		6,075.4	1.3
		45		5,601.8	8.9
		80	15	6,158.2	X
		60		6,079.4	1.3
		45		5,626.3	8.6
Couple with single child	Cool conserver – but half heating hours (33h a week)	80	N/A	6,056.8	X
		60		5,887.7	2.8
		45		5,234.7	13.6
		80	15	6,065.2	X
		60		5,919.4	2.4
		45		5,375.0	11.4
One person over 60	Toasty cruiser	80	N/A	6,261.1	X
		60		6,183.4	1.2
		45		6,023.7	3.8
		80	17	6,261.9	X
		60		6,186.9	1.2
		45		6,049.1	3.4

4.6. 1981-2002 detached dwelling (EPC ~C/D – 149M^2)

Results in Table 10 show the best savings for reducing flow temperature in comparison to other house models. Reducing to 60°C reduces gas use by roughly 5-9%, increasing to 13-20% if reduced to 45°C.

Table 10: simulated annual gas use for 1981-2002 detached dwelling

Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Annual gas use (kWh)	Reduction vs 80°C (%)
Couple with children, family of four	Cool conserver	80	N/A	14,082.4	X
		60		12,831.3	8.9
		45		11,224.6	20.3
		80	15	14,197.7	X
		60		13,142.9	7.4
		45		12,006.5	15.4
One person over 60	Toasty cruiser	80	N/A	16,463.5	X
		60		15,597.5	5.3
		45		14,243.7	13.5
		80	17	16,505.5	X
		60		15,659.4	5.1
		45		14,351.1	13.1

4.7. Salford Energy House (EPC ~D/E – 54M^2)

Results in Table 11 show gas use as stable across 80°C and 60°C, with greater savings of approximately 6-8% when reducing to 45°C.

Table 11: simulated annual gas use for Salford Energy House

Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Annual gas use (kWh)	Reduction vs 80°C (%)
SAP	SAP	80	N/A	7363.3	X
		60		7305.8	0.8
		45		6812.0	7.5
		80	17	7363.2	X
		60		7306.7	0.8
		45		6813.4	7.5
	30 extra minutes of heating before each heating period	80	N/A	7515.2	X
		60		7522.1	(0.1)
		45		7005.9	6.8
	60 extra minutes of heating before each heating period	80	N/A	7646.9	X
		60		7725.5	(1.0)
		45		7206.7	5.8

5. Gas use: two-week simulations

In addition to annual simulations, two-week simulations are undertaken in 'deep' winter and in spring. The purpose of the winter simulations is to illustrate the effects of reducing flow temperature when a boiler is working at its hardest when outside temperatures are very low for consecutive days. The simulations in spring were undertaken to assess whether even lower flow temperatures (such as 45°C) could deliver further increased gas use savings and maintain comfort when outside temperatures are warmer.

As with the annual simulations, reductions in gas use are compared to an 80°C 'baseline' temperature. Also calculated are savings against a 70°C baseline to illustrate the savings that could be seen if a lower flow temperature is already in use.

5.1. Two-week simulation results – summary

A number of conclusions can be made from the two-week simulation results that are described in sections 5.2 to 5.7:

- For most scenarios for two-week winter simulations, reductions in gas use are approximately in line with reductions in gas use for annual simulations in the corresponding house model.
- For some scenarios in spring, gas use is often stable regardless of flow temperature, suggesting limited or no benefit from reducing flow temperature. However, in other scenarios, savings of approximately 3-10% are possible when flow temperature is reduced to 50°C or 45°C.

5.2. Pre-1919 mid-terrace dwelling (70M^2)

Results in Table 12 show gas use reducing in winter when flow temperatures reduce, approximately in line with the savings that were shown in annual simulations. In many instances, gas use in winter for flow temperatures of 60°C, 55°C, and 50°C is stable (varying by <1%), indicating no further benefit from reducing beyond 60°C to 55°C or 50°C. Whilst this is stable and varying by less than 1% for this house model, occasionally the gas use at 55°C is slightly higher than at 60°C (or higher at 50°C than 55°C) suggesting reducing flow temperatures increases costs. This is caused by the heating system being on for a longer period at lower flow temperatures, and this additional time countering the savings from a lower flow temperature. However, it is reiterated that the increase is very small, at less than 1%.

In spring, total gas use is much lower and often stable across flow temperatures, and is again lowest when flow temperature is reduced to 60°C.

Table 12: simulated seasonal gas use for pre-1919 mid-terrace dwelling. Scenarios that are not run are marked 'X'.

				Gas use (kWh)		Reduction vs 80°C (%)		Reduction vs 70°C (%)	
Occupancy profile	**Heating pattern**	**Flow (°C)**	**Setback (°C)**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**
Couple with single child	Cool conserver	80	N/A	431.6	133.7	X	X	X	X
		70		422.3	131.3	2.2	1.8	X	X
		60		418.6	130.3	3.0	2.6	0.9	0.7
		55		419.0	131.1	2.9	2.0	0.8	0.1
		50		417.1	132.0	3.4	1.3	1.2	(0.6)
		45		407.2	131.2	5.7	1.8	3.6	0.0
		80	15	432.9	X	X	X	X	X
		70		423.6		2.2		X	
		60		421.0		2.7		0.6	
		55		421.5		2.7		0.5	
		50		420.0		3.0		0.8	
		45		411.1		5.0		2.9	
		80	16	438.8	X	X	X	X	X
		70		431.6		1.6		X	
		60		426.7		2.8		1.2	
		55		428.0		2.4		0.8	
		50		427.7		2.5		0.9	
		45		420.8		4.1		2.5	
		80	17	452.0	X	X	X	X	X
		70		448.2		0.8		X	
		60		442.7		2.1		1.2	
		55		440.1		2.7		1.8	
		50		440.4		2.6		1.8	
		45		438.3		3.1		2.2	
One person over 60	Toasty cruiser	80	N/A	575.4	208.3	X	X	X	X
		70		569.6	203.2	1.0	2.5	X	X
		60		561.2	201.4	2.5	3.3	1.5	0.9
		55		554.9	201.4	3.6	3.3	2.6	0.9
		50		557.6	204.1	3.1	2.0	2.1	(0.4)
		45		551.5	202.3	4.2	2.9	3.2	0.4
		80	17	594.2	X	X	X	X	X
		70		587.5		1.1		X	
		60		577.3		2.9		1.7	
		55		573.0		3.6		2.5	
		50		574.5		3.3		2.2	
		45		573.1		3.5		2.4	
	Toasty cruiser but only heats living room, keeps radiators off in other rooms	80	N/A	538.3	24.0	X	X	X	X
		70		536.8	23.9	0.3	0.0	X	X
		60		532.0	18.0	1.2	2.6	0.9	2.6
		55		530.4	18.3	1.5	2.5	1.2	2.5
		50		529.3	21.9	1.7	0.9	1.4	0.9
		45		524.8	22.0	2.5	0.9	2.2	0.9
		80	17	534.9	X	X	X	X	X
		70		537.8		(0.5)		X	
		60		534.4		0.1		0.6	
		55		534.2		0.1		0.7	
		50		535.1		0		0.5	
		45		530.8		0.8		1.3	

5.3. 1919-1944 semi-detached dwelling (104M²)

Results in Table 13 show gas use reducing in winter when flow temperatures reduce for most scenarios. Gas use in winter for flow temperatures of 80°C and 70°C is often stable, as is gas use in winter for the 'one person over 60 – toasty cruiser' profile for flow temperatures of 80°C to 50°C (this is further explained in section 7.2). Gas use in winter in the house models without insulation is almost double what it is in the house models with insulation. Like the previous house, gas use at 55°C and 60°C is sometimes stable and sometimes increases at 55°C for the same reasons as identified previously.

Table 13: simulated seasonal gas use for 1919-1945 semi-detached dwelling

Occupancy profile	Heating pattern	Insulation changes	Flow (°C)	Setback (°C)	Gas use (kWh)		Reduction vs 80°C (%)		Reduction vs 70°C (%)	
					Winter	Spring	Winter	Spring	Winter	Spring
Couple with children, family of four	Cool conserver	N/A	80	N/A	543.0	183.0	X	X	X	X
			70		546.5	181.5	(0.6)	0.8	X	X
			60		540.2	182.6	0.5	0.2	1.1	(0.6)
			55		534.4	182.2	1.6	0.4	2.2	(0.4)
			50		532.3	179.7	2.0	1.8	2.6	1.0
			45		499.2	170.8	8.1	6.7	8.6	5.9
		N/A	80	15	543.0	X	X	X	X	X
			70		546.5		(0.6)		X	
			60		540.2		0.5		1.1	
			55		534.4		1.6		2.2	
			50		532.2		2.0		2.6	
			45		499.2		8.1		8.7	
		No loft or wall insulation	80	N/A	1056.1	282.5	X	X	X	X
			70		1030.1	277.8	2.5	1.7	X	X
			60		963.1	284.7	8.8	(0.8)	6.5	(2.5)
			55		911.4	282.2	13.7	0.1	11.5	(1.6)
			50		841.2	269.7	20.3	4.5	18.3	2.9
			45		759.8	255.3	28.1	9.6	26.2	8.1
One person over 60	Toasty cruiser	N/A	80	N/A	695.3	205.0	X	X	X	X
			70		703.1	202.2	(1.1)	1.3	X	X
			60		703.5	201.6	(1.2)	1.6	(0.1)	0.3
			55		705.0	202.0	(1.4)	1.5	(0.3)	0.1
			50		686.7	201.9	1.2	1.5	2.3	0.1
			45		661.5	201.5	4.9	1.7	5.9	0.4
		N/A	80	17	695.5	X	X	X	X	X
			70		703.4		(1.1)		X	
			60		703.5		(1.2)		0.0	
			55		705.0		(1.4)		(0.2)	
			50		686.8		1.3		2.4	
			45		661.5		4.9		6.0	
		No loft or wall insulation	80	N/A	1342.5	402.4	X	X	X	X
			70		1304.7	402.9	2.8	(0.1)	X	X
			60		1208.9	399.1	10.0	0.8	7.3	1.0
			55		1145.5	386.1	14.7	4.1	12.2	4.2
			50		1061.9	382.7	20.9	4.9	18.6	5.0
			45		943.6	370.9	29.7	7.8	27.7	7.9

5.4. 1945-1964 SEMI-DETACHED DWELLING (67M²)

Results in Table 14 show gas use reducing in winter when flow temperatures reduce, approximately in line with the savings that were shown in annual simulations for the 'couple with children' occupancy profile. Like the previous house, gas use at 55°C and 60°C is sometimes stable and sometimes increases at 55°C for the same reasons as identified previously. For the 'couple with children' occupancy profile, higher savings can be realised in spring by reducing flow temperature to 50°C or 45°C.

Results for the 'one person over 60 – cool conserver' are approximately in line with the savings that were shown in annual simulations, but vary for the 'toasty cruiser' heating pattern. For the 'one person over 60' occupancy profile in spring, total gas use is much lower and often stable across flow temperatures. Stable gas use in spring is examined further in section 7.3.

Table 14: simulated seasonal gas use for 1945-1964 semi-detached dwelling

				Gas use (kWh)		Reduction vs 80°C (%)		Reduction vs 70°C (%)	
Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Winter	Spring	Winter	Spring	Winter	Spring
Couple with children, family of four	Toasty cruiser	80	N/A	618.3	256.7	X	X	X	X
		70		613.9	257.0	0.7	(0.1)	X	X
		60		592.0	253.8	4.2	1.1	3.6	1.2
		55		573.9	253.1	7.2	1.4	6.5	1.5
		50		538.7	246.8	12.9	3.9	12.2	4.0
		45		507.1	235.8	18.0	8.2	17.4	8.3
	Cool conserver	80	N/A	519.7	204.9	X	X	X	X
		70		519.3	204.9	0.1	(0.0)	X	X
		60		504.4	203.6	2.9	0.6	2.9	0.6
		55		489.2	201.1	5.9	1.9	5.8	1.9
		50		475.6	193.0	8.5	5.8	8.4	5.8
		45		441.1	182.0	15.1	11.2	15.1	11.2
One person over 60	Toasty cruiser	80	N/A	634.3	220.9	X	X	X	X
		70		628.8	221.9	0.9	(0.5)	X	X
		60		628.0	219.6	1.0	0.6	0.1	1.0
		55		629.4	222.3	0.8	(0.6)	(0.1)	(0.2)
		50		609.4	227.3	3.9	(2.9)	3.1	(2.5)
		45		575.0	216.4	9.3	2.0	8.5	2.5
	Cool conserver	80	N/A	516.9	158.8	X	X	X	X
		70		516.9	160.2	0.0	(0.9)	X	X
		60		510.3	159.9	1.3	(0.7)	1.3	0.2
		55		510.3	159.5	1.3	(0.4)	1.3	0.5
		50		507.4	161.4	1.8	(1.7)	1.8	(0.8)
		45		480.4	160.3	7.1	(0.9)	7.1	(0.0)

5.5. 1965-1980 FLAT (41M^2)

Results in Table 15 show gas use reducing in winter when flow temperatures reduce, approximately in line with the savings that were shown in annual simulations for the 'couple with single child' occupancy profile. For this occupancy profile, higher savings can be realised in spring by reducing flow temperature to 50°C or 45°C. Results for the 'one person over 60' shows smaller savings than were shown in annual simulations; in spring, total gas use is much lower and often stable across flow temperatures.

Table 15: simulated seasonal gas use for 1965-1980 flat

				Gas use (kWh)		Reduction vs 80°C (%)		Reduction vs 70°C (%)	
Occupancy profile	**Heating pattern**	**Flow (°C)**	**Setback (°C)**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**
Couple with single child	Cool conserver	80	N/A	314.2	152.3	X	X	X	X
		70		315.2	152.1	(0.3)	0.1	X	X
		60		309.7	150.8	1.4	1.0	1.7	0.9
		55		308.3	149.9	1.9	1.6	2.2	1.4
		50		305.6	146.9	2.7	3.6	3.0	3.5
		45		288.1	140.1	8.3	8.0	8.6	7.9
		80	15	314.3	X	X	X	X	X
		70		315.3		(0.3)		X	
		60		309.7		1.5		1.8	
		55		308.4		1.9		2.2	
		50		305.6		2.8		3.1	
		45		289.3		8.0		8.2	
Couple with single child	Cool conserver – but half the hours (33h a week)	80	N/A	307.3	152.3	X	X	X	X
		70		307.3	152.1	0.0	0.1	X	X
		60		298.9	150.8	2.7	1.0	2.7	0.9
		55		293.3	149.9	4.6	1.6	4.5	1.4
		50		282.1	146.7	8.2	3.7	8.2	3.5
		45		266.2	137.9	13.4	9.4	13.4	9.3
		80	15	307.9	X	X	X	X	X
		70		308.0		(0.0)		X	
		60		300.5		2.4		2.4	
		55		295.9		3.9		3.9	
		50		286.8		6.8		6.9	
		45		271.4		11.8		11.9	
One person over 60	Toasty cruiser	80	N/A	358.8	133.6	X	X	X	X
		70		362.4	134.9	(1.0)	(1.0)	X	X
		60		356.5	134.4	0.7	(0.6)	1.6	0.4
		55		355.3	134.2	1.0	(0.4)	1.9	0.5
		50		355.4	136.4	1.0	(2.1)	1.9	(1.1)
		45		353.4	134.9	1.5	(1.0)	2.5	0.0
		80	17	359.1	X	X	X	X	X
		70		362.3		(0.9)		X	
		60		356.3		0.8		1.7	
		55		355.6		1.0		1.9	
		50		355.7		0.9		1.8	
		45		354.0		1.4		2.3	

5.6. 1981-2002 DETACHED DWELLING (149M²)

Results in Table 16 show gas use reducing in winter and spring when flow temperatures reduce, approximately in line with the savings that were shown in annual simulations. As with the annual simulations for this house model, the savings are higher than for other house models.

Table 16: simulated seasonal gas use for 1981-2002 detached dwelling

				Gas use (kWh)		Reduction vs 80°C (%)		Reduction vs 70°C (%)	
Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Winter	Spring	Winter	Spring	Winter	Spring
Couple with children, family of four	Cool conserver	80	N/A	880.1	234.9	X	X	X	X
		70		843.7	232.4	4.1	1.1	X	X
		60		790.2	226.2	10.2	3.7	6.3	2.6
		55		767.5	217.5	12.8	7.4	9.0	6.4
		50		737.0	207.7	16.3	11.6	12.6	10.6
		45		694.0	197.1	21.1	16.1	17.7	15.2
		80	15	883.2	X	X	X	X	X
		70		846.9		4.1		X	
		60		804.0		9.0		5.1	
		55		788.4		10.7		6.9	
		50		772.5		12.5		8.8	
		45		747.3		15.4		11.8	
One person over 60	Toasty cruiser	80	N/A	1,085.8	262.6	X	X	X	X
		70		1,061.4	254.7	2.2	3.0	X	X
		60		1,023.8	244.4	5.7	6.9	3.5	4.0
		55		1,001.2	241.6	7.8	8.0	5.7	5.1
		50		970.1	237.7	10.7	9.5	8.6	6.7
		45		923.1	235.2	15.0	10.4	13.0	7.7
		80	17	1,087.9	X	X	X	X	X
		70		1,064.0		2.2		X	
		60		1,026.4		5.7		3.5	
		55		1,003.6		7.8		5.7	
		50		973.5		10.5		8.5	
		45		928.0		14.7		12.8	

5.7. Salford Energy House (54m^2)

Results in Table 17 show gas use reducing in winter when flow temperatures reduce, with savings of approximately 4-5% when reducing from 80°C to 60°C. In spring, gas use increases when flow temperature decreases; this is further explained in section 7.5.

Table 17: simulated seasonal gas use for Salford Energy House

				Gas use (kWh)		Reduction vs 80°C (%)		Reduction vs 70°C (%)	
Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Winter	Spring	Winter	Spring	Winter	Spring
SAP	SAP	80	N/A	716.0	261.3	X	X	X	X
		70		703.0	269.6	1.8	(3.1)	X	X
		60		683.3	277.8	4.6	(6.3)	2.8	(3.0)
		55		668.8	279.7	6.6	(7.0)	4.9	(3.8)
		50		655.1	282.8	8.5	(8.2)	6.8	(4.9)
		45		637.9	259.9	10.9	0.6	9.3	3.6
		80	17	737.0	261.4	X	X	X	X
		70		724.9	269.5	1.6	(3.1)	X	X
		60		704.9	277.8	4.4	(6.2)	2.8	(3.1)
		55		691.0	279.7	6.2	(7.0)	4.7	(3.8)
		50		677.4	282.8	8.1	(8.2)	6.6	(4.9)
		45		661.9	259.8	10.2	0.6	8.7	3.6
	SAP + 30 mins of heat before each heating period	80	N/A	736.6	268.1	X	X	X	X
		70		723.2	273.2	1.8	(1.9)	X	X
		60		700.3	287.7	4.9	(7.3)	3.2	(5.3)
		55		690.6	288.6	6.2	(7.6)	4.5	(5.6)
		50		677.8	292.0	8.0	(8.9)	6.3	(6.9)
		45		660.7	269.9	10.3	(0.7)	8.7	1.2
	SAP + 60 mins of heat before each heating period	80	N/A	752.5	272.1	X	X	X	X
		70		742.6	279.9	1.3	(2.9)	X	X
		60		724.2	293.6	3.8	(7.9)	2.5	(4.9)
		55		707.7	296.2	5.9	(8.9)	4.7	(5.8)
		50		694.5	301.0	7.7	(10.6)	6.5	(7.5)
		45		682.1	279.7	9.4	(2.8)	8.1	0.1

6. Comfort: two-week simulations

In addition to gas use, for the two-week simulations in winter and spring, the temperatures of the living room and the main bedroom are analysed. Temperature data is available for all rooms in all house models, but these two rooms were chosen as they represent the main living spaces on each floor of the dwellings.

All simulations in HED (with the exception of simulations of the Salford Energy House) have a 30-minute warm-up period immediately before each heating period (so if heat is required in the morning and in the evening, two instances of 30-minute warm-ups are added to the start of the heating schedule). This setting reduces the likelihood of the rooms not being at the desired temperature, reducing the chance of the occupants experiencing discomfort but may increase gas use.

Each room is simulated as if it has a thermostat and is simulated with 2°C of hysteresis; if a room is required to be at 20°C, for example, the heating system will not come on until the room is below 18°C.

Two measures of discomfort are analysed and should be assessed in combination. They are:

- **Proportion of time below desired temperature:** for this measure, if the living room or bedroom is desired to be at 20°C from the hours of 17:00 to 22:00, but is below 18°C for 30 minutes, a value of 10% is recorded (30/300=0.1). This proportion is calculated for the whole two-week period[6].
- **Degree minutes:** the previous metric hides how far below the desired temperature a room may be (for example, being at 16°C for 30 minutes would count the same as being at 10°C). To account for this, a measure of 'degree minutes' is calculated. Degree minutes multiplies the number of minutes below the desired temperature setpoint by the number of degrees below the setpoint (for example, 30 minutes 2°C below the setpoint is 60 degree minutes; 30 minutes 8°C below the desired setpoint is 240 degree minutes).

6.1. Results – summary

A number of conclusions can be made from the analysis of discomfort results that are described in sections 6.2 to 6.7:

- In winter at lower flow temperatures (50°C and 45°C, for example), comfort can be more difficult to maintain in many scenarios
- In spring, comfort is often maintained regardless of flow temperature
- Occupancy and heating profiles that require longer hours of heating at higher temperatures are less likely to maintain comfort in comparison to profiles that require shorter heating periods
- The strategy of employing a setback prevents room temperatures dropping too low and therefore helps maintain comfort during hours when heating is required

6.2. Pre-1919 mid-terrace dwelling

Results in Table 18 show that comfort is maintained at almost all flow temperatures in both rooms and in winter and spring for the 'couple with single child' occupancy profile. In this occupancy profile, the desired temperatures are lower ('cool conserver').

The 'one person over 60' occupancy profile has much longer heating periods each day and the 'toasty cruiser' desires warmer temperatures; these two scenarios are therefore less likely to maintain comfort at lower flow temperatures. For the scenario with whole-house heating, comfort is more difficult to maintain at 45°C flow temperature in the living room in winter. In the scenario where only the living room is heated, discomfort is consequently high in the bedroom in winter for all flow temperatures and spring for all flow temperatures. In the living room, comfort is more difficult to maintain at 50°C and 45°C flow temperatures in winter.

[6] The calculation of time that heat is required does not include any time for warm-up

Table 18: Discomfort at different flow temperatures for pre-1919 mid-terrace dwelling

				Bedroom (%)		Living room (%)		Bedroom (degree minutes)		Living room (degree minutes)	
Occupancy profile	**Heating pattern**	**Flow (°C)**	**Setback (°C)**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**
Couple with single child	Cool conserver	80	N/A	0%	0%	0%	0%	0	0	0	0
		70		1%	0%	0%	0%	0	0	0	0
		60		0%	0%	0%	0%	0	0	0	0
		55		1%	0%	0%	0%	0	0	5	0
		50		0%	0%	2%	0%	0	0	39	0
		45		0%	0%	6%	0%	0	0	203	0
		80	15	0%	X	0%	X	0	X	0	X
		70		0%		0%		0		0	
		60		0%		0%		0		0	
		55		0%		0%		0		0	
		50		0%		1%		0		10	
		45		0%		4%		0		98	
		80	16	0%	X	0%	X	0	X	0	X
		70		1%		0%		0		0	
		60		0%		0%		0		0	
		55		0%		0%		0		0	
		50		0%		0%		0		0	
		45		0%		1%		0		3	
		80	17	1%	X	0%	X	0	X	1	X
		70		1%		0%		0		0	
		60		0%		0%		0		0	
		55		0%		0%		0		0	
		50		0%		0%		0		0	
		45		0%		0%		0		0	
One person over 60	Toasty cruiser	80	N/A	0%	0%	1%	0%	0	0	0	0
		70		0%	0%	1%	0%	0	0	0	0
		60		0%	0%	1%	0%	0	0	37	0
		55		0%	0%	3%	0%	0	0	131	0
		50		1%	0%	6%	0%	4	0	378	4
		45		3%	0%	11%	1%	27	0	845	46
		80	17	1%	X	0%	X	0	X	0	X
		70		1%		0%		0		0	
		60		0%		0%		0		0	
		55		0%		0%		0		0	
		50		0%		0%		0		0	
		45		0%		0%		0		0	
	Toasty cruiser but only heats living room, keeps radiators off in other rooms	80	N/A	100%	40%	1%	0%	18,601	4,733	0	0
		70		100%	40%	1%	0%	17,786	4,604	18	3
		60		100%	38%	4%	0%	16,629	4,393	153	25
		55		100%	38%	6%	1%	16,214	4,333	442	59
		50		100%	37%	13%	2%	15,683	4,261	1,133	136
		45		100%	36%	24%	4%	15,126	4,203	2,679	371
		80	17	100%	X	1%	X	18,604	X	1	X
		70		100%		0%		17,851		0	
		60		100%		1%		16,583		18	
		55		100%		4%		16,048		151	
		50		100%		9%		15,567		580	
		45		100%		21%		14,812		1,806	

6.3. 1919-1944 SEMI-DETACHED DWELLING (104M²)

Results in Table 19 show that comfort is maintained at all flow temperatures in both rooms and in winter and spring for both occupancy profiles for the house model with insulation. When the house is modelled without loft or wall insulation, comfort is far harder to maintain regardless of flow temperature and discomfort (or proportion of time below desired temperature) is nearly 20% of the time for the 'one person over 60 – toasty cruiser' profile at a flow temperature of 80°C.

Table 19: Discomfort at different flow temperatures for 1919-1944 semi-detached dwelling

					Bedroom (%)		Living room (%)		Bedroom (degree minutes)		Living room (degree minutes)	
Occupancy profile	**Heating pattern**	**Insulation changes**	**Flow (°C)**	**Setback (°C)**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**
Couple with children, family of four	Cool conserver	N/A	80	N/A	0%	0%	0%	0%	0	0	0	0
			70		0%	0%	0%	0%	0	0	0	0
			60		0%	0%	0%	0%	0	0	0	0
			55		0%	0%	0%	0%	0	0	2	0
			50		0%	0%	1%	0%	0	0	11	0
			45		0%	0%	4%	0%	0	0	70	0
		N/A	80	15	0%	X	0%	X	0	X	0	X
			70		0%		0%		0		0	
			60		0%		0%		0		0	
			55		0%		0%		0		2	
			50		0%		1%		0		11	
			45		0%		4%		0		70	
		No loft or wall insulation	80	N/A	3%	0%	0%	0%	60	0	4	0
			70		11%	0%	1%	0%	219	0	24	0
			60		28%	0%	3%	0%	967	0	88	0
			55		42%	0%	7%	0%	1,952	0	232	0
			50		56%	0%	15%	0%	3,471	0	644	0
			45		74%	0%	26%	0%	5,531	0	1,682	0
One person over 60	Toasty cruiser	N/A	80	N/A	0%	0%	0%	0%	0	0	0	0
			70		0%	0%	0%	0%	0	0	4	0
			60		0%	0%	0%	0%	0	0	8	0
			55		0%	0%	1%	0%	0	0	30	0
			50		0%	0%	2%	0%	0	0	58	0
			45		0%	0%	5%	0%	0	0	195	1
		N/A	80	17	0%	X	0%	X	0	X	0	X
			70		0%		0%		0		4	
			60		0%		0%		0		8	
			55		0%		1%		0		30	
			50		0%		2%		0		58	
			45		0%		5%		0		195	
		No loft or wall insulation	80	N/A	19%	0%	1%	0%	848	0	65	0
			70		26%	0%	3%	0%	1,400	5	163	0
			60		50%	1%	5%	0%	2,997	11	295	0
			55		59%	2%	8%	0%	4,624	28	584	4
			50		71%	4%	12%	1%	6,631	66	1,038	19
			45		90%	6%	32%	1%	9,545	131	3,506	47

6.4. 1945-1964 semi-detached dwelling (67M²)

Results in Table 20 show that comfort is maintained in both rooms in winter and spring for both occupancy profiles for all but the 50°C and 45°C flow temperatures. In spring, comfort is always maintained.

Table 20: Discomfort at different flow temperatures for 1945-1964 semi-detached dwelling

				Bedroom (%)		Living room (%)		Bedroom (degree minutes)		Living room (degree minutes)	
Occupancy profile	**Heating pattern**	**Flow (°C)**	**Setback (°C)**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**
Couple with children, family of four	Toasty cruiser	80	N/A	0%	0%	0%	0%	0	0	4	0
		70		0%	0%	1%	0%	0	0	16	0
		60		0%	0%	3%	0%	0	0	143	0
		55		1%	0%	7%	0%	4	0	375	0
		50		6%	0%	13%	0%	68	0	959	0
		45		26%	0%	22%	0%	416	0	1,786	3
	Cool conserver	80	N/A	0%	0%	0%	0%	0	0	0	0
		70		0%	0%	0%	0%	0	0	0	0
		60		0%	0%	1%	0%	0	0	29	0
		55		0%	0%	3%	0%	0	0	88	0
		50		1%	0%	6%	0%	11	0	244	0
		45		9%	0%	13%	0%	88	0	635	0
One person over 60	Toasty cruiser	80	N/A	0%	0%	1%	0%	0	0	21	0
		70		0%	0%	1%	0%	0	0	64	0
		60		0%	0%	3%	0%	0	0	181	0
		55		0%	0%	4%	0%	0	0	312	0
		50		2%	0%	8%	0%	21	0	718	3
		45		12%	0%	15%	1%	128	0	1,507	25
	Cool conserver	80	N/A	0%	0%	1%	0%	0	0	4	0
		70		0%	0%	1%	0%	0	0	40	0
		60		0%	0%	2%	0%	0	0	117	0
		55		0%	0%	3%	0%	0	0	189	0
		50		1%	0%	5%	0%	3	0	333	0
		45		9%	0%	12%	0%	39	0	892	0

6.5. 1965-1980 FLAT (41M²)

Results in Table 21 show comfort maintained for the 'couple with single child – cool conserver' occupancy profile at all but the lowest flow temperature for both rooms in winter and spring. For the same occupancy profile but with fewer hours of heating[7], comfort is more difficult to maintain in winter, particularly in the living room below 60°C. For the 'one person over 60' occupancy profile, again comfort is more difficult to maintain at the lowest flow temperatures of 50°C and 45°C.

Table 21: Discomfort at different flow temperatures for 1965-1980 flat

				Bedroom (%)		Living room (%)		Bedroom (degree minutes)		Living room (degree minutes)	
Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Winter	Spring	Winter	Spring	Winter	Spring	Winter	Spring
Couple with single child	Cool conserver	80	N/A	0%	0%	0%	0%	0	0	0	0
		70		0%	0%	0%	0%	0	0	0	0
		60		0%	0%	0%	0%	0	0	2	0
		55		0%	0%	1%	0%	0	0	22	0
		50		0%	0%	3%	0%	0	0	106	0
		45		0%	0%	9%	0%	0	0	365	0
		80	15	0%	X	0%	X	0	X	0	X
		70		0%		0%		0		0	
		60		0%		0%		0		2	
		55		0%		1%		0		22	
		50		0%		3%		0		106	
		45		0%		8%		0		269	
Couple with single child	Cool conserver – but half the hours (33h a week)	80	N/A	3%	0%	6%	0%	36	0	411	0
		70		3%	0%	6%	0%	29	0	417	0
		60		5%	0%	8%	0%	45	0	235	0
		55		7%	0%	11%	0%	71	0	392	0
		50		7%	0%	16%	0%	79	0	803	0
		45		8%	0%	26%	0%	67	0	1,567	0
		80	15	4%	X	6%	X	36	X	310	X
		70		3%		6%		25		371	
		60		4%		6%		44		258	
		55		6%		8%		58		241	
		50		6%		13%		53		396	
		45		5%		24%		44		1,066	
One person over 60	Toasty cruiser	80	N/A	0%	0%	0%	0%	0	0	0	0
		70		0%	0%	1%	0%	0	0	1	0
		60		0%	0%	1%	0%	0	0	40	0
		55		0%	0%	4%	0%	0	0	154	0
		50		0%	0%	8%	0%	0	0	475	1
		45		0%	0%	16%	1%	0	0	1,263	20
		80	17	0%	X	1%	X	0	X	0	X
		70		0%		1%		0		0	
		60		0%		1%		0		24	
		55		0%		3%		0		119	
		50		0%		7%		0		409	
		45		0%		15%		0		1,115	

[7] To calculate comfort for this occupancy profile, the number of hours heat is required stays the same, even if the heating is used for just half the hours

6.6. 1981-2002 DETACHED DWELLING (149M^2)

Results in Table 22 show comfort being maintained for most flow temperatures for the 'couple with children' occupancy profile, with comfort only being more difficult to maintain at 50°C and 45°C flow temperatures in winter.

The 'one person over 60 – toasty cruiser' occupancy profile has long heating hours at higher temperatures, consequentially making it more difficult to maintain comfort. The bedroom in winter is difficult to maintain comfort regardless of flow temperature, with the living room in winter only struggling at 45°C flow temperature.

Table 22: Discomfort at different flow temperatures for 1980-2002 detached dwelling

				Bedroom (%)		Living room (%)		Bedroom (degree minutes)		Living room (degree minutes)	
Occupancy profile	**Heating pattern**	**Flow (°C)**	**Setback (°C)**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**	**Winter**	**Spring**
Couple with children, family of four	Cool conserver	80	N/A	1%	0%	0%	0%	1	0	0	0
		70		2%	0%	0%	0%	20	0	2	0
		60		4%	0%	1%	0%	90	0	25	0
		55		6%	0%	2%	0%	173	0	53	0
		50		14%	0%	4%	0%	458	0	152	0
		45		28%	0%	7%	0%	1,188	0	345	0
		80	15	1%	X	0%	X	0	X	0	X
		70		1%		0%		15		0	
		60		2%		0%		44		2	
		55		2%		1%		48		17	
		50		5%		2%		125		46	
		45		15%		4%		372		126	
One person over 60	Toasty cruiser	80	N/A	6%	0%	1%	0%	181	1	8	0
		70		10%	0%	1%	0%	306	2	50	0
		60		18%	0%	2%	0%	548	2	149	0
		55		23%	0%	4%	0%	778	2	259	0
		50		36%	1%	6%	0%	1,481	2	511	5
		45		54%	1%	10%	1%	2,965	2	1,061	20
		80	17	6%	X	0%	X	151	X	0	X
		70		9%		1%		242		7	
		60		17%		2%		487		88	
		55		23%		3%		702		185	
		50		35%		5%		1,373		374	
		45		55%		9%		2,848		776	

6.7. Salford Energy House (54M²)

Results in Table 23 show comfort being maintained in both rooms regardless of flow temperature. Only in the winter with a flow temperature of 45°C, without a setback or additional warm-up time, is comfort more difficult to maintain.

Table 23: Discomfort at different flow temperatures for Salford Energy House

				Bedroom (%)		Living room (%)		Bedroom (degree minutes)		Living room (degree minutes)	
Occupancy profile	Heating pattern	Flow (°C)	Setback (°C)	Winter	Spring	Winter	Spring	Winter	Spring	Winter	Spring
SAP	SAP	80	N/A	0%	0%	0%	0%	0	0	0	0
		70		0%	0%	0%	0%	0	0	0	0
		60		0%	0%	0%	0%	0	0	0	0
		55		0%	0%	0%	0%	0	0	0	0
		50		1%	0%	1%	0%	13	0	13	0
		45		11%	0%	9%	0%	194	0	265	0
		80	17	0%	0%	0%	0%	0	0	0	0
		70		0%	0%	0%	0%	0	0	0	0
		60		0%	0%	0%	0%	0	0	0	0
		55		0%	0%	0%	0%	0	0	0	0
		50		0%	0%	0%	0%	1	0	0	0
		45		8%	0%	0%	0%	119	0	0	0
	30 extra mins of heating before each heating period	80	N/A	0%	0%	0%	0%	0	0	0	0
		70		0%	0%	0%	0%	0	0	0	0
		60		0%	0%	0%	0%	0	0	0	0
		55		0%	0%	0%	0%	0	0	0	0
		50		0%	0%	0%	0%	0	0	0	0
		45		0%	0%	1%	0%	1	0	9	0
	60 extra mins of heating before each heating period	80	N/A	0%	0%	0%	0%	0	0	0	0
		70		0%	0%	0%	0%	0	0	0	0
		60		0%	0%	0%	0%	0	0	0	0
		55		0%	0%	0%	0%	0	0	0	0
		50		0%	0%	0%	0%	0	0	0	0
		45		0%	0%	0%	0%	0	0	0	0

7. Additional simulation details

Some of the results presented in this report require further explanation for them to be understood. This section of the report shows detailed plots from HED, with gas use and room temperatures for multiple flow temperatures shown side-by-side, so that the operation of the boiler and the resulting room temperatures can be further understood[8].

Additional simulation details are shown only for a subset of the results, to illustrate specific examples and explain interesting simulation results.

7.1. Pre-1919 mid-terrace dwelling (70m^2)

For this house model, a comparison was made between two heating strategies that householders may employ: heating the whole house and just heating the living room (including stairs and first-floor landing). Reductions in gas use were made by heating just the living room (including stairs and first-floor landing), but these reductions were only around 10% for the full-year simulations, perhaps not as favourable as may have been expected.

A 2D image of the house model from HED is shown in Figure 2. It shows the living room with two radiators (dark-red boxes) at the front of the house and open plan with the stairs and first-floor landing, meaning a large proportion of the house's floor area is heated. The six radiators are plumbed following the light-red lines from the boiler (marked 'B') to a 'T' junction in the kitchen that has the first-floor radiators on a separate loop. The kitchen radiator is off, meaning heat will flow only to the two living room radiators.

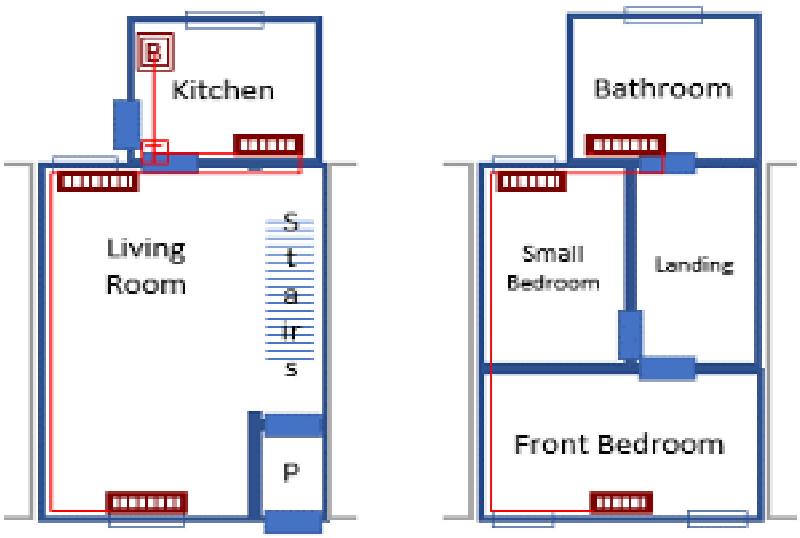


Figure 2: 2D image of the pre-1919 mid-terrace dwelling

Figure 3 shows plots exported from HED, showing gas use and temperature in the living room for a single day. The blue (80°C) and red (60°C) lines show the gas use (top plot) and living room temperature (bottom plot) for the scenario where the whole house is heated, whereas the orange (80°C) and green (60°C) lines show results for the scenario where only the living room (including the stairs and the first-floor landing) is heated. In the temperature plot, the blue and red lines have steeper gradients than their orange and green counterparts; the living room is heating up quicker with the whole house heated, than it is when just the living room is heated, suggesting that heat is 'lost' to other (unheated) rooms in the house[9]. Losing heat to unheated rooms is further confirmed by the steeper gradients when the living room is cooling down (orange and green cool down faster than blue

[8] Simulations were run with a 600-second (10-minute) time interval. In some plots, room temperatures are increasing whilst gas use *appears* to be flat; however, this is not the case. This is due in part to the scale of the plot and the Y-axis values, and in part due to the 'smoothing' of gas use across a 10-minute simulation interval.
[9] Internal doors between rooms are set to be closed for most but not all of the day, with some set to open for short periods to simulate occupants moving around the house (such as using the bathroom, making drinks and meals, etc.).

and red). Subsequently, the profile of gas use between the two scenarios is different, with the blue and red lines showing a large volume of gas being used at the start of the heating period to get the whole house to temperature, whereas the orange and green lines show a smaller volume of gas use. After the heating setpoint is met for the first time, thereafter gas use is typically in smaller volumes for all flow temperatures and scenarios, although the scenario whereby only the living room is heated has more on/off heating 'events'.

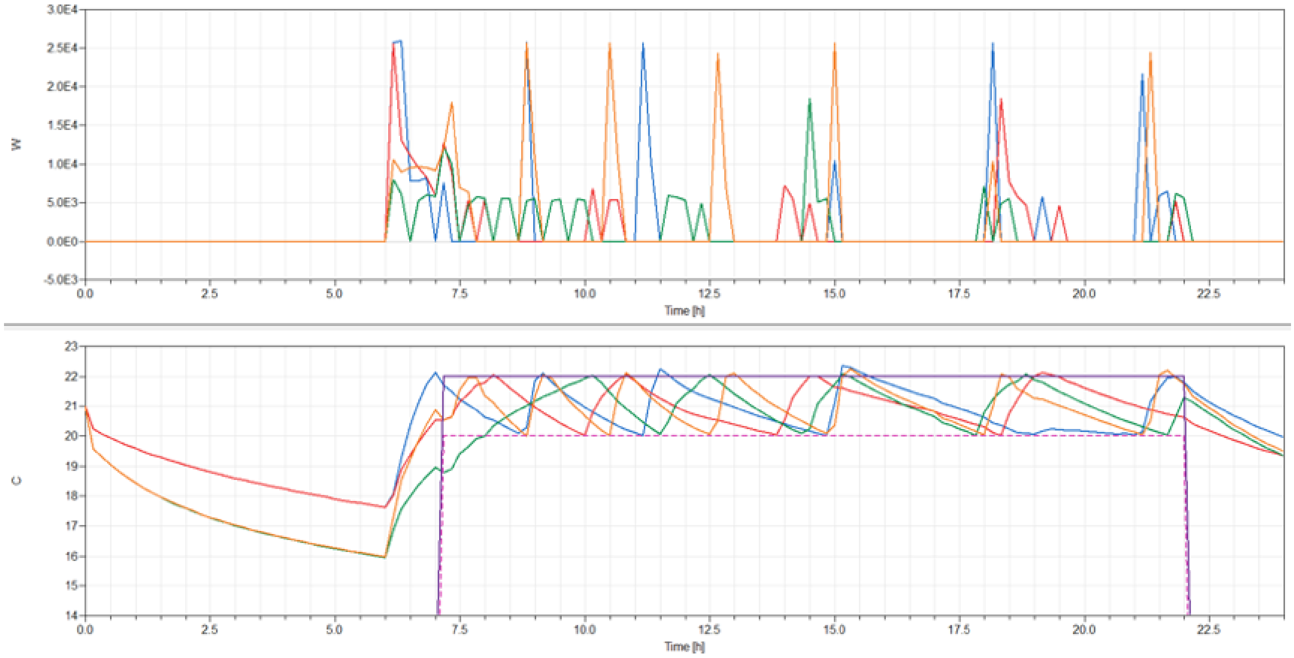


Figure 3: gas use and living room temperature, for 80 ℃ and 60 ℃ flow temperatures, for scenarios with the whole house heated and just the living room heated

7.2. 1919-1944 semi-detached dwelling (104M²)

For this house model, the two-week simulations showed gas use in winter being stable across several flow temperatures (80°C, 70°C, 60°C, 55°C, 50°C) for the insulated house model with 'one person over 60 – toasty cruiser' profile. Figure 4 shows gas use for a single winter day for each flow temperature across three plots; the top plot shows 45°C, the bottom plot shows 80°C, with the middle plot showing the other four flow temperatures. Higher flow temperatures have narrow and tall peaks of gas use, whereas lower flow temperatures have wider and shorter peaks of gas use. The plots of gas use are broken down to provide an easy-to-understand representation of the different ways in which the boiler uses gas to provide space heating at different flow temperatures. These are shown again in Figure 5 along with a plot of cumulative gas use for a single day. The resulting room temperatures are shown in Figure 6; the top plot shows the living room temperature, and the bottom plot shows the main bedroom temperature. In these plots, the longer times that lower flow temperatures require to meet the setpoint can be seen, particularly for the living room.

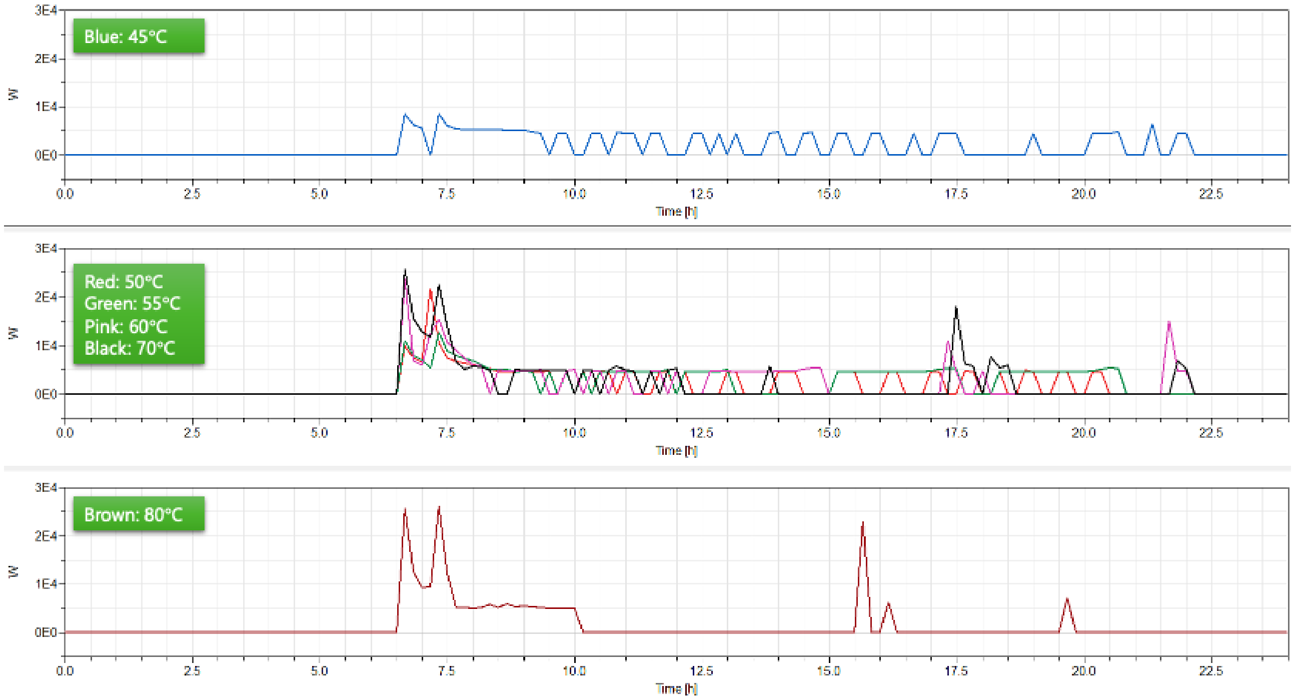


Figure 4: gas use for 'one person over 60 – toasty cruiser' profile for 1919-1944 semi-detached dwelling, for all flow temperatures separately across three plots

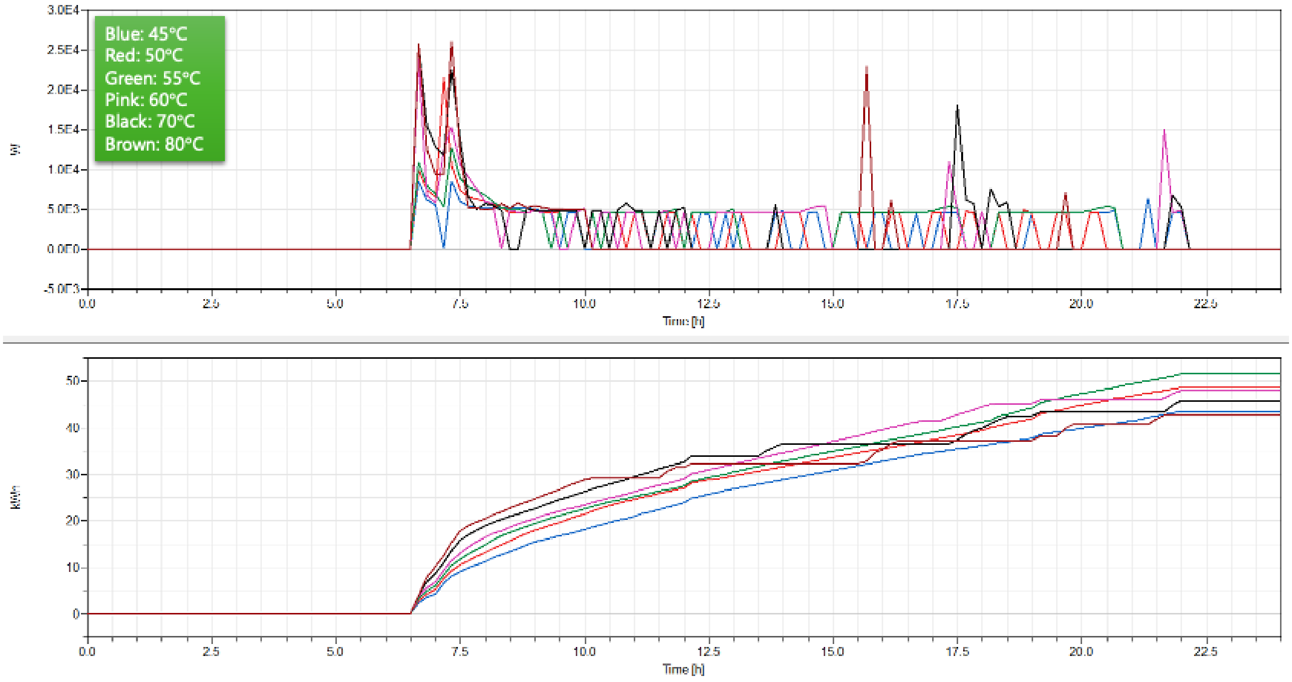


Figure 5: gas use for 'one person over 60 – toasty cruiser' profile for 1919-1944 semi-detached dwelling, for all flow temperatures, and cumulatively

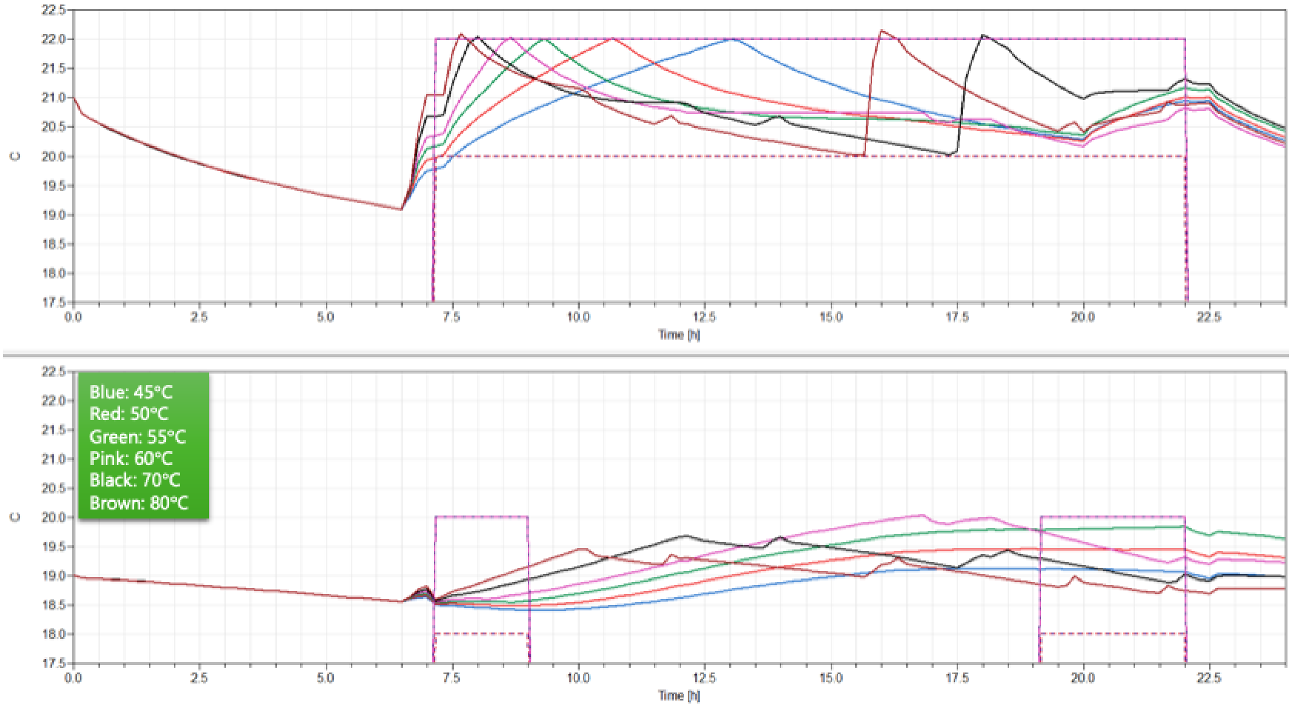


Figure 6: room temperatures for 'one person over 60 – toasty cruiser' profile for 1919-1944 semi-detached dwelling

7.3. 1945-1964 SEMI-DETACHED DWELLING (67M²)

For this house model and a number of other house models, gas use in spring is relatively stable regardless of flow temperature. Figure 7 shows gas use for a single spring day, for each of the six flow temperatures, for the 'one person over 60 – toasty cruiser' occupancy profile. The lower flow temperatures have several smaller peaks throughout the whole day, that in total sum to the same gas use as higher flow temperatures that instead require fewer, taller peaks.

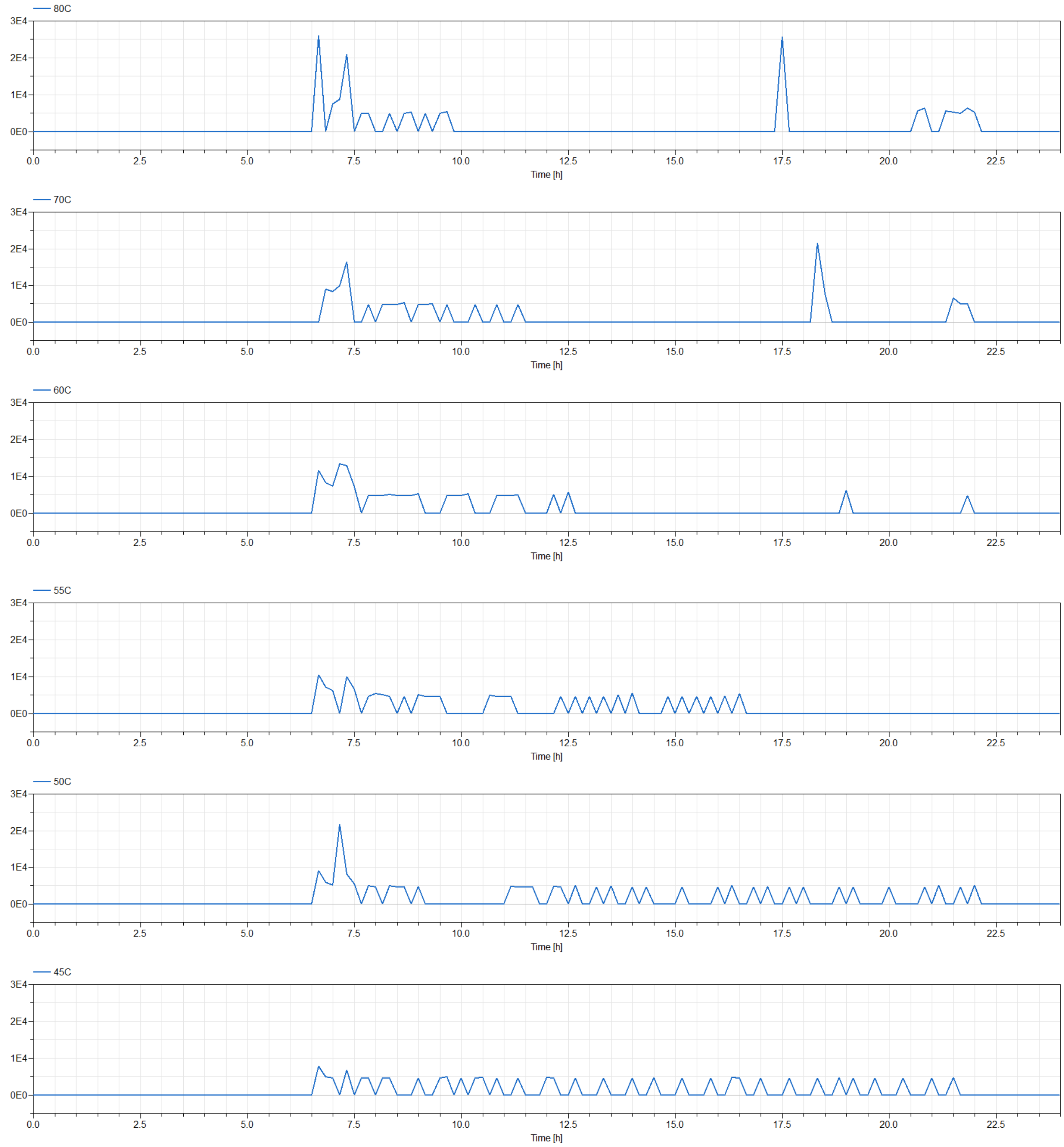


Figure 7: gas use for a single spring day at each of the six flow temperatures, for a 1945-1964 semi-detached dwelling

7.4. 1965-1980 FLAT (41M²)

For this house model, a comparison was made between heating for the 'full' time period and heating for 'half' the number of hours. To halve the number of heating hours, the second half of the hours was removed (for example, if heating is required from the hours of 07:00 to 09:00, it was only provided from 07:00 to 08:00). Figure 8 shows gas use (top plot) and temperatures in the living room (middle plot) and main bedroom (bottom plot) for a single day (note: this is a particularly cold day in the second week of the winter simulations). The red (80°C) and blue (60°C) lines show results for the scenario where the house is heated for the full hours, whereas the orange (80°C) and green (60°C) lines show results for the scenario where the house is heated for half the hours.

The red and orange lines (80°C) for room temperatures track very closely in both the living room and bedroom, suggesting that an 80°C flow temperature can heat the rooms to the desired setpoint within the first half of the heating periods and heat is sufficiently maintained to mean the boiler is not required again during the heating period and occupants are not uncomfortable. Consequently, their profiles of gas use are also very similar. For the 60°C flow temperatures, the time to reach the setpoint is longer and therefore the second half of the heating period is required to get the rooms up to the setpoint. Even so, the temperature does not drop sufficiently for the occupants to be uncomfortable.

The annual saving from halving heating hours is 1.5% at 80°C and 3.1% at 60°C suggesting this strategy has greater impact on gas use at lower temperatures; further halving heating hours *and* reducing flow temperatures reduces annual gas use by 4.3% and is unlikely to dramatically affect comfort.

Figure 8: gas use, living room and bedroom temperatures, for 80 ℃ and 60 ℃ flow temperature, for scenarios with 'full' and 'half' heating hours

7.5. Salford Energy House (54m²)

For this house model, the two-week simulations showed gas use in spring increasing by roughly 8-10% as flow temperature reduced from 80°C to 50°C. Figure 9 shows gas use for a single spring day for each flow temperature across three plots; the top plot shows 45°C, the bottom plot shows 80°C, with the middle plot showing the other four flow temperatures. Across the plots, the initial gas demand at the start of each heating period is typically a large and often narrow spike, with gas use thereafter a shorter but similarly narrow spike. At lower flow temperatures, more of these shorter narrow spikes of gas use are required, whereas at higher flow temperatures fewer are required to maintain room temperatures.

These are shown again in Figure 10 along with a plot of cumulative gas use for a single day. The resulting room temperatures are shown in Figure 11; the top plot shows the living room temperature, and the bottom plot shows the main bedroom temperature. In these plots, the longer times that lower flow temperatures require to meet the setpoint can be seen, particularly for the living room.

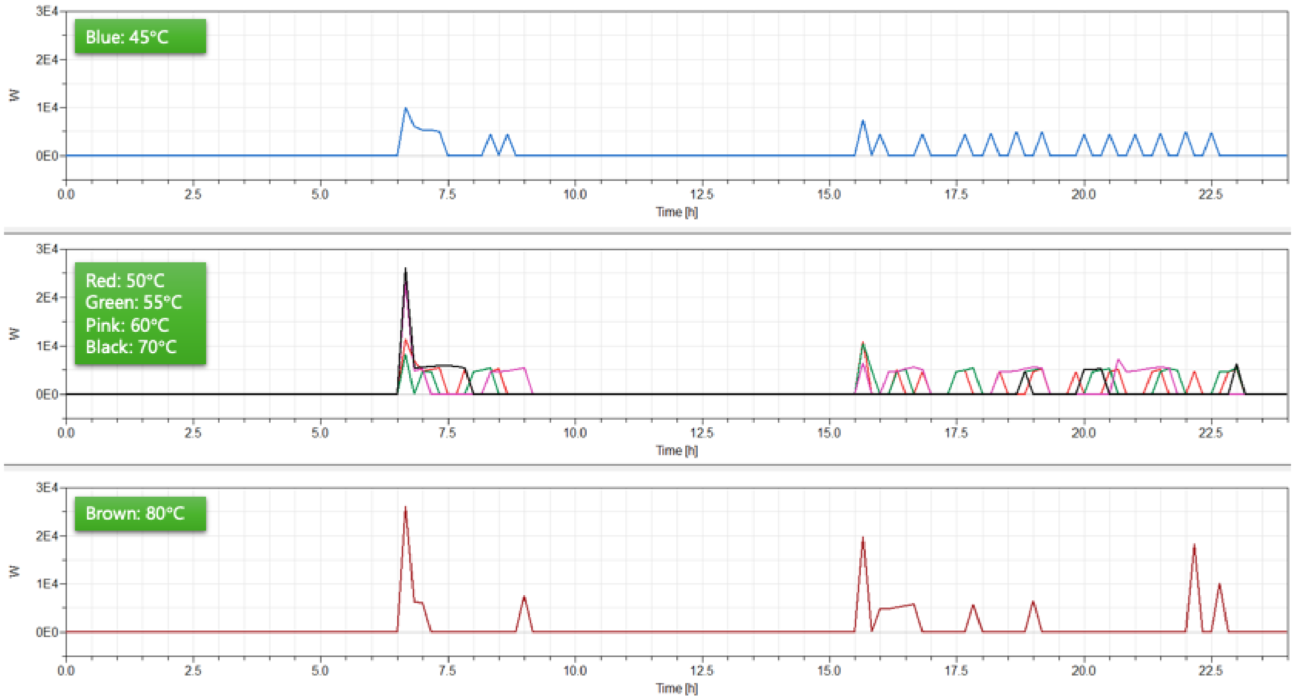


Figure 9: gas use for Salford Energy House for a single day in spring, for all flow temperatures, across three plots

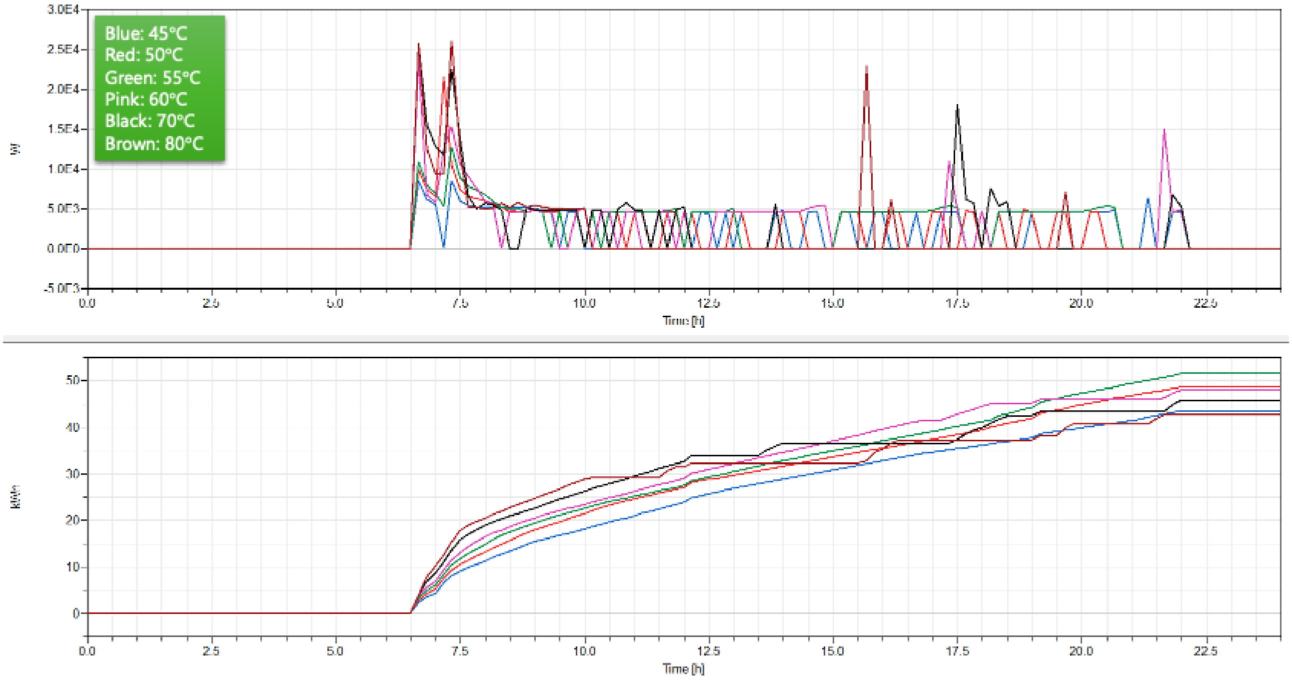


Figure 10: gas use for Salford Energy House for a single day in spring, for all flow temperatures and cumulatively

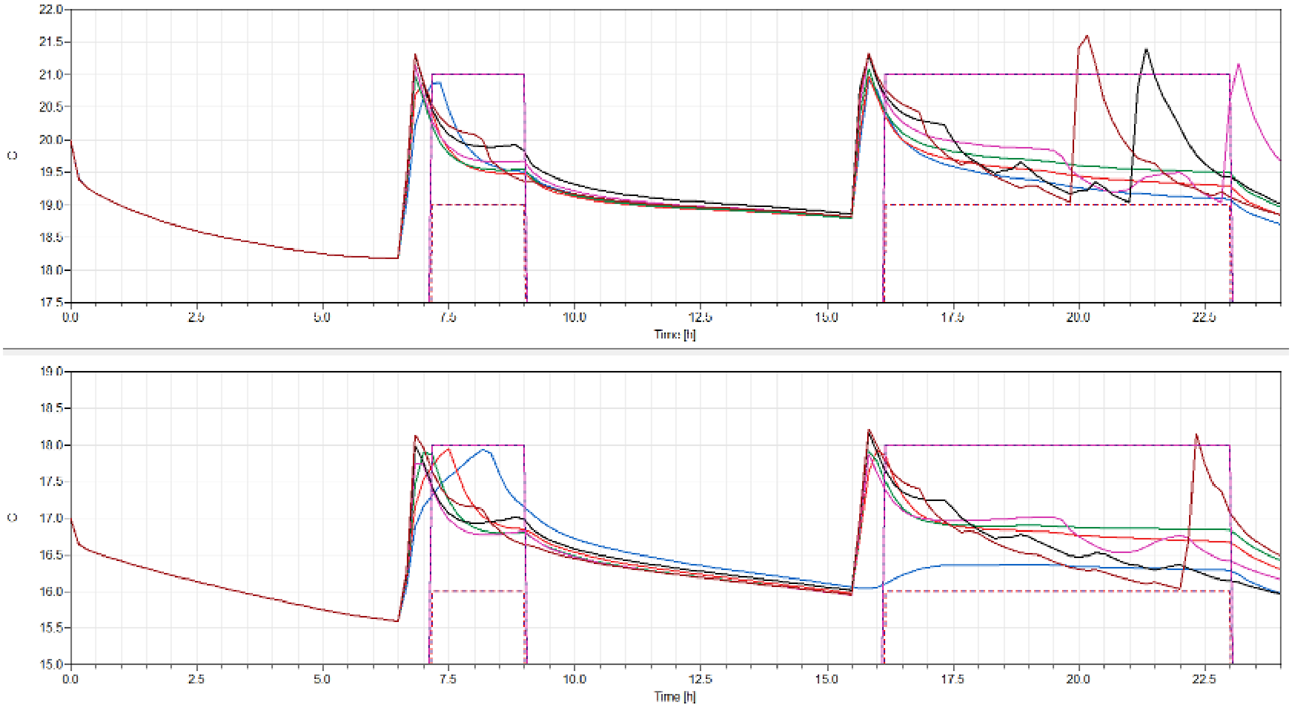


Figure 11: room temperatures for Salford Energy House for a single day in spring

8. Conclusion

In summary, reducing flow temperature from 80°C to 60°C shows savings in annual gas use and has minimal impact on occupant comfort. In certain circumstances, for example in larger or less well-insulated houses that have higher gas use, reducing the flow temperature to 60°C can produce greater reductions in gas use, often more than 10%. The effects of reducing flow temperature on occupant comfort are only a concern when reducing below 55°C.

In spring, gas use is stable across flow temperatures, suggesting limited savings from making changes. This suggests strategies such as 'weather compensation' that may be employed by heating controllers may have limited effect on gas use when paired with a gas boiler. Other strategies, such as reducing the number of rooms that are heated, reducing the number of hours that heat is provided to the house or using a setback temperature, have limited effect on gas use.

Other trends and patterns in gas use were looked for but not identified. These included comparing across heating patterns (for example, do 'cool conservers' save more or less than 'toasty cruisers' when lowering flow temperature?) or heating strategies (does employing a setback save more or less than no setback when lowering flow temperature?). Further, when characteristics are combined (for example, 'cool conserver' without setback versus 'toasty cruiser' with high setback), again the proportionate savings made from lowering flow temperatures are comparable. However, savings of 20-30% can sometimes be seen when a 'toasty cruiser' with a high setback lowers flow temperature from 80°C to 60°C and switches to being a 'cool conserver' without a setback temperature.

Employing a number of strategies in combination may result in greater overall gas use reductions. For the 1945-1964 semi-detached dwelling, for example, switching from a 'family of four – toasty cruiser' with a flow temperature of 80°C to a 'family of four – cool conserver' with a flow temperature of 60°C reduces annual gas use by almost 20%.

Although not analysed in this project, it was noted that electricity use increased when flow temperatures decreased. With lower flow temperatures, the heating system is typically on for longer periods of time requiring the (electric) pump within the gas boiler to run for longer and subsequently increasing electricity demand. With the unit cost of electricity typically three times that of gas, savings may be reduced or negated.

9. Appendix 1 – House models

Please note: the characteristics of these house models are 'as found' during detailed surveys. They may not be representative of dwellings of the same age and built form.

Table 24: details of house models simulated

Year built	Built form	Approximate proportion of housing stock (%)	Size (m^2)	Number of bedrooms	Heating system type	Number of radiators	Floor insulation		Wall insulation		Loft insulation		Doors and windows
							Present	Thickness (mm)	Present	Thickness (mm)	Present	Thickness (mm)	
Pre-1919	Mid terrace	10.8	70	2	Gas combi-condensing boiler	6	No	N/A	No	N/A	Yes	<100	Double glazed (after 2002)
1919-1944	Semi-detached	7.7	104	3	Gas combi-condensing boiler	10	No	N/A	Yes	<100	Yes	>200	Double glazed (after 2002)
1945-1964	Semi-detached	7.8	67	3	Gas combi-condensing boiler	8	No	N/A	Yes	<100	Yes	>200	Double glazed (after 2002)
1965-1980	Flat – top	5	41	1	Gas combi-condensing boiler	4	No	N/A	Yes	<100	Yes	100 to 200	Double glazed (Pre-2002)
1981-2002	Detached	5.4	149	5	Gas combi-condensing boiler	11	No	N/A	Yes	<100	Yes	100 to 200	Double glazed (after 2002)

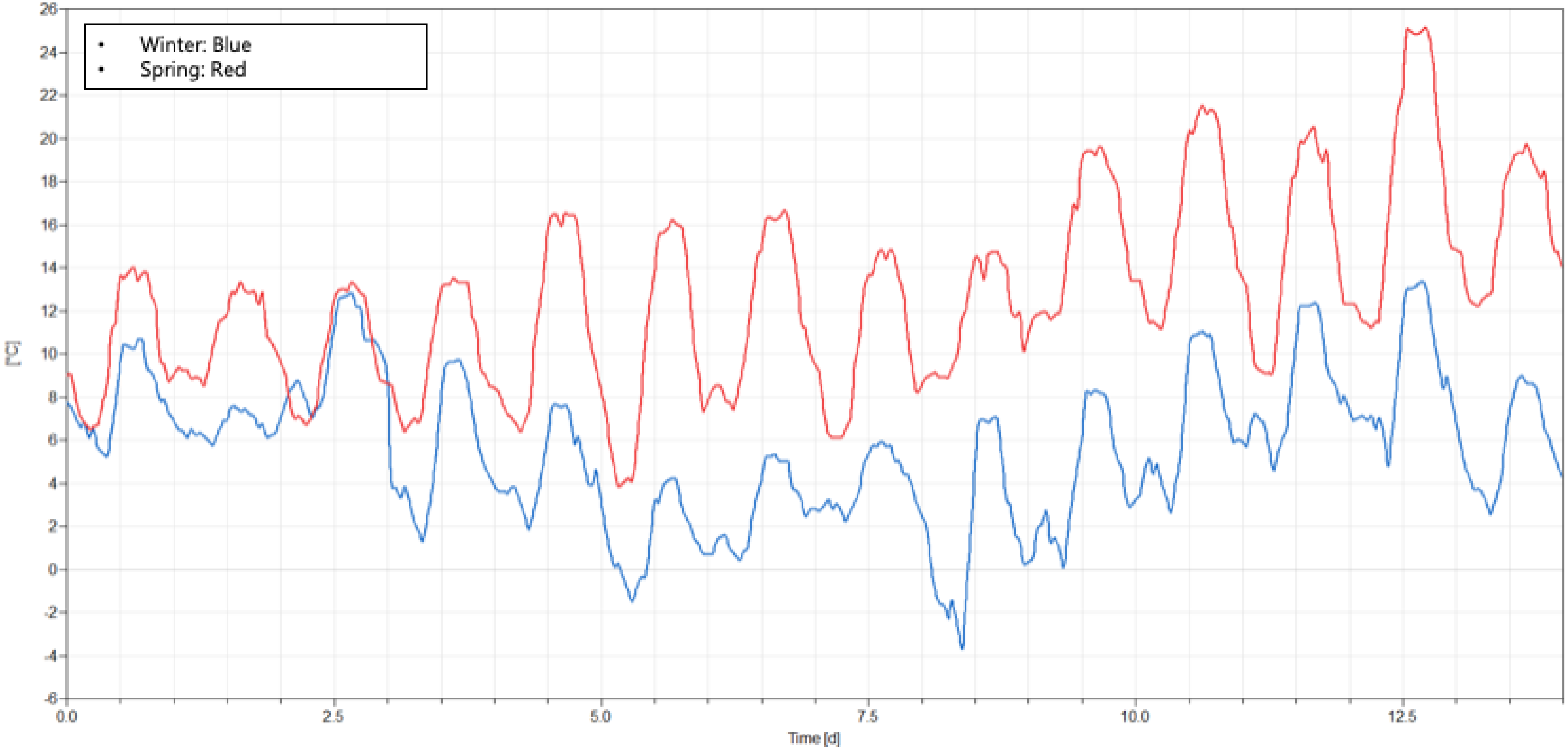
10. Appendix 2 – Occupancy profiles

Please note: the 'toasty cruiser' and 'cool conserver' occupancy profiles are based on monitoring data from households in ESC's Living Lab and interviews with householders. They represent a subset of how people heat their homes.

Table 25: details of occupancy profiles simulated

Household types	Toasty cruiser (22/20°C)				Cool conserver temperature setpoint (20/18°C)				SAP (21/18°C)	
	Weekdays		Weekends		Weekdays		Weekends		Weekdays	Weekends
	Ground floor	Upstairs/bedrooms	Ground floor	Upstairs/bedrooms	Ground floor	Upstairs/bedrooms	Ground floor	Upstairs/bedrooms	N/A	
Couple with single child	06:00-08:00 and 15:00-22:00	06:00-07:30 and 19:00-22:00 in main bedroom, and 06:00-07:30 and 17:00-21:00 in other bedrooms	09:00-21:00	07:30-09:30 and 20:00-23:00 in main bedroom, 08:30-10:00 and 16:00-21:00 in other bedrooms and bathroom	06:00-08:00 and 17:00-22:00	06:00-07:30 and 19:00-22:00 in main bedroom, and 06:00-07:30 and 17:00-21:00 in other bedrooms	09:00-21:00	07:30-09:30 and 20:00-23:00 in main bedroom, and 08:30-10:00 and 16:00-21:00 in other bedrooms and bathroom	07:00-09:00 and 16:00-23:00	07:00-23:00
One person over 60	07:00-22:00 (all day heating except for nights)	07:00-09:00 and 19:00-22:00 in main bedroom, and 07:00-0900 and 20:00-22:00 in other bedrooms	07:00-23:00	07:00-09:00 and 19:00-22:00 in main bedroom, and 07:00-0900 and 20:00-22:00 in other bedrooms	07:00-21:00	07:00-08:00 and 19:30-21:00	07:00-11:00 and 17:00-21:00	07:00-08:00 and 19:30-21:00	07:00-09:00 and 16:00-23:00	07:00-23:00
Couple with children, family of four	06:00-08:00 and 15:00-22:00 (9h heating)	06:00-07:30 and 19:00-22:00 in main bedroom, and 06:00-07:30 and 17:00-21:00 in other bedrooms	09:00-21:00	07:30-09:30 and 20:00-23:00 in main bedroom, and 08:30-10:00 and 16:00-21:00 in other bedrooms and bathroom	06:00-08:00 and 17:00-22:00	06:00-07:30 and 19:00-22:00 in main bedroom, and 06:00-07:30 and 17:00-21:00 in other bedrooms	09:00-21:00	07:30-09:30 and 20:00-23:00 in main bedroom, and 08:30-10:00 and 16:00-21:00 in other bedrooms and bathroom	07:00-09:00 and 16:00-23:00	07:00-23:00

11. Appendix 3 – Weather profiles



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