

Building performance evaluation of low-energy dwellings with and without smart thermostats

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Abstract

Smart thermostats allow continuous learning, remote scheduling and control of indoor temperature. This paper empirically evaluates indoor environmental conditions, occupant experiences and prevalence of summertime overheating in three low-energy dwellings with smart thermostats and compares the results with three similar dwellings with standard programmable thermostats. The study uses building performance evaluation methods combining time-series data on temperature, relative humidity and window opening with survey data on occupant perception of thermal comfort and heating control over the period 2019–2020. While there was little difference observed in the measured and perceived indoor temperatures between dwellings with and without smart thermostats, the six dwellings were different in the way they heated their homes and controlled their indoor environment. A wide indoor temperature range of 16°C–22°C was observed in dwellings with smart thermostats during the heating season. The majority of dwellings also experienced summertime overheating with temperatures in bedrooms going up to 34°C. Individual heating preferences dominated the use of smart or standard thermostats ranging from *Cool Conserver*, *On-off Switcher* to *On-demand Sizzler*. It is vital that energy models consider a range of heating preferences to avoid a gap between expectation and reality. Practical application: Actual in-use performance of dwellings with smart thermostats is necessary for their large-scale deployment. A wide range of thermostat behaviours are documented; therefore, it is vital that energy models consider a range of heating preferences to minimise the gap between energy models and reality. As smart home appliances and controls become more commonplace, the findings demonstrate their need for resident training and trouble-shooting support to ensure smart thermostats deliver their expected benefits. Since most of the case study dwellings experienced summertime overheating, it is also vital that building design tackles overheating through passive measures.

Keywords

building performance evaluation, monitoring, smart thermostat, thermal comfort

Introduction

The UK government is committed to achieving a legally binding target of net zero greenhouse gas emissions throughout the UK economy by 2050¹; furthermore, they have set into law the world's most ambitious emissions target of a 78% reduction by 2035 compared

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to 1990 levels.² Efforts made to achieve this to date have included improving consumer advice, improving gas boiler standards, phasing out the installation of fossil fuel heating in areas not on the gas grid, developing the details for the 2025 release of the Future Homes Standard and encouraging more control over energy use through smart technologies.¹ In addition, exploratory research projects and voluntary standards^{3,4} have successfully driven the development of more advanced levels of fabric and system efficiency in housing beyond UK building regulations.

As one measure to decarbonise the housing sector through fabric and systems in new dwellings, the UK government recently completed a *Future Homes Standard* consultation which assessed future proofing of new dwellings through high levels of energy efficiency and integration of low carbon heating.⁵ The *Future Homes Standard* is set for 2025, but consultation recommended incrementally moving towards the Standard by ramping up UK Building Regulations through conservation of heat and power, ventilation and renewables. The principle is to improve the fabric performance of new dwellings as much as possible to avoid the need for short-term retrofitting of the fabric which can be more costly and disruptive.⁶

Furthermore, the UK government is focussing on ways to reduce the carbon emissions from heating demand throughout the 2020s as only about 5% of the UK's total heat demand in buildings is currently met by low carbon sources.^{7,8} Currently, 2% of residential heating is provided by district heating networks; whereas, the target is 24% by 2050.⁸ The Committee on Climate Change (CCC) recommends that from 2025 at the latest, no new homes should be connected to the gas grid.⁷ Notably, the Committee on Climate Change's 2020 *Progress Report to Parliament on Reducing UK Emissions*⁹ recommends that electrification and district heating schemes should offer the primary route to zero-carbon heating systems. Furthermore, it is recommended that innovation support is provided for smart heating controls among other low carbon heating measures.⁹

On the controls front, the UK government initiated the Boiler Plus scheme in 2018 and the Green Homes Grant scheme in 2020 (already expired). In the Boiler Plus scheme, a customer who bought a new gas combi boiler was provided with calculated insight into

further measures which will enhance the efficiency of the boiler, including smart heating controls.¹ Domestic smart heating control technologies allow continuous learning for reportedly more efficient comfort, remote scheduling and control of space heating.

One energy company in the UK is using ECO funding to trial the installation of free smart thermostats for 2000 members who live in the West Midlands. The intent is to expand out to 30,000 homes. The company expects the smart thermostats to assist in reaching net zero, though no details are provided beyond the expectation that the smart thermostat would naturally reduce energy consumption.¹⁰ A similar smart thermostat trial will be rolled out in Autumn 2021 to a second energy company's customers who have smart meters. The intent of this trial is to allow customers to see the correlation between how the smart thermostat is operated and the resultant at-time-of-operation impact on energy consumption via their smart meter.¹¹

Because smart heating controls, including smart thermostats,¹ are connected directly to the internet or operate via a gateway device connected to a smart meter, they can enable shifting of energy demand timing in response to price or other signals, thereby providing demand side response (DSR). As an example, California is urgently trying to integrate batteries, smart thermostats and other sources of load flexibility to participate in California's power markets under the control of aggregators to reduce demand in anticipation of summer heatwave induced rolling blackouts like the ones that occurred in 2020.¹²

Decarbonisation of heating coupled with intelligently constructed efficient fabric has the added benefit of improving thermal comfort,⁸ indoor air quality (IAQ), indoor environment quality (IEQ) and reduced fuel poverty. As generally increased time indoors have also shown to cause health problems related to IAQ,¹³ getting IAQ right is more important than ever. Additionally, as improved insulation and air tightness, district heating and smart thermostats become more widespread in UK households driven by policy measures and user demand, it becomes necessary to understand the actual indoor environmental conditions achieved and how residents interact with them. It is within this context that the current paper presents an evaluation of the monitored indoor environment, perceived thermal comfort and

control in three new-build dwellings connected to a district heating network and in which smart thermostats were installed. The results are also compared with three dwellings located in the same development with identical construction that do not have smart thermostats installed in their homes.

Evidence to date

Smart thermostats belong to the category of energy management and control systems¹⁴ in a broader group of technologies called smart home technologies (SHTs) which includes sensors and monitors that detect presence and environmental factors; interfaces including tablets, phones and smart meter displays; and controllable appliances such as security cameras, fridges, TVs and garage doors all networked together to enable automation and remote control of a home's environment and experience. The range of reported benefits from SHTs include enhanced energy management, improved security, thermal comfort, healthcare provision and enhanced entertainment.¹⁵

In contrast to the basic on/off interfaces or programmable thermostats, smart thermostats allow for greater granularity of user control through highly detailed app scheduling, remote schedule changes, adaptation to occupant presence through occupancy sensors and/or geolocation software. Outside of direct user control, smart thermostats may also incorporate learning algorithms to predict occupant presence with the intent to optimise heating energy use without the occupant's involvement in programming.¹⁶

Consumer uptake and acceptance

One of the first long-term in-depth qualitative studies on SHTs,¹⁷ in which two of three which were smart heating controls (one, a smart thermostat and the other a smart radiator valve), found that SHTs are not only technically disruptive but are also socially disruptive and can require adaptation from householders that may limit their use. Going into the field trial, four distinct motivations for participation were identified (in order of prevalence)¹⁷:

1. The desire to save energy and money,
2. Interest in new technology and home automation; what Mamonov and Koufari¹⁸ refer to as 'techno-coolness',²

3. Overall concern for the environment (however most were sceptical of SHT's ability to reduce energy use) and
4. Greater level of control over the home.

Over the long-term, users were found to settle into a pattern of using the SHTs less rather than going deeper into maximising the advanced functionality. Participants were concerned; however, that they were not using the systems to their full advantage and often called for help. Overall, learning to use SHTs is demanding and time-consuming and there is currently little support for the householder.¹⁷

Reluctance for uptake has been cited as concern over greater dependence on smartphones, automation evolving into laziness, inability to control or maintain the systems,¹⁷ concern over incompatibility with existing systems and privacy concerns.¹⁸ Despite public and media attention on privacy and data security issues, a large market study of prospective SHT users (over 1000) in the UK found the following to be of greater concern: risks associated with increased dependence of domestic life on interconnected systems and the electricity network, and reduced autonomy.¹⁵ The trust divide between smart meters and other SHTs appears to be the lack of clarity over value provided to householders from smart meters versus marketed SHTs and the method of smart meter rollout from energy utilities.¹⁵

The unique security challenges in the smart home are not without evidence, however. Hernandez, Arias¹⁹ demonstrate how one smart thermostat could be hacked to attack other devices on the local network and Kafle, Moran²⁰ demonstrated how they were able to remotely disable a security camera via a compromised light switch app. Overall, there appears to be a strong market potential for SHTs given the perceived value proposition for control and convenience.

Energy implications

According to three leading smart thermostat websites, energy savings can range from £115–130 per year in the UK with no evidence provided,^{21, 22} 10–15% or \$131–145 (£95–105) in the US citing three US studies²³ and up to 23% on annual energy costs when contrasted with a constant 22°C hold.²⁴ Based on a

review of studies performed in the US, Pang, Chen²⁵ found potential energy savings ranging from 2–22%. However, despite the many studies, Pang, Chen²⁵ found the following questions unanswered: *What is the impact of occupant temperature preference? How do these savings vary from region to region? and How do these savings vary based on HVAC system type?*

The savings sound promising; however, according to a large literature review on smart home technology,¹⁴ the aggregated research on smart thermostats presents as many questions as it has answers about their ability to reduce energy consumption. Furthermore, according to another large literature review on domestic heating controls,¹⁶ there is evidence that smart thermostats may not save energy as compared to non-smart thermostats but could in fact increase energy demand. This observation is also shared by Hargreaves, Wilson.¹⁷ In one case, a field trial in the US modelled learning algorithms of smart thermostats and demonstrated an increase in energy demand from 2–4%. However, there was a moderate quality of evidence that zoned heating controls (e.g. heating only part of the house based on presence), as opposed to whole house control, could save energy.¹⁶

A simulation study evaluating potential energy savings for smart thermostats in the US evaluated various settings and all climate regions. The study found that adjusting the set point during unoccupied periods has a higher savings ratio in hot climates zones, though cold climates can save via this method.²⁵ Ultimately, the greatest savings appear to be simply a result of the depth of set point setbacks^{25,26} though the magnitude of savings can vary based on several external factors. For most of the cases in the US study, 2°C of setback during the occupied period could result in a 20% reduction and 40% in extreme cases.²⁵ One German study considered smart thermostats a beneficial low-cost investment opportunity to reduce heating energy consumption in dwellings that have a low to medium efficiency standard and can be an attractive option for tenants who have limited options for improving the energy efficiency in their home.²⁷

One concern from the reviews is that all field studies in smart thermostats have been over short periods of observation where long-term drifts in energy demand and potential change in occupant

interest were not observed. Definitive evidence would likely require large-scale, multi-disciplinary, multi-year field trials.¹⁶ Overall, evidence has shown that it cannot be assumed that smart systems will reduce energy consumption; however, energy savings appear to be highly dependent on the behaviour of the occupant before and after installation of the system. According to Stopps and Touchie,²⁶ the limitations to the smart features and the overall realisation of these savings stem from ability or willingness to correctly program the smart thermostat to maximise features and achieve savings.

Behaviour and thermal comfort implications

On studying thermostat behaviours, heating set points, length of time heated and periods of time heated are found to vary widely,²⁸ smart thermostats, through greater control, tend to allow these differences to diverge even more. A smart thermostat trial in 100 smart homes throughout England identified six distinct heating behaviours²⁸:

1. 'Cool Conservers' never heat above 20°C and actively focus on keeping cooler temperatures to reduce bills;
2. 'Hot and Cold Fluctuators' have unpredictable heating schedules and are always adjusting their temperature (most temperature variation);
3. 'On-demand Sizzlers' Always like it around 23°C, sometimes as high as 26°C and never below 20°C;
4. 'Steady and Savvy' rarely adjust settings, only seasonally, generally maintaining temperatures between 18–20°C;
5. 'On-off Switchers' vary set point least (maintain 20°C), only turning heat on or off (usually from winter to summer); and
6. 'Toasty Cruisers' similar to 'Sizzlers' but maintain temperatures a little lower, between 21–22°C.

The outcome of the heating behaviour study emphasised with a high degree of confirmation that people care deeply about being warm and comfortable and less so with minimising cost; however, use



Figure 1. Smart thermostat (left) and standard programmable thermostat (right).

of heat is highly diverse.²⁸ With respect to taking advantage of smart controls, two studies found smart thermostat overrides to be infrequent and for short durations.^{26,29} Though overrides generally were used to maintain comfortable temperatures outside of schedules or to less energy-efficient set points, the short duration of the overrides resulted in minimal energy increase.²⁹

As a contribution to the collection of work on the assessment of the indoor environment in new low carbon dwellings, the objective of this paper is to explore how the indoor environment varies in new low carbon dwellings with smart thermostats. The primary focus is on the environmental and occupant findings in three dwellings with smart thermostats but three additional dwellings with conventional thermostats are included to assess the difference.

Case study and methods

Case study dwellings

The UK case study dwellings are in a new eco-development consisting of 489 dwellings, on the edge of the city of York, England. All dwellings in the development are built to higher thermal standards (CSH 4) than typical new-build UK dwellings and are connected to a centralised district heating system. The dwelling forms are representative of typical detached and semi-detached homes found in the UK. This study

will focus primarily on three case study dwellings as they had smart thermostats (Figure 1) installed and had more intensive monitoring. These three dwellings, the *Zero Plus* (ZP) dwellings, were constructed in 2019. Three other dwellings, *non-Zero Plus* (NZP), were constructed in 2016 and were equipped with standard programmable (non-smart) thermostats (Figure 1). These three dwellings will be used at times to briefly compare findings. Table 1 shows relevant characteristics for all dwellings.

Methods

Environmental monitoring

Hobo data loggers for indoor temperature and relative humidity (RH) were installed in the six case study dwellings. Hobos were located in living rooms and main bedrooms (where the parents slept) and I-buttons were installed in secondary bedrooms. Additionally, outdoor temperature and RH data were collected from a centrally located onsite weather station. Smart thermostats in the ZP dwellings were located in two zones: ground floor in the living room and first floor directly outside of the main bedroom. The model of installed smart thermostat works with any new or existing heating system and can be controlled using voice commands, or remotely through any web-connected device such as smartphone or tablet. The thermostat can also be controlled like a traditional

Table 1. Dwelling characteristics.

	ZP1	ZP2	ZP3	NZP1	NZP2	NZP3
Form	2-storey semi-detached	2-storey semi-detached	2-storey detached	2-storey semi-detached	2-storey detached	2-storey semi-detached
No. of bedrooms	2	2	3 + study	3	3	2
Number of occupants	3	3	4	4	4	2
Household	1 adult/2 children	2 adults/1 child	2 adults/2 children	2 adults/2 children	3 adults/1 child	1 adult/1 child
Declared occupancy	24 h	24 h	24 h	0–9, 16–24	24 h	24 h
Total Floor area (m ²)	84	84	130	93	130	84
Heating set point	30°C	24°C	18°C	18°C	Occupant unaware	20°C
Period heated	Oct–May	Jan ^b –Apr	Sep–Apr	Not available		
SAP ^a rating (design)	B - 82	B - 82	B - 83	B - 83	B - 83	B - 82

^aStandard Assessment Procedure.

^bZP2 did not occupy dwelling until late Jan 2020.

thermostat, for example, via direct device control and scheduling. From the data available through monitoring of the smart thermostat use, heating on/off status, heating set point and indoor temperature as measured at the smart thermostat were assessed. All dwellings in addition to their respective thermostats, had conventional radiator valves for additional room-level control. The specifications for the monitoring loggers are listed below in Table 2.

Building performance evaluation and thermal comfort survey

Building performance evaluation (BPE) questionnaires and right-here-right-now thermal comfort (TC) surveys (Figure 2) were implemented in all six dwellings for the winter season in February 2020. All questionnaires were performed in person, before the Covid-19 lockdown which took place around the 23 March 2020. Online versions of the questionnaires were distributed in the summer (August 2020).






The BPE questionnaire covered demographic questions, symptoms of sick building syndrome (SBS), perception of ventilation, temperature, noise,

lighting and odours and means of control for thermal comfort. The thermal comfort survey asked about the occupant's feeling of comfort, comfort preference, activity, clothing and the researcher took temperature and RH measurements onsite. Table 3 lists the categories of questions and variables collected in surveys.

Thermal comfort and overheating assessment

In winter, temperature recommendations in the living room ranges from 18°C–22°C; in the bedroom this is 18°C–20°C. CIBSE Guide A (v.2015)³⁰ recommended comfort criteria suggest 22°C–23°C in living rooms for specific activity and clothing. Though it is considered safe to have temperatures as high as 24°C in the living room,³¹ various recent online sources^{32–34} recommend a maximum setting of 21°C–22°C out of concern for energy consumption and costs. The UK Health Security Agency (formerly Public Health England) recommend heating homes to at least 18°C in winter as this is the temperature deemed to pose minimal risk to the health of a sedentary person, wearing suitable clothing. However, in bedrooms, for healthy individuals below the

Table 2. Specification, accuracy and resolution of installed data loggers.

Data logger		Specifications	
INDOOR Temperature and RH sensor HOBO UX100-003 Battery powered logger		Temperature Range: -20°C – $+70^{\circ}\text{C}$ Accuracy: $\pm 0.21^{\circ}\text{C}$ Resolution: 0.024°C at 25°C Monitoring frequency: 0.1°C at 30 min	RH Range: 15%–95% Accuracy: $\pm 3.5\%$ Resolution: 0.07% Monitoring frequency 0.1% at 30 min
INDOOR Temperature Sensor I-button Battery powered logger		Temperature Range: -40°C – $+85^{\circ}\text{C}$ Accuracy: $\pm 0.5^{\circ}\text{C}$ Resolution: 0.0625°C Monitoring frequency: 0.001°C at 1 h	
Window state data logger HOBO U9-001 Battery powered Logger		Time accuracy Approximately ± 1 min per month at 25°C (77°F) Operating temperature: -20° – 70°C Humidity range: 0–95% RH	
INDOOR Thermostat readings Hardwired – transmit to WiFi		Monitoring frequency: 1°C and on/off (1/0) at 15 min interval	
OUTDOOR Temperature Humidity: Davis Instruments Vantage Vue		Temperature Range: -40°C – $+65^{\circ}\text{C}$ Accuracy: $\pm 0.3^{\circ}\text{C}$ Resolution: 0.1°C Monitoring frequency: 15 min interval	RH Range: 1–100% Accuracy: $\pm 2\%$ Resolution: 1%


age of 64 with sufficient bedding, this threshold is less important.³¹

In summer, the temperature recommendation in the living room is 25°C ; in the bedroom this is 23°C . These temperatures are based on CIBSE Guide A (v.2006)³⁵ generally acceptable summer temperature in dwellings without air conditioning. Anything below this will also be acceptable. The static and dynamic (adaptive) methods were used to assess the risk of summertime overheating in the dwellings. For static overheating criteria in non-air-conditioned dwellings, CIBSE's Environmental Design Guide A^{30,35} recommends that values for indoor comfort temperatures should be 25°C for living areas and 23°C for bedrooms. CIBSE notes that temperatures are expected to be lower at night with people finding


that sleeping in warm conditions is difficult, particularly above 24°C . Environmental Design Guide A provides these static benchmark summer peak temperatures and overheating criteria:

- 1% of annual occupied hours over 28°C in living rooms
- 1% of annual occupied hours over 26°C in bedrooms

Alternatively, dynamic/adaptive overheating criteria were developed taking the outdoor conditions and human adaptation into account by identifying comfort limits based on a running mean of outdoor temperature and the quality of the thermal comfort required. Based on this, the CIBSE TM52³⁶ document



Thermal Comfort Survey



Survey details

Dwelling ID: _____ Name: _____ Date: _____ Time: _____

Spot measurements

Temperature: _____ RH: _____ Air speed: _____ Location: _____

1. FEELINGS: At present I feel...

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
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2. PREFERENCE: I would prefer to be...

Much warmer	A bit warmer	No change	A bit cooler	Much cooler
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3. CLOTHING: I am currently wearing... (tick all that apply)

Short sleeve shirt/blouse	Long sleeve shirt/blouse	Trousers/ Long skirt	Shorts/ Short skirt
Vest	Dress	Pullover	Jacket
Short socks	Long socks	Tights	Cardigan
Shoes	Sandals	Boots	Slippers
Other (specify): _____			

4. ACTIVITY: In the last 15 minutes I have been...

Sitting (passive work)	Standing relaxed	Walking indoors
Sitting (active work)	Standing working	Walking outdoors
Laying down	Other (specify): _____	

5. CONTROLS: Where I am there is... (tick all that apply)

Internal door open	Blinds/curtains down	Air conditioning on	Fan on
Window open	Lights on	Heating on	Extra heater on
Other (specify): _____			

Please answer the following questions regarding your perception of your home.

2. Between which hours are you at home? (you can mark more than one range, as needed)

☐ 00 – 06
☐ 06 – 12
☐ 12 – 16
☐ 16 – 20
☐ 20 – 24

3. Which one of the following options describes best your work in the specific location you are at the time of this survey?

☐ Resting
☐ Cooking
☐ Cleaning
☐ Studying/reading
☐ Other, please specify _____

4. In the following list mark any symptoms you experience after 4 hours at home (you may mark more than one):

☐ Fatigue
☐ Sleepiness
☐ Eye irritation
☐ Headache
☐ Nose irritation
☐ Dry skin
☐ Sore throat

5. Are the symptoms you marked usually relieved when you leave the building?

☐ Yes
☐ No

6. Please highlight your level of satisfaction with the following:

Ventilation:	<input type="checkbox"/> Very poor	<input type="checkbox"/> Poor	<input type="checkbox"/> Indifferent	<input type="checkbox"/> Good	<input type="checkbox"/> Very good
Temperature:	<input type="checkbox"/> Very poor	<input type="checkbox"/> Poor	<input type="checkbox"/> Indifferent	<input type="checkbox"/> Good	<input type="checkbox"/> Very good
Noise: ⁽¹⁾	<input type="checkbox"/> Very poor	<input type="checkbox"/> Poor	<input type="checkbox"/> Indifferent	<input type="checkbox"/> Good	<input type="checkbox"/> Very good
Lighting:	<input type="checkbox"/> Very poor	<input type="checkbox"/> Poor	<input type="checkbox"/> Indifferent	<input type="checkbox"/> Good	<input type="checkbox"/> Very good
Odors: ⁽²⁾	<input type="checkbox"/> Very poor	<input type="checkbox"/> Poor	<input type="checkbox"/> Indifferent	<input type="checkbox"/> Good	<input type="checkbox"/> Very good

(1) It refers only to equipment noise (refrigerator, PC, fluorescent tubes etc.) or outside noises
(2) Odors from dust, mold, bathrooms or carpets

Figure 2. Thermal comfort survey (left) and BPE questionnaire (right).

Table 3. Categories of questions and variables collected in surveys.

Category	Variables	Survey
Live measurements	Temperature, RH, airspeed, location	TC, BPE
Thermal comfort perception	Feeling at present, preference	TC
TC influencing factors	Clothing, activity	TC
Demographic questions	Gender, age, country of origin, education, occupation, hours of occupancy	BPE
Perception of dwelling	Symptoms of SBS, satisfaction with environment (ventilation, temperature, noise, lighting, odours)	BPE
Methods and perception of controlling the indoor environment	Use of windows, doors, thermostat, satisfaction with ease and effectiveness of control methods	BPE

provides a series of criteria by which the risk of overheating can be assessed. These are as follows:

- Criterion 1: hours of exceedance – limit for the number of hours that the operative temperature can exceed the threshold comfort temperature
- Criterion 2: daily weighted exceedance – severity of overheating within any 1 day

- Criterion 3: upper limit temperature – temperatures which exceed the absolute maximum temperature are unacceptable

For Category II, *normal expectation for new buildings and renovations*, the first criterion recommends that the number of hours during which the indoor temperatures are 1 K higher or equal to the

upper comfort limit during the period from May to September should not exceed 3% of occupied hours. The calculations for the criteria will not be repeated here as they are well documented in several references provided in the literature review, for example,³⁷ as well as in the original document.³⁶ As is common in many domestic monitoring studies, indoor air temperature is monitored in the study rather than operative temperature (used in overheating criteria). However, Lomas and Porritt³⁸ suggest that commonly used sensors (such as those used in this study) are likely to record a mix of air and radiant temperatures, making them closer to temperatures experienced by occupants.

Results

Indoor environmental conditions

This section describes analysis of the monitored temperature and relative humidity (RH). The sub-sections analyse the relationship between (1) indoor and outdoor temperature, indoor temperature and RH, (2) indoor temperature and window opening patterns and (3) overheating. The assessment primarily covers the data on a seasonal basis. These seasons are defined as follows: Winter = Dec–Feb, Spring = Mar–May, Summer = Jun–Aug and Autumn = Sep–Nov.

Winter averages in the dwellings range from 17°C in ZP3 to 22°C in ZP2. ZP3 consistently kept the dwelling at temperatures that would be considered cold and borderline potentially harmful for vulnerable occupants³¹ in the winter. ZP2 kept the temperature on the high end of what is recommended and ZP1 retained a reasonable range as per recommendations. Interestingly, as will be seen later, ZP1 considered the temperature in winter to be ‘poor’, whereas the others considered it to be ‘good’. ZP1 did, however, have the largest range between max. and min. (Figure 3). ZP2, who did not prefer a change in thermal comfort, maintained a constant average of 22–23°C throughout the year.

Figure 3 shows the seasonal temperature ranges in all ZP dwellings on the ground floor for all hours. The temperature ranges on the ground floor and first floor (not shown) are fairly aligned with their averages matching in ZP1, slightly lower in ZP2 for all seasons and matching in ZP3. Additionally, quartiles

1–3 in the winter showed a smaller range on the first floor as compared to the ground floor for all dwellings.

The wintertime over- and under-heating of ZP2 and ZP3, respectively, can be seen in Figure 4. The dashed boxes in the images show the recommended heating ranges for the living room and bedrooms. It is theorised from the data that the bedrooms are too warm in the winter for a majority of the time in ZP2; however, the occupant did not prefer the home to be warmer or cooler. Figure 5 shows the same for summer with an additional box on the left side showing the range at which summertime overheating is possible. This is explored in further detail later. For the most part, summer temperatures are mostly contained in the recommended range in the living rooms of all dwellings. Though bedrooms have a smaller recommended range and lower overheating tolerance, they also showed a greater count of higher maximums.

A range recommendation box is also shown for the relationship between indoor temperature and RH. In Figure 6, winter, ZP3 has higher levels of RH than the other dwellings (even higher in the bedroom – not shown). This is likely a result of window opening behaviour as shown in the next section. In the summer, RH is well within recommended range for the dwellings. All dwellings in summer averaged 51%RH in the living rooms and 53–55%RH in the bedrooms.

Window opening. Window opening was measured in the living room and main bedroom of each dwelling during the winter and summer periods. In the living room, the window opening loggers were installed on (full glass) doors leading to the rear (private) garden. ZP3 by far opened their living room garden doors more than any other dwelling’s windows or garden doors (Figure 7). ZP3 had two small dogs and it is likely this was the reason for the great frequency of door opening to the garden. This could further explain the shortness of how long the doors were open as can be seen in Figure 8. In fact, on average the doors to the garden were only open for about a minute at a time. This is a reasonable expectation in the winter. However, ZP3 left the bedroom window open throughout the night from 20:00–06:00. This, coupled with cooler temperatures, is highly likely the reason for higher RH in ZP3 bedroom in winter. In contrast, ZP1 and ZP3 left the bedroom windows

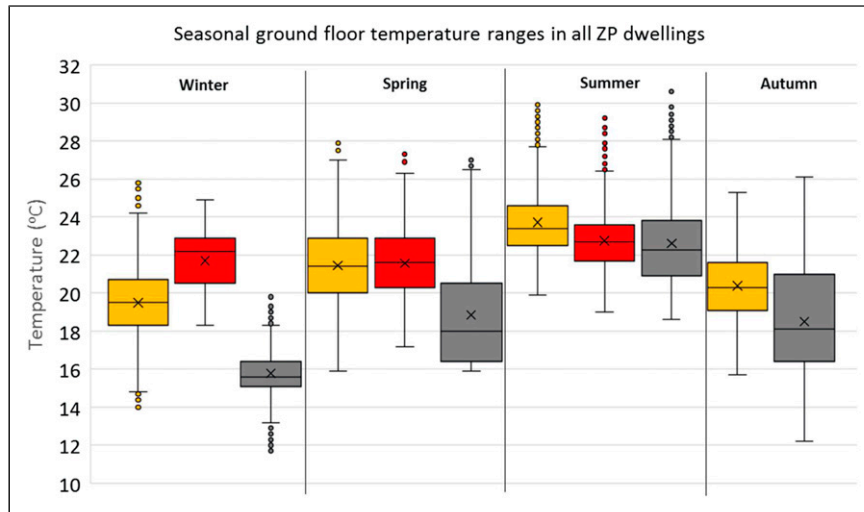


Figure 3. Seasonal temperature box plots on the ground floor in all ZP dwellings (yellow = ZP1, red = ZP2 and grey = ZP3).

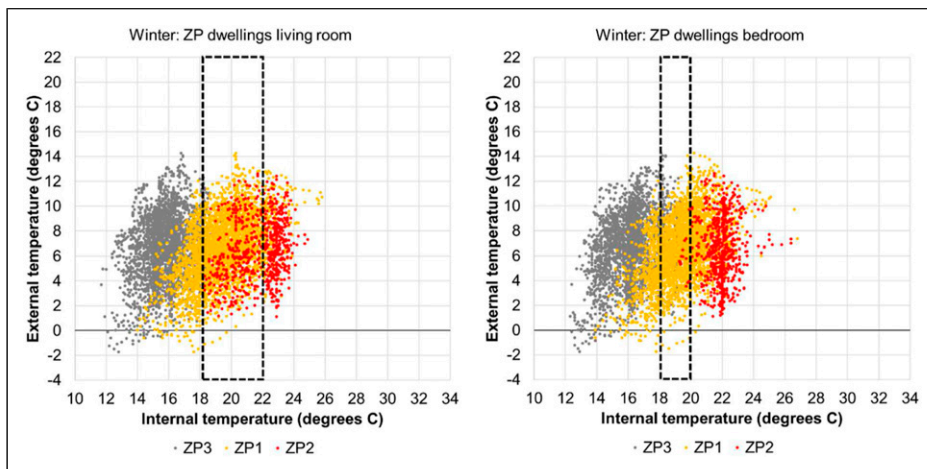


Figure 4. Winter temperatures for all hours: indoor versus outdoor (yellow = ZP1, red = ZP2 and grey = ZP3).

open only during the day, less frequently and for different periods of time and shut the windows entirely at night.

In the summer, windows were opened more frequently as expected. Dwelling ZP2 left the bedroom window open during daytime and nighttime for 26% of the time in summer. In ZP3, the garden door was opened less frequently in summer, but it was left open much longer at a time, possibly because the pet

dogs were left outside for a longer period of time as compared to the winter period.

Overheating assessment. For overheating analysis, the ‘non-heating season’ is considered to run from 1 May–30 September. The overheating potential is assessed within this period which includes a month before and a month after the ‘summer’ season (June to August) used in the above analyses.

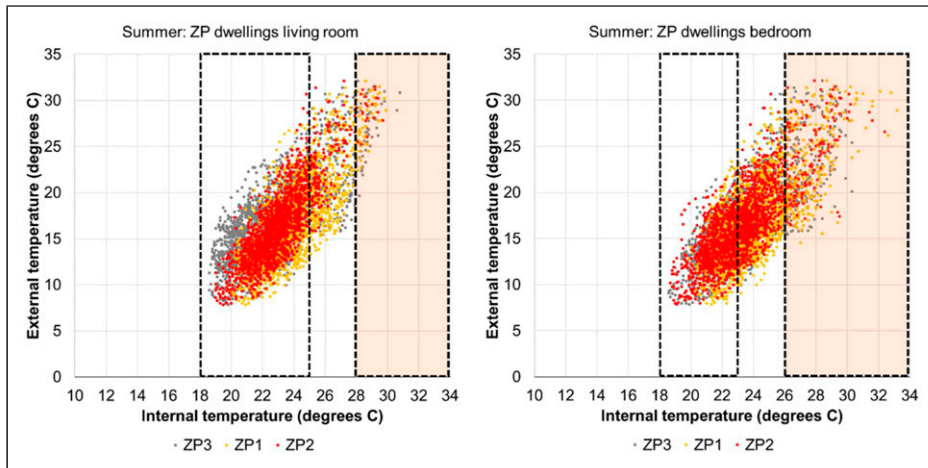


Figure 5. Summer temperatures for all hours: indoor versus outdoor (yellow = ZP1, red = ZP2 and grey = ZP3).

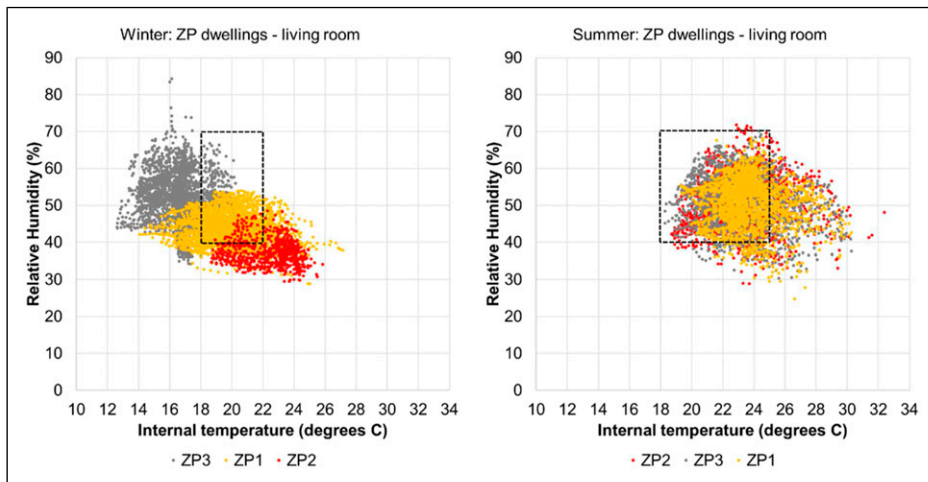


Figure 6. Winter (left) and summer (right) temperature and RH in the living room for all hours (yellow = ZP1, red = ZP2 and grey = ZP3).

The summer of 2020 was measured to be hotter than the typical reference year (TRY) with 20 h of temperatures greater than 30°C (zero for TRY) and 71% more hours in the range of 25–30°C. For the TRY the maximum temperature is 28.8°C and the average temperature is 13.9°C. For the summer of 2020 the maximum temperature was 32.1°C and the average temperature is 15.9°C.

The summer of 2020 in York had three heatwaves.³ Those were as follows:

1. Four days from 23–26 June with maximum of 29.7°C.
2. Three days from 10–12 August with maximum of 31.2°C.
3. Five days from 23–27 August with maximum of 31°C for 2 days in a row; this one would have been considered a heatwave in London (maximum 28°C threshold).

In the third heatwave, during the last week of August, the dwellings experienced high indoor

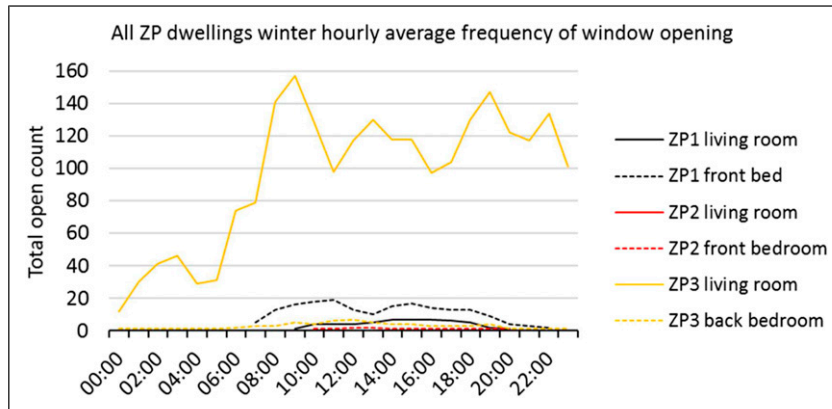


Figure 7. Hourly average total window opening count in winter (all dwellings).

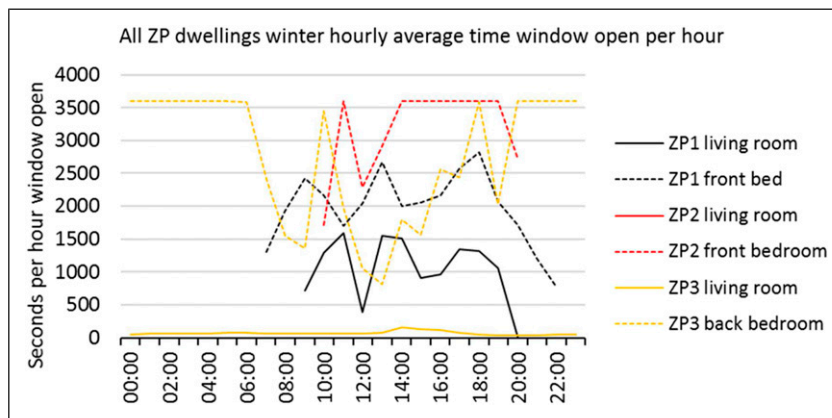


Figure 8. Hourly average period of time in seconds when window is open in winter (all dwellings).

temperatures. Figure 9 shows the temperature readings in the living rooms and bedrooms of the ZP dwellings during this heatwave. In the living room, a high of 30°C was recorded in ZP1 and temperatures above 34°C were recorded in the bedroom of ZP3.

In detail:

- **ZP1** had a habit of opening windows in late morning in the living room (Figure 10) and late morning to early afternoon in bedroom. This created an indoor environment that matched exterior peaks (more so in bedrooms). In contrast to the other dwellings, the ZP1 bedroom was able to reach lower troughs at night.
- **ZP2** had almost no window opening during the period (only once for a short period in the living room on the evening of the 27th; not shown below). As a result, the indoor temperatures in ZP2 had less daily variation than the other dwellings. Most notably the daily highs remained 3–4°C cooler than in the other dwellings.
- **ZP3** opened windows and doors the most. The living room garden doors were opened frequently, and often left open for hours at a time between 5am and midnight almost every day (Figure 10). The windows in the bedroom were left open for the entire period. ZP3 had the

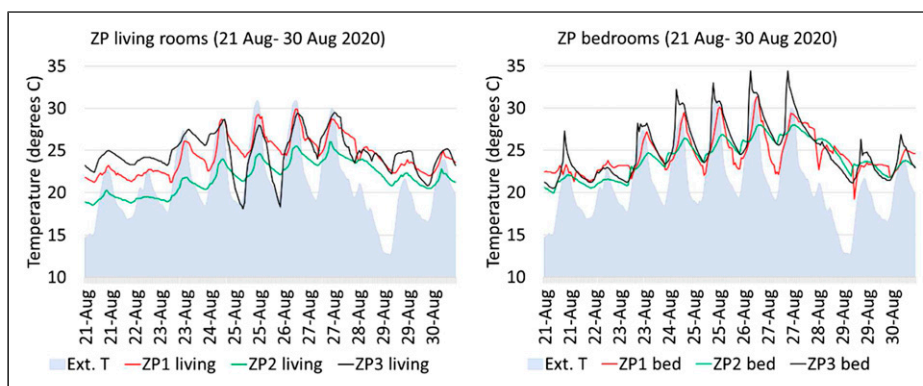


Figure 9. Living room (left) and bedroom (right) temperatures during August 2020 heatwave.

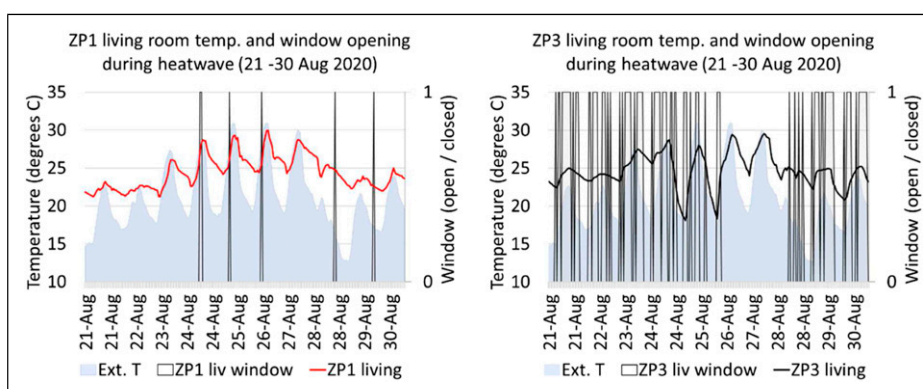


Figure 10. ZP1 (left) and ZP3 (right) living room temperatures and window opening during August 2020 heatwave.

highest temperatures during the period most notably in the bedroom where daily peaks were exceeding outdoor temperatures.

Overall, it appeared that window opening led to higher indoor temperature and higher highs during the heatwave period in the dwellings. It was possible to achieve cooler temperatures at night by opening windows, but the timing of window opening appeared to be crucial for success in cooling off spaces overnight.

The overheating assessment considered both static and adaptive methods for an overall view of overheating in the dwellings. Table 4 shows the overheating assessment results for the ZP dwellings and the overheating thresholds are described in the table. Under the static method almost every room has some overheating.

The main bedroom in ZP3 overheats the most with 268 occupied hours above the threshold. This is the same bedroom that registered significant peaks above the other dwellings during the heatwave period. Using the adaptive method, three bedrooms failed at least one criterion and two bedrooms failed two criteria. Failing at least two criteria is what is required to overheating using the adaptive method. Figure 11 shows the static overheating data in a bar graph along with the non-Zero Plus homes. Total hours are also shown to demonstrate the condition if the room were occupied at all times by someone who could not vacate the room. This indicates where overheating is happening in the space outside of designated occupied hours. With the exception of NZP3 the ZP dwellings appear to experience the prevalence of summertime overheating.

Table 4. Overheating results.

Dwelling	Room	Window orientation/ floor	Occupancy hours	Static method		Adaptive method	
				Overheating test % occupied hours >27.9 in living rooms; >25.9 in bedrooms	Total occupied hours above threshold	Criterion 1: hours of exceedance % of hours over adaptive comfort limit at category II in living rooms and category I in bedrooms	Criterion 2: Daily weighted exceedance and criterion 3: Upper limit temp
ZP1	Living room	ENE and WSW/ ground floor	7:00–9:00/ 16:00–23:00 (10 h)	1.7% - Overheated	63 h	0.9% (pass)	None failed
	Bedroom 1 (front)	ENE/First floor	0:00–7:00/ 21:00–24:00 (10 h)	3.6% - Overheated	132 h	0.3% (pass)	None failed
	Bedroom 2	WSW/First floor	0:00–7:00/ 21:00–24:00 (10 h)	2.3% - Overheated	84 h	0.4% (pass)	None failed
ZP2	Living room	ENE and WSW/ ground floor	8:00–23:00 (16 h)	0.4% (pass)	24 h	0.2% (pass)	None failed
	Bedroom 1	ENE/First floor	0:00–7:00/ 21:00–24:00 (10 h)	1.5% - Overheated	51 h	0.1% (pass)	C2: failed C3: failed
	Bedroom 2	WSW/First floor	0:00–7:00/ 21:00–24:00 (10 h)	1.6% - Overheated	58 h	0.1% (pass)	None failed
ZP3	Living room	ENE and WSW/ ground floor	8:00–23:00 (16 h)	1.5% - Overheated	86 h	0.6% (pass)	None failed
	Bedroom 1	WSW/First floor	0:00–7:00/ 21:00–24:00 (10 h)	7.3% - Overheated	268 h	2.9% (barely pass)	C2: failed C3: failed
	Bedroom 2	ENE/First floor	0:00–7:00/ 21:00–24:00 (10 h)	4.0% - Overheated	145 h	1.6% (pass)	C2: failed

Set point and indoor temperature

To evaluate the use of the smart thermostats, the relationship between set point and indoor temperature are examined using statistical analysis. The results are presented in Table 5. The indoor temperature reading was taken 30 min after the set point trigger reading to

allow the indoor temperature to regulate in response to the temperature setting. The table shows that ZP1 as a standard practice did not use the set point to achieve actual desired temperature in the dwelling. As was gathered from the BPE survey, the occupant used radiator valves and window opening to control room temperatures. This pattern of control is most obvious

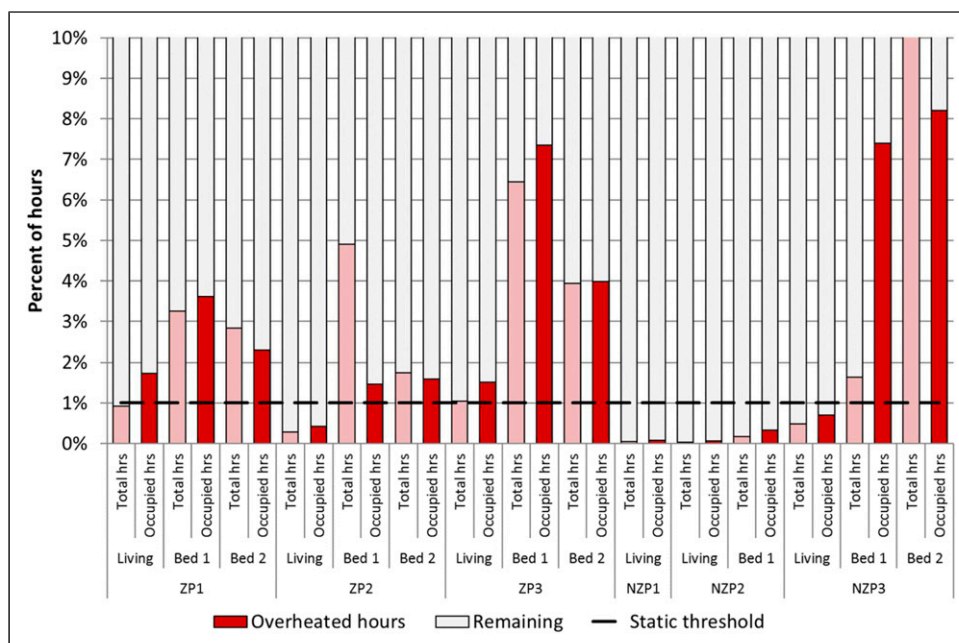


Figure 11. Static overheating bar graph for ZP and Non-ZP dwellings.

in the difference between the average set point temperature and the average indoor temperature (9.8°C). Over three-quarters of the time that heating was on in ZP1, the set point was set to either 31°C or 32°C whereas the mean indoor temperature was 20°C. Effectively, ZP1 was using the thermostat set point of 32°C as an on/off switch. ZP2 and ZP3 appeared to use the heating set point to reach closer to desired temperatures. In these dwellings, the difference between the set point and the indoor temperature was around 1°C or less. In ZP2, most of the time that heating was on, the set point was between 23–24°C achieving an average heating ON indoor temperature of 22°C. In ZP3, when heating was on, the set point was between 16–18°C achieving an average heating ON indoor temperature of 16°C. ZP3 was significantly under-heating as compared to ZP1 and ZP2.

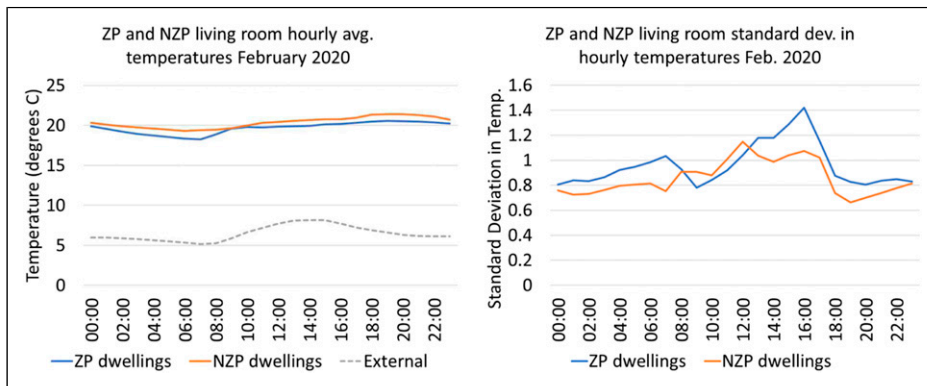
Generally, the heating season in all dwellings was from October through March with limited heating in April and even less in September. February 2020 was selected for winter indoor temperature analysis as it was the second coldest month on average for the monitoring period and allows for ZP2 data to be

observed as the occupants did not occupy the dwellings until the end of January 2020. Figure 12 shows the hourly average temperatures and standard deviation of hourly temperatures in February for the ZP and NZP dwellings as clusters. The hourly average between the two groups are close although the NZP dwellings as a group maintained slightly higher temperatures throughout the day. The highest (mean 22.3°C) and lowest (mean 17°C) heat consumers are both smart thermostat users (ZP2 and ZP3).

The ZP dwellings had a greater standard deviation in hourly temperature. This would suggest that the smart controls were less used to maintain constant comfort temperatures and possibly more actively used to meet on-demand temperatures. The largest difference in deviation was at 7:00 and 16:00, morning and afternoon peak hours. In detail, ZP1 and ZP2, two dwellings with the smart thermostats had much greater indoor temperature swings than the NZP dwellings. This may suggest more hands-on control of the smart thermostat but may also indicate control through other means such as at the radiator and window opening.

Table 5. Descriptive statistics of set point temperatures for ZP dwellings with smart thermostats.

	ZP1		ZP2		ZP3	
	GF	FF	GF	FF	GF	FF
Max. set point/indoor (°C)	32/25	32/23	26/25	26/24	20/19	25/18
Mean set point/indoor (°C)	30/20	30/20	24/22	23/22	16/16	16/16
Min. set point/indoor (°C)	20/17	20/17	20/19	20/19	15/15	16/16
Avg. diff. between set point and indoor temperature (°C)	9.8	9.8	1.3	0.8	0.1	0.1

**Figure 12.** Hourly average temperatures in the ZP and NZP dwellings (left) and average standard deviation in hourly temperatures in ZP and NZP dwellings for February (right).

The distribution of temperature for the month of February for all hours in the living room and bedroom of all dwellings (Figure 13) show the presence of a wider distribution and more outliers in the ZP dwellings. This may also indicate frequent use of the thermostat to control the indoor environment outside of a set schedule. Overall winter data indicated an additional 2–3°C difference in spread between upper quartile and the maximum, and higher outlier temperatures in the ZP dwellings which would indicate more use of on-demand heating when desired, potentially resulting in more energy use.

Space heating energy use data was available for the ZP dwellings, although, 75% of data for ZP1 and 33% of data for ZP2 had to be estimated through simulation. Annually, space heating energy was found to be 26.4 kWh/m² in ZP1, 44.6 kWh/m² in ZP2, 37.1 kWh/m² in ZP3. In most months, as with temperatures, space heating in ZP2 was highest with the

exception of March 2020, where space heating was higher in ZP3.

Perception of comfort, indoor environment and control

The BPE surveys were performed in person for the winter period (mid-February 2020) and through online questionnaires (COVID-19 protocol) for the summer period (early August 2020). For each survey period, four responses were returned (one in ZP1, one in ZP2 and two in ZP3). All respondents were fairly young with young families; native to England and typically spending most time at home. Their self-reported health condition is nearly equally split between 'usually healthy' and 'chronic condition' (one with asthma (ZP2) and one with Ehlers–Danlos syndrome (ZP3), the latter with potential impact on blood vessels and inner organs, which could lead

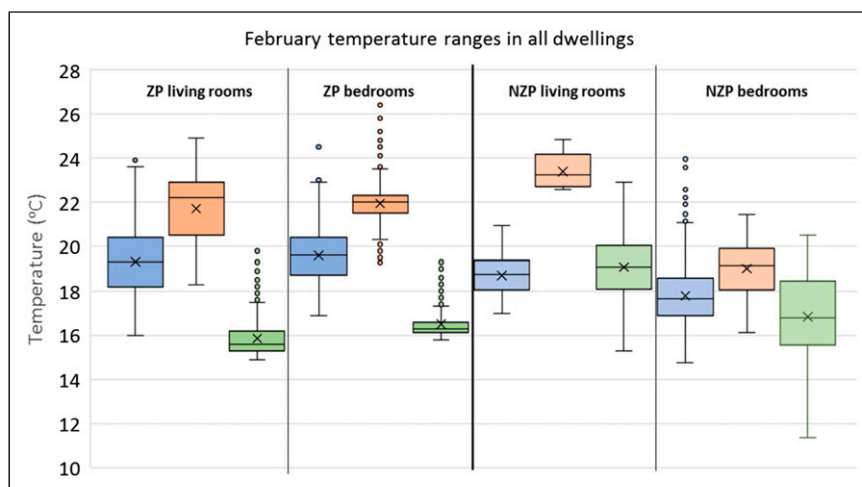


Figure 13. Temperature distributions in February 2020. Note: Dwellings are shown in order from left to right, that is, ZP1, ZP2, ZP3/NZP1.

to a general discomfort in poor environmental conditions).

In the winter period, perception of temperature, ventilation, noise, lighting and odours were mostly 'very good' and with some 'good' and two 'poor' votes (Table 6). The 'poor' votes were with respect to temperature in ZP1 and noise in ZP3. In the summer period, ZP3 saw some improvement in their perception of the indoor environment, ZP1 remained the same and ZP2 considered lighting and odours to be 'good' as opposed to 'very good'.

In the winter period, all but ZP2 reported that they open windows to control the thermal environment (Table 7). Review of window opening behaviour in the winter confirms that ZP2 did not open living room windows and bedroom windows were opened minimally. Furthermore, window opening in the summer was also minimal but necessary for ventilation. This window opening behaviour would make sense considering the occupant reported having chronic asthma. In the summer, all dwellings reported opening windows and doors to control the thermal environment. At the same time, all respondents but the female in ZP3 stated that the dwelling was generally 'too warm' in the summer and difficult to cool down. The perception of the impact of opening the windows and doors to cool down the

space varied between respondents from 'usually', 'more or less' and 'slightly' effective.

The BPE questionnaire asked the occupants to rate the heating system on two points.

1. Overall, how easy is it to control the heating? Very difficult [1] to [7] very easy.
2. Overall, how effective is the heating system at maintaining comfortable conditions? Ineffective [1] to [7] effective.

Overall, the ZP dwellings (with smart thermostat) rated their ease of control and effectiveness of the systems slightly higher in control but lower in effectiveness (mean control = 6 & effectiveness = 6.5) than the NZP dwellings (mean control = 5.5 & effectiveness = 7). ZP1, for example, considered the response to both questions to be [7] *very easy/effective*, they also counterintuitively considered the indoor temperature in winter to be *poor* (Table 8). They also noted that they use the radiator valves to control room temperatures which would make sense given their set point control pattern outlined in the Set point and indoor temperature. Though ease of control was considered lower in NZP3 (4 - neutral), they also stated that they do not use the main thermostat but control rooms via radiator valves. NZP2

Table 6. Perception of indoor environment (W = winter/S = summer).

	Ventilation		Temperature		Noise		Lighting		Odours	
	W	S	W	S	W	S	W	S	W	S
ZP1	VG	—	P	—	VG	VG	VG	VG	VG	VG
ZP2	G	—	G	I	VG	VG	VG	G	VG	G
ZP3 (m)	VG	—	G	G	P	G	VG	VG	VG	VG
ZP3 (f)	VG	—	G	VG	G	G	VG	VG	VG	VG

Table 7. Control of indoor environment (W = winter/S = summer).

	Windows (open/ close)		Doors (open/ close)		Heating (on/off) W	Do these changes make a difference?	
	W	S	W	S		W	S
ZP1	Yes	Yes	Yes	Yes	No	Thermal comfort and IAQ	No difference
ZP2	No	Yes	No	Yes	Yes	Only thermal comfort	Thermal comfort and IAQ
ZP3 (m)	Yes	Yes	No	Yes	Yes	Thermal comfort and IAQ	Only thermal comfort
ZP3 (f)	Yes	Yes	No	Yes	Yes	Thermal comfort and IAQ	Thermal comfort and IAQ

stands out among the others as stating that they do not understand how to use the (conventional) thermostat.

In comparing the mean temperatures and standard deviations to the perceived overall comfort (Table 8), it is evident that different mean temperatures can be perceived as *good* and *very good*.

Discussion

The presence of smart thermostats did not indicate more adequate temperature management in the ZP dwellings as compared to NZP dwellings with standard thermostats. The most notable difference was more upper quartile and outlier temperatures in the ZP dwellings which indicate regular use of on-demand heating when desired, potentially leading to more energy use. Borrowing from Sovacool et al.²⁸ defined heating behaviours and the monitoring results discussed in the section before, the following findings emerge:

- ZP1 is considered to be an ‘On-off Switcher’ or ‘Steady and Savvy’ as they varied their set point the least and were able to maintain a household range between 18 and 20°C.

- ZP2 is considered either an ‘On-demand Sizzler’ or a ‘Toasty Cruiser’, maintaining set points mostly between 22–24°C with household temperatures around 22–23°C
- ZP3 is considered to be a ‘Cool Conserver’ never heating above 20°C; however, it is not known whether their motivation was due to concern for energy costs.
- NZP1 and NZP3 are considered ‘Steady and Savvy’ as they generally maintain temperatures between 18–20°C in the living rooms; however, their bedroom temperature changes may qualify as a different category; generally cooler preferences in NZP3.
- NZP2 is considered an ‘On-demand Sizzler’ with a tight temperature range around 23°C though it appears they prefer to sleep much cooler than they keep their living room.

The above variation across a small sample of six dwellings shows the significance of resident expectations and behaviour related to indoor heat management. It is clear that ‘smart’ features of a thermostat may not lead to energy conserving behaviours on its

Table 8. Perception of indoor environment and statistics in ZP and NZP dwellings.

	Perception Temperature in winter	Mean winter temperatures		Standard dev	
		Living room	Bedroom	Living room	Bedroom
ZP1	Poor	19.5°C	19.6°C	1.7	1.5
ZP2	Good	21.7°C	21.9°C	1.5	0.9
ZP3	Good	15.8°C	16.2°C	1.2	1.2
NZP1	Very good	18.2°C	17.1°C	0.9	1.4
NZP2	Indifferent	22.5°C	18.4°C	1.2	1.2
NZP3	Very good	18.2°C	17.3°C	1.2	1.9

own, unless there is awareness raised amongst residents about the link between heating behaviours, energy use and climate emergency. Interestingly, dwellings with smart thermostats, that had more options over thermostatic control (assuming they took on a higher level of control), had slightly less satisfaction with their overall winter temperatures and their thermal comfort surveys indicated a preference for higher temperatures, implying that in some periods the controls did not work as expected. The ZP dwellings' perceived greater control over their environment could have been a perception of control due to the expectation of the potential of the smart thermostat technology despite lack of confidence in how to use it.

Though the occupants of the ZP dwellings were instructed on how to use the smart thermostats it appears that they would have benefited from a follow-up session from the housing provider or the energy company. In ZP3's particular set point pattern, from October–January, there was active variation in the set point from hour to hour; however, from February on, the occupants appeared to have either become accustomed to how they would prefer to operate the thermostat or became disinterested or even frustrated with trying to learn/use the fine-tuning features. A similar sentiment was found while studying smart thermostat users in Hargreaves, Wilson¹⁷; Lomas, Oliveira¹⁶ furthermore, were concerned with long-term drifts in energy demand and potential change in occupant interest not being observed in short-term studies.

Given poor ratings related to ease of control in the NZP dwellings and one dwelling outright saying that

they do not know how to use the programmable thermostat, it is likely there was no training on how to use the programmable thermostats. There may be an assumption that people already know how to use 'standard' thermostats, thereby neglecting much needed training on how to set useful schedules, for example. As a lesson learnt, it is important to integrate training to use not only smart thermostats but also what are considered standard thermostats to influence desirable heating patterns. In addition, NZP occupants that appeared to be hesitant or unable to use their thermostat may benefit from smart thermostat accompanied with training on how to use it and or the smart learning feature in contrast to 'always on' high temperatures.

Conclusion

The paper analysed objective data on indoor/outdoor temperature and subjective data on thermal comfort in six similar dwellings located in the same development. Three out of the six dwellings were equipped with smart thermostats and three had standard programmable thermostats. The intent was to examine if there was any difference in the measured indoor thermal conditions and perception of thermal comfort across these dwellings.

While there was no apparent difference in the measured and perceived indoor temperatures between homes with and without smart thermostats, the six dwellings were different in heat management, ability and ways of controlling the internal environment. Since the six dwellings were similar in built form and construction, it is evident that heating preferences and

expectations can overtake the capabilities of a smart thermostat or a standard programmable thermostat. In light of the wide variation in measured indoor temperature across the six dwellings, it is vital that energy models consider a range of heating preferences to avoid a gap between expectation and reality.

Assuming indoor temperature during the heating season as proxy for heating energy consumption, the highest and lowest consumers were found to both be smart thermostat owners. This would suggest that factors such as resident expectations, preferences and understanding of heating controls are more consequential than simply installing a smart thermostat. Without appropriate training, overarching preferences and behaviours of the occupants can be carried from one type of thermostat to the next, negating any special or 'smart' features.

For the upcoming ECO smart heating technology rollouts, it is vital to have training of residents on use of the system and trouble-shooting should the control not yield the expected result. The different needs and requirements of the occupants need to be addressed and the solution will need to be highly customisable to the user. This will be an important step in achieving the intended energy savings of these smart controls that are expected to become widespread in a smarter energy system.

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Notes

1. The smart thermostat, the device used in this study, is a sub-category of smart heating controls. Smart heating controls can also include smart thermostatic radiator valves and hot water controls.
2. Techno-coolness encompasses the perceptions that a smart home technology can make a home look modern and futuristic, be fun to use and make the user feel technologically advanced.
3. Heat wave: a period of at least three consecutive days with maximum temperatures meeting or exceeding a heatwave temperature threshold. For Yok this temperature is 25°C. <https://rmet.sagepub.com/doi/full/10.1002/wea.3629#:~:text=A%20UK%20heatwave%20is%20met,is%20shown%20in%20Figure%201.>

References

1. DBEIS. *Heat in Buildings*, <https://www.gov.uk/government/groups/heat-in-buildings> (2021, accessed 13 April 2021).
2. DBEIS & Prime Minister's Office. *UK Enshrines New Target in Law to Slash*, 2021. emissions by 78% by 2035, <https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035> (accessed 28 April 2021).
3. Palmer J, Godoy-Shimizu D, Tillson A, et al. *Building Performance Evaluation Programme: Findings from Domestic Projects Making Reality Match Design*. Innovate UK, 2016.
4. Gupta R, Gregg M, Passmore S, et al. Intent and outcomes from the Retrofit for the Future programme: key lessons. *Build Res Inf* 2015; 43: 435–451.
5. Ministry of Housing Communities and Local Government. *The Future Homes Standard 2019: Consultation on Changes to Part L (Conservation of Fuel and Power) and Part F (Ventilation) of the Building Regulations for New Dwellings*. London: Ministry of Housing, Communities and Local Government, 2019.
6. Blackman D. *The Future Homes Standard: Get Ready for a Domestic Revolution*, 2019, <https://www.building.co.uk/focus/the-future-homes-standard-get-ready-for-a-domestic-revolution/5103031.article> (accessed 30 April 2020).
7. CCC. UK housing. *Fit for the Future?* London: Committee on Climate Change, 2019.

8. Rosenow J, Lowes R, Broad O, et al. *The Pathway to Net Zero Heating in the UK: A UKERC Policy Brief*. London: UK Energy Research Centre, 2020.
9. CCC. Reducing UK Emissions. Progress Report to Parliament. 2020. London: Committee on Climate Change, 2020.
10. Clothier S. *Trialling Technology to Help Our Members Save*, 2021, <https://bulb.co.uk/blog/trialling-technology-to-help-our-members-save> (accessed 13 April 2021).
11. Jones J. *Smart Thermostat-Linked Smart Meters to Be Trialled for Energy Management in UK*, 2020, <https://www.smart-energy.com/industry-sectors/smart-meters/smart-thermostat-linked-smart-meters-to-be-trialled-for-energy-management-in-uk/> (accessed 13 April 2021).
12. St. John J. *California's Big Decision on Grid Reliability: Expand Supply or Manage Demand?*, 2021, <https://www.greentechmedia.com/articles/read/californias-big-decision-for-2021-grid-reliability-go-big-on-supply-or-expand-demand> (accessed 28 April 2021).
13. Moreno-Rangel A, Sharpe T, McGill G, et al. Indoor air quality in Passivhaus dwellings: A literature review. *Int J Environ Res Public Health* 2020; 17: 4749.
14. Del Rio DDF, Sovacool BK, Bergman N, et al. Critically reviewing smart home technology applications and business models in Europe. *Energy Policy* 2020; 144: 111631.
15. Wilson C, Hargreaves T and Hauxwell-Baldwin R. Benefits and risks of smart home technologies. *Energy Policy* 2017; 103: 72–83.
16. Lomas KJ, Oliveira S, Warren P, et al. Do domestic heating controls save energy? A review of the evidence. *Renew Sust Energy Rev* 2018; 93: 52–75.
17. Hargreaves T, Wilson C and Hauxwell-Baldwin R. Learning to live in a smart home. *Build Res Inf* 2018; 46: 127–139.
18. Mamonov S and Koufaris M. *It's Cool! Analysis of Factors that Influence Smart Thermostat Adoption Intention*, 2020.
19. Hernandez G, Arias O, Buentello D, et al. *Smart Nest Thermostat: A Smart Spy in Your Home*. Black Hat USA, 2014.
20. Kafle K, Moran K, Manandhar S, et al. Security in Centralized Data Store-based Home Automation Platforms: A Systematic Analysis of Nest and Hue. *ACM Trans Cyber-Physical Syst* 2020; 5: 1–27.
21. Centrica. Hive research shows you could save £115 a year on energy, <https://www.centrica.com/media-centre/news/2020/hive-research-shows-you-could-save-115-a-year-on-energy/> (2021, accessed 14 April 2021).
22. Centrica. Five ways to save money with a smart home thermostat, <https://www.hivehome.com/discover-hive/smart-heating/five-ways-to-save-money-with-a-smart-thermostat> (2021, accessed 14 April 2021).
23. Nest Labs. Energy Savings from the Nest Learning Thermostat: Energy Bill Analysis Results, <https://nest.com/thermostats/real-savings/https://storage.googleapis.com/nest-public-downloads/press/documents/energy-savings-white-paper.pdf> (2015, accessed 14 April 2021).
24. Ecobee. Smart thermostats, <https://www.ecobee.com/en-us/smart-thermostats/> (2021, accessed 14 April 2021).
25. Pang Z, Chen Y, Zhang J, et al. How much HVAC energy could be saved from the occupant-centric smart home thermostat: A nationwide simulation study. *Appl Energy* 2021; 283: 116251.
26. Stopps H and Touchie MF. Residential smart thermostat use: An exploration of thermostat programming, environmental attitudes, and the influence of smart controls on energy savings. *Energy Buildings* 2021; 238: 110834.
27. Schäuble D, Marian A and Cremonese L. Conditions for a cost-effective application of smart thermostat systems in residential buildings. *Appl Energy* 2020; 262: 114526.
28. Sovacool BK, Osborn J, Martiskainen M, et al. Testing smarter control and feedback with users: Time, temperature and space in household heating preferences and practices in a Living Laboratory. *Glob Environ Change* 2020; 65: 102185.
29. Huchuk B, O'Brien W and Sanner S. Exploring smart thermostat users' schedule override behaviors and the energy consequences. *Sci Technol Built En* 2020; 27: 195–210.
30. GVA/15. *Environmental Design*. CIBSE Guide A.
31. Wookey R, Bone A, Carmichael C, et al. *Minimum Home Temperature Thresholds for Health in Winter—A Systematic Literature Review*. London: Public Health England, 2014.
32. Marcus S. *What's the Ideal Room Temperature for Your Home?*, 2020, <https://www.ovoenergy.com/>

- [guides/energy-guides/average-room-temperature](#) (accessed August 4 2021).
33. TheGreenAge. How warm should my house be?, <https://www.thegreenage.co.uk/how-warm-should-my-house-be/> (2018, accessed August 4 2021).
34. UK Power. How to get help with fuel poverty, https://www.ukpower.co.uk/home_energy/fuel_poverty (2018, accessed August 4 2021).
35. CIBSE. *Environmental Design Guide A*. London, UK, 2006.
36. CIBSE. TM52. *The Limits of Thermal Comfort: Avoiding Overheating in European Buildings*. CIBSE, 2013.
37. Sameni SMT, Gaterell M, Montazami A, et al. Overheating investigation in UK social housing flats built to the Passivhaus standard. *Build Environ* 2015; 92: 222–235.
38. Lomas KJ and Porritt SM. *Overheating in Buildings: Lessons from Research*. Taylor & Francis, 2017.