Vestemi Radbot ECO3
Demonstration Action Independent Report

Conducted by Build Test Solutions

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Introduction

Radbot is a smart thermostatic radiator valve that incorporates environmental sensors and embedded AI algorithm intelligence in order to detect and predict room occupancy and automatically regulate radiators. This claims to provide radiator by radiator zoning, allowing temperatures in unoccupied spaces to be reduced and thus reducing fuel bills and saving energy. The total running cost savings claimed by Vestemi in the original Demonstration Action application form was £24 per Radbot valve/year, assuming four Radbots this would equate to £96 per annum. Based on a typical dual fuel bill of £1,200, this would equate to approximately an 8% total fuel bill saving. This is of course likely to vary subject to the type and overall efficiency of the existing heating system and emitters.

This independent report provides an analysis of in-use performance data for the Radbot product, gathered as part of the ECO3 Demonstration Action programme. The objective of the study is to validate the above stated performance claim of the product being capable of delivering a £24 fuel bill saving per valve and an 8% total household fuel bill saving on average. The field trial was carried out on a total sample of 545 installed Radbots across 125 properties between October 2018 and April 2020. Data collection issues, however, reduced the sample size to 105 properties with temperature and relative humidity data and 37 with gas consumption data.

The Radbot devices were installed onto approximately 50% of the radiators within each home and data captured both pre and post installation of the upgrade included:

- Temperature and humidity in multiple locations throughout each home
- Gas consumption data in 37x homes (30%)
- Thermal comfort surveys completed by residents three times in each home

Homes were recruited from 5 geographic clusters across the UK with a mix of property types and sizes that aimed to be representative of the UK housing stock. The overall primary objective of the study being to determine the fuel bill cost savings delivered by installing Radbot.

Disclaimer: *The analysis herein has been carried out by Build Test Solutions (BTS) as an independent third party. It should be noted however that the role of BTS has been solely to review and analyse the data arising from the field work, having had no involvement in the design of the methodology, deployment of sensors and hardware or the associated data collection.*

Report Aims

The aims of this report are to:

- Review the data collected and compare it to the original proposed methodology
- Provide an accurate and unbiased assessment of the trial and the arising data
- Impartially present the key insights from the data gathered over the period of the trial

Monitoring Methodology Overview

Data Collection

The data which has been used by BTS in the analysis for this report includes internal temperature and relative humidity, gas consumption, comfort surveys and external temperature to calculate Heating Degree Days. The table overleaf provides an overview of the data collection equipment and techniques used.

Measurement	Equipment	Logging Frequency	Responsible Party
Internal temperature and relative humidity	ALTA Wireless Humidity & Temperature Sensor - Coin Cell Powered	15 minutes in each room with a Radbot installed	Parity Projects/ University of Salford
Internal temperature and relative humidity v2 (not used in analysis)	On-board sensors in Radbot equipment	15 minutes	Vestemi
Gas consumption	Various equipment including: - Loop optical meter reader (52) - Pulse logger (22) - Smart meter data (8)	15 minutes	Parity Projects/University of Salford
Manual meter reads		Start and end of monitoring	Vestemi
Comfort surveys	Undertaken by Vestemi	At 3 points: - Pre-works - After first period (with Radbot in either active or inactive state) - After second period in other state	Vestemi
External temperature data for calculation of Heating Degree Days	Sourced online from the Met Office	Daily	Parity Projects

In total, monitoring equipment was installed in 125 properties. Of these 125, 6 households withdrew from the project during the monitoring. 545 Radbot devices were installed across the 125 properties, with 21 of those in the 6 households that withdrew.

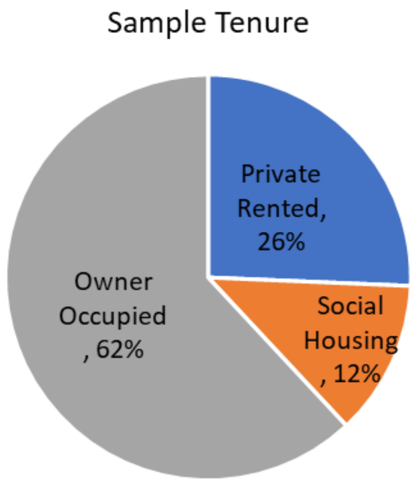
Data collection issues were experienced for both temperature and gas consumption data which reduced the sample of dwellings for which data was successfully collected, they are detailed in the table below.

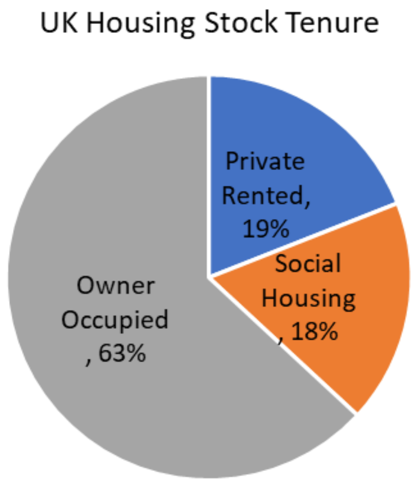
Measurement	Dwellings with Equipment Installed	% of Target Sample of 125	With-drew	Data Collection Issues	Successful Data Collection	% of Target Sample with Data
Internal Temperature & RH	125	100%	6	4	115	92%
Gas Consumption	83	66%	1	25	57	46%
- Of which optical meter reader or pulse logger	*74*	*59%*	*1*	*24*	*49*	*n/a*
- Of which smart meter data	*9*	*7%*	*0*	*1*	*8*	*n/a*

Building and Tenure Sample Statistics

The sample contains a good mix of building tenure, age and built form. Compared to the UK housing stock the sample:

- Closely matches in the mix of tenures
- Is slightly skewed to have fewer older buildings, containing more buildings from the period between 1945-1980
- Is skewed in the breakdown of built forms, with fewer detached and more semi-detached properties.





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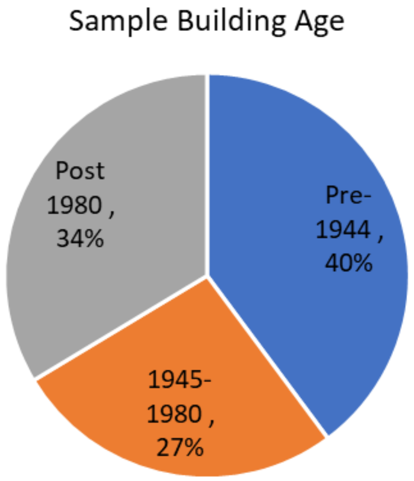
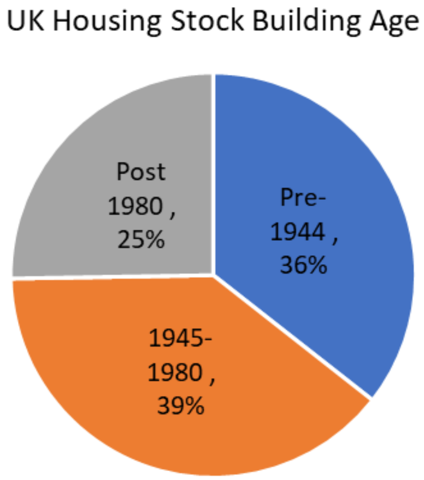
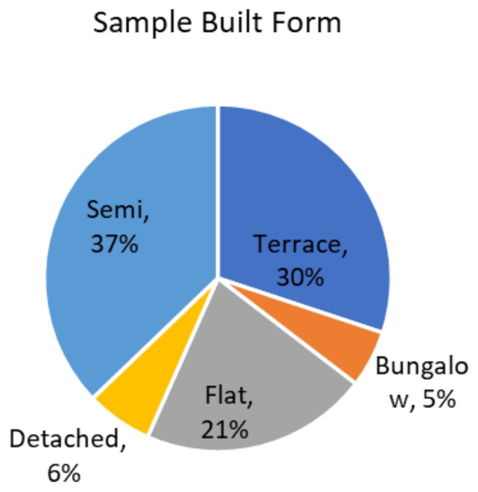
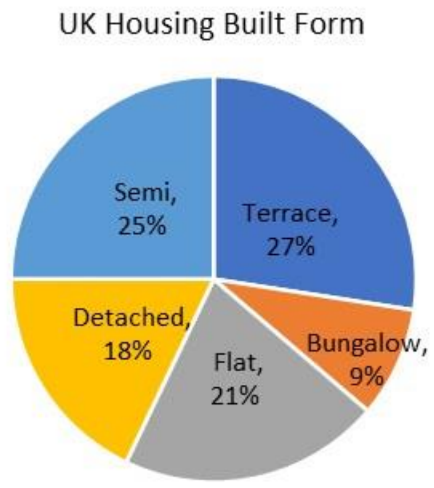




Source[2]

[1] https://www.ons.gov.uk/peoplepopulationandcommunity/housing/datasets/dwellingstockbytenureuk
[2] https://files.bregroup.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf





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Building Locations

The sample includes buildings from a wide range of locations, with a wide spread across England and Wales.

The table below compares the location of each dwelling (or group of dwellings if located within the same postcode area) to the location of the weather station which was used to provide weather data. The weather stations were on average 15 miles away from the houses, with a maximum distance of 34 miles.

Postcode			Weather Station		
Outcode	**Lat**	**Long**	**Lat**	**Long**	**Distance (miles)**
BN3	50.83	-0.18	50.84	-0.29	5.09
BN11	50.81	-0.38	50.84	-0.29	3.96
CF43	51.66	-3.45	51.41	-3.44	17.42

Min:	1.64
Max:	34.26
Mean:	14.77

SA1	51.63	-3.94	51.41	-3.44	26.45
CF43	51.66	-3.45	51.41	-3.44	17.42
CF43	51.66	-3.45	51.41	-3.44	17.42
CF39	51.60	-3.43	51.41	-3.44	13.60
SA12	51.61	-3.79	51.41	-3.44	20.70
CF39	51.60	-3.43	51.41	-3.44	13.60
EX2	50.71	-3.52	50.74	-3.40	5.14
GL20	52.00	-2.13	52.15	-2.04	10.76
GL51	51.90	-2.11	52.15	-2.04	17.61
GL17	51.85	-2.51	52.15	-2.04	28.40
GL10	51.74	-2.28	52.15	-2.04	29.75
GL1	51.86	-2.25	52.15	-2.04	21.90
GL11	51.69	-2.36	52.15	-2.04	34.26
TW12	51.42	-0.37	51.48	-0.45	5.27
TW1	51.45	-0.33	51.48	-0.45	5.57
SW17	51.43	-0.17	51.48	-0.45	12.68
KT18	51.32	-0.26	51.48	-0.45	13.64
HA6	51.61	-0.42	51.48	-0.45	9.13
BD3	53.80	-1.73	53.81	-1.87	5.59
WF1	53.68	-1.50	53.81	-1.87	17.35
LS8	53.82	-1.51	53.81	-1.87	14.40
BL7	53.63	-2.42	53.36	-2.38	18.62
CV32	52.30	-1.53	52.36	-1.33	9.55
CV37	52.19	-1.71	52.36	-1.33	20.11
CV35	52.23	-1.60	52.36	-1.33	14.20
PL5	50.41	-4.17	50.35	-4.12	4.43
PL1	50.37	-4.15	50.35	-4.12	1.64
GU21	51.32	-0.58	51.30	-0.09	21.08
KT22	51.30	-0.34	51.30	-0.09	10.70
GU22	51.31	-0.55	51.30	-0.09	20.02

Data Filtering

The dataset was filtered before analysis so that it only covered active heating periods and a consistently applied pre and post operational duration. Findings herein are therefore based on measurements recorded only during the periods of **01 October 2018 to 30 April 2019** and **01 October 2019 to 30 April 2020**.

Additionally, for data to be included in the analysis, it must have been attributable to a Radbot operating mode (either smart or manual emulation) for a period of **at least 21 days**. During each unique period, the data was aggregated to provide a comparison between operating modes on a location by location basis.

A location would typically be analogous to a single room in a house, other than where rooms had multiple Radbots installed, in which case multiple locations will exist within a single room. Each location was categorised as either Zone 1 (living room) or Zone 2 (elsewhere).

The comparison of each location was further filtered to only include results within 2 standard deviations (σ) of the mean. This is to remove outliers where, for instance, the reported change in temperature or gas consumption were outside of what could reasonably be expected.

This filtering process further reduced the total number of houses for which suitable data was available to be used in the data analysis, resulting in 105 houses with temperature and relative humidity data and 37 houses with gas consumption data. All 10 houses which were filtered out of the sample of temperature and relative humidity monitoring were removed because there was insufficient data during either the active or inactive phases to allow a direct comparison for that property.

Measurement	**Dwellings with Data**	**% of Target Sample of 125**	**Filtered Out**	**Included in Analysis**	**% of Target Sample Analysed**
Internal Temperature & RH	115	92%	10	105	84%
Gas Consumption	57	46%	20	37	30%

There were several reasons why properties with gas data were filtered out and not used in the final data analysis. For example, even in properties where gas data was successfully collected there were issues with the data collection which meant that data wasn’t collected successfully for the whole period of the study. This caused problems such as having insufficient data for either the active or inactive phase meaning that the consumption during each in the same property couldn’t be compared, or only having data for a period outside of the winter.

Eight properties were also filtered out on the basis that they had very low gas use. This is surprising as the data was collected during the heating season, and looking at more detail in these houses we can see that the gas data was collected during the middle of winter, November-February, and not in shoulder seasons.

Reasons for Filtering out Gas Consumption Datasets	**Frequency**
Low gas use	8
Data collected outside of winter periods	3
Gas data only available for either active or inactive phase	6
Outside percentile	2
No temperature data	1
TOTAL	*20*

Data Analysis Findings

Radbot Device

BTS performed a comparison of the measured internal temperature and relative humidity as reported by the Radbot device itself across operating modes.

The data sample included 103 properties and 377 locations in total, split by 90 locations in Zone 1 and 287 in Zone 2. There were two properties in which the temperature monitoring data from the Radbots was not successfully collected, but the data from the Monnit sensors was, that's the reason why a total sample size of 105 properties is reported for the study but only 103 in this section. As explained in the following section, the data analysis for assessing the Radbot performance is based only on temperature and relative humidity data collected by the Monnit devices.

The results (Appendix A.5) showed a mean change in internal temperature of **0.51°C decrease** in Zone 1 and **0.57°C decrease** in Zone 2 when in smart mode. The mean change in relative humidity was found to be **1.85% increase** and **2.09% increase** respectively.

Overall, the spread of observed change across the sample was from a **3.17°C decrease** to a **2.22°C increase** in internal temperature (within 2σ).

The accuracy of the Radbot sensors are unknown to BTS as they are not published in the technical specification area of the instruction manual.

Radbot vs Monnit Temperature and RH Data

There was a significant difference in observed temperatures and RH between the Radbot device and Monnit sensors.

Spot observations were conducted to directly compare Radbot temperatures to Monnit temperatures (Appendix A.7) which show that Radbot is reporting higher temperatures than Monnit when heating is active and, conversely, Radbot is reporting lower temperatures than Monnit when heating is inactive.

These higher temperature readings will very likely be as a result of the proximity of the Radbot TRV to the radiator panel itself. But the lower temperature readings may be caused by one or more of the following:

- Systematic error in the Radbot sensors
- Different installation heights causing Monnit sensors to read different temperatures due to the effects of stratification
- Radiative cooling on the Radbot sensors from external walls and/or floors (as radiators are often mounted on external walls).

It is worth noting that these considerations are not unique to Radbot and would apply to manual TRVs as well. Due to these issues with the Radbot temperature measurements, only data from the Monnit sensors is used in the analysis of the effect of the Radbots.

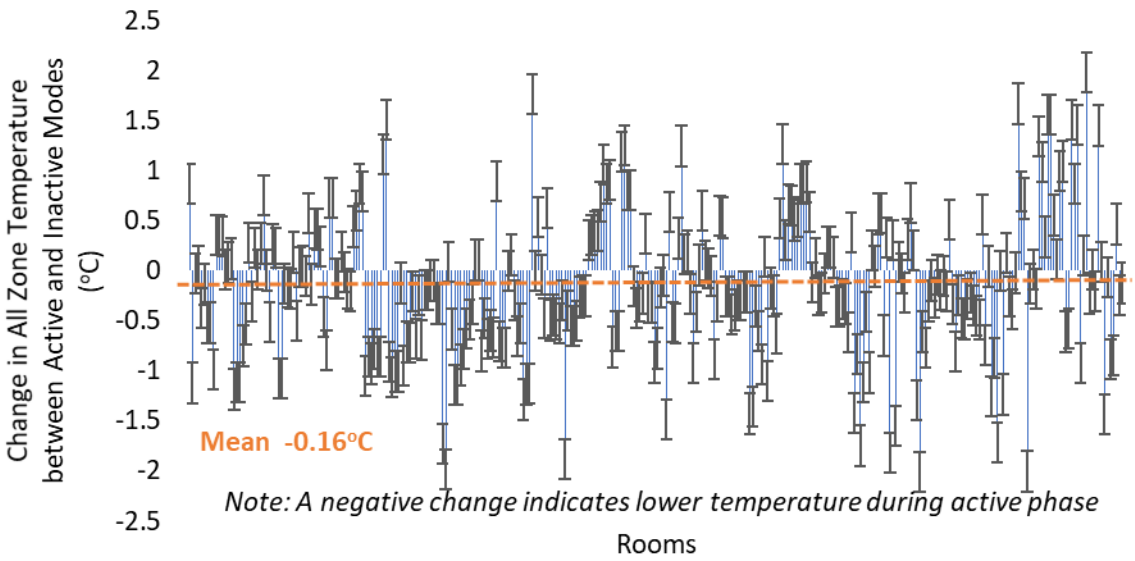
Monnit Sensors

Data from the third party Monnit sensors installed within the same locations as the Radbots devices provided a comparable sample of 105 properties and 313 locations in total, split by 84 locations in Zone 1 and 229 in Zone 2.

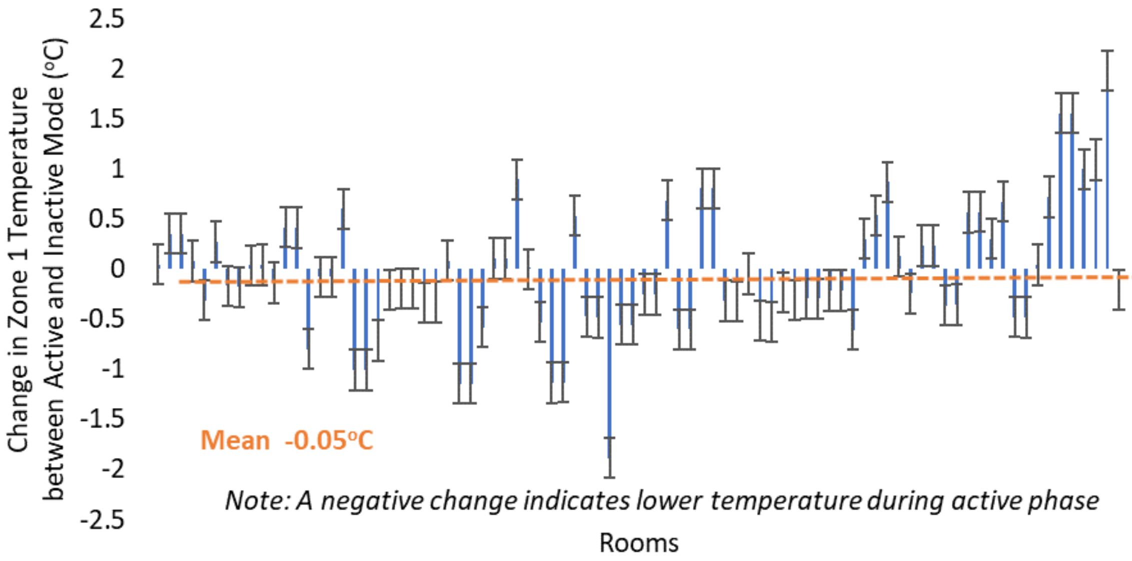
The difference in number of locations between the Monnit and Redbot devices is understood to be due to multiple radiators existing within some rooms with Radbots installed. By comparison, only a single Monnit sensor was installed in a room. Additional Monnit sensors were also placed in the hallway or close to the thermostat in houses which didn't have a Radbot installed in that area.

The Monnit results (Appendix A.5) showed a mean change in internal temperature of **0.05°C decrease** in Zone 1 and **0.20°C decrease** in Zone 2 when in smart mode compared to when they were inactive (± 0.2°C). There was a **0.16°C decrease** in internal temperature for active periods compared to inactive periods across all zones. The mean change in temperature observed is very small, and is of the same order of magnitude as the accuracy of the sensors used.

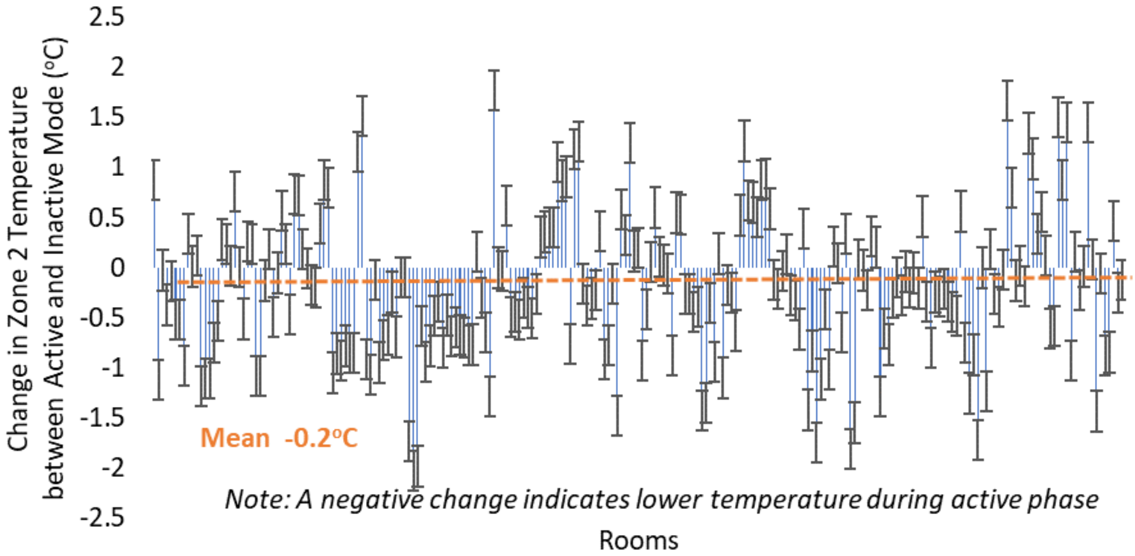
Overall, the spread of observed change across the sample was from a **2.01°C decrease** to a **1.98°C increase** in internal temperature (± 0.2°C, within 2σ). Within that spread, there was significant variation in the changes in temperature across the sample. The temperature decreased in 64% of rooms when the Radbots were in active mode, and increased in 36%.



The mean change in temperature for rooms in zone 1 was extremely small, with a pretty even split between those with a higher temperature during active operation (43%) and those with a lower temperature (57%).

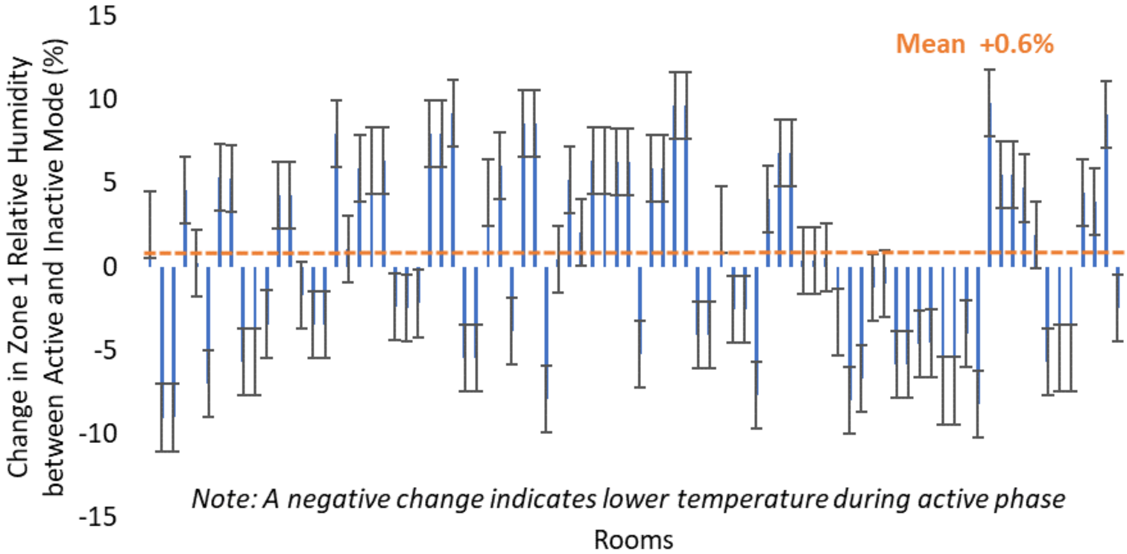


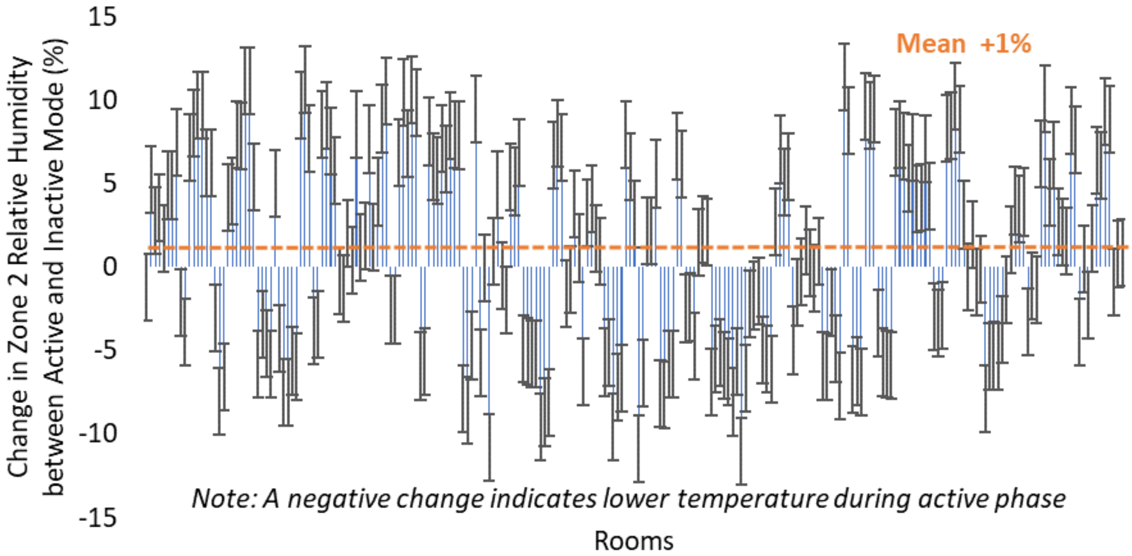
The mean temperature difference for zone 2 was slightly larger but still very small, a decrease of 0.2ºC in active mode. For zone 2 the temperature was lower in active mode for 65% of rooms.



The internal temperature is dependent on several variables beyond the effect of the Radbot mode, particularly the weather and set point temperature at the time of monitoring. Although these effects have been mitigated as far as possible by concentrating on temperature differences in the same houses for the same households over a significant period for both active and inactive modes, this may help explain the large variation in effect over the sample.

The mean change in relative humidity was found to be **0.55% increase** in zone 1 and **1.02% increase** in zone 2 (±2% between 0-80% RH). As for the temperature data, there was a variation in the effect across the sample, with 56% of zone 1 rooms having higher relative humidity when the Radbots were in active mode and 55% of zone 2 rooms. The observed mean differences were very small and within the uncertainty interval of the sensors.





Thermal Comfort

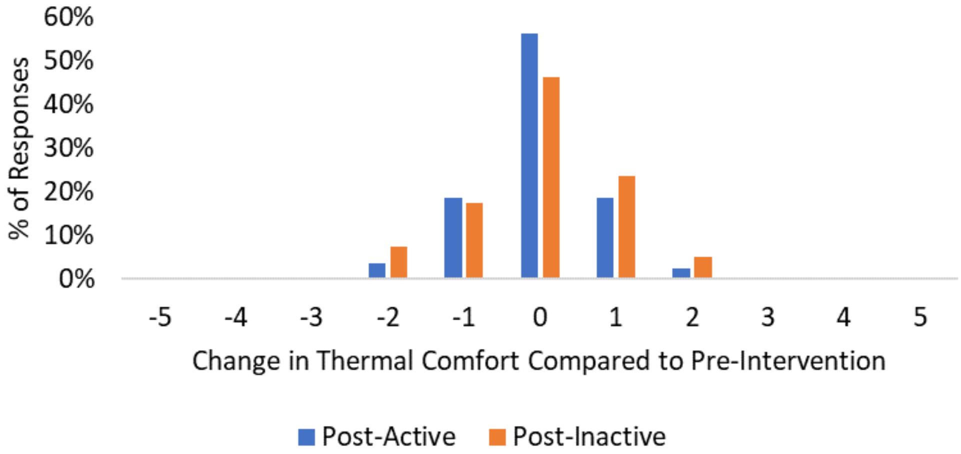
Thermal comfort surveys were carried out by Vestemi at the start, in the middle, and at the end of trial; in 97 properties with usable data the surveys were completed for all three stages. Survey results were only included in the analysis for the 105 properties for which there was usable temperature data from the Monnit sensors so that they cover the same sample as the rest of the analysis. At least one survey was completed in all properties, but in some houses not all three were completed.

As part of the survey residents were asked *"Generally, how would you rate your level of comfort in your home?"* with the available responses being Very Poor, Poor, Average, Good or Very Good. For this analysis those responses have been coded 1 (Very Poor) to 5 (Very Good).

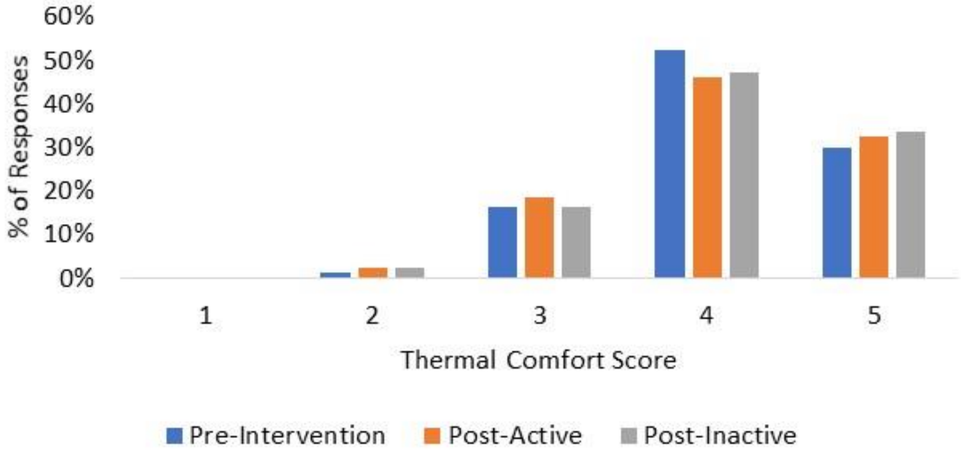
Each house has a period where the Radbot was active and inactive, but were not always in the same order (44% were active first and 56% inactive). There was no difference in the mean thermal comfort response in any of the three survey stages, indicating that the use of the Radbot did not affect the thermal comfort of the residents.

Survey Stage	Mean Thermal Comfort Response
Start of trial (survey 1)	4.1
After Radbot inactive period (survey 2 or 3)	4.1
After Radbot active period (survey 2 or 3)	4.1

Although the mean response was the same at each phase, there were some respondents who reported a change in thermal comfort between the surveys conducted after the active and inactive phases compared to their thermal comfort prior to the intervention. These were approximately evenly matched between people who reported higher and lower thermal comfort, with a maximum difference of 2 points on the 1-5 scale.



In general, the thermal comfort of the respondents was quite high, with the vast majority (around 80%) reporting a thermal comfort of either 4 or 5 out of 5 in each of the three surveys.



In some cases, there was not very good alignment between the date on which the survey was carried out and the date on which the Radbot was switched between active and inactive mode. Despite these issues it seems clear that there was very little change in the residents' reported thermal comfort throughout the survey, regardless of whether the Radbot was active or not. This is unsurprising given that there was a very small change in the internal temperature when the Radbot was active or inactive.

For a mean decrease of only 0.16°C (all zones), any change in the perceived thermal comfort of occupants would almost certainly be as a result of external factors such as: solar gains, wind conditions (draughts) and other external weather conditions, rather than as a direct result of the temperature change.

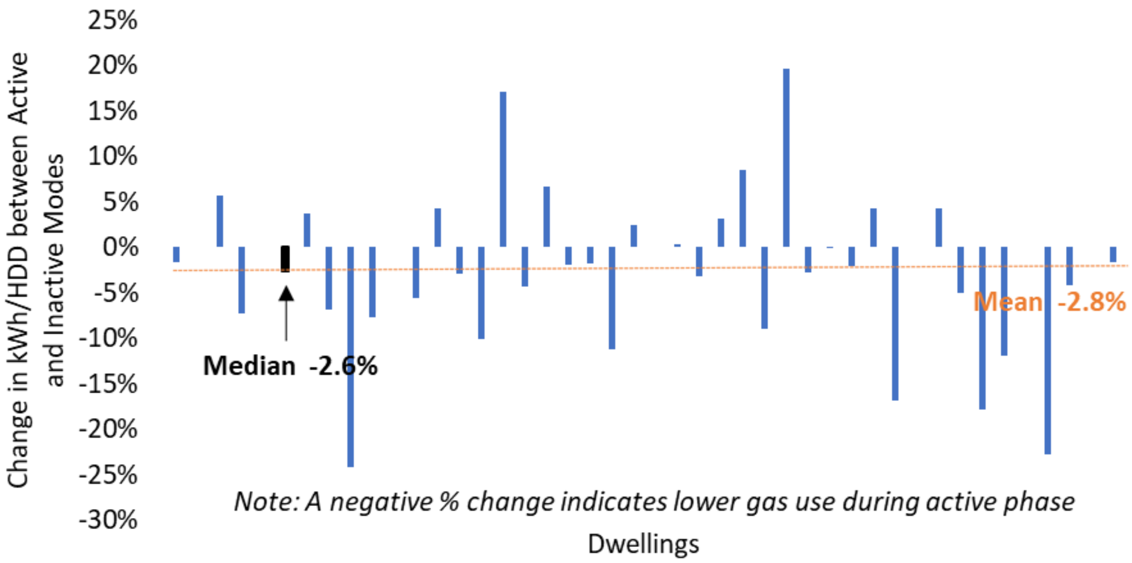
Gas Consumption

Gas data was filtered by matching properties with Monnit temperature sensors along with average daily consumption being above a baseline of 10 kWh/day ensuring that space heating was in use. Once filtered, there are a total of 37 properties with usable gas consumption data.

Heating degree days (HDD) were calculated for each day based on external temperature readings from a nearby weather station and using a base temperature of 15.5°C. It should be noted that there is likely to be significant uncertainty in the HDD figures for reasons explained in more detail in the Limitation of the Analysis section.

For the 37 properties, the mean change in gas consumption was found to be -0.20 kWh/HDD equivalent to a **2.8% decrease** in gas use (Appendix A.6). With a spread of change of -1.87 to +1.93 kWh/HDD (within 2σ). Gas use was lower with the Radbots in smart mode for 25 of 37 properties, and higher for 12. The median change in gas consumption was very similar to the mean, a 2.6% decrease.

Gas consumption data was collected either directly from the service meter in the case of smart meters, or from secondary optical meter readers and pulse loggers connected to a service meter. Gas meters have a statutory limit for accuracy of ±2%[3], which give an estimate of the uncertainty of the measurements taken. The measurement uncertainty is of a similar magnitude to the size of the observed saving, although the metric considered is the change in gas consumption measured by the same meter. It is likely that the precision of the gas meter measurements is higher than the limits for absolute accuracy, and hence the uncertainty in the change in gas consumption is lower than for the absolute consumption. It's not possible to calculate this though as the specific model of gas meter was not noted for each dwelling.



For these 37 properties a paired sample t-test has been used to test if the difference in sample means is statistically significant (i.e. to disprove the hypothesis that there was no difference between pre- and post-retrofit performance). At a 95% significance level, there is a statistically significant difference in the means for the two datasets with a p-value of 0.04 (sample t-statistic 2.12>2.03, which is the critical value for the sample).

It was possible to obtain a sub-sample of 13 properties for which the floor area is also known. This resulted in a mean change per square metre of floor area of **4.2% decrease** when Radbot was in smart mode**.** Though it should be noted the floor areas provided to BTS are rounded to nearest $10m^2$ and is of unknown accuracy.

With the data available to BTS about the methods and equipment used to collect gas consumption data it is not possible to accurately compute the uncertainty in gas consumption data. As a guide, the uncertainty in gas service meters is mandated to be less than +-3.5% but the uncertainty in recording the changes in the service meter readings by the project's monitoring equipment is unknown. Further uncertainty will be introduced to the compound statistics when gas consumption is normalised by HDD and floor area. Although the statistical significance of the sample addresses this somewhat, we are unable to report an overall uncertainty for the gas consumption savings reported.

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[3] The Gas (Meters) Regulations 1983. https://www.legislation.gov.uk/uksi/1983/684/contents/made

Other notable points

Weather Stations

BTS have calculated degree days for the same weather stations that Vestemi used in their original report. As BTS only have access to partial postcodes (outcodes) for each property, the straight line distance was computed from each weather station to the geographical centre of the postcode area represented by the outcode. For each unique outcode, the minimum distance was found to be 1.6 miles in the case of PL1 postcode properties (Plymouth) and the maximum distance was 34 miles for GL11 postcode properties (Dursley, Gloucester).

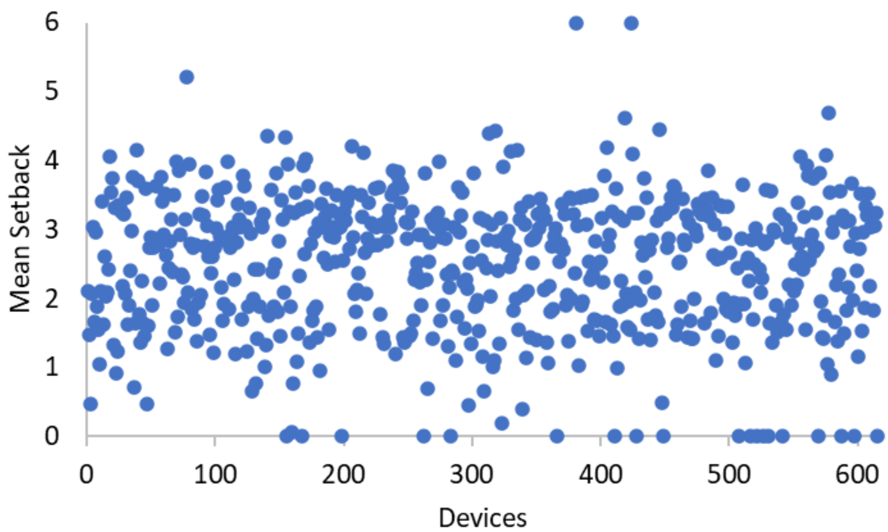
Overall, the mean distance from the postcode area to the weather station used for calculating degree days was found to be 15 miles (Appendix A.8).

Other Performance Metrics

As well as the temperature and relative humidity data already analysed, the Radbots provide a number of other metrics on their performance.

At each time interval the Radbot sends the current battery Voltage, which can be used to analyse how many of the batteries ran out over the monitoring period. Each Radbot uses 2AA batteries, each nominally providing 1.5V. The minimum operating Voltage for the Radbots is not known, but typically for an AA battery is around 1.2V. Of 528 Radbots for which there is Voltage data, 29 (5%) reported a minimum Voltage lower than 2.4V (2x 1.2V) which gives an indication of the number which will have been at risk of battery failure during the monitoring period.

The Radbot also reports the 'set-back' at each time interval, this is a dimensionless number between 0-6 with 6 being the maximum set-back for the device. There was a large range in the mean average setback setting with the Radbot in smart mode across the 525 devices for which there was data, with a range of 0 (for 15 devices, 2.9%) to 6 (for 2 devices, 0.4%) and a median of 2.7. The mean average setback setting for a particular device encompasses both the amount of time that it is applying some setback, and also the size of setback which has been applied.



The vast majority of Radbots (97.1%) did apply a setback in smart mode, which would reduce the internal temperature compared to a standard TRV, with the majority applying a setback around 50% or lower of the highest possible setting.

The Radbots also provide an estimate of the likelihood of the room being occupied at each time step, ranging from 0-3 where 0 means definitely unoccupied and 3 definitely occupied. The mean and median reported mean occupancy level were both 1.1, with a rather low standard deviation of 0.1. These reported occupancy levels indicate that most rooms were regularly used even if predominantly unoccupied, which may account for there being few rooms with setback levels greater than 4.

Limitations of the Analysis

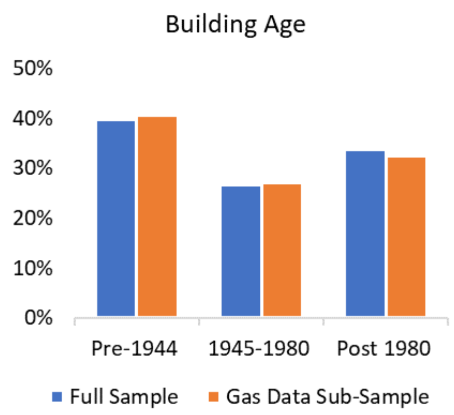
Data Collection

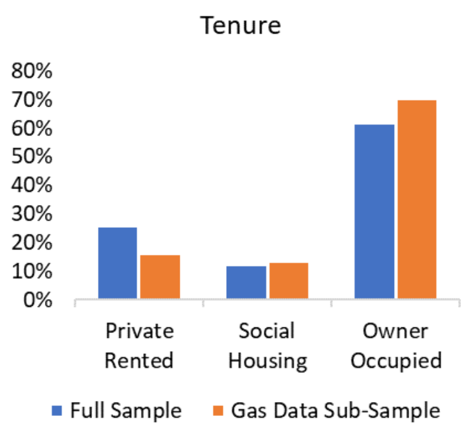
Significant issues were encountered with data collection, in particular with collecting gas consumption data, which reduced the available sample for analysis. There were many cases where optical meter readers and pulse loggers did not reliably measure gas consumption (24 of 74 installations), as smart meter data becomes available for more houses it's likely that this monitoring will become easier but at this time still represents a significant challenge within a reasonable equipment budget. Floor area was also not routinely measured on site which limited the options for normalising gas use by building dimensions.

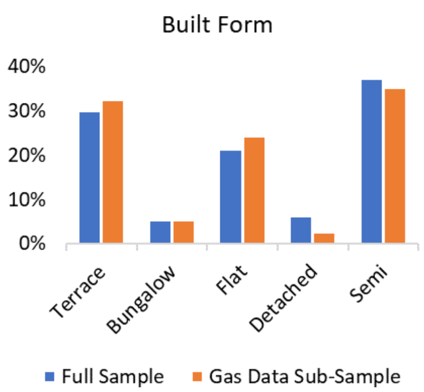
Energy Data

Limited gas data consumption data was collected, and no data was collected to disaggregate total gas consumption into that for space heating, hot water production and cooking. As Radbot only affects the space heating component of total gas consumption data it would have been possible to carry out more focussed analysis had the disaggregated data been available, this would have added significant extra cost and disruption, however, requiring heat metering within home's heating systems. There was also no monitoring of electricity consumption data which could have been used to help better correct for internal gains from appliance use.

The reduced sample of 37 buildings for which gas data was successfully collected has a very similar profile of building ages, built forms and tenure to the full dataset. Fortunately, therefore, this randomly applied reduction to the sample did not create a bias to any particular building type.







Use of Heating Degree Days for Weather Normalisation
Heating Degree Days provide a relatively simple way to correct for the effect of external temperature, i.e., that more energy consumption for heating is likely when the external temperature is lower. They do have several limitations, however, including:

- No compensation for other weather effects such as heat gains from the sun or cooling and extra air infiltration caused by high wind speeds
- A standard base-temperature of 15.5ºC is used for all buildings (this is the external temperature below which it is assumed that heating is provided), not accounting for differences in their thermal performance
- No compensation for different heating behaviours and preferences
- No compensation for different levels of internal gains from occupancy or electricity use which would affect the base-temperature
- When calculating HDD it is assumed that heating is constant above the base-temperature, but in use intermittent heating profiles are common.

Lack of Occupancy Data
Limited data was collected on the occupancy profiles in the houses studied, as Radbot is designed to save energy use by preventing unnecessary heating of unoccupied rooms the occupancy profile clearly has a significant impact on the energy savings. To mitigate these issues as much as possible, the data analysis focussed on differences in temperature, gas consumption and thermal comfort for the same home and household, which should help to reduce the effect of these unknown variables to some extent. The comparisons were also carried out over a relatively large sample of homes, but the sample was not selected to be statistically representative of any particular occupancy profile or building type.

COVID-19
The final month of the monitoring for the project coincided with the start of the first COVID-19 lockdown restrictions in the UK. This disrupted final data collection and also is very likely to have affected occupancy patterns within the household, in particular making it more likely that the house was occupied which may have reduced the opportunity for the Radbot devices to provide energy savings.

Conclusion

Vestimi Radbot sought to deliver a low-cost Demonstration Action trial across 125 homes. Although equipment was installed in 125 properties, issues with data collection and households withdrawing from the project reduced the that sample down to 105 with temperature monitoring and 37 with half hourly gas consumption monitoring (where the device operated in both smart and manual emulation mode, each for at least 21 days in winter). The properties in the sample provided a good representation of building types, tenures, ages and locations across England and Wales.

Data analysis has been carried out to determine the difference in internal temperature, relative humidity and gas consumption from Radbot operating in smart mode by looking at the average changes on a property by property basis. This comparison helps to mitigate the impact that changes in households and buildings could have on the changes in conditions, by controlling these to be as similar as possible during the monitoring in Radbot smart mode smart and manual modes.

There was a mean change in internal temperature of **0.16°C decrease** (all zones), split by **0.05°C decrease** in Zone 1 (main living room) and **0.20°C decrease** in Zone 2 (all spaces other than main living room). This was across 105 properties, split by 84 locations in Zone 1 and 229 in Zone 2. The spread of observed change across this same sample was from a 2.01°C decrease to a 1.98°C increase in internal temperature. The mean change in internal temperature was small and similar in magnitude to the accuracy of the sensors used. As for the relative humidity, the mean change in was found to be small, with a **0.55% increase** in Zone 1 and **1.02% increase** in Zone 2. The change in average relative humidity across the sample is less than the uncertainty of the sensors used.

After processing, there were 37 properties where the heating system was known to be active and for which sufficiently granular gas data was available. Here, the mean change in gas consumption was found to be a decrease of 0.20 kWh/HDD equivalent to a **2.8% decrease** in gas use (Appendix A.6). With a spread of change of -1.87 to +1.93 kWh/HDD. Of these, it was possible to obtain a sub-sample of 13 properties for which the floor area was known as well, which resulted in a mean change per square metre of floor area of **4.2% decrease** when Radbot was in smart mode**.**

With respect to the sample size and its statistical significance, temperature analysis has been reported for 105 homes (84%) and 37 of these have accompanying gas data (30%). Of this gas sub sample, there was a statistically significant difference in the mean gas consumption with the Radbot in smart and manual modes (p-value of 0.04). Despite the reduced sample size, therefore, the sample is sufficient to prove the hypothesis that the properties had lower gas consumption with the Radbots in smart mode compared to manual mode. The observed saving of 2.8%, however, is significantly lower than the expected saving of around 8%.

The observed mean difference in gas consumption is rather small, and only slightly larger than the mandated accuracy of a gas service meter of ±2%. While gas consumption per HDD day was lower on average with the Radbots in smart mode, there were also 12 (of 37, 32%) properties where gas consumption per HDD was higher. There are lots of reasons beyond the performance of the Radbots why gas consumption could change, such as changes in heating and hot water use behaviour or solar gains, so the mean saving will not be achieved in every case. The reduction in mean gas use is consistent with an observed small reduction in internal temperature which further supports that the Radbots did reduce overall heating use, with no observed difference in thermal comfort and with only a very small impact on the internal relative humidity (which is as expected given the small change in internal temperature).

The data shows a mean average reduction in gas use of 2.8% as a result of Radbot being in smart mode. If applied to the Ofgem medium Typical Domestic Consumption Value of 12,000kWh/year this would result in a saving of 336kWh/year. At the per unit gas price used in SAP9.92, 3.48p/kWh, this reduction in gas consumption relates to a cost saving of **£11.69/year**. Based on a measure lifespan of 12 years, this equates to a lifetime fuel bill saving of **£140.28** for a whole home installation. These calculations are based on a statistically significant observed difference in gas consumption when the Radbots were in smart mode, but care should be taken in their interpretation as the mean change in gas consumption was quite small and of the same order of magnitude to the uncertainty in a single measurement of gas consumption.

There were also a significant number of houses where the gas consumption was higher with the Radbots in smart mode than when they were in manual mode, the overall range in observed lifetime savings was £1,206 to -£982 (i.e., for one property the gas use and therefore cost was 20% higher with the Radbot in smart mode, resulting in additional costs over the measurement lifetime of £982). Given the number of uncontrolled variables in this study, the most reliable estimate of the saving is based on the mean gas consumption saving, resulting in a predicted lifetime fuel bill saving of £140.28.

Appendix A.1 - Radbot and Monnit Sensor Results in Smart Mode

	Radbot Smart Mode				
	No. of Properties	**No. of Locations**	**Days per Location**	**Mean Value**	**Unit**
Radbot Device		(Radiators)			
Mean Temperature Zone 1	71	105	126	19.57	°C
Mean Temperature Zone 2	108	346	120	18.86	°C
Mean Temperature All Zones	110	451	121	19.03	°C
Mean RH Zone 1	71	105	126	55.14	%
Mean RH Zone 2	108	346	120	57.36	%
Mean RH All Zones	110	451	121	56.84	%
Monnit Sensors (in Radbot room)		(Rooms)			
Mean Temperature Zone 1	68	99	128	19.73	°C
Mean Temperature Zone 2	110	279	127	18.73	°C
Mean Temperature All Zones	112	378	128	18.99	°C
Mean RH Zone 1	68	99	128	55.46	%
Mean RH Zone 2	110	279	127	56.65	%
Mean RH All Zones	112	378	128	56.34	%

Appendix A.2 - Gas Consumption Results in Smart Mode

	Radbot Smart Mode				
	No. of Properties	**No. of Locations**	**Days per Location**	**Mean Value**	**Unit**
Monnit Sensors (whole house)		(Rooms)			
Mean Temperature Zone 1	86	118	163	19.76	°C
Mean Temperature Zone 2	112	454	170	19.04	°C
Mean Temperature All Zones	112	572	168	19.19	°C
Mean RH Zone 1	86	118	163	54.80	%
Mean RH Zone 2	112	454	170	55.81	%
Mean RH All Zones	112	572	168	55.60	%

Gas Consumption			(per Property)		
By Degree Days	44		65	7.23	kWh/HDD
By Degree Days and Floor Area	15		69	0.08	kWh/HDD/m²

Appendix A.3 - Radbot and Monnit Sensor Results in Manual Mode

	Radbot Manual Mode				
	No. of Properties	**No. of Locations**	**Days per Location**	**Mean Value**	**Unit**
Radbot Device		(Radiators)			
Mean Temperature Zone 1	68	99	84	20.42	°C
Mean Temperature Zone 2	104	329	91	19.65	°C
Mean Temperature All Zones	106	428	90	19.83	°C
Mean RH Zone 1	68	99	84	52.20	%
Mean RH Zone 2	104	329	91	54.13	%
Mean RH All Zones	106	428	90	53.68	%
Monnit Sensors (in Radbot room)		(Rooms)			
Mean Temperature Zone 1	65	93	88	20.07	°C
Mean Temperature Zone 2	106	262	100	19.20	°C
Mean Temperature All Zones	109	355	97	19.43	°C
Mean RH Zone 1	65	93	88	53.51	%
Mean RH Zone 2	106	262	100	55.60	%
Mean RH All Zones	109	355	97	55.05	%

Appendix A.4 - Gas Consumption Results in Manual Mode

	Radbot Manual Mode				
	No. of Properties	**No. of Locations**	**Days per Location**	**Mean Value**	**Unit**
Monnit Sensors (whole house)		(Rooms)			
Mean Temperature Zone 1	86	115	107	20.07	°C
Mean Temperature Zone 2	109	429	114	19.46	°C
Mean Temperature All Zones	109	544	112	19.59	°C
Mean RH Zone 1	86	115	107	53.57	%
Mean RH Zone 2	109	429	114	54.77	%
Mean RH All Zones	109	544	112	54.52	%
Gas Consumption			(per Property)		
By Degree Days	42		66	7.65	kWh/HDD
By Degree Days and Floor Area	14		64	0.09	kWh/HDD/m²

Appendix A.5 - Radbot and Monnit Sensor Change (Smart vs Manual mode)

	Instances with both Radbot Smart and Manual modes (values within 2 standard deviations of mean)						
	No. of Properties	**No. of Locations**	**Min Change**	**Max Change**	**Mean Change**	**Unit**	**% Change**
Radbot Device		(Radiators)					
Mean Temperature Zone 1	64	90	-2.74	1.63	-0.51	°C	-2.3%
Mean Temperature Zone 2	100	287	-3.17	2.22	-0.58	°C	-2.7%
Mean Temperature All Zones	103	378	-3.17	2.22	-0.57	°C	-2.7%
Mean RH Zone 1	64	90	-11.78	12.27	1.85	%	4.7%
Mean RH Zone 2	100	286	-11.12	13.66	2.09	%	4.6%
Mean RH All Zones	103	377	-13.28	13.66	1.99	%	4.5%
Monnit Sensors (in Radbot room)		(Rooms)					
Mean Temperature Zone 1	61	84	-1.88	1.98	-0.05	°C	-0.1%
Mean Temperature Zone 2	102	229	-2.02	1.77	-0.20	°C	-0.9%
Mean Temperature All Zones	105	314	-2.01	1.98	-0.16	°C	-0.7%
Mean RH Zone 1	61	84	-9.03	9.81	0.55	%	1.5%
Mean RH Zone 2	102	229	-11.06	11.37	1.02	%	2.2%
Mean RH All Zones	105	314	-11.06	11.17	0.92	%	2.0%

Appendix A.6 - Gas Consumption Change (Smart vs Manual mode)

	Instances with both Radbot Smart and Manual modes (values within 2 standard deviations of mean)						
	No. of Properties	**No. of Locations**	**Min Change**	**Max Change**	**Mean Change**	**Unit**	**% Change**
Monnit Sensors (whole house)		(Rooms)					
Mean Temperature Zone 1	81	104	-2.01	2.15	-0.12	°C	-0.5%
Mean Temperature Zone 2	105	390	-2.28	2.25	-0.12	°C	-0.5%
Mean Temperature All Zones	105	495	-2.31	2.25	-0.13	°C	-0.6%
Mean RH Zone 1	81	104	-9.13	9.65	0.16	%	0.6%
Mean RH Zone 2	105	390	-10.41	10.60	0.50	%	1.2%
Mean RH All Zones	105	495	-10.41	10.34	0.45	%	1.1%
Gas Consumption							
By Degree Days	37		-1.87	1.93	-0.20	kWh/HDD	-2.8%
By Degree Days and Floor Area	13		-0.017	0.006	-0.003	kWh/HDD/m²	-4.2%

Appendix A.7 - Radbot vs Monnit Temperatures

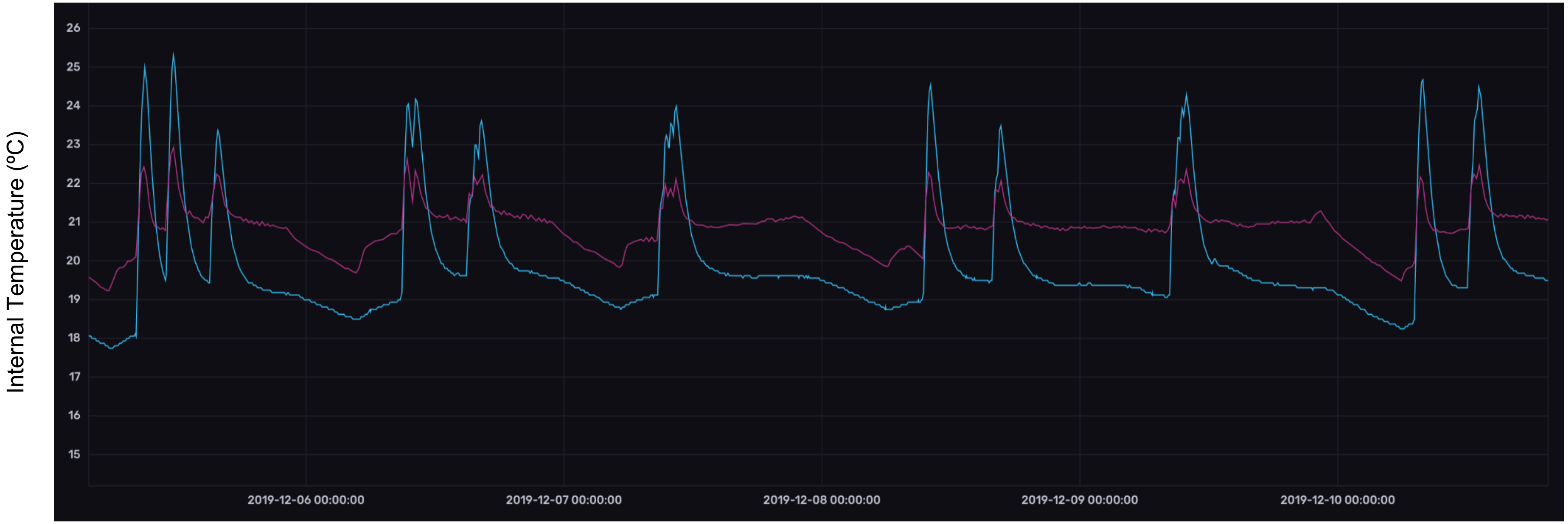


Chart of Radbot vs Monnit temperatures from Property 1CR

Radbot internal temperature

Monnit internal temperature