SmartHTC Validation Report

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Executive Summary

SmartHTC is a non-invasive method to measure the thermal performance of buildings, this report describes a thorough validation of the method carried out over two-years and including field trials in more than 200 buildings and testing in the Energy House laboratory at the University of Salford.

The inputs for SmartHTC are a very basic building survey and internal temperature and energy consumption monitoring for a 21-day period during winter (October-March inclusive, in the UK). While the monitoring is carried out the building may be occupied as normal. Half-hourly energy data can be provided from the smart meter, or via standard meter readings at the start and end of the temperature monitoring period if smart meter data is not available.

The output is a measurement of the overall thermal performance of the building, defined by its Heat Transfer Coefficient (HTC). The HTC is a measure of the rate of heat loss per degree temperature difference between inside and out, all models of thermal performance or energy consumption in buildings are based upon this measure of thermal performance.

The validation process included 41 direct comparisons with a baseline measurement by a co-heating test, and more than 300 SmartHTC measurements in total. The co-heating test has been the most common method to measure the HTC of buildings, but has been limited to specialist applications because of its cost and invasiveness, with the test requiring a building to be vacated for two weeks and costing several thousand Pounds. The highlights of the validation are:

- 41 comparisons were made with a baseline co-heating test measurement, in 40 of which the results agreed to within the combined uncertainty margins. The one comparison that didn't agree was part of a 3rd party review and the co-heat result is not yet available to BTS.
- The comparisons with baseline measurements included a range of building types, including flats and mid-terraced houses.
- SmartHTC was accurate in three newly built flats with Passive House thermal performance.
- SmartHTC results were highly repeatable, with a mean RPD of <1% for tests in the same building. SmartHTC and co-heat results agreed in 99% of valid 21-day subsamples (704 total).
- The mean difference between SmartHTC results with or without smart meter data was <1%, with a maximum difference of 6%.
- Where smart meter data was available the mean confidence interval in the SmartHTC measurement was ±17%, without smart meter data the mean confidence interval was ±24%.
- SmartHTC results can be successfully calculated with a single internal temperature measurement. This is at the expense of some accuracy, however, with the average confidence interval around 5% larger than when using multiple sensors.

The validation showed that SmartHTC produced accurate and repeatable measurements in a wide range of building types and different weather conditions. The cost and invasiveness of previous HTC measurement methods have limited the total number of HTC measurements ever completed to a few hundred ever, this exercise alone therefore demonstrates an unprecedented level of scalability.

At the heart of SmartHTC is an algorithm which is hosted in the cloud and accessed via APIs. This enables automated integration and almost instant HTC calculations; this means that smart technology manufacturers that are already collecting the necessary input data could provide HTC measurements at a tiny fee compared to traditional methods costing thousands of pounds per property. The performance gap is a well-known and concerning phenomenon which has previously lacked proper quantification, SmartHTC provides the capability to change that.

1. Introduction

This report describes the validation of SmartHTC, a method to measure the thermal performance of buildings as defined by their Heat Transfer Coefficient (HTC). The validation has been carried out over two winters, and includes:

- 40 successful demonstrations of SmartHTC vs. a baseline measurement by a co-heating test, carried out in a range of building types and performance levels.
- High levels of repeatability in each test, with a mean RPD of less than 4% across repeated measurements in the same dwelling.
- Successful demonstrations of SmartHTC in the Energy House research laboratory at the University of Salford across a range of internal and external conditions
- Non-invasive and cost-effective testing in more than 200 houses.

SmartHTC requires monitored internal temperature and energy use data collected over a period of 3 weeks during winter, along with a short building survey. The monitoring can be carried out while the building is occupied as normal and the installation process can generally be completed in around half an hour, providing a test that is very non-invasive as well as low cost in terms of hardware requirements. During the monitoring there must be a significant average daily temperature difference (>7°C) between inside and out. In practise the temperature difference between inside and out is unlikely to be lower than this in a heated house during winter in the UK, defined as October-March inclusive.

At the core of SmartHTC is a cloud-based algorithm which processes this data and accounts for the effects of occupants and variations in weather to determine just the thermal performance of the dwelling. The HTC measurement includes all heat transfer through building, including through the fabric (walls, floor, windows, doors, roof), by thermal bridging and by air movement (both infiltration and ventilation).

In being cloud-hosted and accessed via APIs, the system has been designed so that SmartHTC is flexible and technology agnostic. This means that any sensors can be used to collect the monitoring data, and that communications with the SmartHTC algorithm are automatable through the APIs; enabling easy integration with other systems. SmartHTC can then be delivered in multiple ways, either in a traditional method of an assessor visiting a home and collecting information or by integration with systems already collecting the required data such as smart thermostats or smart meter devices. BTS have developed a simple user interface accessed through a web browser (smart-htc.com), so that the algorithm is also accessible for those without the ability to interface directly with the APIs.

Measurement of the thermal performance of buildings is essential to understand how they operate in-situ. Previous measurement studies have shown that the actual thermal performance of buildings typically varies widely from predicted values, with the largest studies showing average variations of 20%[1] and 60%[2] across their samples and variations of more than 100% for an individual dwelling in each case. Variations in thermal performance will obviously cause greater than expected energy use but will also have wide reaching further unintended consequences such as fuel poverty, poor thermal comfort, inappropriate ventilation, condensation and mould growth.

[1] Gupta, R., Kotopouleas, A., 2018. Magnitude and extent of building fabric thermal performance gap in UK low energy housing. Available at: https://www.sciencedirect.com/science/article/pii/S0306261918304343#b0240.
[2] Johnston, D., and Miles-Shenton, D., and Farmer, D., (2015) Quantifying the domestic building fabric 'performance gap'. Building Services Engineering Research and Technology, 36 (5). 614 - 627

The problem up to this point has been that the standard method for measuring the thermal performance of buildings, the co-heating test, is too expensive and invasive for widespread testing. The co-heating test has been a vital research tool to identify the existence of the performance gap, but the test requires that a dwelling be vacated for a period of 2 weeks and typically costs upwards of £4,000 per property. This has limited the total number of performance measurements to only a few hundred tests ever carried out. By contrast, the cost of a SmartHTC measurement ranges from as little as £1 for high volume integration with an existing system to a few hundred pounds if including visits to the property to carry out the survey, install and remove monitoring equipment.

Due to the previous cost and invasiveness of testing, almost all regulation around the energy performance of buildings is based on predicted rather than measured performance. This is particularly striking as in the UK buildings are the biggest consumer of energy, with 20% of total energy use used for space heating alone[3]. Given the scale of the performance gap and energy use and carbon emissions for heating buildings, the huge value of and requirement for building performance measurement is clear. In-situ measurement would enable quality assurance of new build and retrofit works, better targeting of works to alleviate of fuel poverty and unhealthy living circumstances, better targeting of energy improvement measures and quantitative assessment of demand-side policy measures.

At the time of writing in December 2020 there are clear signs that regulations in the UK are moving towards in-situ measurement. The 2020 review of Parts F and L of the UK Building Regulations the performance gap featured prominently, with nine separate mentions. The 2020 Energy Performance Certificate (EPC) Action Plan[4] goes further, setting out a schedule to consider the inclusion of HTC measurement in EPCs by the end of 2021 and looking forwards to the next anticipated EPC and Building Regulations review in 2025. In-situ performance measurement is already incentivised through the Energy Company Obligation (ECO), where measuring the actual performance of buildings that have been retrofitted gains additional credit towards an energy company's obligation. SmartHTC was used successfully in this role in the 2018/19 winter and is continuing to do so. CIBSE's TM61 provides excellent further information on this topic[5] and provides a further demonstration of growing appreciation of the importance of in-situ measurement.

This report describes in great depth more than two years of testing designed to demonstrate the accuracy and repeatability of SmartHTC. It provides more detail than the casual reader requires, but has been produced to allow a thorough critical review of the validation process. BTS are absolutely committed to making performance measurement mainstream as what you don't measure you can't manage. Space heating in the UK accounts for at least 20% of all carbon equivalent emissions and at present we can't even be certain why. It's clear therefore that this is something that *needs* to be better managed and understood.

The development and validation of SmartHTC has been enabled by a grant from the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) under the Building Thermal Efficiency Innovation grant scheme. Further funding and field trialling were provided by participation in the BEIS-funded Smart Meter Enabled Thermal Efficiency Rating (SMETER) project.

[3] Data from Digest of UK Energy Statistics 2018 and 2013 UK Housing Fact File
[4] The EPC Action Plan is available here:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/922660/EPC_Action_Plan.pdf
[5] CIBSE TM61: Operational performance of buildings (2020) is available here:
https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000I0NKeQAN

1.1. SmartHTC

SmartHTC is a technology agnostic method to measure the thermal performance of buildings. It requires a small amount of information about a property, and monitored data for internal temperature and energy consumption collected for at least three weeks during winter.

The output of SmartHTC is a measurement of the Heat Transfer Coefficient (HTC) as well as the confidence interval of the measurement. This Confidence Interval (CI) may also be referred to as the uncertainty interval and is dependent on the input data for each SmartHTC calculation.

There is a small set of required information about the building for SmartHTC, and some optional additional information (Table 1). The required information has been designed such that it is all available from an EPC certificate. If the optional additional information is provided it will increase the accuracy of the HTC measurement, and decrease the accompanying confidence interval. The effect of including each piece of additional information on the HTC and CI is different for each calculation, but will rarely be larger than 5% (see section 6.3 for more detail).

Required Information	Optional Additional Information
Floor area	Built form
Location	Party wall area
	Attachment
	Boiler winter seasonal efficiency
	Window dimensions and orientation
	Glazing type, overshading and frame type
	Number of occupants

Table 1: List of required and optional additional building information.

As for the building information, there are required and optional data inputs for SmartHTC (Table 2). All data must be provided to SmartHTC in half-hourly increments, with the exception of energy meter readings. Where smart meter data is not available, it is still possible to use SmartHTC by providing service meter readings taken at the start and end of the internal temperature monitoring period. This is an important provision at this time as smart meter data is not yet available in all properties.

Required Data	Optional Additional Data
Energy consumption at the service meter	Internal temperatures in up to 10 locations
Internal temperature in one central location	Internal relative humidity in up to 10 locations
	Smart meter data
	Disaggregated heat input for space heating
	Disaggregated heat input for water heating
	Local external temperature
	Local global solar irradiance
	Metabolic gains
	Presence of occupants

Table 2: List of required and optional additional monitoring data.

The more data is provided the greater the accuracy of the HTC measurement and the smaller the confidence interval. There is more detail on the effect of providing additional data on the HTC and confidence interval in section 6. Providing more data, in particular smart meter data and more internal temperature measurement locations (particularly in larger buildings), can significantly reduce the size of the confidence interval. In some cases, the size of the confidence interval can be reduced by more than 25% by providing more data.

The SmartHTC calculator is cloud hosted and can be accessed in an automated fashion through APIs or using BTS' browser User Interface (UI). These provisions allow for direct integration with smart technology or existing systems, or simple drag and drop uploads, so that all customers are catered for. The SmartHTC user journey is described in Figure 1.

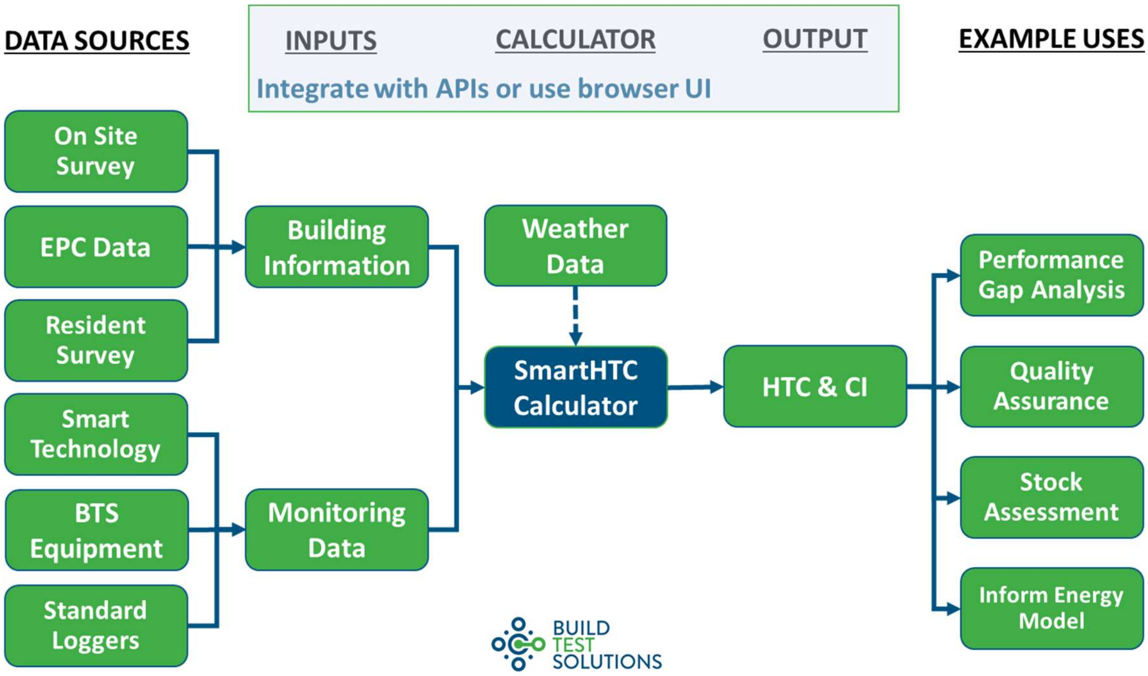

Figure 1: SmartHTC user journey.

1.2. The Heat Transfer Coefficient (HTC)

The HTC of a dwelling describes the total rate of heat transfer through the building fabric and by ventilation, with units of Watts per degrees temperature difference between inside and out. In winter, the HTC defines the rate of heat loss from the building and hence is critical to defining the energy requirement to maintain a comfortable internal temperature difference.

The predicted HTC of a dwelling is calculated in energy models in order to define the heat demand for a dwelling, this means that the measured HTC can be directly compared with the predicted HTC. The difference between the predicted and measured HTC is commonly referred to as the *performance gap*.

The HTC prediction in an energy model can be replaced with the measured value to calculate more accurate predictions of energy demand, cost and carbon equivalent emissions.

The HTC of a building is not normalised by any metric, so that a larger dwelling will have a larger HTC than a smaller dwelling of the same thermal performance. This can be useful to give an indication of the likely heating demand, but is not as useful to be able to compare the relative thermal performance of dwellings.

1.3. Heat Loss Parameter (HLP)

There are two obvious options for normalising an HTC value, dividing by floor area or total surface area. Normalising the HTC by dividing by floor area gives a good measure of the thermal performance per usable space in the building, and would include the important thermal benefits of efficient built form (reducing exposed surface area). Furthermore, floor area is readily available (from EPC data) for most properties in the UK, else it is easily measured.

Dividing by the total surface area of the building (as for air permeability) is an alternative that would give a more direct analysis of the thermal performance per unit area, but would not include the benefits of built form which are key to final building performance. A benefit of dividing by surface area is that the resultant metric would be equivalent to the average U-value (or R-value) for the whole dwelling, which is a more widely known metric.

SmartHTC utilises a HLP defined as the HTC divided by floor area. The floor area is the total usable floor area across all storeys, including everything within the heated space of the building[6].

1.3.1. What's a Good HLP?

BTS have proposed a simple scale to allow a quick interpretation of the thermal performance of a building based on the HLP (Figure 2).

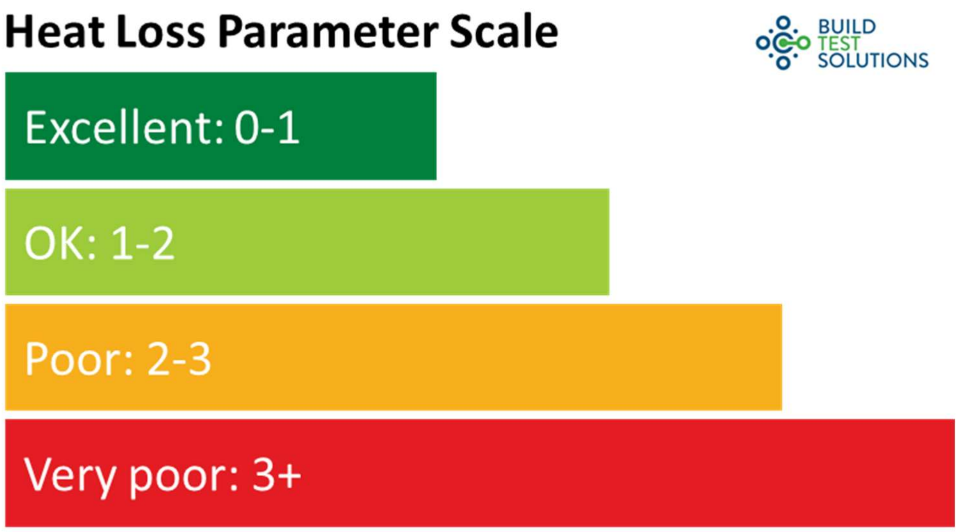

Figure 2: Heat Loss Parameter scale.

For reference, we can consider the HLP of a two-storey detached house with different levels of thermal performance. For simplicity of calculations in this example, the house is a 5x8x5m box.

EXAMPLE	ELEMENT	PERFORMANCE	HLP
EXISTING SOLID WALLED HOUSE	Solid walls (U-value)	1.6	
	Double glazed (U-value)	2.2	
	Solid floor (U-value)	0.6	**4.16**
	100mm loft insulation (U-value)	0.3	
	Not very airtight ($m^3/m^2.h@50Pa$)	12	
RETROFITTED SOLID WALLED HOUSE	Solid wall with 150mm EWI	0.23	
	Double glazed	2.2	
	Solid floor with 80mm insulation	0.28	**1.57**
	300mm loft insulation	0.14	
	Fair airtightness	6	
2016 BUILDING REGULATIONS PART L	Walls	0.3	**1.82**
	Windows and doors	2	

[6] A full definition of how to calculate the floor area can be found in the UK Standard Assessment Procedure (SAP), www.bregroup.com/sap/.

LIMITING FABRIC PERFORMANCE[7]	Floor	0.25	
	Roof	0.2	
	Airtightness	10	
FUTURE HOMES PART L CONSULTATION LIMITING VALUES	Walls	0.3	
	Windows and doors	2	
	Floor	0.25	**1.56**
	Roof	0.2	
	Airtightness	10	
PASSIVE HOUSE EXAMPLE[8]	Walls	0.13	
	Windows and doors	0.88	
	Floor	0.2	**0.93**
	Roof	0.14	
	Airtightness	0.6	

Table 3: Comparison between the HLP for the same building with a number of different fabric specifications.

1.4. Thermal Performance Measurement

Thermal performance measurement for dwellings has been carried out in small numbers for many years, with interest developing primarily after the oil crisis of the 1970s.

The most common method of thermal performance measurement up to this time has been the co-heating test. During a co-heating test a building is heated to an elevated internal temperature using electric heaters for a period of around 2 weeks, the building must be unoccupied during testing.

The co-heating test is based upon an assumed steady-state energy balance where the heat inputs to a dwelling are carefully measured to infer the rate of heat loss. In order to closely control the heat input, the building is unoccupied during the test and all normal heat sources are turned off replaced by thermostatically controlled electric heaters. The internal temperature is maintained at an elevated temperature, usually around 25°C, to ensure significant and measurable heat loss throughout. During the test the air is mixed using fans to ensure an even heat distribution around the building, so that each part of the building envelope is exposed to the same internal conditions. The test is carried out over an extended period in order to ensure that there is approximately net zero heat storage during the test, i.e. to ensure that the measurement is of the heat lost to outside rather than used to heat up the fabric of the dwelling.

The length and complexity of the co-heating test has limited the scale at which measurements can practically be carried out, with only a few hundred ever completed. The disruption limits realistic opportunities to test in occupied houses and the complexity drives costs into the £1000s. SmartHTC has been developed in response to these practical limitations to enable thermal performance measurement on a much greater scale.

1.5. The Performance Gap

The co-heating test has been an extremely valuable tool to improve knowledge of the performance of buildings in-situ. Studies using co-heating tests have shown that there is commonly a

[7] The limiting values given in Part L of the building regulations are the worst permissible performance levels for each element, to comply with the regulations it's likely that better fabric performance levels would be required, and hence result in a better HLP.

[8] Roughly based on the elemental performance from this project described on the Passive House Trust UK website, https://www.passivhaustrust.org.uk/UserFiles/File/UK%20PH%20Awards/2015/2015%20posters/UKPHAwardsPoster_Retrofit_Admirals%20Hard.pdf

'performance gap' whereby actual in-situ thermal performance is different, and typically worse, than predicted by an energy model.

In the two largest published studies measured thermal performance was 60% and 20% worse than predicted (Figure 3 and Figure 4). In each study there was a large distribution in the magnitudes of the performance gap between different buildings, ranging from some buildings that performed similarly or better than predicted to others where the measured HTC was more than double that predicted.

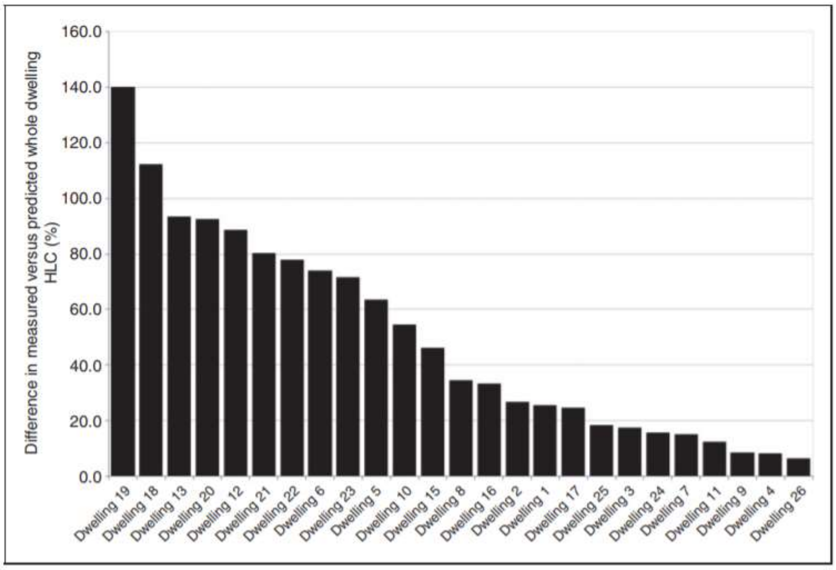

Figure 3: Chart showing the difference between measured and expected thermal performance (defined by the Heat Loss Coefficient, HLC, which is equivalent to the HTC), in this study the mean measured HLC was 60% higher (worse)[9].

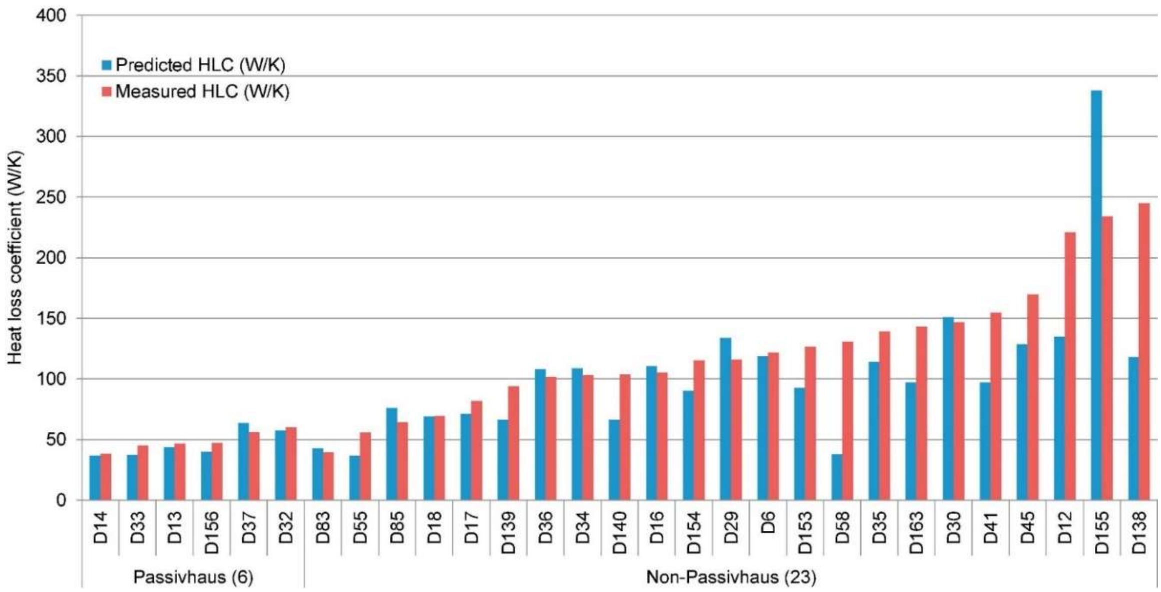

Figure 4: A second chart showing the difference between predicted and measured thermal performance, in this case the mean measured performance was 20% higher[10].

[9] Figure from: Johnston, D., and Miles-Shenton, D., and Farmer, D., (2015) Quantifying the domestic building fabric 'performance gap'. Building Services Engineering Research and Technology, 36 (5). 614 – 627.

[10] Figure from: Gupta, R., Kotopouleas, A., 2018. Magnitude and extent of building fabric thermal performance gap in UK low energy housing. Available at: https://www.sciencedirect.com/science/article/pii/S0306261918304343#b0240.

Variations in the thermal performance of buildings from design intent of this magnitude will dramatically alter the way that the building operates. There is a clear implication for energy demand and heating cost, but there could be wide ranging further unintended consequences such as poor thermal comfort, poor ventilation, condensation, mould growth or noise issues.

It's clear that given the prevalence and size of the performance gap observed it's necessary to carry out thermal performance measurements on a much larger scale to manage buildings in an informed manner. From a wider perspective this is important for two reasons; there are significant health implications to spending time in unhealthy environments, and heating buildings accounts for a large proportion of energy use and carbon equivalent emissions. Until measurement is more commonplace, the industry at large simply cannot expect to close feedback loops and address the causes and effects of design vs. as-built performance.

2. Validation Design

SmartHTC has been validated through field trials carried out over two consecutive winters (2018/19 and 19/20) and through a series of tests carried out under controlled conditions in the Energy House at the University of Salford. The testing was designed to provide a thorough test of the accuracy and repeatability of SmartHTC. Through the laboratory testing in the Energy House and the field trials three measures have been used to demonstrate SmartHTC:

- By comparison with a measured baseline. The best test of accuracy is by comparison with a measured baseline, the baseline will be measured using the industry-standard co-heating test. Co-heating tests are expensive and invasive, so this forms a subset of the wider field trial.
- Repeatability. By collecting data for a period of longer than three weeks several SmartHTC calculations can be carried out on the same property, the repeatability of these HTC measurements is a key metric in the success of SmartHTC.
- Comparison with a predicted baseline from the Standard Assessment Procedure. It is well established that actual performance varies significantly from predicted performance, so this comparison is of limited value, but it should at least highlight if the measurements is of the right order of magnitude. This comparison will also generate interesting insights into the performance gap.

2.1. Field Trial

Field trial comparisons with co-heating tests were gathered in two ways. 11 of the comparisons were carried out by BTS as part of an internal field trial, the method for carrying out those co-heating tests is described in section 2.1.2. A further 30 comparisons were carried out as part of the SMETER project, this testing was carried out by an independent consortium of universities and is described in section 2.3.

2.1.1. Co-heating Testing

Co-heating tests were carried out according to the method described by Leeds Beckett University[11]. 2kW fan heaters were thermostatically controlled to provide a constant internal temperature, while large 20-inch fans were used to mix the internal air and ensure a constant temperature throughout the space (Figure 5). The number of heaters used was adjusted depending on the size of the dwelling, with at least 1 set per large room.

[11] Available here: https://www.leedsbeckett.ac.uk/-/media/files/research/leeds-sustainability-institute/ing-method-for-whole-house-heat-loss/lsi_cebe_coheating_test_method_june2013.pdf

Figure 5: Example installations of thermostatically controlled heaters and air mixing fans.

The internal temperature was measured at mid-height in the centre of the room using a data logger with an internal thermocouple mounted on a tripod (Figure 5). Where possible the heat flux through party surfaces was measured in 2-3 locations using heat flux plates. (Figure 6).

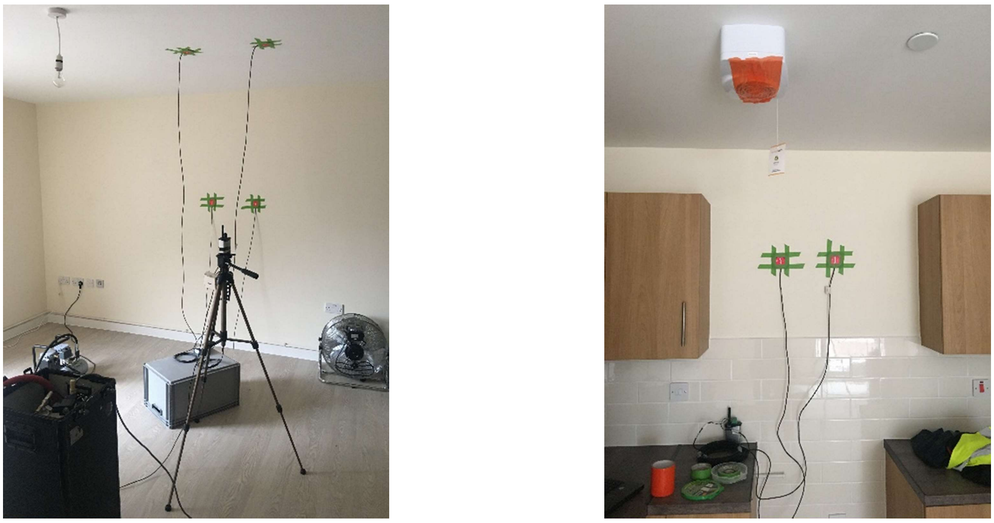

Figure 6: Heat flux plates in place on party surfaces in the top floor flat at FT262 and FT263.

Function	Equipment Set 1	Equipment Set 2
Internal temperature loggers	Tinytag Transit 2 Temperature Data Logger	Eltek GD10 Temperature Humidity Transmitter
External temperature logger	Tinytag Plus 2	N/A
Energy consumption measurement	Energenie MIHO004 Monitor Adapter Energenie MIHO006 Whole House Energy Monitor Energenie MIHO001 Gateway	Eltek GC62 pulse logger connected to Elster A100V 100a kWh meter
Heaters	Dimplex 2kW fan heater	Stanley 2kW fan heater

Temperature controller	Inkbird ITC-306T	TMS ABS3216LSSR Temperature Controller Box with RTD sensor
Fans	20” floor fan	240v Prem-I-Air 12" Air Circulator Fan
Heat flux measurement for party surfaces	BTS In-Situ U-value Measurement Kit with Hukseflux HFP01 heat flux plates	Eltek GS44H logger with Hukseflux HFP01 heat flux plates and GS24 type K thermocouple transmitter with 5m Bead Welded Probe Type K Thermocouple
Datalogger	Separate logger for each equipment	Eltek RX250AL Receiver/ Logger
External conditions measurement (temperature, wind speed, global solar irradiance)	Accessed via Weatherbit historical data API	
Airtightness measurement	Pulse 40l	Energy Conservatory Minneapolis blower door system

Table 4: Co-heating test equipment list.

Weather data was accessed from the Weatherbit.io weather API, this data has a resolution of 15-25km, depending on location, this was thought preferable to attempting to measure weather onsite given the difficulties of measuring irradiance and wind speed without the influence of shading in typical suburban environments. External temperature was also logged on site using a standalone logger to cross check with the Weatherbit API data, but the Weatherbit data was used in the analysis.

An internal set point temperature of 21°C was used most commonly, although an increased temperature of 23°C was used in one test to ensure a sufficient heat input signal as the building was of very high thermal performance (built to the Passive House standard). Previous co-heating tests have typically used a higher set point temperature, often 25°C. A lower set point temperature was used in these tests to limit the temperature difference to attached buildings and hence increased heat transfer through party surfaces which would not occur during normal use of the building.

Where heat flux plates were used to measure heat flux through party surfaces, the mean heat flux measurement was multiplied by the area of the party surface and subtracted from the overall heat loss. This method is imperfect as the heat flux was only measured in 2-3 locations where the heat flux plates were located, this problem was avoided as far as possible by using thermography to try to locate the heat flux plates in areas with a representative surface temperature (i.e. particularly hot and cold spots were avoided).

Although party wall heat losses will occur during normal use, and hence should arguably be included in a measurement of the thermal performance of a dwelling, they will be increased during co-heating tests due to the elevated internal temperature and hence were subtracted where possible. The method used to account for party wall heat loss is described in detail in Appendix I.

Solar gains were accounted for, and the final HTC calculated, using the Siviour regression method described in the Leeds Beckett co-heating method.

2.1.2. SmartHTC Equipment

The equipment required for SmartHTC is relatively simple. In most of the dwellings temperature and relative humidity readings were collected using Elitech RC-4HC loggers (Figure 8), these log locally and were downloaded after being collected from the property. Either 4 or 5 sensors were used in each house, with an additional sensor deployed if the house was particularly large. In some dwellings a different, but similar, Tinytag logger was used (Figure 8), the decision on which sensor to use was based simply on availability at the time of testing.

Elitech RC-4HC, cost c.£20/sensor

Tinytag Transit 2 TG-4081, cost c.£40/sensor

Figure 7: Temperature sensors used in the field trial.

Measurement	Equipment	Accuracy
Internal temperature and relative humidity	Elitech RC-4HC	Temperature ±0.6°C, RH ±5%
Internal temperature	Tinytag Transit 2 Temperature Data Logger	±0.4°C
Energy consumption at service meters	Hildebrand GlowStick Zigbee CAD	Same as service meter

Table 5: Field trial equipment list

Energy consumption was measured at the service meter if an appropriate smart meter was installed. Energy consumption was either measured by connecting a Consumer Access Device and downloading data through Hildebrand's Glow system, or through Octopus' API in one case. If an appropriate smart meter was not installed energy consumption was recorded by manual meter reads.

2.1.3. Equipment Calibration

Heat flux plates that were outside of the manufacturer's calibration period were recalibrated in channel prior to testing at the University of Salford's UKAS accredited Thermal Measurement Laboratory.

All temperature sensors used were provided with a manufacturer's calibration, in addition they were check calibrated against the other sensors in the kit prior to testing.

The Pulse airtightness kit was calibrated by the manufacturer and blower door equipment calibrated by BSRIA, all to UKAS standards.

2.1.4. Sample

The total sample size for field trial is 314 measurements over 203 dwellings, in 111 dwellings there were measurements before and after a retrofit. The sample includes 11 dwellings in which BTS have carried out co-heating tests (in addition to the 30 carried out through the SMETER project).

The recruitment method was opportunistic, and was not focussed on generating a representative sample. Despite this, by creating a large sample we have been able to carry out measurements in buildings of different sizes and ages (Figure 8) that are well spread across Britain (Figure 10).

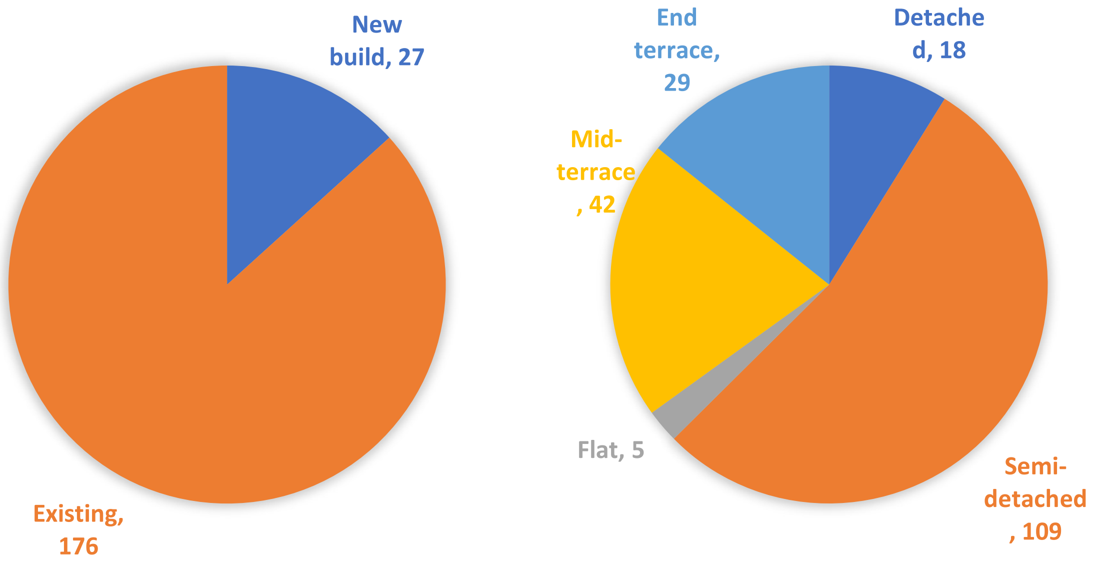

Figure 8: Summary statistics for the SmartHTC field trial.

The sub-sample of dwellings in which a baseline co-heating test measurement was carried out is much smaller, but still shows a good variety of dwelling types and ages (Figure 9). In total we have results for 26 co-heating tests for the analysis (not all of the results have been released for the SMETER project at the time of writing).

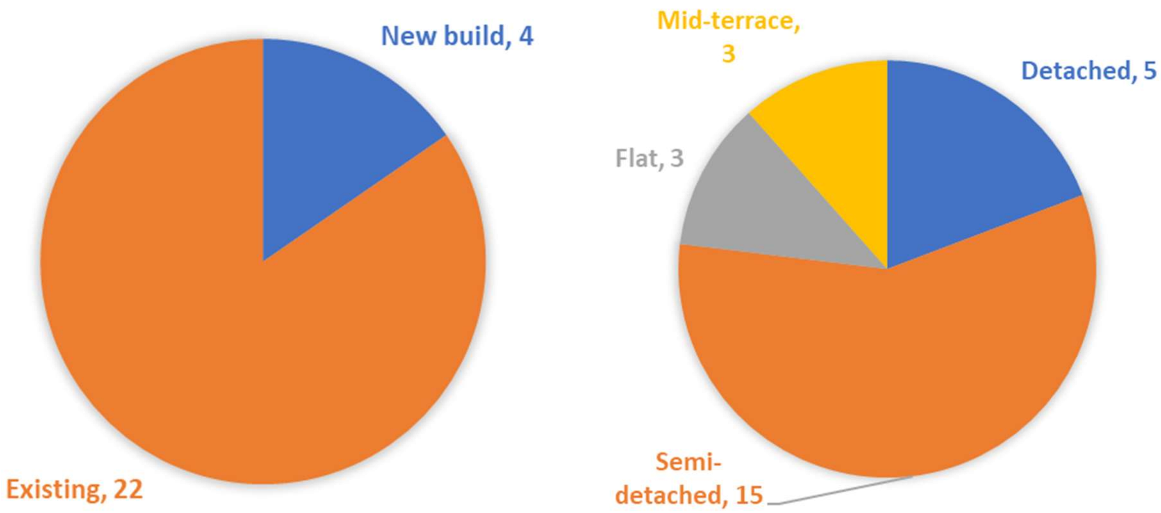

Figure 9: Sample statistics for the dwellings in which co-heating tests were carried out.

Figure 10: Geographic spread of the SmartHTC field trial sample (in some cases several dwellings in the same area were included, these are represented by a single marker).

2.2. Energy House Testing

During development of the SmartHTC system, two blocks of laboratory testing were conducted at The University of Salford's Energy House to investigate the performance of SmartHTC. In the first block of testing different heating patterns, external weather and synthetic occupancy were used to test that SmartHTC could produce a repeatable result in controlled conditions. In the second block of testing, which followed the first year of field trials, the Energy House was used to investigate particular factors in detail, these were the impact of solar gain, rainfall and metabolic gains (further work) on the HTC measurement of a property.

The Energy House (Figure 11) is the only fully climate-controlled research facility in the world. Built in 2011, this two-bedroom solid-walled terraced house is built inside an environmental chamber and can replicate a wide variety of weather conditions. The house was demolished on a site local to the university, and rebuilt brick by brick within the chamber. It is fully furnished and packed with a vast array of sensors that can monitor a wide range of variables throughout the house and chamber. Internally, the house is equipped to synthesise a wide range of occupied conditions, such as people, appliance use, domestic hot water and central heating.

The Energy House is an end-terrace, with an exposed wall on one side and a simulated building next door. The next-door property is not full size, but has a party wall and the internal temperature can be controlled.

Figure 11: The Energy House at the University of Salford.

2.2.1. Testing Block One Programme

The Energy House provides a building with a well-defined level of performance in controlled conditions, allowing testing of hardware and algorithms from the building blocks up to a working system. The first aim for the testing was to establish the accuracy to which the HTC of the building can be measured using non-invasive equipment.

Having established the uncertainty in ideal conditions, the further target was to identify the size and characteristics of the additional uncertainty introduced by a number of varying conditions reflective of occupied houses in outdoor conditions. By collecting data in controlled conditions data was gathered to inform algorithm development to account for the synthesised factors in real houses.

The testing was carried out in six phases (Table 6), each of three days in length. The internal temperature was controlled by the installed thermostat and central heating system.

Phase	Objective	Conditions
1	Test SmartHTC in controlled conditions	Internal: 21°C External temperature: 5°C
2	Introduce dynamic heating	Internal: Dynamic, SAP schedule (06:30-09:00/15:30-23:00) External temperature: 5°C
3	Test the effect of window opening	Internal: Dynamic, SAP schedule (06:30-09:00/15:30-23:00) External temperature: Dynamic, typical Salford winter day **Window opening:** Kitchen window, open 18:30-18:45. Bathroom window, open 07:30-08:00. Bedroom windows (front and rear facade), open 08:00-08:15.

4	Test the effect of hot water use	Internal: Dynamic, SAP schedule (06:30-09:00/15:30-23:00) External temperature: Dynamic, typical Salford winter day **Hot water use:** SAP-predicted hot water usage for the Energy House
5	Test the effect of full synthetic occupancy	Internal: Dynamic, SAP schedule (06:30-09:00/15:30-23:00) External temperature: Dynamic, typical Salford winter day **Additional conditions:** Synthesised metabolic gains, hot water usage, lighting and appliance usage, window opening
6	Test the effect of a change in weather, possible thermal mass charging	Internal: Dynamic, SAP schedule (06:30-09:00/15:30-23:00) External temperature: Dynamic, typical Salford winter day with an increase of 2°C to the profile each day. No synthetic occupancy applied.

Table 6: Programme for the first block of Energy House testing.

2.2.2. Testing Block Two Programme

Testing was carried out over 16 days in 8 consecutive phases. Each phase consisted of a variation of internal and external conditions of increasing complexity, to assess the performance of the SmartHTC algorithm and its inherent assumptions. Each phase ran for 2 days to account for any transitional performance characteristics of the house (i.e. thermal capacity).

The testing had a particular aim, which was to better understand how well solar gains are accounted for in the SmartHTC algorithm and in particular solar gains through opaque building elements (i.e. everything apart from the windows, including the roof, walls and doors).

Phases 1 – 4 were designed to isolate the influence of opaque solar gains by covering the windows externally in a reflective foil to stop radiative gains through the windows while various simulated solar conditions were applied. To allow a direct comparison the external conditions during these phases were repeated after the foil had been removed from the windows (phases 5-7). The baseline HTC with foil on the windows was measured in phase 4, so that any change in the thermal performance caused by the application of the foil (though likely to be minimal) could be accounted for.

The solar irradiance was simulated on the front of the building only (shown with the front door in it in Figure 11), this corresponds to the lamps numbered 5-12 in the Energy House. When lamps 5-12 were switched to 100% power, this provided approximately 200 – 210 W/m^2 of solar irradiance at the façade of the building which is roughly equivalent to the south facing solar irradiance during a sunny mid-winter day.

The final phase (phase 8) was designed to test the impact of intermittent rain on the HTC measurement combined with sunny conditions.

ID	Objective	Conditions	Dates/Time
Phase 1	Measure radiative solar gain component through **opaque** elements under **static**	**Solar gain through opaque elements only - static** Internal Conditions: Steady state, 21°C	*2pm 02/10/19 to 2pm 04/10/19*

	conditions similar to a south-facing wall on a sunny mid-winter day in the UK. Static conditions used to minimise thermal mass effect (no direct solar through glazing)	External Conditions: Steady state, 5°C including steady solar gain (100% on lamps 5-12 inclusive) Additional Conditions: Cover front windows with reflective foil (externally)	*[2 days]*
Phase 2	Measure radiative solar gain component through **opaque** elements under **step** change conditions (no direct solar through glazing). A step change was introduced as a simplified transition from day to night.	**Solar gain through opaque elements only – dynamic [step]** Internal Conditions: Steady state, 21°C External Conditions: Steady state, 5°C including steady solar gain (100% on lamps 5-12 inclusive from 22:00 – 06:00 only i.e. switch on at 22:00 and off at 06:00) Additional Conditions: Cover front windows with reflective foil (externally)	*2pm 04/10/19 to 2pm 06/10/19 [2 days]*
Phase 3	Measure radiative solar gain component through **opaque** elements under **dynamic** solar conditions similar to a sunny UK mid-winter day (no direct solar through glazing)	**Solar gain through opaque elements only – dynamic [profile]** Internal Conditions: Steady state, 21°C External Conditions: Steady state, 5°C including steady solar gain Lamps 5-12 inclusive profile on as follows: 22:00 – 20% 23:00 – 50% 00:00 – 70% 01: 00– 100% 02:00 – 100% 03:00 – 90% 04:00 – 60% 05:00 – 40% 06:00 – 0% Additional Conditions: Cover front windows with reflective foil (externally)	*2pm 06/10/19 to 2pm 08/10/19 [2 days]*
Phase 4	Measure **baseline** HTC of Energy House with foiled windows to determine if the foil changed the performance of the house	**Baseline – Foiled Windows** Internal Conditions: Steady state, 21°C External Conditions: Steady state (NO SOLAR) Additional Conditions: Cover front windows with reflective foil (externally)	*2pm 08/10/19 to 2pm 10/10/19 [2 days]*
Phase 5	Baseline measurement of **solar gain** (through all elements) contribution to HTC	**Solar gain static** Internal Conditions: Steady state, 21°C External Conditions: Steady state, 5°C including steady solar gain (100% on lamps 5-12 inclusive)	*2pm 10/10/19 to 2pm 12/10/19 [2 days]*

	under **static** conditions	Additional Conditions: REMOVE FOIL for remaining tests	
Phase 6	Measure radiative **solar gain** component through all elements under **step** change conditions, simulating a simplified transition from day to night.	**Solar gain – dynamic [step]** Internal Conditions: Steady state, 21°C External Conditions: Steady state, 5°C including steady solar gain (100% on lamps 5-12 inclusive from 22:00 to 06:00 only i.e. switch on at 22:00 and off at 06:00) Additional Conditions: Windows unblocked	*2pm 12/10/19 to 2pm 14/10/19 [2 days]*
Phase 7	Measure radiative **solar gain** component through all elements under **dynamic** solar conditions similar to a sunny UK mid-winter day.	**Solar gain – dynamic** Internal Conditions: Steady state, 21°C External Conditions: Steady state, 5°C including steady solar gain Lamps 5-12 inclusive profile on as follows: 22:00 – 20% 23:00 – 50% 00:00 – 70% 01: 00– 100% 02:00 – 100% 03:00 – 90% 04:00 – 60% 05:00 – 40% 06:00 – 0% Additional Conditions: Windows unblocked	*2pm 14/10/19 to 2pm 16/10/19 [2 days]*
Phase 8	Test additional heat loss due to **rain** under **dynamic** solar gain conditions (through all elements) similar to a sunny UK mid-winter day.	**Additional Testing – Rain, dynamic** Internal Conditions: Steady state, 21°C External Conditions: Steady state, 5°C including steady solar gain Lamps 5-12 inclusive profile on as follows: 22:00 – 20% 23:00 – 50% 00:00 – 70% 01: 00– 100% 02:00 – 100% 03:00 – 90% 04:00 – 60% 05:00 – 40% 06:00 – 0% Additional Conditions: Simulated rain on 2 occasions; 2pm 16/10/19 and 2pm 17/10/19	*2pm 16/10/19 to 5pm 18/10/19 [2 days]*

Table 7: Energy House testing block two programme.

Throughout the testing a number of other conditions were controlled and held constant while the changes described in Table 7 were adjusted:

- Internal temperature held at 21°C in the Energy House and adjacent void.

- Radiation shield fitted to mid-room temperature sensors in living room and main bedroom to ensure accurate air temperature measurement.
- All internal lights switched off throughout testing to avoid internal gains.
- Any entry to the property during testing period logged via sign-in sheet (times and quantity of people) and doors closed and locked behind.
- Solar gain measured externally (in-front of main bedroom window) and internally (approximately 50cm inside of the window) via Huskeflux HFP01 heat flux plates coated in black tape. The plates were exposed to air movement in front and behind.
- Heat flux measured internally on solar incidence wall in 4 locations using the same equipment mounted inside the windows.

2.3. SMETER Project

BTS have taken part in the Smart Meter Enabled Thermal Efficiency Rating (SMETER) project organised by BEIS. The SMETER project has two main elements, one of which is a field trial carried out in 30 occupied homes in the North West of England. The field trial was carried out by the 'TEST' team, which included Loughborough University, Leeds Beckett University, University College London and Halton Housing, a housing association based in Halton, Cheshire.

The aim of the SMETER project was to enable development of methods to measure the thermal performance of dwellings using smart meter data and other monitoring. BTS had already developed SmartHTC and carried out initial validation through field trials prior to the SMETER project. BTS delivered a SMETER project in partnership with Elmhurst Energy, Hildebrand and the University of Salford to further validate SmartHTC and develop products which used SmartHTC, such as the Measured Energy Performance service now provided by Elmhurst Energy.

In each of the 30 houses a co-heating test was carried out by the TEST team; the houses were then occupied and monitoring was carried out. The equipment for each participating group was installed by the TEST team, with the other participating groups never attending the houses in the field trial. As six teams took part in the project, it was not practical to install six different sets of measurement equipment in each house. For that reason, each team's equipment was installed in only ten houses, in the other twenty houses the measurements were gathered by the TEST team to each participating team's specification. Having collected the required data, the participating teams were then required to report their calculated HTCs to the TEST team to allow a blind assessment of the accuracy of the methods compared to a baseline co-heat HTC measurement.

This process provides an excellent third-party assessment of SmartHTC. In addition to leading a project, BTS also provided HTC calculations via SmartHTC to another project group led by Switchee. Switchee manufacture smart thermostats designed for social housing, through the SMETER project BTS and Switchee worked together to integrate SmartHTC into Switchee's system through the SmartHTC APIs. BTS developed a bespoke version of SmartHTC for Switchee to utilise additional measurements made within the Switchee thermostat, for example detection of whether occupants are present. As a result of carrying out the calculations for Switchee as well as BTS, there are two SmartHTC calculations for each property, i.e., 60 calculated results over 30 properties.

BTS had no involvement in selection of the sample, or knowledge of the dwellings beyond the usual SmartHTC inputs when calculating the HTC results. The BTS equipment for the testing included 5 temperature and humidity sensors per house, connected via Bluetooth to a central hub to allow remote access. Consumer Access Devices were also installed in each house ready for connection to a smart meter, although smart meters were not actually available in the properties so the TEST team gathered energy consumption data through a second meter connected in line with the service meters.

The data used for the calculations through the Switchee system was collected by the Switchee hardware, which was installed centrally in each house, usually in the hallway. Only a single temperature sensor was therefore used, additionally Switchee provided half-hourly data on whether the dwelling was occupied based upon their sensors and an internal algorithm.

3. Comparison with Baseline Measurement

- 41 comparisons were made between SmartHTC and the co-heating test method.
- All 11 comparisons carried out by BTS showed excellent agreement, well within the combined uncertainty margins of the tests.
- SmartHTC worked in all instances to accurately measure the in-situ heat transfer coefficient of the properties using only energy consumption and internal temperature data measurement.
- SmartHTC also worked on three very-low HTC properties, using only meter readings and summertime data (March – July).
- Of the tests carried out through the SMETER project, the SmartHTC and co-heat results agreed within the combined uncertainty margins for 29 of the 30 properties.
- The average confidence interval of SmartHTC was ±17%.

During two winter periods (2018/19 and 2019/20), co-heating tests were undertaken by BTS at 11 field trial properties to provide a baseline against which the performance of SmartHTC could be measured. In addition, SmartHTC and co-heating results were compared in 30 houses through the SMETER project, resulting in a total of 41 comparisons with a baseline measurement.

15 of 30 results from the co-heating tests carried out through the SMETER project have been kept partially confidential at the time of writing. In these 15 cases BTS have only been informed that the SmartHTC result agrees to within the combined confidence interval of the co-heating and SmartHTC tests in 14 of 15 cases. The full results of the other 15 of 30 co-heating tests are available to BTS, so that there are 26 detailed comparisons between co-heat and SmartHTC measurements in total (11 carried out by BTS and 15 from the SMETER project).

SmartHTC results using just start and end meter readings were calculated for the whole monitoring period on each of these properties to confirm the suitability of the method where smart meter data is not available. For 6 of the sample properties, no smart meter data was available, hence only a single HTC calculated using meter reads is reported.

In all 26 properties the confidence intervals of the co-heating test and the SmartHTC measurement overlap and are therefore determined to agree (Figure 12). On average, the results showed <1% deviation and the difference between results ranged from -20% (co-heat HTC lower than SmartHTC) to +18% (co-heat HTC greater than SmartHTC).

The average confidence interval of the SmartHTC measurement across all field trial properties (including those without co-heating tests conducted) was ±17%. The average SmartHTC confidence interval using meter readings for the same dataset was ±23%.

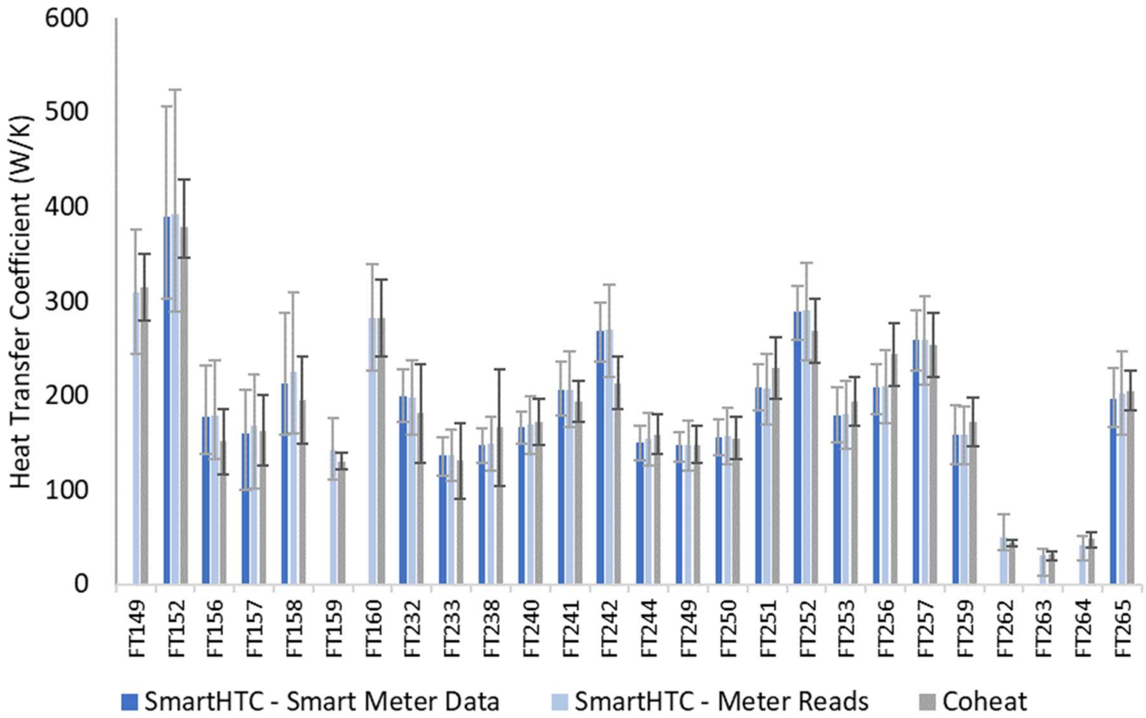

Figure 12: Comparison between SmartHTC and co-heat test HTC measurements, the SmartHTC results calculated using smart meter data and starting and ending meter reads are both shown.

The results for FT262, FT263 and FT264 were particularly notable (to the right-hand side of Figure 12). These very low HTC properties were co-heated at the end of winter 2020 and the SmartHTC data (manual meter readings and standalone internal temperature sensors) were due for collection 21 days after those tests. However, due to COVID-19 restrictions, it was not possible to collect data until July 2020. Despite the summer monitoring period, all three properties showed excellent agreement between the co-heat and SmartHTC results suggesting that the method can be applied for a longer period of the year than October to March. It is worth noting that the confidence intervals for these properties were much higher than other tests (ranging from ±31% to ±45%) but the measured HTC in each case was close to the co-heat result. Section 8.2 outlines future development work to enable SmartHTC to be used outside of winter conditions.

3.1. SMETER Field Trial Results

At the time of writing the full results of the SMETER project are yet to be released. At this time each team has been notified whether their HTC results and the results of the co-heating tests agreed to within the combined confidence intervals of the measurements, but without being informed of what the baseline measurement and its confidence interval are.

In the SMETER project BTS provided SmartHTC calculations for both our own and Switchee's projects, in this section the results of all 60 of these calculations (30 properties, with two calculations for each) are reported.

Across the SmartHTC measurements carried out by BTS, the co-heat and SmartHTC measurements agreed to within the combined confidence interval of the measurements in 58 of 60 (97%) instances. This shows a very high level of agreement in this blind comparison. At present, the full set of co-heat HTC results have not been published by BEIS so it is not possible to tell if the SmartHTC and co-heat measurements were significantly or slightly different where they varied. The houses where the results disagreed were both semi-detached. In such houses with a party wall it is particularly difficult to carry out a co-heating test without causing additional party wall heat loss as the internal temperature of the house being tested is deliberately raised above the likely temperature of the adjacent house.

BTS supplied SmartHTC calculations using data collected in three different configurations (Table 8). In each house where either the BTS or Switchee hardware was installed the measurements agreed to within the combined confidence intervals of the tests in every case, demonstrating an excellent 100% success rate where the relevant hardware was in place.

Hardware Specification	Agreement
Data collection by BTS's hardware, 5 measurement locations per house	10/10
Data collection by Switchee's thermostat, single central measurement location	10/10
Data collection by the TEST team to BTS configuration	19/20
Data collection by the TEST team to Switchee	19/20

Table 8: Results summary of the SMETER field trial, 'agreement' means that the co-heat and SmartHTC measurements were within the combined confidence interval of each test.

4. Repeatability

- SmartHTC shows excellent repeatability.
- The mean RPD across the dataset was less than 1%.
- The SmartHTC and co-heat results agreed for 99% of valid 21-day subsamples (704 in total).

The repeatability of SmartHTC measurements in the same building was investigated by dividing the dataset for each property into a series of 21-day long subsamples, SmartHTC was then applied over each time period. This process was carried out for all SmartHTC measurements with half-hourly smart meter data and had monitoring periods greater than 21 days. The Relative Percentage Difference (RPD) was be calculated to quantify the repeatability. This applied to 33 properties in total (including 1 where monthly meter readings were used, FT157). RPD is a useful tool to give a measure of the repeatability of the HTC calculations from the subsamples where there is no 'correct' reference answer to compare against. The RPD compares each subsample's result with the result for the full sample to give a measure of the size of variation for each.

RPD = (Subsample HTC – Full sample HTC) / Full sample HTC

The mean RPD for a set of subsamples taken in a single property is the mean average of the calculated RPD figures for each of the subsamples. A low RPD indicates that the measurements were very similar to each other and hence a high degree of repeatability.

The maximum and minimum RPD are also reported, these give an indication of if there were any outlier results. When considering the RPD statistics a useful comparator is the typical confidence interval for a SmartHTC measurement of around 15-20%, if the RPD is lower than this it indicates that the variation is within the confidence interval of the measurement.

The mean RPD was consistently less than 4% across all 33 properties (Figure 13). The maximum and minimum RPD of any individual sample across all the dwellings was between -18% and +15%, and was significantly lower than this for the majority of properties. The mean RPD indicates a generally excellent level of repeatability across different weather and internal conditions, while the maximum and minimum RPDs show that even in extreme cases the SmartHTC result falls within the confidence interval of the measurement.

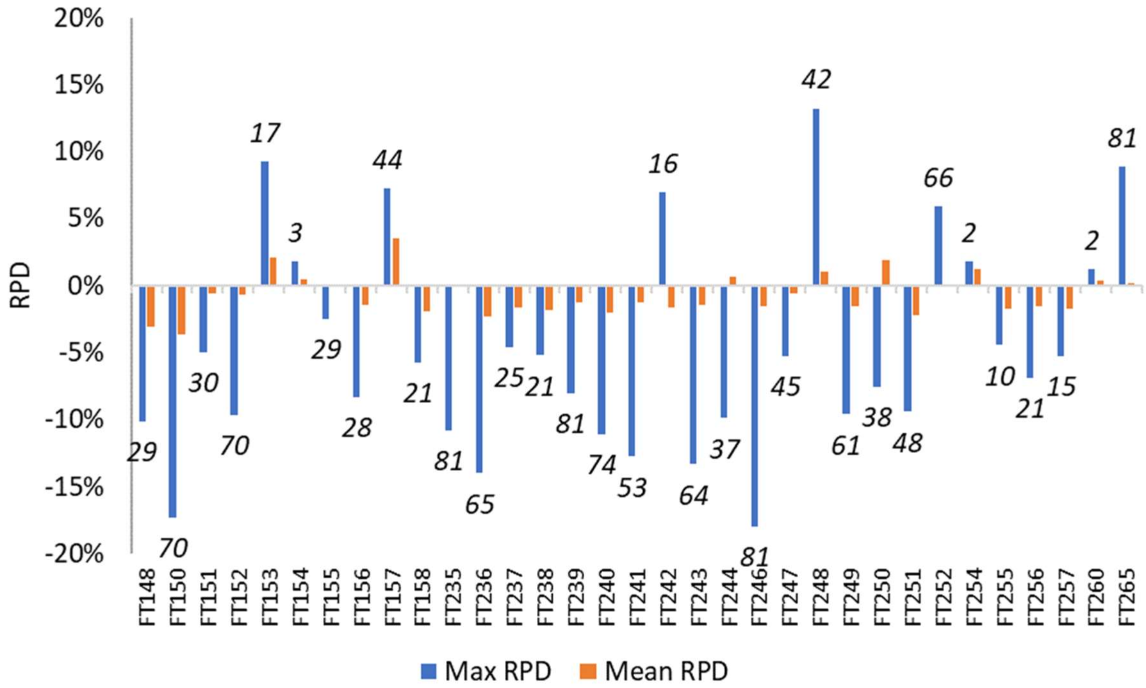

Figure 13: Maximum and average RPD for each dwelling with suitable data, the numbers in italics give the number of 21-day subsamples for each dataset.

Where co-heating results were available, the 21-day samples (of which there were 704 in total across 26 suitable field trial properties), showed 99% agreement with the co-heating tests. Data for an example property, FT152, shows an example of excellent repeatability of 21-day samples (Figure 14). The monitoring period ran from 1/1/19 to 31/3/19, it's clear that any of the 21-day SmartHTC results within that period gives an accurate HTC measurement (in agreement with the co-heating test).

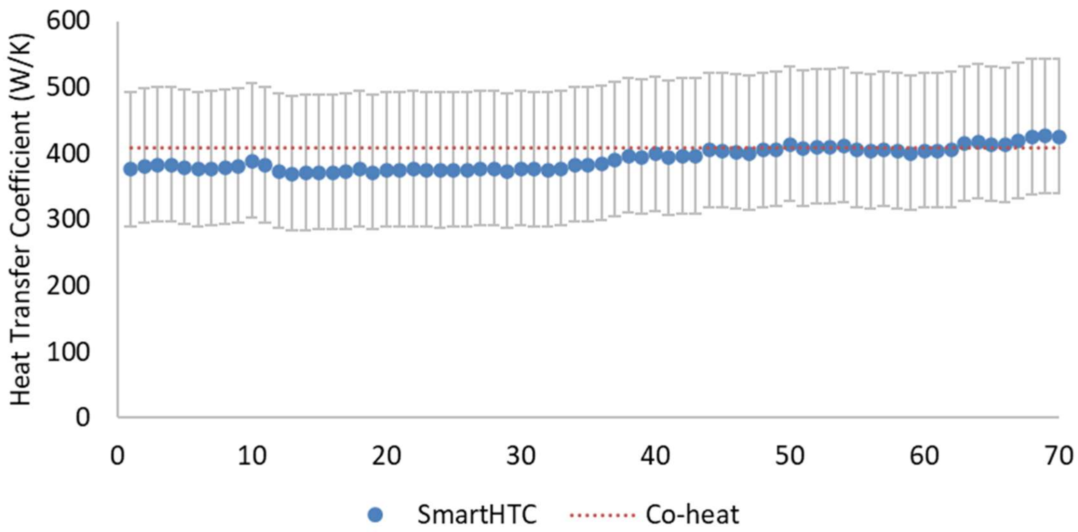

Figure 14: HTC calculations for FT152 subsamples, there is 100% agreement between SmartHTC and co-heating results.

5. Energy House Testing Results

5.1. Testing Block One

Testing block one was designed to test the fundamental feasibility of accurately calculating HTC values using discrete temperature sensors when the building is heated by the existing heating system.

The results showed that an accurate HTC measurement was made by using the SmartHTC equipment, both under unrealistic steady-state conditions, and more excitingly under dynamic conditions and with synthetic occupancy conditions applied.

Dynamic temperature profiles were used in the testing to investigate the effect on the calculation of the HTC caused by the charging and discharging cycles of the thermal mass that they would cause. It is clear that the dynamic temperature profiles had a clear and immediate impact on the calculated HTC (Figure 15) using a steady-state calculation method with a short time step (1 hour), but that this is largely damped out if a longer time step is used (1 day). There is a clear drop in the daily HTC value immediately after the dynamic internal profile is introduced, this suggests that there was a temporary imbalance in thermal mass storage at this point.

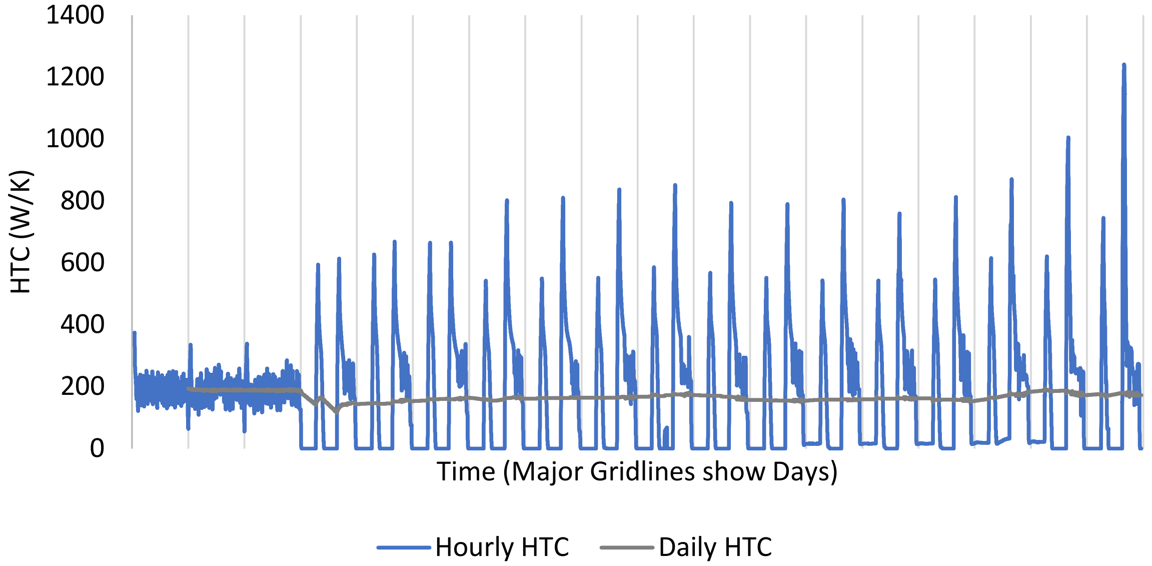

Figure 15: Basic HTC calculations across the first block of Energy House testing using data for the previous hour and day.

Despite all of the different synthesised variables applied during the testing, the SmartHTC measurement (189W/K-27+24) was very close to the baseline measurement (197W/K±10%), despite a reduced testing time of only 18 days compared to the usual SmartHTC requirement of 21 days.

To analyse the repeatability of the measurement across the across the measurement period, the whole dataset was broken down into a series of 7-day long subsamples. This is an even shorter sample, and much shorter than the required minimum of 21 days. Despite the sequential application of different synthetic variables and the shortened data samples, the SmartHTC measurement was very repeatable. The result for every subsample comfortably agreed with the baseline co-heat measurement within the SmartHTC confidence interval (Figure 16).

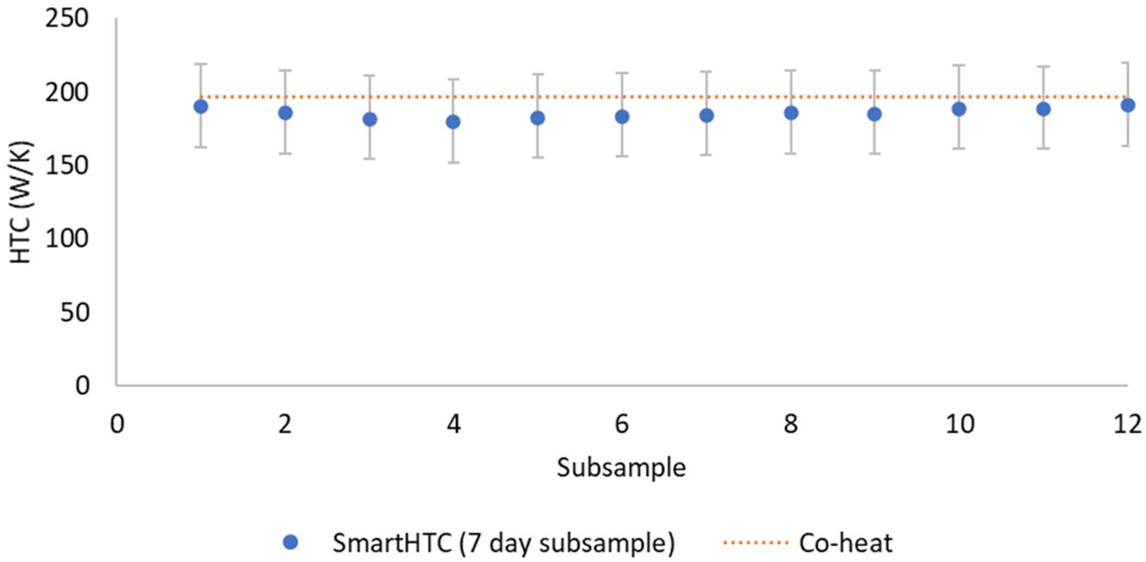

Figure 16: SmartHTC measurements throughout the first block of testing in the Energy House, a reduced monitoring period of 7 days is used for the subsamples in order to allow a measure of the repeatability of the test.

The results of the first set of testing in the Energy House were very positive, demonstrating the capability of SmartHTC to accurately the HTC despite varying internal and external conditions and the application extreme examples of synthetic occupancy variables (metabolic heat gains, appliance use, lighting, internal door opening and closing and hot water use).

5.2. Testing Block Two

The second block of testing in the Energy House was 16 days long and designed specifically to investigate the performance of SmartHTC in calculating solar gains. The Energy House is a unique resource for this investigation as the sun can be turned up, down, on or off on demand. The configuration of the Energy House has been adjusted slightly (as part of a different project) between the two blocks of testing, such that the baseline HTC measurement was different for each.

The testing included a repeated set of three phases of testing, phases 1-3 were carried out with the windows blocked with reflective foil to isolate the effect of solar gains through the opaque elements (i.e. not the glass) and phases 5-7 with the windows unblocked. The three phases represented varying levels of solar radiation, from extremely high levels for winter (phases 1 and 5) to solar conditions representative of a sunny mid-winter day in the UK (phases 3 and 7). The SmartHTC results were accurate and consistent across all phases (Figure 17 and Table 9), showing excellent compensation for solar gains in the algorithm.

SmartHTC accurately measured the HTC in conditions with no (phase 4) or typical winter (phase 7) solar gain conditions. The HTC measured in Phase 7, the most realistic winter condition simulated, was within 1% of the baseline HTC measured in the Energy House.

Comparing phases with windows foiled and un-foiled (Phase 1/5, Phase 2/6 and Phase 3/7), SmartHTC measures the solar gain contribution with excellent accuracy. The maximum difference between simulations (opaque solar only or total solar gain) is 4.3% (Table 9). The SmartHTC results with only opaque solar gain were lower in each case, however, although the differences were very small (4.3% at most) and well within the measurement uncertainty. It appears, therefore, that SmartHTC may very slightly underestimate the contribution of opaque solar gains although the size of the differences makes this impossible to state with certainty.

Comparing all phases, the SmartHTC result was furthest from the baseline co-heat measurement for phases 1 and 5, during both the SmartHTC result was around 12% lower than the co-heat result. This is unsurprising, as these phases had the highest simulated solar intensity. During phases 1 and 5 constant solar gains of approximately 200W/m^2 were simulated, this is much more solar gain than would occur during the winter in the UK with an average intensity similar to a summer day. These results indicate that for highest accuracy SmartHTC testing should be carried out in winter, but that summer testing may be possible given the results were still within the confidence interval of the baseline measurement despite the extreme solar conditions.

The simulated rainfall had the most significant impact on the results, increasing the measured HTC by approximately 25% (Phase 8). During this phase rainfall and solar radiation were simulated together, and it seems likely that this caused a significant additional heat loss where the solar lamps evaporated the simulated rain which was on the surface of the house. This may have been exacerbated as the temperature of the simulated rain was rather high, it was 17^{o}C when it was released from the storage tanks. Although this simulation is not perhaps very realistic, the extreme conditions highlight a possible unaccounted for heat loss in the SmartHTC algorithm.

The SmartHTC results for each phase were calculated using data from 1 day only, whereas SmartHTC in practise requires 3 weeks of data. Analysing the data for the whole period (including all simulated conditions), the SmartHTC result is 161±15W/K showing extremely close agreement with the baseline co-heat measurement of 164W/K±10%. This suggests that although prolonged periods of certain conditions (e.g. rain, high solar gain, and particularly the two together) might temporarily affect the calculation, over a longer period there is an averaging effect which results in an accurate SmartHTC result.

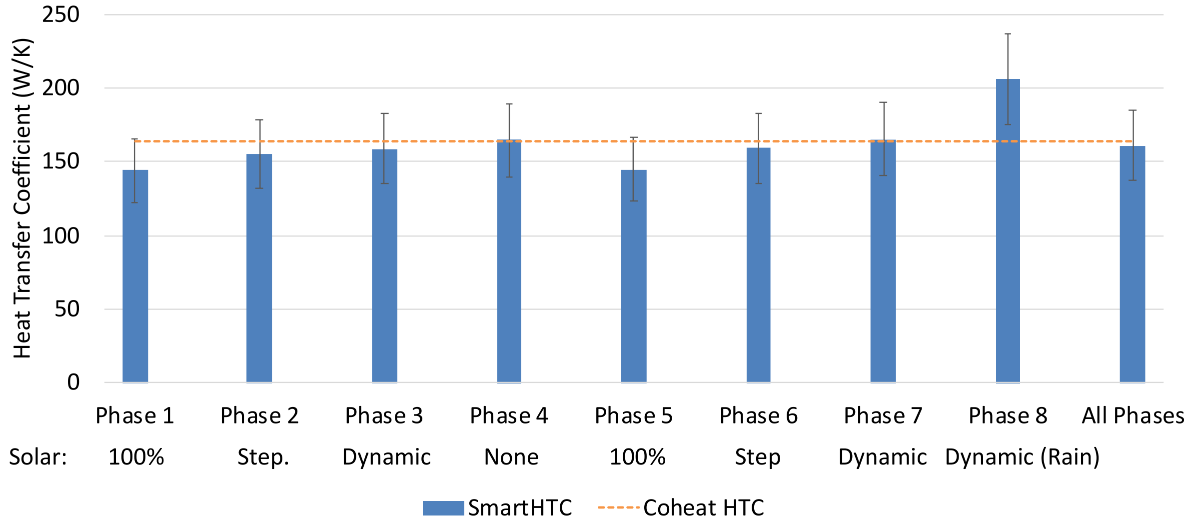

Figure 17: SmartHTC results for each phase of the second block of Energy House testing.

Opaque Solar Gains Only		Total Solar Gain		Difference
Simulated Conditions	SmartHTC (W/K)	Simulated Conditions	SmartHTC (W/K)	
Phase 1 – 100% Solar	144.3	Phase 5 – 100% Solar	144.9	0.4%
Phase 2 – Solar Step	155.4	Phase 6 – Solar Step	159.4	2.6%
Phase 3 – Dynamic Solar	158.6	Phase 7 – Dynamic Solar	165.5	4.3%
Phase 4 – Baseline	164.6	Phase 8 – Rain	206.3	25.4%

Table 9: SmartHTC results for each phase of the second block of Energy House testing, including a direct comparison between results for opaque solar gains only vs. total solar gain simulation.

6. Sensitivity to Input Data

A sensitivity analysis was conducted to assess the impact of two key SmartHTC input variables; smart (half-hourly) meter data vs manual meter readings, and the number of internal temperature sensors.

Summary of Findings: Smart Meter vs Manual (Start and End) Readings

- Results derived from manual meter readings taken at the start and end of a monitoring period provide excellent agreement with the smart meter results (±6% max, but on average <1% different).
- It is not possible to be as confident in the manual meter reading approach. Confidence intervals using manual meter readings are, on average, 26% larger than when using full half hourly data. The increase in confidence interval was (on average) from ±16.5% to ±21.4%. Further confidence in the results can also be taken from analysing the repeatability of the SmartHTC measurement over different 21-day periods when sufficient smart meter data is available.
- The simplicity of manual meter readings is attractive for implementation of SmartHTC either where smart meter data is unavailable or overly complicated to access, or to provide a check measurement in the case of metering issues.

Summary of findings: Number of Temperature Sensors

- It ***is*** feasible to use a single temperature sensor to measure the HTC via SmartHTC but the accuracy of the measurement is significantly reduced (i.e. larger confidence interval) and the measurement itself can differ from the 5x sensor measurement by approximately ±16%.
- On average, the confidence interval by using 5x sensors is 5% less than if using only a single sensor. The average confidence intervals across all field trial properties are; -17.8% and +20.5% for a single sensor compared to -14.3% and + 15.4% for 5x sensors.
- Based on individual room temperatures there is not a clear location that would be most suitable to increase the accuracy of a single sensor system. The living room or the thermostat are logical candidates but depending on the use and operation of the house, these may be less accurate than other rooms. Prohibitively, it is not possible to know which room is best to use without monitoring multiple rooms.
- Utilising multiple sensors enables other metrics to be reported more usefully within a property, including (for instance) damp and mould risk, and overheating risk.

Summary of findings: Building Information

- Accurate HTC measurements can be carried out without the optional additional building information.
- Providing optional additional building information has a relatively small effect on the HTC, less than 5% for any one piece of information.
- Providing the window dimensions and orientations and boiler efficiency have the largest effect on the calculated HTC.
- The calculation of the confidence interval works well to compensate for a lack of optional additional information.

6.1. Smart Meter Data

SmartHTC is designed to utilise smart (half-hourly) meter readings as one of the inputs. This relies on half hourly data being accessible from the gas and electricity meter, normally via a CAD (Consumer Access Device) or via the utility supplier or Data Communications Company (Smart DCC) directly. However, the smart meter roll-out is still underway and there are a variety of issues with some installations meaning that smart meter data is not always accessible.

As of December 2020, BEIS report that a third of all domestic meters are smart (and operating in smart mode). The majority of meters in the UK therefore only permit manual meter reading. Our experience has also shown that accessing data from a smart meter can be problematic depending on the combination of supplier and meter (amongst other factors). It is notable that under the BEIS funded SMETERS project the TEST team installed their own secondary gas and electric meters to ensure access to energy data was possible.

To improve the robustness and applicability of the SmartHTC system, an option to utilise meter readings at the start and end of a test period was investigated. The results of SmartHTC calculations using smart meter data and meter readings were compared across the 40 field trial properties where both datasets were available[12] (Figure 18).

[12] Note that this is limited by the number of properties where smart meter data is available. In circa 200 field trial properties, only 40 were available; approximately 20%. This highlights the difficulty in accessing smart meter data.

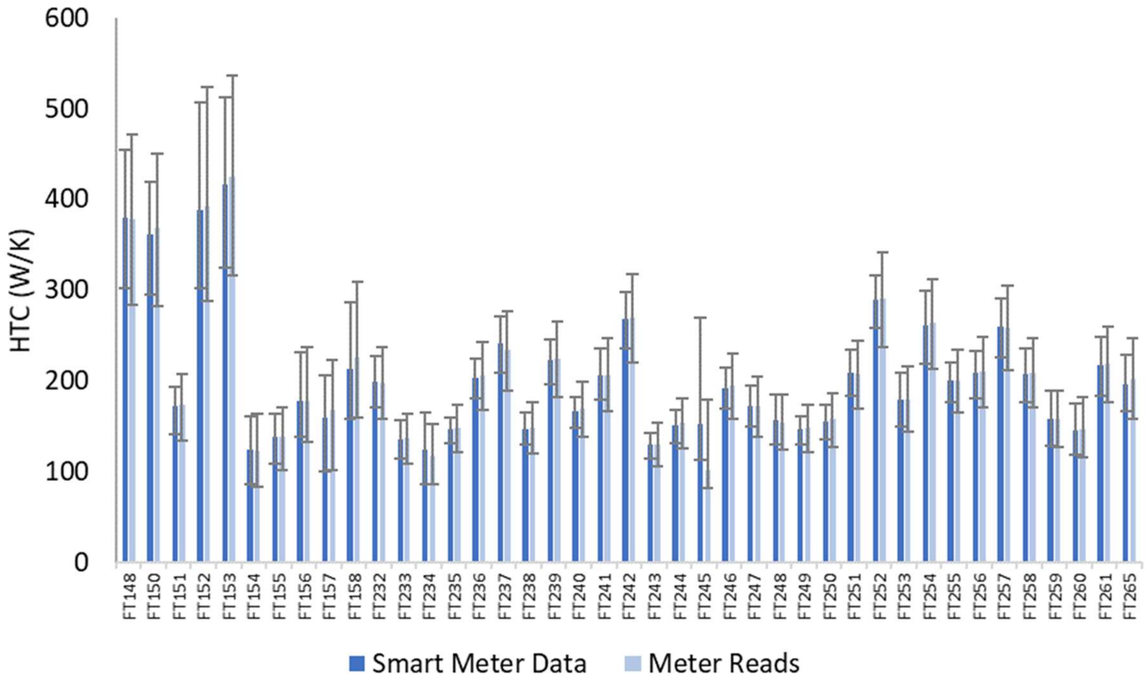

Figure 18: SmartHTC results using half-hourly smart meter data and meter readings.

Figure 19 shows the relative difference between the results using smart meter data and meter readings and the average difference for the whole dataset. The SmartHTC calculation using meter reads was within ±6.3% of the result using smart meter data in every case. The average difference across the 40 field trials was only 0.5%.

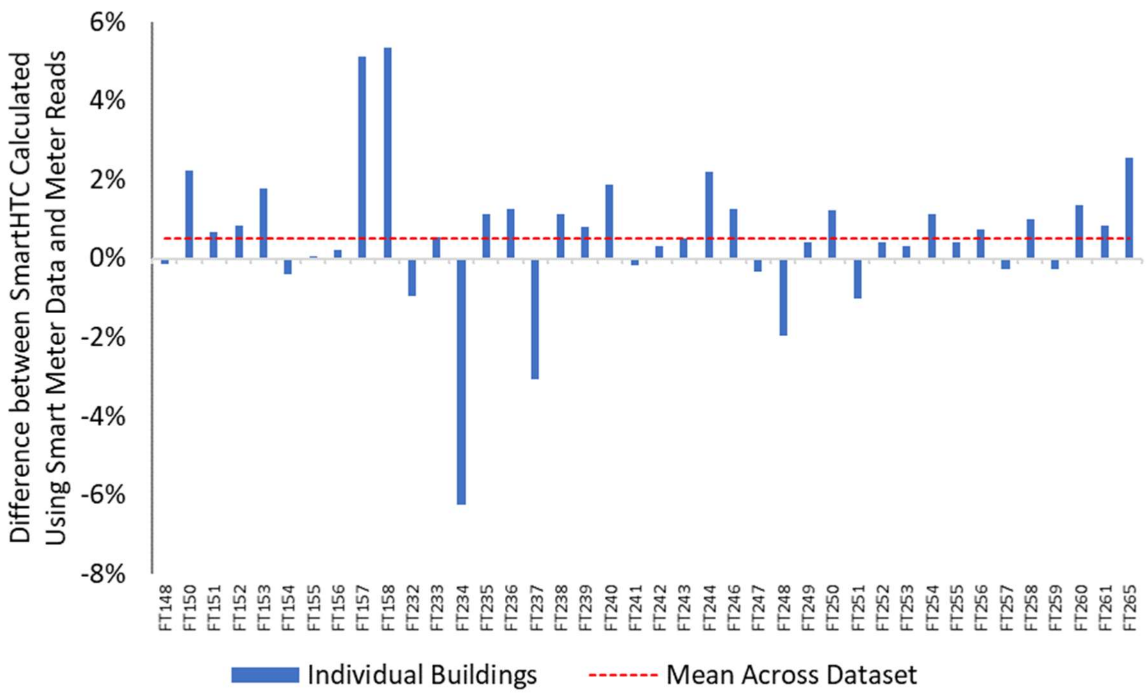

Figure 19: Difference between SmartHTC results using smart meter data and meter reads, if the difference is positive the HTC calculated using smart meter data is smaller.

This is a positive finding that opens up the use of SmartHTC in a wider cross-section of UK properties, regardless of whether smart meters are installed. It also provides a backup option for projects, protecting against potential energy data loss or access restrictions.

As well as the HTC, using smart meter data or meter readings affects the size of the confidence interval (Figure 20). On average, using meter readings increases the average confidence interval from (approximately) ±16.5% to ± 21.4%, or by 26% on average (i.e. there is less confidence in the result).

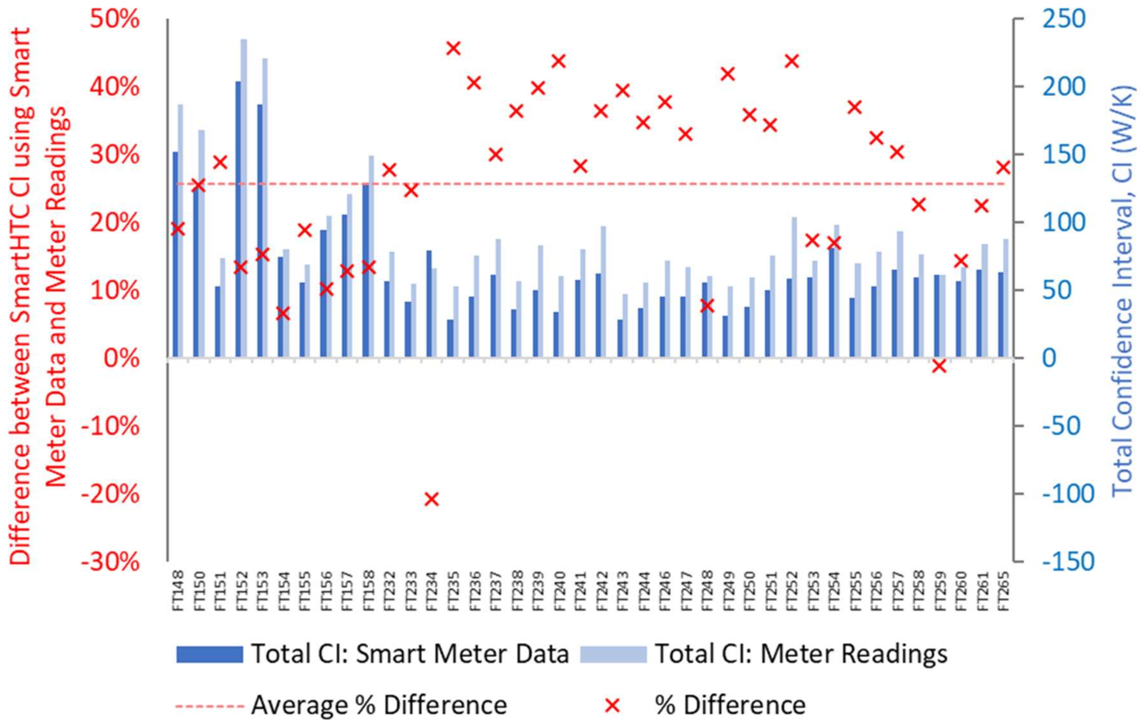

Figure 20: Comparison between the size of the total confidence interval (CI) using smart meter data or meter readings.

Because the SmartHTC results using meter readings shows very little deviation from those using smart meter data it may be possible to reduce the size of the confidence interval on these measurements. However, because of the limitations of using meter readings, in particular not being able to easily determine the repeatability of the measurement, reducing the CI should be done with some caution.

It is worth noting that there are other benefits of utilising smart meter data too, in particular with respect to potential additional metrics, but also to ensure repeatability. For instance, Figure 21 below shows the running 21-day HTC calculation for two of the field trial properties. FT240 (top) was normally occupied across the whole period and the SmartHTC calculation shows excellent repeatability across the whole period. FT245 (bottom) was unoccupied through the monitoring period but had a few periods of sporadic heating (for unknown reasons). The repeatability of the measurement is poor for FT245 accordingly and meter readings at the start and end would only provide a single data point with no transparency to the repeatability or accuracy of the result.

This is an extreme example (given the unusual usage of FT245) but it demonstrates an important benefit of being able to access smart meter data if possible. However, in controlled situations (i.e. where it is known that the property is being normally occupied and heated) then there is a benefit in being able to use meter readings in place of smart meter data if necessary.

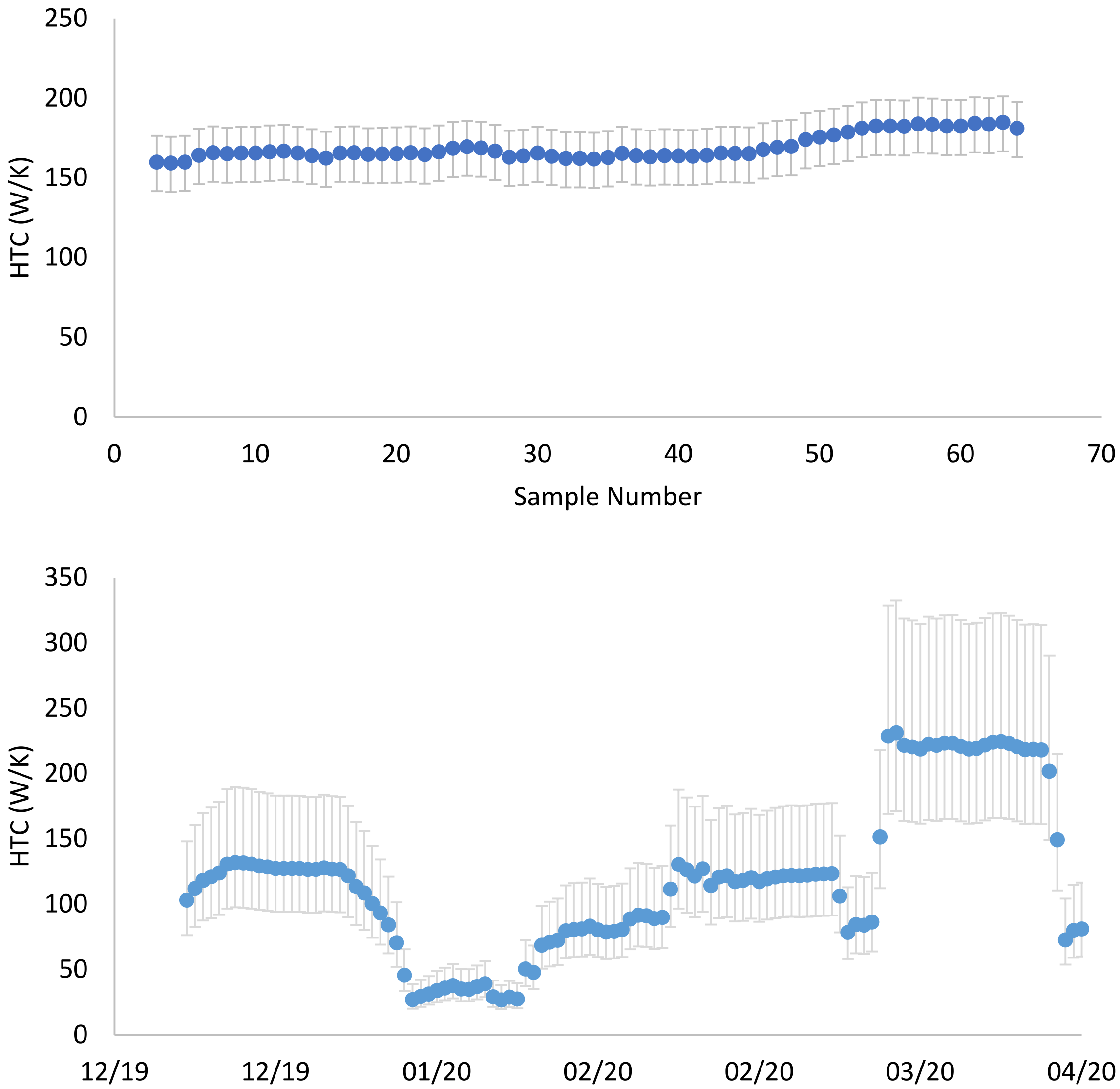

Figure 21: FT240 (top) and HH245 (bottom) running 21-day HTC using smart meter data.

6.2. Number of temperature sensors

The initial design of the SmartHTC system required 5x internal temperature sensors. These would typically be located in the Living Room, Kitchen, Main Bedroom, Bathroom and Thermostat location (or other representative room). The logic is that temperature variation across homes can be significant, especially where some spaces are sporadically heated or unused, and therefore a single sensor wouldn't always accurately measure the average internal temperature. Multiple room measurement also facilitates other metrics to be developed, in particular condensation and damp mould risk.

To investigate the impact on the HTC calculation (and confidence intervals) the 30 SMETERS (TEST) field trial properties were remodelled using a single temperature sensor. The sensor located at the main thermostat was utilised as it is expected that this should best represent the average temperature in the home (noting the aforementioned issues with temperature variation throughout a home). Furthermore, in 2018, 6% of UK homes were reported to own a smart thermostat device and the market has been continually growing, and so this location is logical to permit interfacing with smart home technology.

The SmartHTC results fell within the same confidence interval for all 30 datasets using either multiple temperature sensors or a single centrally located sensor (Figure 22), successfully demonstrating that a single sensor can be used for an accurate HTC measurement. However, further analysis was conducted to determine the average change in HTC measurement and confidence interval to demonstrate the benefit or limitation of either sensor approach.

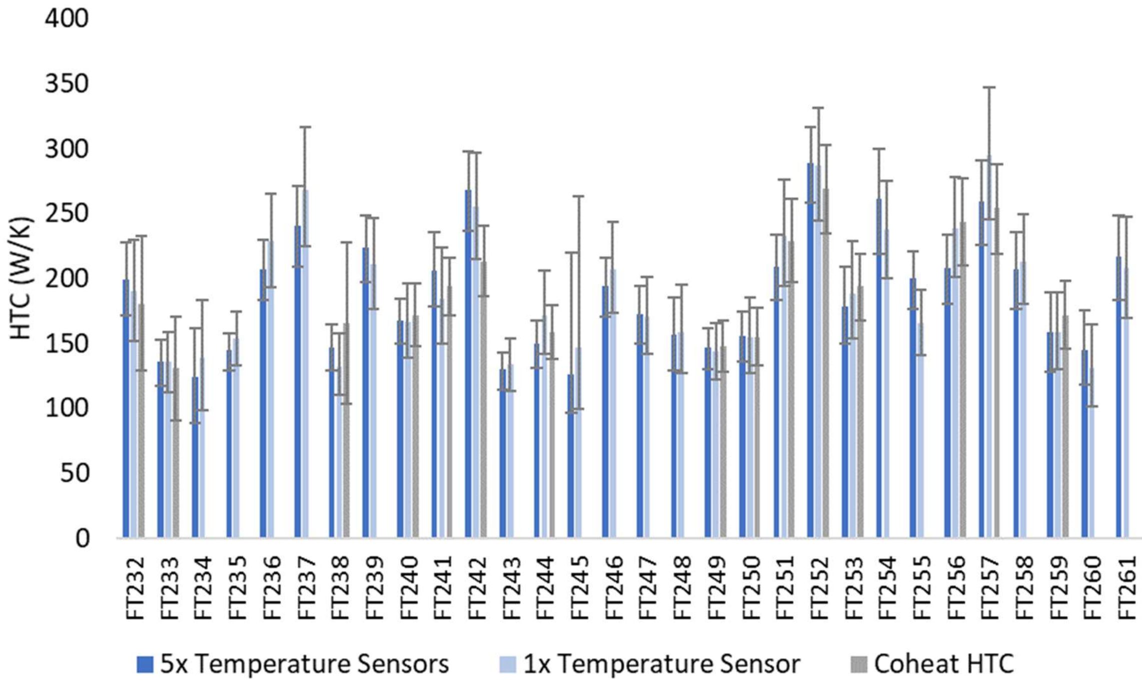

Figure 22: Comparison between SmartHTC results using 5x internal temperature sensors vs. 1 (placed at the main thermostat), for comparison the co-heat HTC is presented where available.

To further analyse the effect of using fewer temperature sensors on the HTC result and confidence interval, the proportional differences in results were compared (Figure 23). There was a range of approximately ±16% in the HTC values, i.e. the HTC measured using a single sensor can be anywhere between -16% and +16% of a 5x sensor approach.

This is significant because the average confidence intervals (across all field trial properties) for the 5x temperature sensor approach are -14.3% and + 15.4%. It is therefore possible that the measurement from a single sensor could fall outside the confidence intervals of a 5x sensor approach.

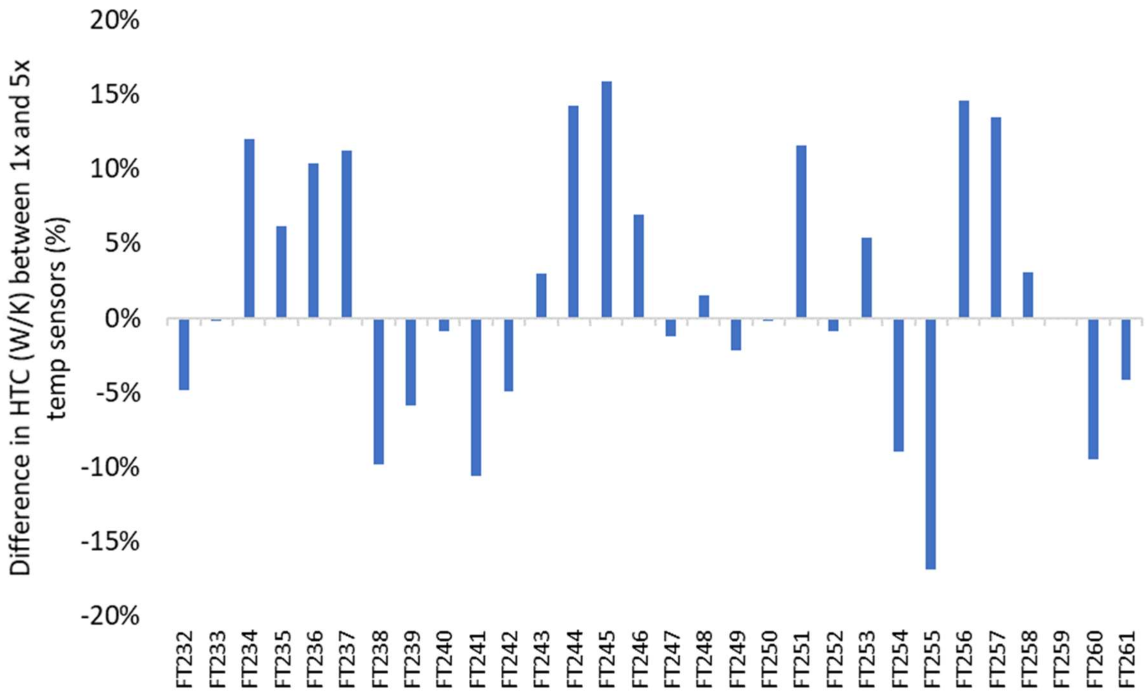

Figure 23: Proportional difference between HTC measurement using 5x internal temperature sensors or 1 (at the thermostat).

The SmartHTC algorithm has been developed to calculate the specific confidence interval based on the number of temperature sensors used. Therefore, the confidence intervals for a single sensor approach are different and are analysed in Figure 24 below. This graph shows the total confidence interval (-ve + +ve CI) for each TEST field trial property using each sensor method. The proportional difference between the results is shown on the right axis.

On average, the total confidence intervals for 5x temperature sensor are 25% smaller than those for a single sensor. In all but two instances, the total CI for multiple sensors is smaller than for a single sensor. The reduction in CI (i.e. improved accuracy) ranges from -9% to -43% across the field trial properties. It is worth noting that the average confidence intervals for a single temperature sensor (across all field trial properties) are; -17.8% and +20.5% (compared to -14.3% and + 15.4% for 5x sensors).

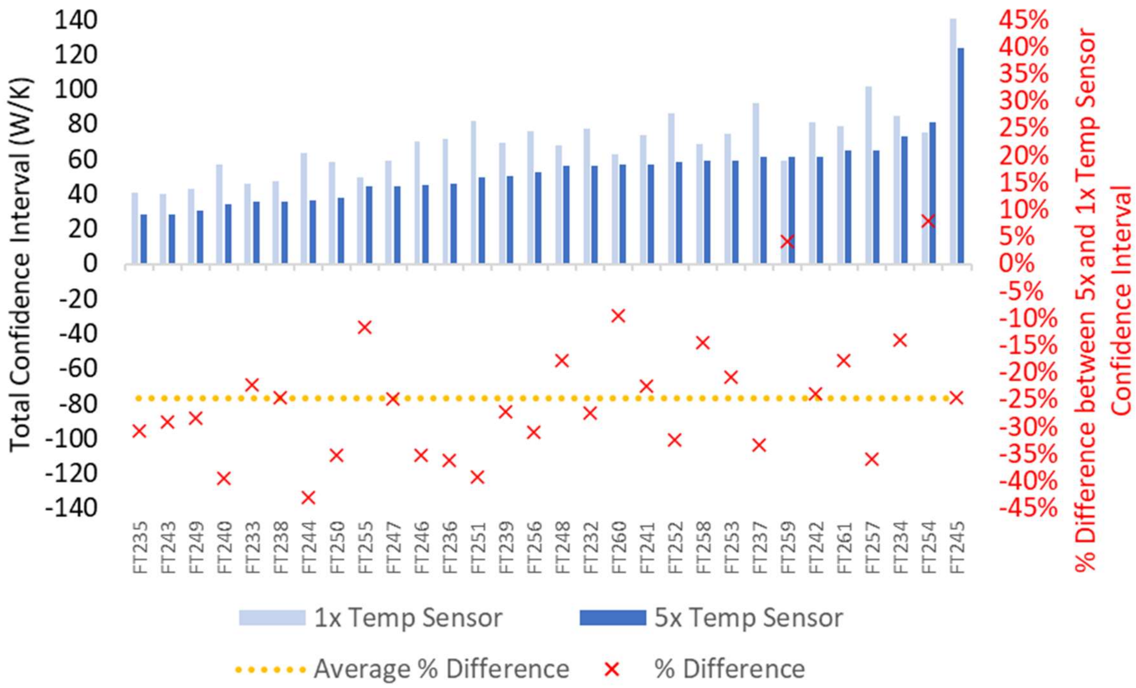

Figure 24: Total confidence interval size (CI, the range between the negative and positive intervals) and the percentage difference in the size of the confidence interval using 5x internal temperature sensors or 1 (at the thermostat).

Following HTC and CI analysis, a short investigation was undertaken to review the temperature variation across the field trial homes, to better understand if there was a consistent location that gave an accurate average internal temperature from a single sensor (if only one was used). Table 10 below shows the average internal temperature in each property and the individual room average temperatures. Rooms with average temperatures closer to the whole house average are highlighted in green. Those with poor agreement are shown in red.

The living room is marginally better than most other rooms for estimating the average, whole-house internal temperature from a single sensor. However, for some properties, it is the worst estimate. It is therefore difficult to specify a suitable location for a single sensor to improve accuracy.

Average Internal Temp (SmartHTC)							
	Average	Living	Kitchen	Main Bed	Thermostat	Spare Bed	Bath
HH01	21.15	21.24	20.91	20.82	21.06	21.71	-
HH02	24.07	-	-	-	-	-	-
HH03	18.63	-	-	-	-	-	-
HH04	21.37	22.52	20.08	22.57	20.88	-	20.80
HH05	21.29	22.22	20.43	21.56	21.02	-	21.22
HH06	20.04	20.78	19.79	20.33	18.62	-	20.69
HH07	17.23	17.75	16.45	17.96	16.79	-	17.18
HH08	20.16	20.34	19.56	20.21	20.94	-	19.77
HH09	16.91	17.08	15.49	18.03	-	-	17.05
HH10	16.25	16.98	17.34	15.32	16.04	-	15.59
HH11	19.86	20.27	19.91	20.07	20.37	-	18.70
HH12	20.48	20.98	19.10	19.25	-	-	22.60

HH13	17.36	16.44	20.08	17.42	18.10	14.74	-
HH14	12.92	-	-	-	-	-	-
HH15	20.19	19.48	19.73	20.89	20.69	-	20.18
HH16	19.27	19.41	18.11	20.49	18.47	-	19.87
HH17	17.74	18.04	17.27	17.66	17.38	-	18.38
HH18	20.82	21.38	22.17	20.91	21.22	-	18.43
HH19	19.03	20.36	18.94	19.69	19.65	-	16.52
HH20	19.58	21.21	21.52	18.95	18.12	-	18.12
HH21	19.87	20.06	21.27	19.20	-	19.35	19.49
HH22	18.74	18.93	18.03	19.62	18.94	-	18.18
HH23	22.40	24.10	22.53	20.72	22.24	-	-
HH24	19.01	20.86	18.38	20.09	17.53	18.21	-
HH25	22.66	22.22	24.14	23.15	23.16	20.63	-
HH26	20.13	20.27	20.24	21.09	20.96	18.07	-
HH27	20.26	20.20	20.20	20.38	19.80	20.73	-
HH28	19.06	19.71	19.88	18.33	18.32	-	-
HH29	19.31	20.56	19.53	19.55	18.48	-	18.44
HH30	20.73	21.07	20.70	20.35	21.39	-	20.14

Table 10: Average internal temperature and per sensor average for field trial properties

In summary, a number of conclusions can be drawn;

- Using a single temperature sensor (at the thermostat location) is viable and can provide a reliable measurement of an HTC.
- Using multiple temperature sensors systematically improves the confidence interval that is reported with the HTC value. This is logical as a primary input for the calculator is "average internal temperature" and so better measurement of this directly improves the accuracy of the system.
- Based on individual room temperatures there is not a clear location that would be most suitable to increase the accuracy of a single sensor system.
- Utilising multiple sensors enables other metrics to be reported more usefully within a property, including (for instance) damp and mould risk, and overheating risk.

6.3. Building Information

SmartHTC users are required to provide a small amount of information about the dwelling for which they're calculating the HTC, further to this they can provide a set of optional additional pieces of information to increase the accuracy of the HTC calculation.

During the development of SmartHTC the calculation of the confidence interval was designed to take into account which pieces of additional information (if any) had been provided. A sensitivity analysis was carried out upon the results to test the assumptions inherent to the algorithm design, and to understand the effect on the HTC result of providing the additional information.

For each of the HTC calculations in the field trial the HTC was calculated with and without all of the available building information, each piece of additional information was then added separately and the effect on the HTC and confidence interval observed. The effect of each variable was studied separately as each dataset could have a different range of optional information, so that a direct comparison between the HTC with no optional data and all optional data across the field trial sample could be biased.

The results of the sensitivity analysis showed that the effect of including each of the optional variables is rather small, with none over 5% (Table 11) providing confidence in the assumptions within the algorithm. Providing the additional information generally decreases the size of the confidence interval, again by a small amount in each case. The following sections provide more information for each variable.

Variable	Mean Effect on HTC	Mean Effect on Confidence Interval Size
Boiler efficiency	+3.2%	-4%
Window dimensions and orientation	-5%	-7%
Window type and overshading	0%	-1%
Number of occupants	0%	+3%

Table 11: Results summary of the sensitivity analysis, showing the effect of providing optional additional information on the calculated HTC and confidence interval compared to a calculation with no optional additional information.

6.3.1. Boiler Efficiency

There were 262 SmartHTC calculations in the field trial sample for which the listed boiler efficiency was available, and the sensitivity analysis was carried out on this sample.

The calculated HTC was 3.2% higher on average when the boiler efficiency was provided compared to the calculation with an assumed boiler efficiency across the 262 properties where the efficiency was available. There was quite wide variation in the effect of providing the efficiency (Figure 25), with a standard deviation of 3.1% and outliers of 6.5 and -6.3%.

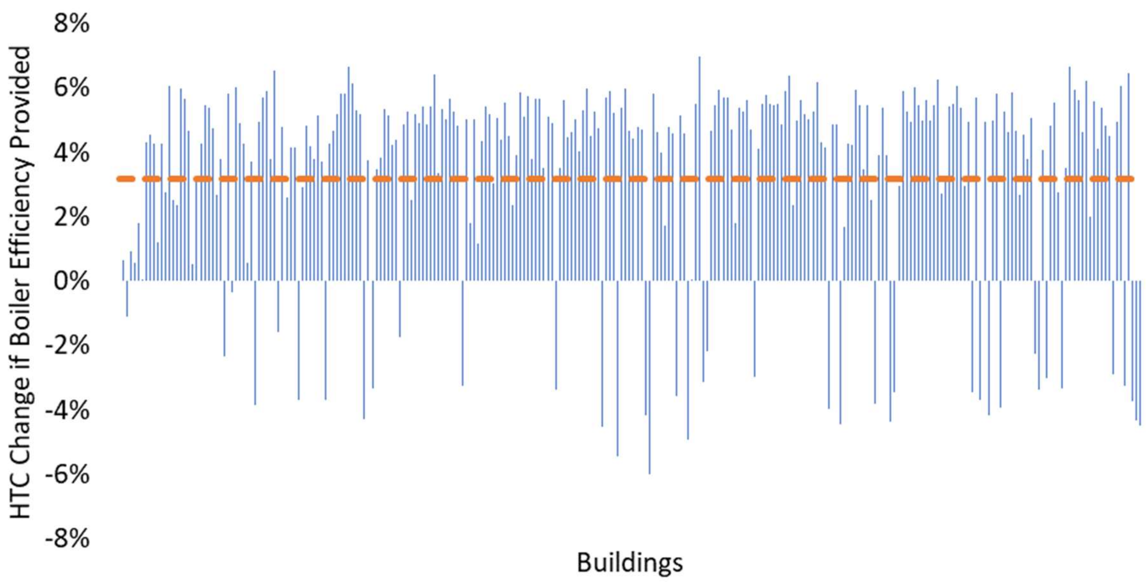

Figure 25: Percentage change in calculated HTC if boiler efficiency is provided.

When shown as a histogram (Figure 26) it's even more clear that there is a clear skew towards an increase in the HTC when the boiler efficiency is provided. The HTC is higher in these cases because the boiler efficiency was higher than the assumed value, as a result a higher heat input was calculated for the same gas input which in turn resulted in a higher calculated HTC value. The mean boiler efficiency across the sample where it was provided was 88.5%, compared with the assumed value of 84%.

The histogram (Figure 26) also shows a smaller group to the left where the HTC was reduced with the boiler efficiency input, this indicates that the listed boiler efficiency was lower than the assumed value of 84%. If the assumed boiler efficiency was increased, then the HTC calculation without the efficiency input would be closer to the value when it is provided in the vast majority of cases. While this is positive, increasing the assumed efficiency would also significantly increase the risk that the HTC calculation using an assumed efficiency would be incorrect for these few cases where the listed efficiency was lower than 84%. On balance, the assumed efficiency is suitable to minimise the risk of an incorrect HTC calculation despite the actual listed efficiency being higher in the vast majority of cases.

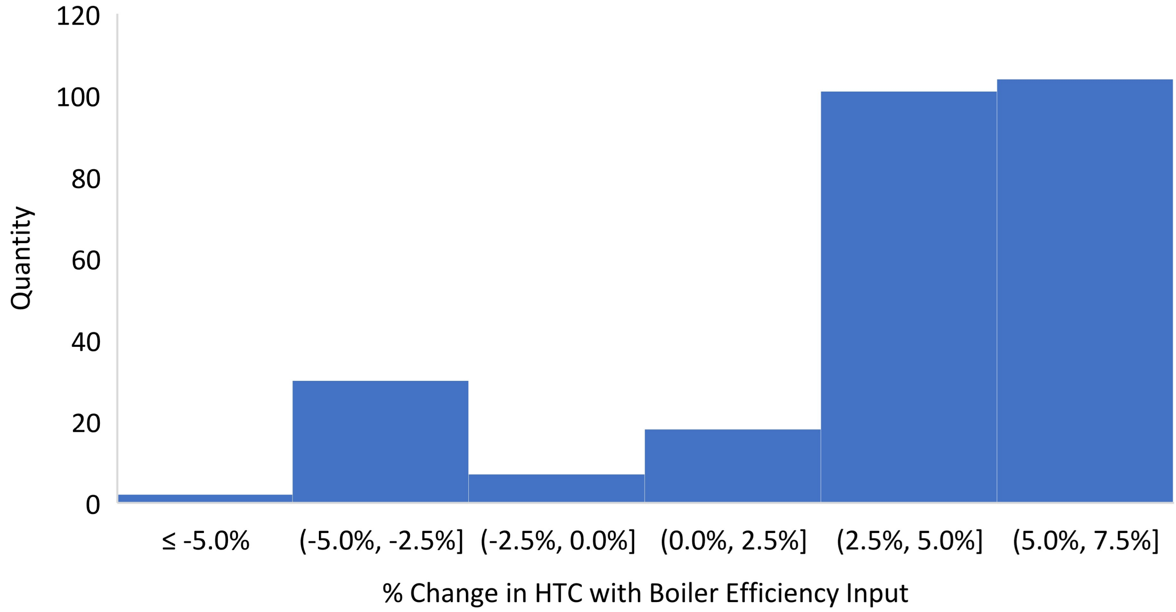

Figure 26: Histogram showing the effect of providing the boiler efficiency.

Inputting the boiler efficiency also has an effect on the confidence interval, compared to providing no optional information providing the boiler efficiency decreases the overall size of the confidence interval by 4%. The change is greater to the lower confidence interval than the upper confidence interval (Figure 27 and Figure 28), this is because studies have shown it is much more likely that in-situ boiler efficiency will be lower than listed than higher so that the uncertainty in the efficiency is asymmetric.

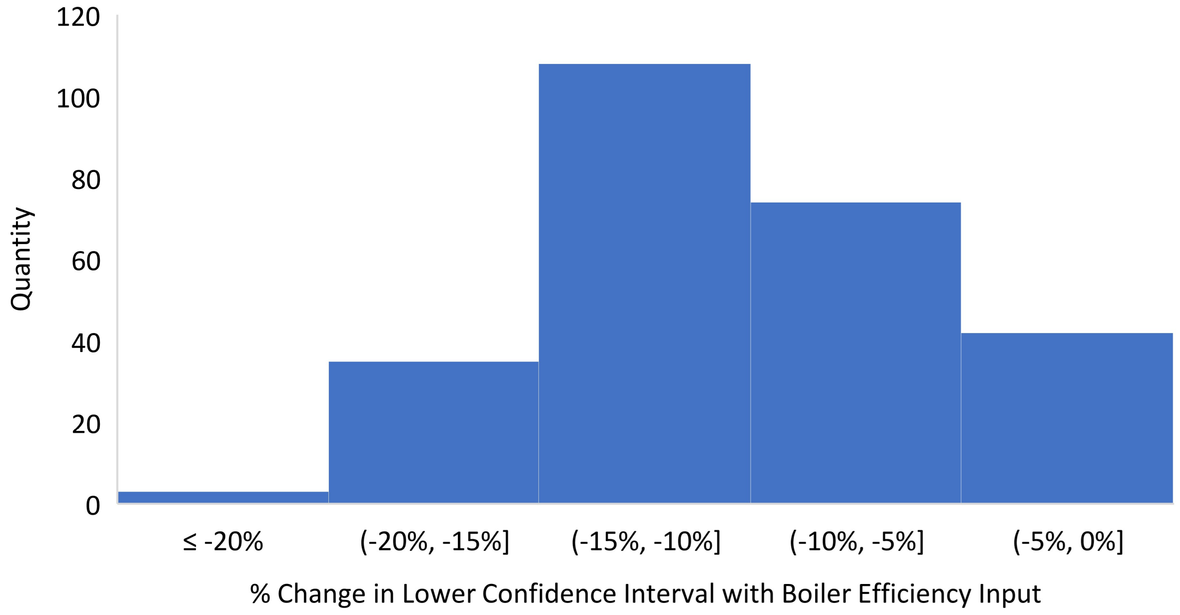

Figure 27: Histogram showing the change in lower confidence interval when the boiler efficiency is provided compared to the calculation with no optional data provided.

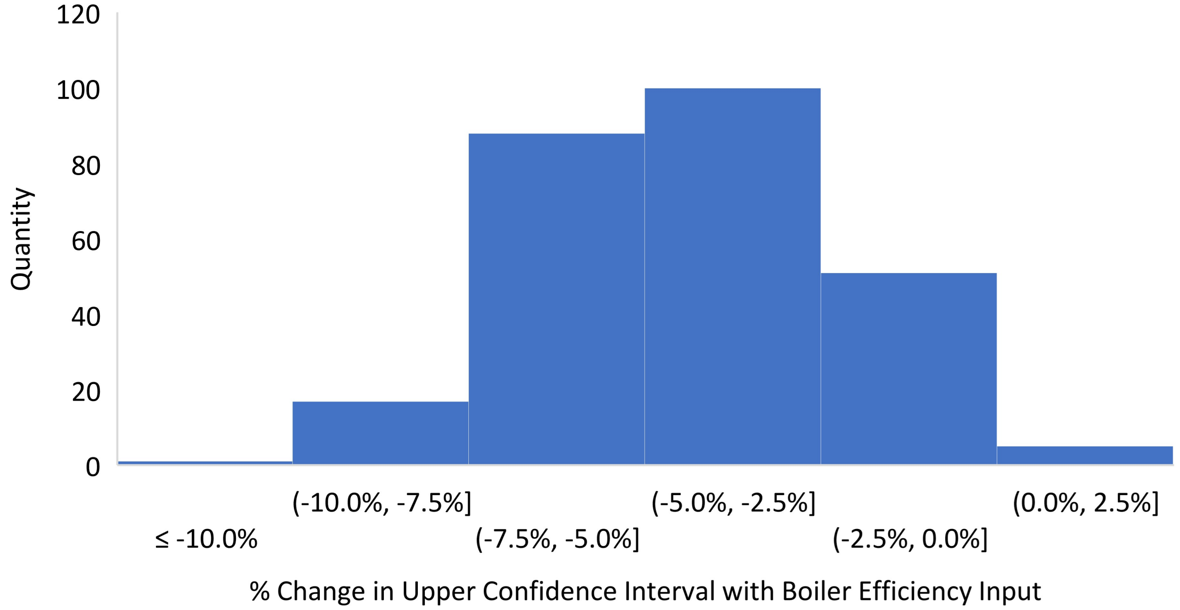

Figure 28: Histogram showing the change in upper confidence interval when the boiler efficiency is provided compared to the calculation with no optional data provided.

6.3.2. Window Dimensions and Orientations

Window dimensions and orientation are optional inputs to SmartHTC, with assumed values based on the available data about dwelling used if they are not. Dwellings are almost infinitely variable in their shapes and sizes, so an assumed value cannot be correct in all cases and the sensitivity analysis carried out to test the performance of the assumptions. There were 281 SmartHTC calculations with window dimensions and orientations available on which the sensitivity analysis was carried out.

Providing the window dimensions and orientations decreased the average HTC by 5% compared to the HTC with no optional data provided, with quite a wide range of results (Figure 29).

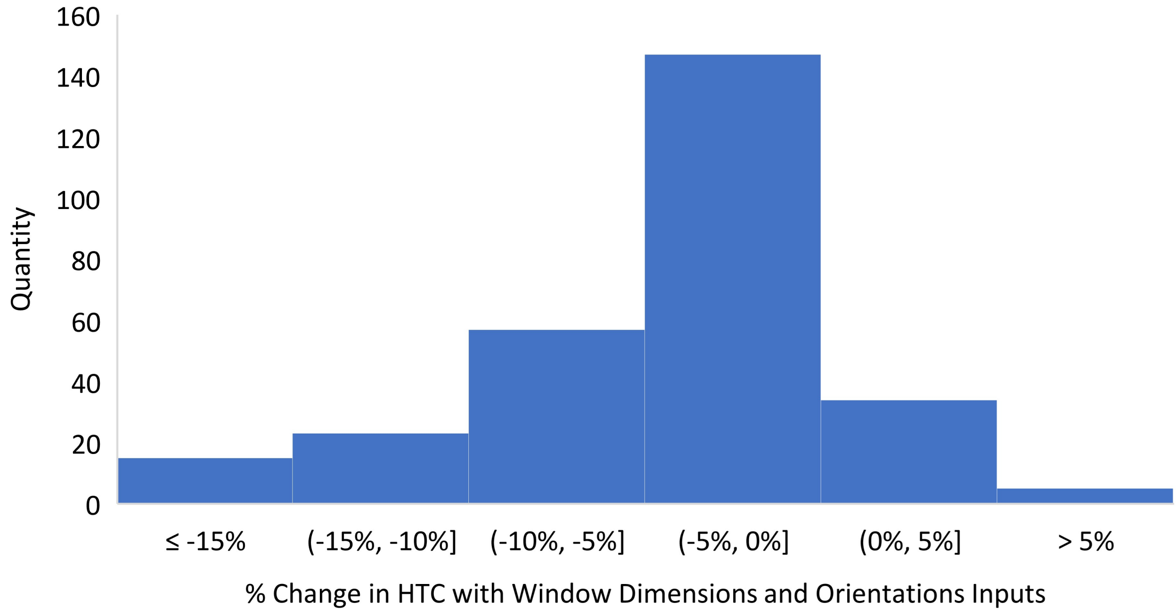

Figure 29: Histogram showing the percentage change in HTC if window dimensions and orientations are inputted.

Inputting the window dimensions and orientations reduces the size of the overall confidence interval by 7% on average. The changes occur evenly to the upper and lower confidence intervals (Figure 30 and Figure 31), there is a wide range in the effect for different calculations, reflecting the wide range of window arrangements in buildings.

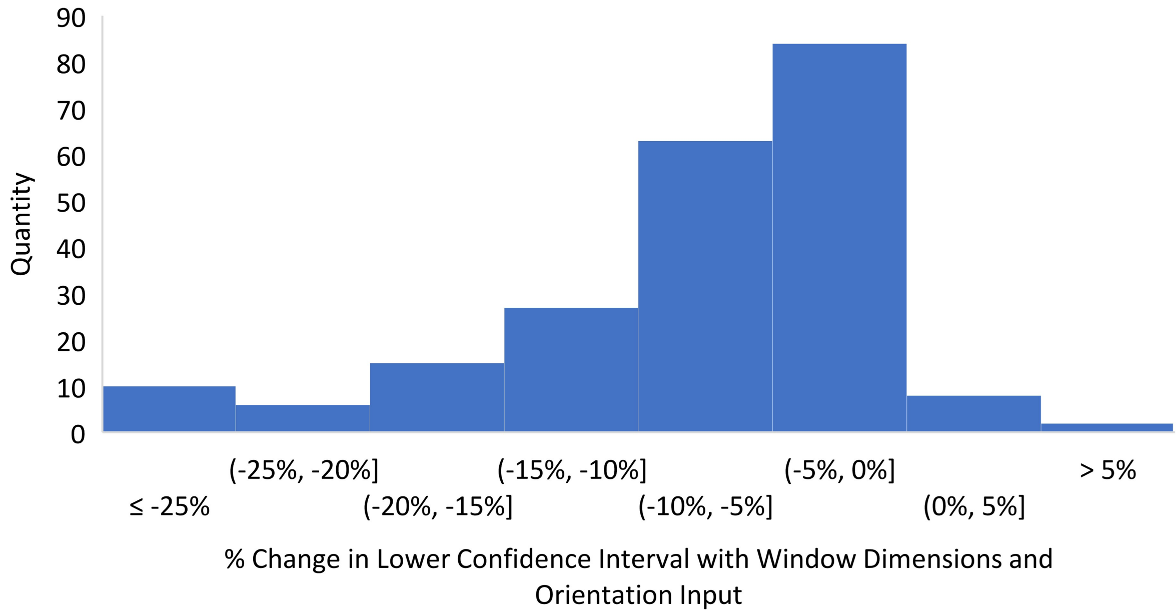

Figure 30: Histogram showing the change in lower confidence interval when window dimensions and orientations are provided compared to the calculation with no optional data provided.

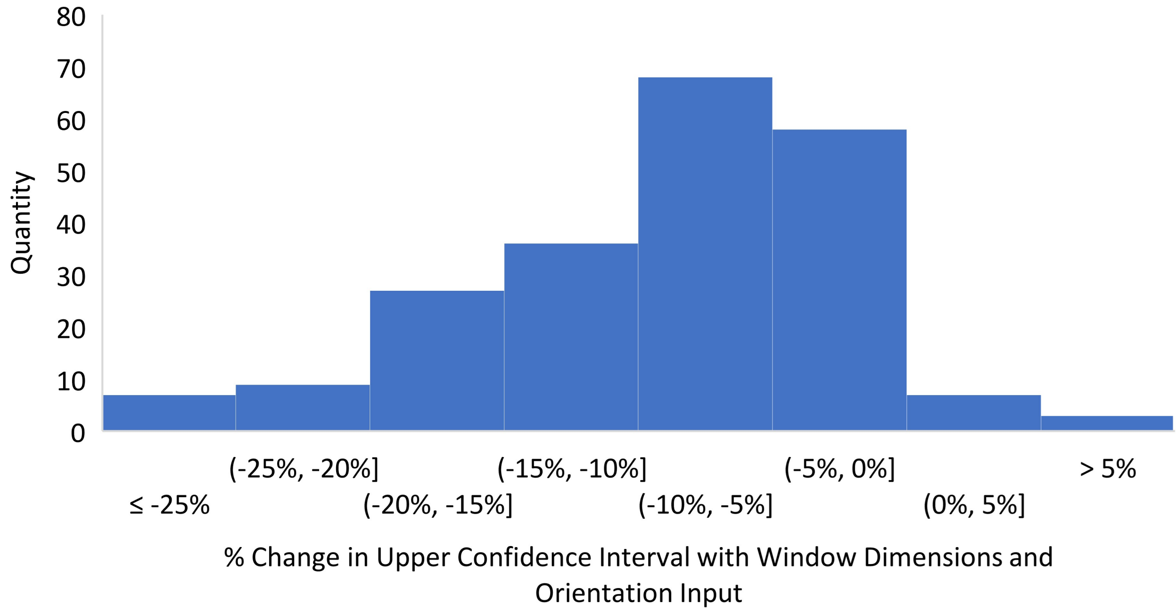

Figure 31: Histogram showing the change in upper confidence interval when window dimensions and orientations are provided compared to the calculation with no optional data provided.

6.3.3. Window Type and Overshading

As well as the size and orientation of the windows, SmartHTC users have the option to provide information about the glazing and frame type and the overshading of the windows. The overshading can only be provided as a single scaling metric, which is a rather blunt instrument, but at least allows some input.

There were 197 calculations across the field trial which had window type and overshading variables available and formed the sample for this sensitivity analysis. Providing all of these variables caused a change in the HTC of less than 1% on average, when compared to the HTC calculation without any of the optional additional information provided. This indicates either than the assumptions within SmartHTC are particularly good, or that the sample was not very varied. The confidence interval showed a similarly small effect, with the total size reduced by 1.5% on average.

6.3.4. Number of Occupants

There was a total of 215 calculations in the field trial for which the number of occupants was known and the sensitivity analysis was carried out on this subsample. There was little effect on the HTC calculation, with the result increasing by less than 0.5% on average, there was some variation in the effect but in the vast majority of cases the effect was less than ±2.5% (Figure 32).

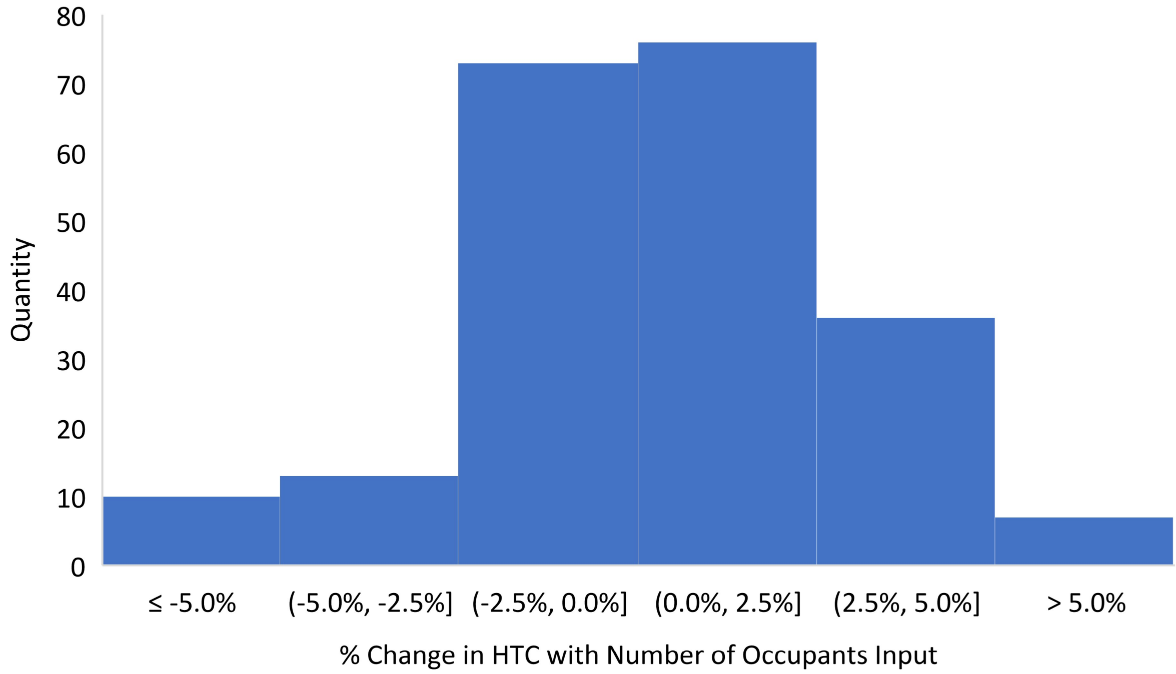

Figure 32: Histogram showing the effect on the HTC when the number of occupants is provided.

Adding the number of occupants input increases the size of the total confidence interval by 3% on average. In the majority of cases including the number of occupants slightly reduces the size of the confidence interval (Figure 33 and Figure 34), but in some cases the size of the confidence interval is increased by a larger amount. This is because in some cases the input highlights that a building is over occupied, and hence the metabolic gains form a larger part of the total heat gains. In turn, this means that uncertainty in this heat source causes a larger relative uncertainty in the total heat input.

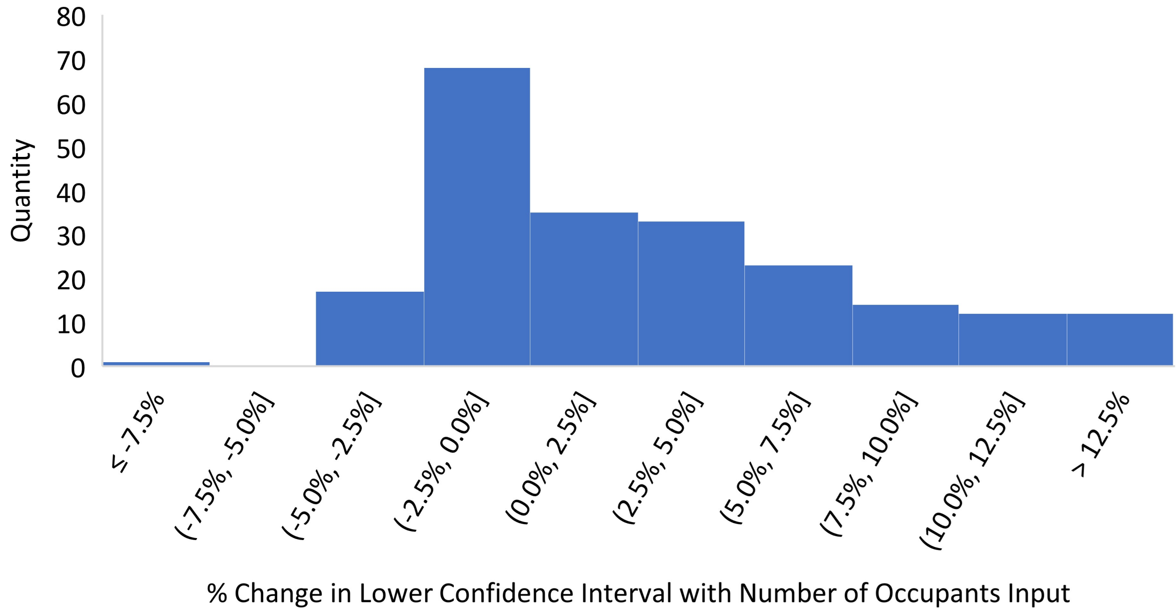

Figure 33: Histogram showing the effect of the number of occupants input on the lower confidence interval.

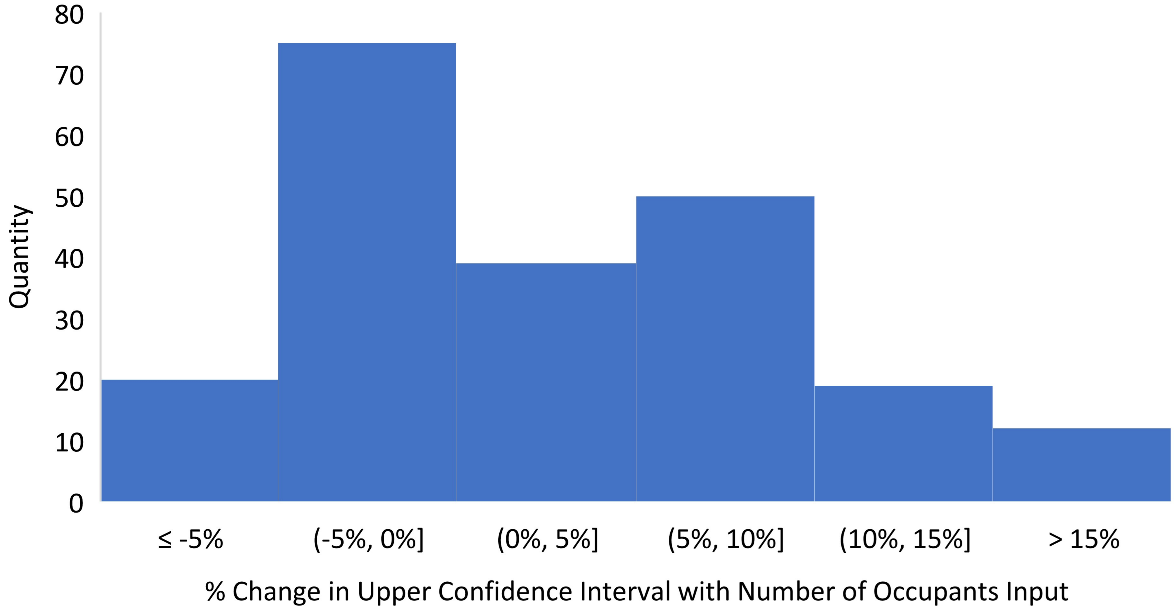

Figure 34: Histogram showing the effect of the number of occupants input on the upper confidence interval.

7. Practicalities

SmartHTC has been developed as a response to the problem that actual building performance measurement has been proven to be very valuable in demonstrating the performance gap, but too expensive and invasive to be widely used. A key determinant to the success of SmartHTC will therefore be the cost for a measurement and the disruption to the occupant.

7.1.1. Cost

SmartHTC can be carried out in two broad methods; either it can be delivered as a self-contained measurement service or integrated into existing hardware.

As a measurement service, the costs to the user include hardware, time to visit the house to install and remove the sensors, and cost to access the calculator. For integrating SmartHTC into existing hardware, the costs are to set up the integration and then a cost for ongoing usage.

Calculator costs are common to both product types. SmartHTC calculations are charged on a per use basis, with pricing based on the volume of usage ranging from 60p/calculation for a high user to £8/calculation for the lowest tier. Any user has the choice to use a web browser based user interface provided by BTS or to integrate directly with the APIs. The browser interface allows for simple entry of building information via input fields and drop-down boxes, and upload of monitoring data through a standard template csv. Alternatively, users can integrate through the APIs, these are relatively simple and BTS estimate that setting this up would take a developer no more than two days.

For the measurement as a service model, the SmartHTC user would also require sensor hardware. BTS can provide a set of five temperature sensors including a hub to allow remote access to the sensors for £200, the calculator is technology agnostic and any temperature sensors can be used for the data collection so users may already have the required equipment.

The most significant cost for a measurement service product offering is likely to be in the time required for an operative to visit the site, collect the building information and install the sensors, then return after the monitoring period to collect the sensors. Depending on which sensors are used, they may then need to be downloaded and the data arranged so that it can be uploaded to the user interface. Throughout the field trial it was found that half an hour was comfortably enough time for the first visit and 5-10 minutes enough for the second, the total time required per site would of course be heavily dependent on factors like the location of the site and the number of sites in a similar area.

Initial set-up and ongoing costs have been calculated for example users of both product offerings described (Table 12). The example users are a single operator running a small measurement service and a larger smart technology provider adding HTC measurement capability to their existing offering. In either case, the costs to the user are tiny in comparison to previous HTC measurement costs, which have been several thousand pounds for a co-heating test.

	Set-Up			**Per Property**		
Product Type	**Uses /Month**	**Hardware Cost**	**Integration/ training Cost**	**Site time**	**Calculator**	**Total**
Measurement service	30	£150	£300	30 mins	£8	Set-up: £450 Per calc: £8 + site/travel time
Integrated in smart tech	5000	n/a	Basic set up c.£1000	n/a	£0.60	Set-up: £1000 Per calc: £0.60

Table 12: Indicative estimated costs for example SmartHTC users.

The cost to a user providing a measurement service are similar to that for Energy Performance Certificate (EPC) assessors, in fact it may make sense to combine the two in order to enable a comparison between the predicted and measured performance for a dwelling. The per calculation costs for an integrator after the initial set up are such that for the first time, validated dependable HTC measurement may be readily integrated into a wide range of IoT based devices and service propositions.

Given the prevalence of EPC assessments today, with millions carried out, and the similar or much lower costs for SmartHTC it is clear that the method is highly scalable.

7.2. User Interface (UI)

A browser user interface has been developed to allow users to access SmartHTC without having to communicate directly with the APIs. The SmartHTC UI is designed to allow a simple upload of the required input data and near instant return of the calculated HTC.

It is intended to be used by potential new users to help them understand how SmartHTC works, and for users who do not wish to interact directly with the APIs. The UI is designed to carry out 1 HTC calculation at a time, so is more suitable for users carrying out small numbers of HTC calculations (i.e. in the 10s rather than 100-1000s).

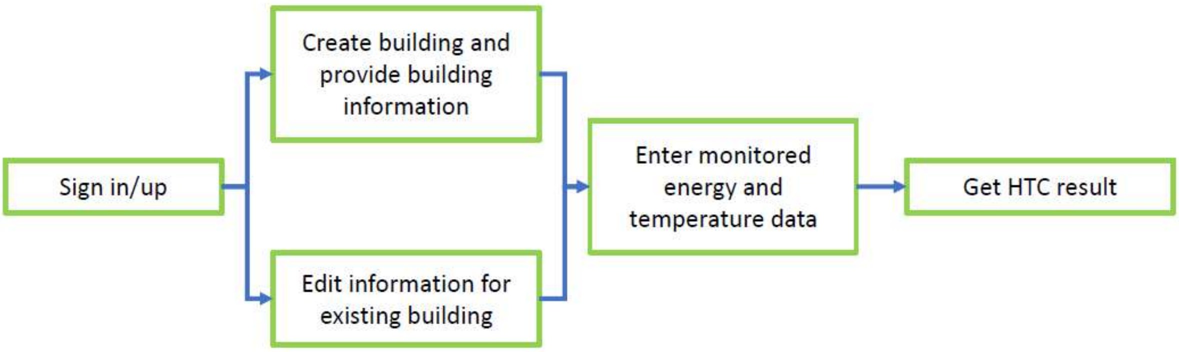

Figure 35: Basic process map for the SmartHTC UI.

The UI is simple to use, with a form to be filled in that guides the users through the required and optional inputs and how to upload monitoring data. The data for a single calculation can be inputted and the result returned within moments.

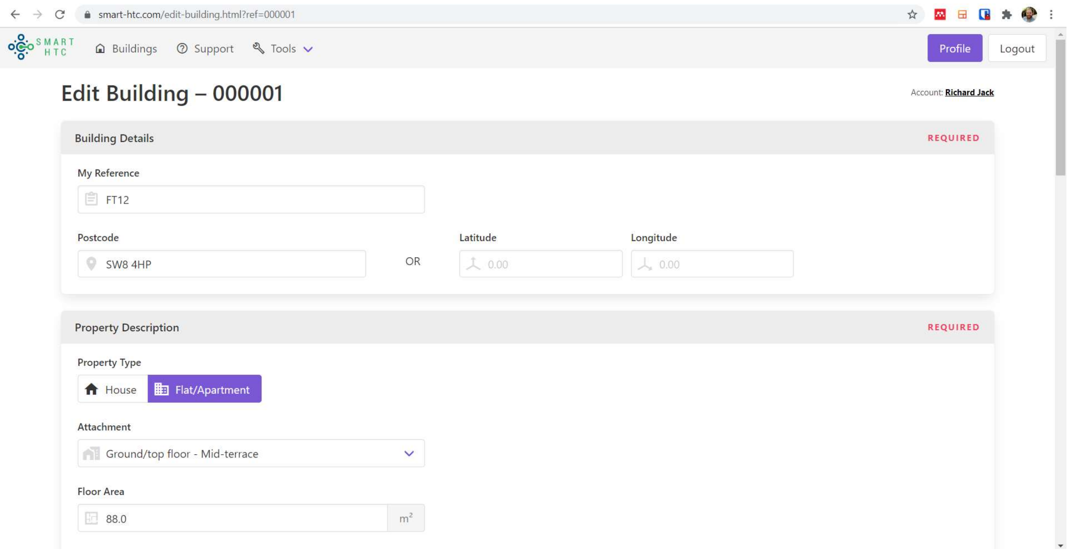

Figure 36: Screenshot from the SmartHTC UI.

7.3. Invasiveness

A key requirement for SmartHTC is that it can be applied without significant disruption to the occupant. In light of this, some qualitative research was carried out throughout the field trials to understand the experience from a resident's point of view.

During the field trial BTS staff made two visits to the property, and left temperature loggers (described in section 2.1.2) in place for at least 3 weeks. The residents were simply asked what their experience of the SmartHTC measurement was and how much impact it had on their use of their home. On the experience of having the sensors in place:

> *"They don't get in the way at all: unless you were actively looking for them, you'd hardly know they were there."*
>
> *"Not very invasive, the products are small and inconspicuous, you barely notice that they are there."*
>
> *"The sensors are placed out of the way, so much so that I often forget they are around the house until I stumble across one when cleaning."*

On the experience of installation:

> *"The installation and preparation was not at all disruptive. The installation of measurement devices took me about 15 minutes. The little measurement devices were unobtrusive and appeared to be quite robust and, because they were placed discretely, they only needed touching when I dusted"*
>
> *"The testing equipment was installed with no disruption, and when in place it was very discreet and easily forgotten about. The testing units are small and easily placed unobtrusively in different parts of the house. We really didn't know they were there. Having information tailored to the house is useful."*

In some cases BTS also carried out co-heating tests in addition to the usual two SmartHTC visits, some residents provided a comparison between the two methods:

> *"I went away for a few days and allowed Build Test Solutions to trial conventional co-heating against their new SmartHTC method. The co-heating test cost over £150 in electricity, involved loads of equipment being lugged into the house and it's no wonder only academics traditionally do this type of testing! SmartHTC on the other hand required just some temperature sensors and a couple of meter readings and provided the same result. All very exciting and crucially I now have a baseline measurement before embarking on some retrofit works. I have a serious heat loss issue I need to address!"*

> *"We had the HTC measurement and a co-heating test done at ours whilst away for X-mas last winter. During the trip we kept joking how we would get back to a burnt-down house, but BTS were very careful and effective in setting everything up and we needn't have worried. And the best thing: the days of invasive co-heating tests are over. With their new HTC measurement, you don't even need to be away to get a glimpse of the thermal properties of your house. I would recommend BTS to anyone planning a retrofit of their property."*

As part of the field trial BTS trained three people to carry out SmartHTC measurements, one of the installers provided some feedback on that experience:

> *"I was surprised with the ease of implementation of the Smart HTC when I first used it, and continue to be amazed, having now carried it out dozens of times. The equipment itself can be installed in less than 5 minutes and processing the data has been made very simple."*

These quotes reflect that the objective of providing a non-invasive measurement has been successfully achieved. The sensors can be placed discreetly such that people often quickly forgot that they were there. The installation process as well, with its light touch survey, was found to be completed quickly and without major disruption for both the resident and the installer.

The comparisons with co-heating tests in particular highlight the difference in experience between the two measurements. These respondents were both at the outset of a series of home improvement retrofit works in which they were particularly involved, which partially explains their particular interest in the measurement and highlights a group of potential early adopters.

8. Future Development

8.1. Damp and Mould Risk Indicator

The temperature and relative humidity sensors used in a SmartHTC measurement create a platform for insights into a building beyond its thermal performance. Condensation and mould growth risk has been identified as a first priority, due to the effect of poor air quality on health. The intention is that the likely occurrence of condensation and mould can be identified before it becomes an issue, stimulating appropriate and necessary improvements in insulation and ventilation.

There is a direct benefit of this analysis to social housing providers and owner-occupiers alike, particularly with increased use of homes for working due to Covid-19. When coupled with an HTC measurement as well as other BTS technologies, such as Pulse for measuring background ventilation, the team at BTS considers its mould and condensation risk indicator as another metric that stands to further strengthen the case for as-built/in-use performance measurement.

The current iteration of the BTS condensation and mould growth risk indicator uses three main SmartHTC dynamic inputs to determine the level of risk in individual rooms:

- External temperature
- Internal temperature (in 5+ rooms)
- Internal relative humidity (in 5+ rooms)

Additionally, the wall construction type is also determined to estimate the wall U-value, used to infer operating surface temperature. With these inputs, the algorithm runs multiple calculations to determine the level of condensation and mould risk, as follows:

1. **Dynamic Sedlbauer Isopleths:**

The Sedlbauer isopleths utilise the concept that mould growth is a by-product of both the internal conditions which are favourable for mould growth and the duration of exposure to those conditions. Mildly favourable conditions for a long period of time may present the same risk as very favourable conditions for a short period. The algorithm continually monitors the risk conditions and identifies when any of the durations exceed "safe" limits. For instance, in the example below, the 2day, 4day and 8day mould growth conditions are high risk and so the whole wall is at high risk of mould growth.

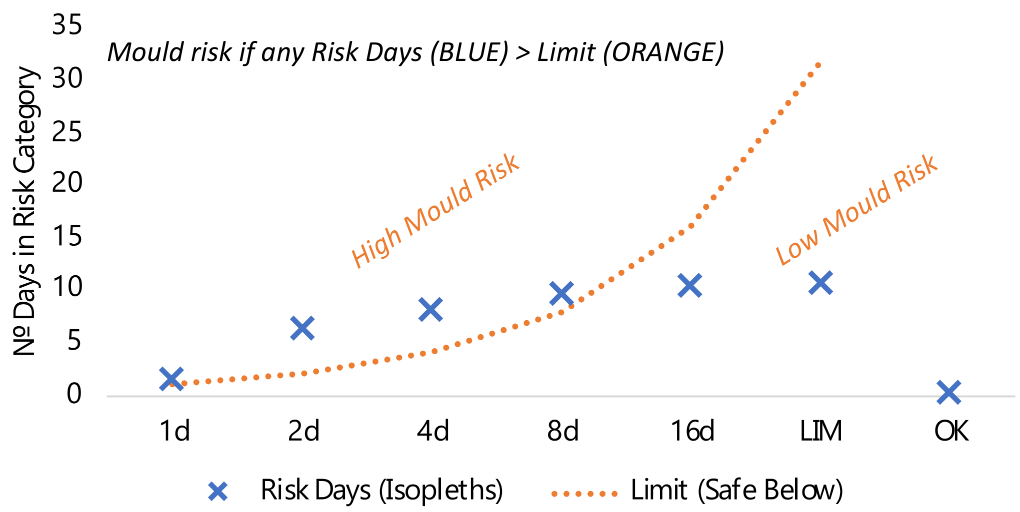

Figure 37: Output from Isopleth mould risk analysis. Any blue crosses above the orange dotted line show mould risk.

2. **Dynamic Dew Point Analysis**

a. Condensation: The difference between estimated wall surface temperature and dew point temperature is calculated. Condensation risk occurs when wall surface temperature < dew point temperature. In the example below, there is low (2.3%) condensation risk.

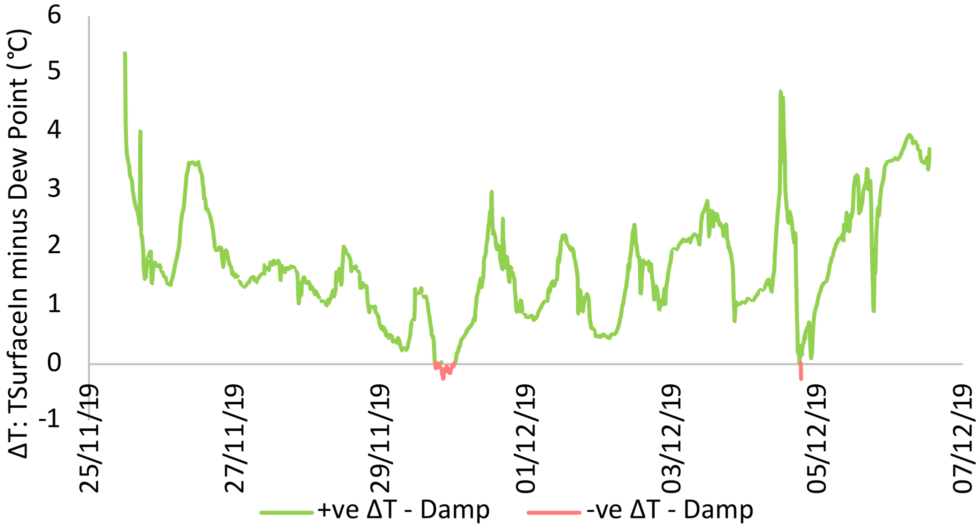

Figure 38: Output from dynamic dew point condensation risk analysis. Green data (+ve ΔT) and red data (-ve ΔT) relate to low and high condensation risk respectively.

b. Mould: The difference between estimated wall surface temperature and 80% RH dew point temperature is calculated (80% RH is assumed appropriate for mould growth). Mould risk occurs when wall surface temperature < 80% RH dew point temperature. In the example below (same wall as above), there is high (91.9%) mould risk.

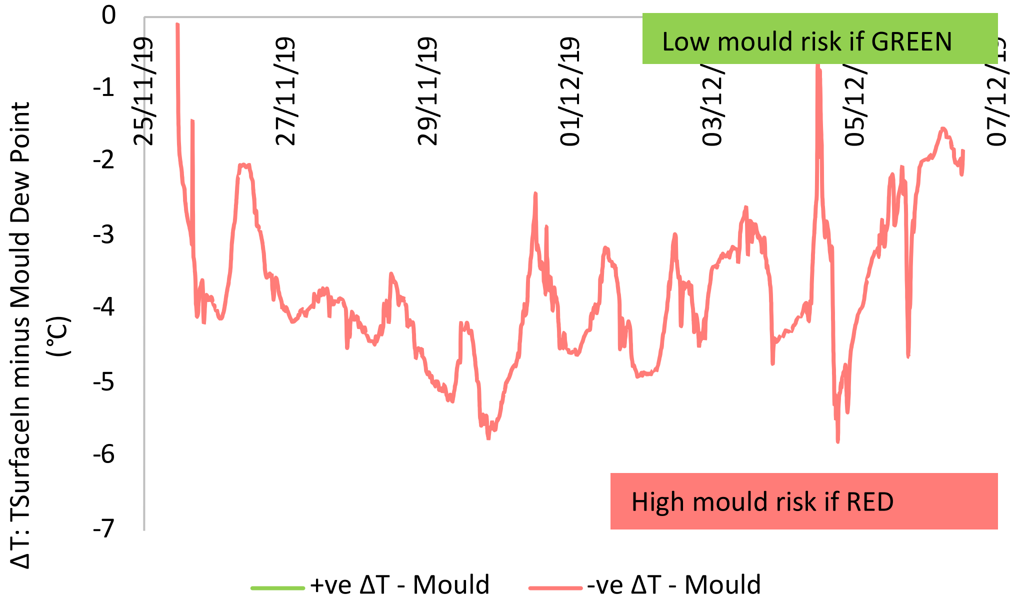

Figure 39: Output from dynamic dew point mould risk analysis. Green data (+ve ΔT) and red data (-ve ΔT) relate to low and high mould risk respectively.

3. Static Temperature Factor

Based on thermal bridging assessment from BRE IP 1/06 (and used in PAS2035), the bulk temperature factor of the construction is calculated and where this is < 0.75, a mould risk is noted.

Further development, refinement and field testing of these metrics is planned to integrate the risk indicator into the SmartHTC offering. The commercial model means that clients who wish to undertake thermal performance monitoring, could benefit from risk assessment, and vice versa. This would be possible at a small cost given that the same inputs are used.

8.2. Year-Round Measurement

SmartHTC is recommended for implementation during the winter months (October – March) and where the internal to external temperature difference is greater than 7°C. This maximises the certainty of the measurement and has shown excellent accuracy and repeatability throughout field trialling. However, it is recognised that year-round measurement would be beneficial to users, in particular new build where completion dates may not align with potential fabric testing periods.

To analyse and develop the potential for year-round measurement, extended monitoring in field trial properties is being undertaken. This includes months from April through September and all temperature differences greater than 0°C[13]. Figure 40 below shows an example of this measurement in a field trial property (FT252). The measurement period was from December 2019 through to August 2020 and each individual point (in blue) represents the 3-week HTC measurement (i.e. if only 3 weeks data had been collected at this point in time, a single point would be valid). The co-heat measurement is shown in red and it is clear that 100% of the SmartHTC measurements agree with the co-heat value (i.e. their confidence intervals overlap). Whilst there is some variability in the measured HTC (some of which may be expected due to the specific building physics), the overall result is highly repeatable and could be suitably undertaken in the summer.

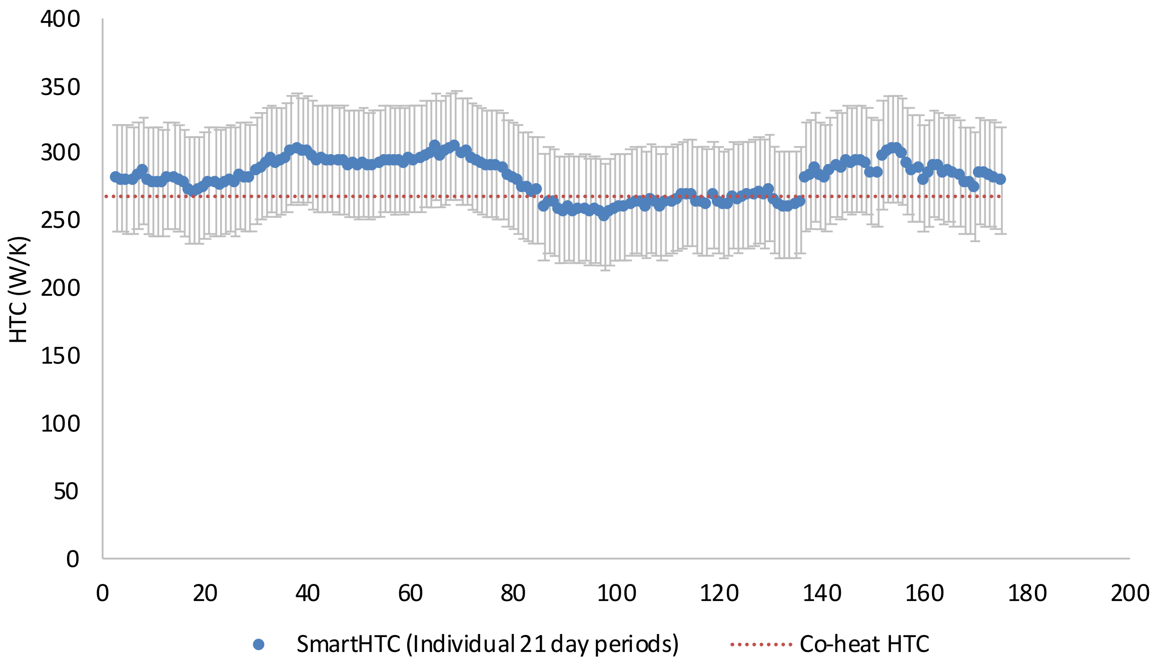

Figure 40: HTC measurements in Field Trial Property. (FT252), including summer; 23/12/19 to 6/8/20.

This is an example of a stable measurement. However, some properties exhibit reduced stability during the summer months and further investigation is required to determine the driving factors for variability. The intention is that if the factors can be identified more accurately then the algorithm can be refined and modified to accommodate them, therefore permitting year-round measurement.

8.3. Rapid Measurement

Reducing the measurement period from 21-days is of interest to enable rapid measurement of SmartHTC. An experiment using data from FT152 (shown below in Figure 41) shows the results of a

[13] Negative (average) temperature differences are not processed in the algorithm due to theoretical and mathematical complexity

7-day SmartHTC calculation. The variation is considerable when compared to the 21-day result (Figure 14). However, it must also be noted that 88% of the 7-day values showed agreement with the co-heating test result (including summer condition data).

Further investigation is required to analyse the feasibility of using a shorter monitoring period and any alterations that would be required to the calculation (and confidence intervals) to enable this. This work is ongoing.

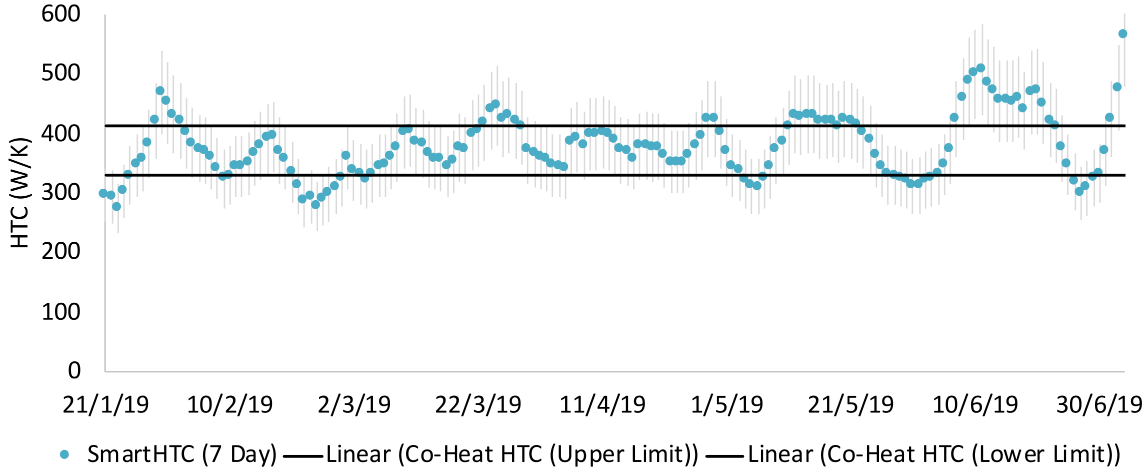

Figure 41: SmartHTC 7-Day Calculation Trial (FT152).

8.4. Interfacing with Smart Home Thermostats

The smart home technology market is growing rapidly, including a proliferation of smart thermostats (i.e. Hive, Nest, Evohome, Netatmo, Tado, Wiser, Switchee etc.). SmartHTC can accept existing datasets rather than requiring dedicated hardware to be installed and this presents another route to market for the system.

Some initial field trial work has been conducted to assess the feasibility of using smart thermostat data as an input for SmartHTC. The example below shows temperature comparisons in 4 rooms in one of the field trial properties which has a Honeywell Evohome system installed. Evohome utilises a digital TRV on each radiator and this data can be accessed via API. Section 6.2 reviews the impact of using a single temperature sensor for SmartHTC (which many smart thermostats would be limited to) which is why a case study with multiple temperature sensors was selected.

Data shows that the average internal temperature measured by the SmartHTC system was on average 0.8°C colder than the Evohome data. It's worth noting that this is the average across the whole house which included 8x Evohome vs 4x SmartHTC sensors. The graphs below show those rooms measured via the SmartHTC system and the Evohome. It is clear that in 2 rooms (living room and spare bedroom) the SmartHTC sensor showed significantly colder temperatures than the Evohome TRV. Across these 4 rooms, the average internal temperature measured via SmartHTC was 0.6°C colder than the Evohome measurement (similar to the whole house measurement). This is likely due to the location of the sensors (the TRV being attached to the radiator vs the SmartHTC sensors normally being located on a shelf in the room away from the radiator).

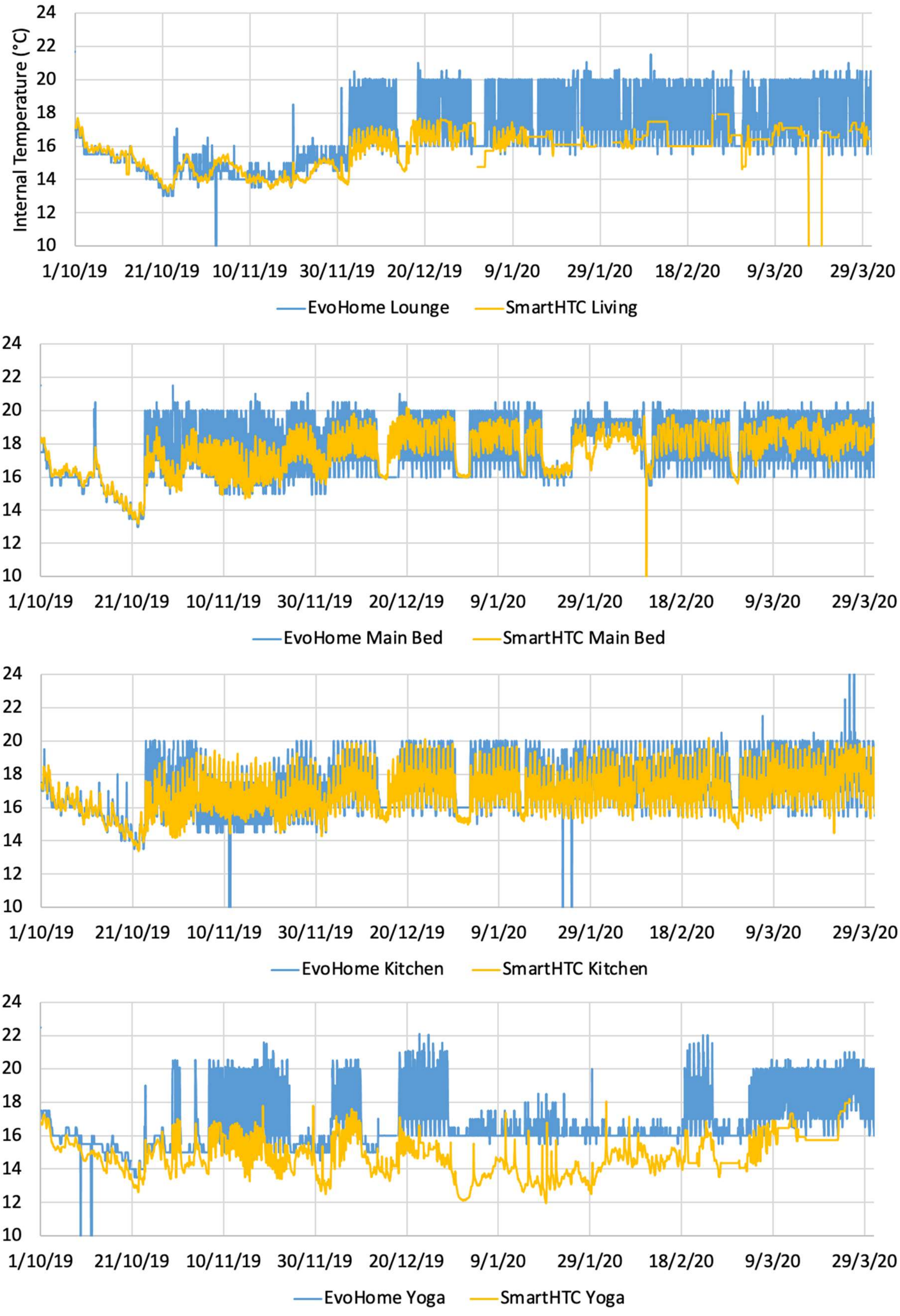

Figure 42: Comparison of SmartHTC (yellow) and Evohome (blue) temperature data in 4 field trial rooms.

The accuracy of existing data sources should be reviewed before processing a SmartHTC result and incorporated in the confidence interval. Fundamentally, connection to an existing temperature dataset is possible and further work will be conducted with different technologies to determine the best method for data access and integration.

8.5. Comparison with Predicted Performance

One of the clearest use cases for an HTC measurement is to compare the actual and predicted performance to identify and quantify a possible performance gap. This is important for both under and over performance, with unexpected performance having the potential to cause problems beyond energy consumption, such as damp and mould growth, fuel poverty, poor noise attenuation and high emissions.

HTC predictions are carried out on a mass scale at present, with the clearest example being through the EPC assessment. The EPC uses an HTC calculation, in addition to estimates of system performance, weather and occupant behaviour, to inform predictions of energy use, cost and emissions.

At present, HTC calculations carried out for EPC assessments are not stored in the central database or presented in the EPC, which makes comparison slightly more time consuming. BTS are working with others in the industry to promote the use of HTC and HLP as a fabric performance metric, and believe that the calculated values from EPC assessments are likely to be available in future.

The HTC is available through a full SAP calculation, however, which makes comparison with a measurement easy for newly built properties and by recalculation of EPC assessments for existing buildings and retrofits also.

Given the importance of the thermal performance of buildings, and the oft-repeated advice to use a fabric-first approach, the presentation and general wider understanding of HTC values is a major lacking piece of information about buildings. If knowledge of the performance gap is to become commonplace, which is essential to provide healthy homes and meet carbon emissions targets, then the thermal performance of houses must become a standard reported metric in energy performance assessments.

9. Summary

A major validation project has been carried out to that demonstrates the accuracy and repeatability of SmartHTC to measure the thermal performance of buildings. The method has functioned remarkably well, providing accurate and repeatable measurements across a wide sample of buildings.

A sample of 41 comparisons with a co-heating baseline test is not statistically significant, but when compared to a total of only a few hundred co-heating tests ever carried out represents one of the largest validations of an HTC measurement yet undertaken.

Beyond the comparisons with a measured baseline, the repeatability of the SmartHTC measurements was extremely high across different time periods in the same building. This is an important measure of the success of the test, as it indicates that the algorithm is successfully compensating for different weather conditions. It also provides assurances that the algorithm successfully accounts for variations in occupant behaviour, which are naturally likely to vary over time and in different seasons.

The size of the field trial sample has allowed further analysis to show that measurements can successfully be carried out using standard meter reading, removing a dependency on smart meter data which is yet to be ubiquitous. Measurements were also shown to be accurate when using a single temperature sensor, which opens more possibility for integration with smart technologies. This capability is limited to some extent by the size and orientation of the house to ensure that a representative internal temperature measurement is achieved.

The delivery of the field trial has demonstrated that the test is non-invasive, with residents' feedback that the sensors were very discreet and didn't interrupt their use of their homes. The application of HTC measurement at a scale never previously achieved demonstrates that the measurement can be carried out at a cost and time investment which is highly scalable.

- END -

Appendix I. Party Wall Adjustment Method for Co-heating Tests

Co-heating tests were conducted following the guidance provided by Leeds Metropolitan University[14] wherever possible. However, this method requires parallel control of adjacent properties, heating them to the same temperature as the test property to counteract any potential party wall heat loss (which is not included in the definition of the HTC). During field trial testing, it was not always possible to control adjacent properties. Two alternative methods were developed and implemented in these cases to adjust the measured co-heat to exclude any party wall contribution. These two methods are outlined below.

1. **Direct measurement of party wall heat flux**

Where adjacent properties cannot be controlled directly, it is possible to measure the heat flux to adjacent spaces directly via heat flux plates. Heat flux plates are installed on representative locations on party walls, floors and ceilings (when measuring flats). At least 2 heat flux plates are placed on each party wall and measurements of heat flux are recorded throughout the duration of the co-heating test. Total party wall heat flux is then estimated (for deduction from the co-heating energy balance calculation) by calculating the average daily heat loss (or gain) through each party wall. Table 13 below provides an overview of the calculation of daily average heat loss per party wall area.

	Heat Flux 1	Heat Flux 2	Avg. Heat Flux	Daily Avg. Heat Loss
Time	W/m^2	W/m^2	W/m^2	W
00:00	$HF1_1$	$HF2_1$	=average($HF1_1$,$HF2_1$)	= average ("Avg. Heat Flux") * ("party wall area")
00:30	$HF1_2$	$HF2_2$	=average($HF1_2$,$HF2_2$)	
01:00	$HF1_3$	$HF2_3$	=average($HF1_3$,$HF2_3$)	
…	…	…	…	
23:00	$HF1_{47}$	$HF2_{47}$	=average($HF1_{47}$,$HF2_{47}$)	
23:30	$HF1_{48}$	$HF2_{48}$	=average($HF1_{48}$,$HF2_{48}$)	

Table 13: Estimation of party wall heat loss by using heat flux measurement

The heat loss calculated by this method is then directly subtracted from the daily heat gain (heating + solar + metabolic + internal gains + hot water – ventilation – inferred party wall heat loss) and the HTC is then calculated normally.

In the absence of ability to control neighbouring properties, this method provides some logical adjustment to the measured HTC. However, it is limited in that;

- The party wall u-value may not be consistent and therefore the heat flux measurement location may not be representative of the average heat flux across the whole area. Multiple sensors are used to minimise the risk of this issue
- The adjacent temperature may vary across the party wall area which would affect the measured heat flux. Where possible, adjacent temperatures are measured directly, although this is generally also not feasible if adjacent control is not possible
- Any party wall "chimney" effect would be deducted from the HTC, whereas if the adjacent property was temperature controlled, this heat loss would be included (rightfully) in the heat balance

2. **Estimation of party wall heat loss**

[14] https://www.leedsbeckett.ac.uk/-/media/files/research/leeds-sustainability-institute/coheating-method-for-whole-house-heat-loss/lsi_cebe_coheating_test_method_june2013.pdf

Where it is not possible to measure the heat flux to adjacent spaces directly (either measurement equipment is not available or the location does not suit direct measurement), estimation of the party wall heat loss is required to adjust the measured HTC. To do this, the party wall u-value is estimated based on its construction (typically solid wall or unfilled cavity). For reference, the u-values utilised are:

- Solid Wall = 1.7 $W/m^2.K$
- Cavity Wall = 0.5 $W/m^2.K$

The estimated u-value is then multiplied by the party wall area to calculate an equivalent heat loss coefficient (W/K). This value is then multiplied by the temperature difference, estimated from the measured internal temperature minus an assumed adjacent temperature (18°C). The resultant heat loss (W) is deducted from the daily measured heat gain (heating + solar + metabolic + internal gains + hot water – ventilation – estimated party wall heat loss) and the HTC is then calculated normally.

If the internal temperatures are measured in the adjacent property, then the actual average adjacent temperature is used (although this is seldom possible).

This method is the least accurate option but necessary to adjust the test result to make some account for adjacent heat loss, particularly when high internal temperatures are used (>21°C). SmartHTC has the benefit that it is measured at normal operating temperatures and so party wall heat loss is low (compared to a co-heating test) because adjacent properties are more likely to have similar internal temperatures. However, there is always potential for under or over-heated adjacent properties and so SmartHTC accounts for potential party wall heat losses in the confidence interval.