Energy Pathology: Measuring a dwelling's energy performance using smart meter and IOT data.

Dr Richard Fitton, Reader in Energy Performance of Buildings.

Applied Building and Energy Research Group, University of Salford.

Abstract:

This paper aims to introduce and give an understanding of the process of determining a building's energy performance using smart meters and "on- board equipment" such as sensors found in smart thermostats or even low-cost sensing equipment. The rationale for this type of examination of a dwelling is given, alongside figures around accuracies, costs and time scales are highlighted. This will be presented alongside the current and more complex methods of measuring this type of performance indicator.

Introduction

A sensible and well recognised way of measuring the energy performance of a motor vehicle is well recognised in the UK as being the MPG (miles per gallon). Putting to one side the imperial misgivings of this measure, it is a figure that most people can understand and use to compare to other vehicles and to change driving habits for improved efficiency. This paper presents a similar approach to this for domestic properties. It allows for a dwelling to be compared to a modelled performance figure, another building, or baseline value.

This figure is known as the HTC (Heat Transfer Coefficient), this is defined in ISO 13789 as the "*heat flow rate divided by temperature difference between two environments*" It represents the steady-state aggregate total fabric and ventilation heat transfer from the entire thermal envelope in Watts, per kelvin of temperature difference (ΔT) between the internal and external environments, and is expressed in Watts/Kelvin (W/K) [1]. In straightforward terms this is a **Whole House Heat Loss** figure, and includes heat loss through conduction, convection (airtightness) and radiation.

To explain the HTC value in more detail; when a building requires either heating or cooling (more often than not in the UK domestic sector we add energy for heat) then a certain amount must be added to elevate the indoor temperature, however this amount of energy required is of course affected by the weather outside. The energy needed to lift the temperature by 1 degree Celsius is given in Watts and the difference between the internal and external temperature (known as the Delta T) is given in Kelvin. This presents us with the Watts/Kelvin figure.

It should be noted that this figure is not weighted or normalised in any way. A large home will generally have a greater HTC than a smaller home, and vice versa, in this way an HTC can sometimes be misunderstood if not explained.

The HTC is used extensively in building physics, energy modelling and research. It is, for instance a significant modelled component in the background of an EPC calculation. The value is useful as it can be modelled (this is typically the case) it can also be measured. This measurement is the subject of this paper.

[1] BSI, 'BSEN ISO 13789:2017 - Thermal Performance of Buildings - Transmission and Ventilation Heat Transfer Coefficients - Calculation Method', *October*, 2017 <https://doi.org/10.1016/j.ijar.2006.06.024>.

There are many reasons that this method can be employed, from quality assurance, validation of measures, calibrating energy models right the way through to pure academic research (which is the most common use currently). However, these can all be defined as Energy Pathology which is defined as follows:

The systematic investigation of the energy performance of buildings; with the aim of detecting any elements that's performance in energy terms is not as intended

Performance Gap

One typical and beneficial use of the HTC is to examine the performance of a building that has been previously modelled, here one can measure if the building is performing as estimated in terms of heat loss. This can be used to examine existing buildings, new buildings or buildings that have been subject to fabric improvements (pre or post retrofit). It is not unusual to find a gap between the modelled or predicted value for a property and the actual measured figure, this is generally known as the "performance gap". Studies have found these performance gaps to be upwards of 100% (the heat loss in the measured building was twice that of the predicted/modelled value) according to recent study by Leeds Beckett University in new build properties (n=25) this is illustrated below in Figure 1. It is important to note that all the buildings examined has greater heat loss than that predicted by the designers/energy model. Retrofit has similar issues with gaps arising of up to 71% between modelled and measured performance in UK retrofits found in a study by Leeds Beckett University [2]. The predicted heat loss in these cases are calculations using the SAP calculation methodology which is used for new build and existing dwellings in the UK

[2] Dominic Miles-Shenton, *Energy Efficient Renovation of an Exisiting Dwelling: Evaluation of Design and Construction and Measurement of Fabric Performance* (Leeds: CEBE, 2011).

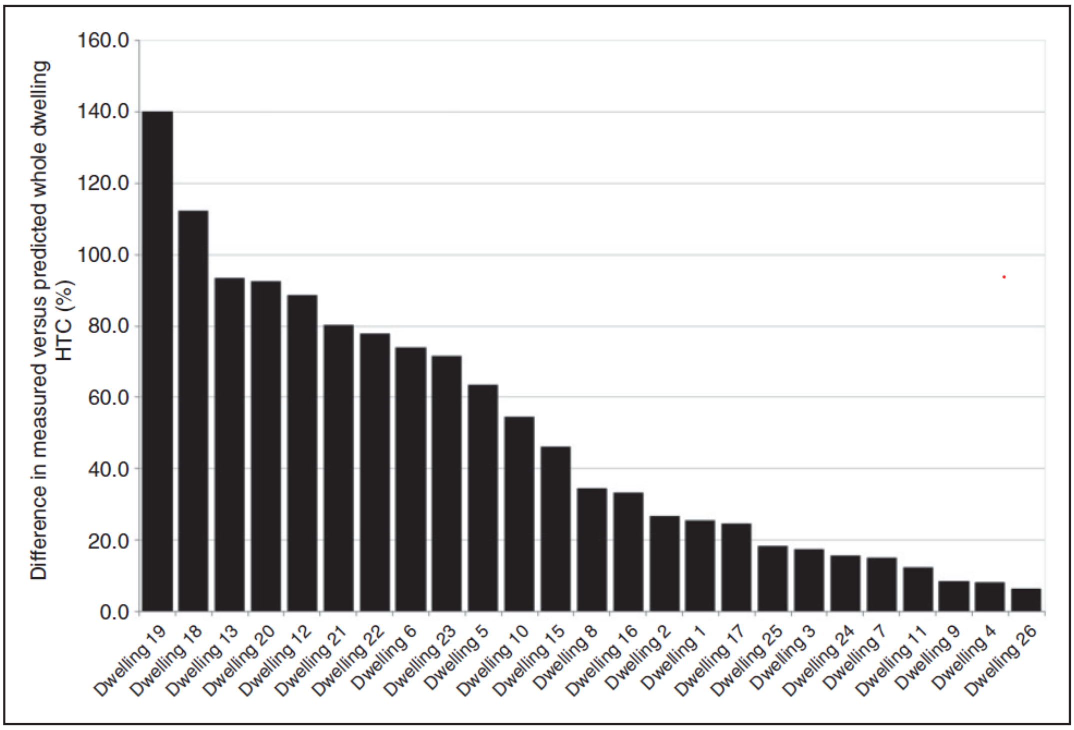

Figure 1 Results from a campaign of HTC measurement, illustrating the difference between predicted and measured heat loss in a sample of new build homes in the UK [3].

As more and more evidence builds towards the recognition of a performance gap in the construction industry, which was formalised in the Zero Carbon Hub in their report "Closing the gap between design & as-built performance" [4]. One of the main outcomes of this report was to define and standardise methods that could be used to identify and minimise performance gap issues. Ultimately, stakeholders need to know what is causing the gap, is it a modelling issue, is it construction quality etc? These investigation techniques are the topic of the next section in this paper.

How do we currently measure an HTC?

The generally accepted method of measuring the HTC is known as Coheating. This method provides the investigator with a complex method of defining/measuring the performance of a dwelling to a reasonably accurate standard, around 8-10% uncertainty is the current thinking around this method, although this is difficult to define [5].

The test method is simple in terms of experimental setup, an electric heater and fan is placed in the centre of each room of the home (more can be added if larger rooms are present or more heat loss is expected). These heaters raise the temperature of the home to around 25 °C, the fans ensure that

[3] Miles-Shenton.

[4] Zero Carbon Hub, *Closing the Gap between Design and as Built Performance* (London, 2014) <http://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf> [accessed 23 September 2015].

[5] Richard Jack and others, 'First Evidence for the Reliability of Building Co-Heating Tests', *Building Research & Information*, 46.4 (2018), 383–401 <https://doi.org/10.1080/09613218.2017.1299523>.

the warm air generated is well mixed to ensure homogenous heating throughout the home, an example of this equipment is shown in Figure 2. The method generally includes an air permeability, or "blower door test ". This helps to separate the component of heat loss attributed to air exchange through gaps in the fabric.

As this test can only be carried out during the heating season, arguably between October and March in the UK, this elevated internal temperature creates a difference in temperature between the inside and outside of the building. The energy needed to lift the building by 1 degree, can now be calculated, this calculation process is not intended to be the topic of this paper but can be found in a methodology produced by Leeds Beckett University [6].

Figure 2 Image of Coheating test being performed.

The process of measurement of the HTC is carried out infrequently in the UK, and indeed globally, for the following reasons:

I. It is costly, a typical Coheating test can cost between £6,000-£10,000, largely due to the required level of expertise, also initial equipment investment is costly;
II. It is time consuming; a typical test can take from 7-14 days dependant on the building and external temperatures;
III. It requires a vacant home; due to the requirements of a stable and evaluated temperature (25°C) this is not suitable for an occupied dwelling;
IV. It is cumbersome; many heaters and fans are required alongside a series of power and temperature measurement equipment;
V. There is a belief in industry that if the building is built "OK" and to design then it will perform so scant regard is given to extra measurements, construction tends to only do what regulation requires and not extras that are not seen to offer any extra value.

[6] David Johnston and others, *Whole House Heat Loss Test Method (Coheating)* (Leeds: CEBE, 2010).

These reasons do not paint the Coheating method in a good light, however the method is generally accepted to the be the highest accuracy testing method. Other similar methods provide a similar output but still require the home to be empty for several days or weeks with a substantial requirement for extra heating rigs and monitoring equipment, as well as requiring expert personnel.

All of the above reasons add up to a case to provide the whole house heat loss from a dwelling in less invasive ways. The response to this has been extensive, however it is NOT the purpose of this paper to go into depth about all possible ways of measuring this metric, this has been done in depth recently by several authors, the most comprehensive being Bauwens, this paper lays out in detail the Coheating and other in-situ based assessment techniques [7]. The next section will deal with the latest incarnation of the HTC, one which can be measured using only equipment that **already exists in the home**. These are known colloquially as **"on-board devices"** examples of these are as follows:

- Smart meters (Gas and electricity)
- Connected thermostats such as Nest and Hive
- Connected boiler systems
- Weather stations, personal/commercial

Smart meters

The UK has an adventurous smart meter rollout plan, with the aim to offer all households smart meters gas and electric by the end of 2024. This plan is well underway (although the rollout has recently been extended by 4 years) with 14 million meters currently installed in homes (8 million electric and 6 million gas) [8]. This rollout began slowly but has recently been accelerated, as shown in Figure 3.

[7] Geert Bauwens and Staf Roels, 'Co-Heating Test: A State-of-the-Art', *Energy and Buildings*, 82 (2014), 163–72 <https://doi.org/10.1016/j.enbuild.2014.04.039>.
[8] BEIS, *Smart Meter Statistics in Great Britain: Quarterly Report to End September 2019*, 2019 <https://www.gov.uk/guidance/smart-meters-how-they-work> [accessed 21 January 2020].

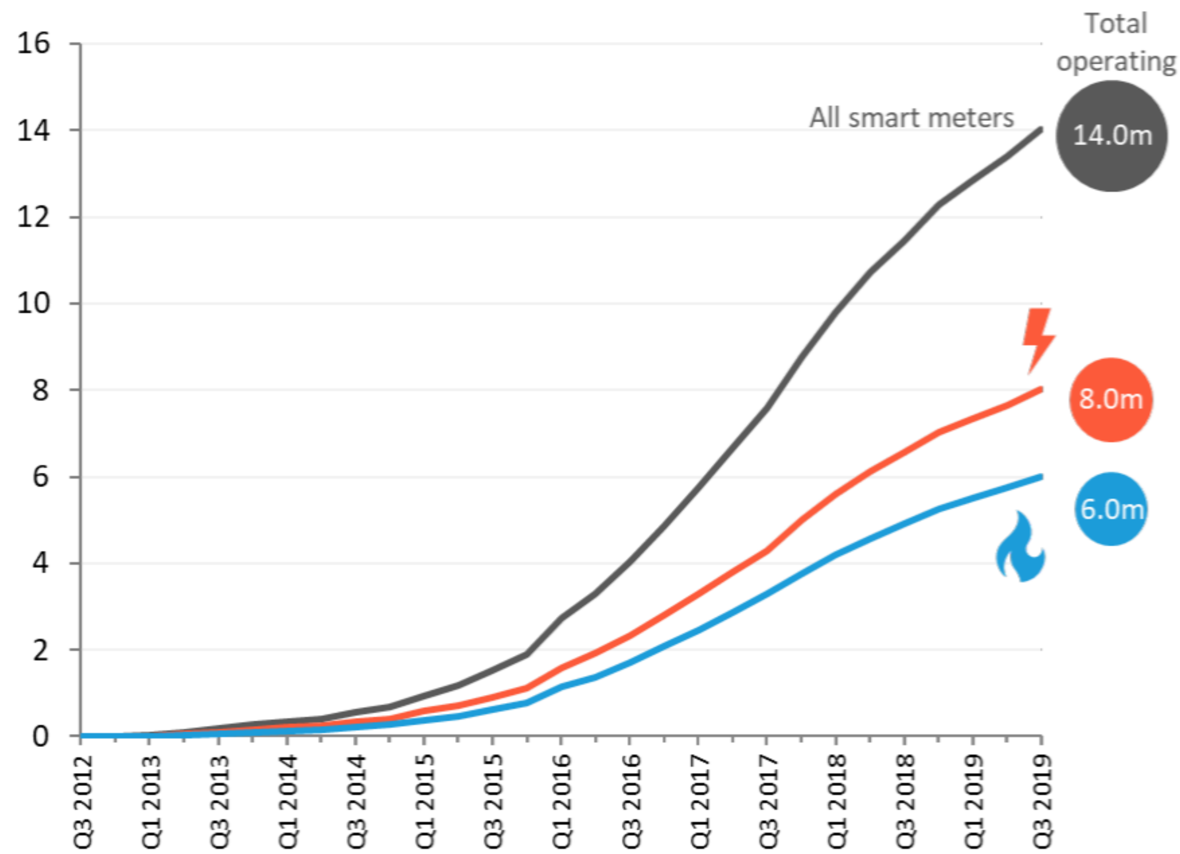

Figure 3 Illustrating the progress of the Smart Meter Rollout in Great Britain [9]

A significant innovation that smart meters introduce is the ability to access the energy consumption remotely from the meter, readings of 30 minutes for gas and up to 10 seconds for electricity can be accessed. This data can be acquired through the customer, a data portal or remotely using a consumer access device (A small box connecting the smart meters to the web). Previous to smart meters this process would rely on systems being added onto meters and other wireless communication system, which proved to be expensive and often fail [10].

This shift in technology make the data acquisition relatively simple and cost effective for a single property right through to large field trial of thousands of properties.

Work on this topic is being carried out globally, this work has also been accelerated over the past 5 years given the rollout of smart metering products and IOT devices globally. An example of this would be the rollout across EU states which is complete in some states and well advanced in many other states, this is illustrates in Figure 4 [11]

[9] BEIS, *Smart Meter Statistics in Great Britain: Quarterly Report to End September 2019*.
[10] Richard Fitton, 'Energy Monitoring in Retrofit Projects', in *Retrofitting the Built Environment* (Wiley, 2013), p. 256.
[11] European Commision, 'Benchmarking Smart Metering Deployment in the EU-27 with a Focus on Electricity', *European Commision*, 2014, 1–10 <https://doi.org/10.1017/CBO9781107415324.004>.

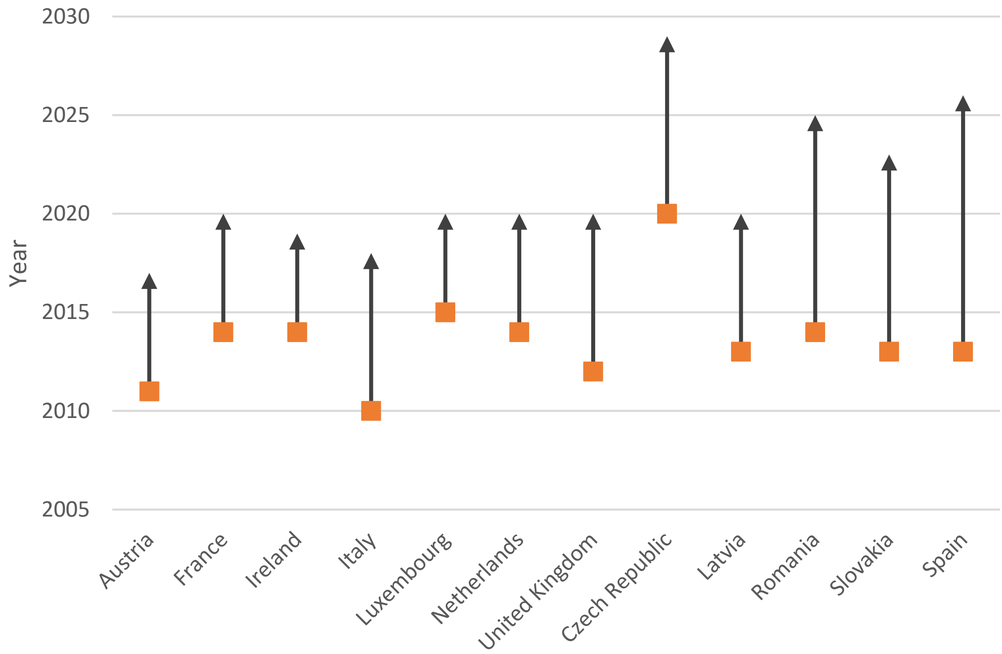

Figure 4 Installation programme for Smart Gas Meters in EU [12] Squares indicating the start date the states rollout, triangles indicating the completion date,(*some of these figures have changes since this report was collated)*

Smart Controls and IOT Devices:

Smart Heating Controls

There is an increasing prevalence of connected devices in homes. The exact numbers are not publicly but in 2018 the number of homes with a smart thermostat installed in the UK was estimated to be over 1.5 million [13], a conservative prediction by the author is that this figure could now be around 2 million. Many of these thermostats have the ability for the internal temperatures to be recorded, saved on a server and accessed by the customer. Researchers can access this data with the permission of the occupier.

External Temperature/Weather:

Whether making an in-situ measurement of an HTC or analysing on board data, the outside temperature is a key factor, this is one of the most important drivers for energy use in a building after all. Outside air temperature and solar radiation levels are the most frequently used inputs with some researchers also using wind and rain, but this is rare. Whilst some smart heating controls do have an external air temperature sensor (this is used to compensate for the weather) this is not often found. Another way to approach this is to use online historical weather data, this is collected from a portfolio of public and private weather stations and satellite data, and uses computer models

[12] European Commision.

[13] Energy Live News, 'Smart Thermostat Usage Hots up across 1.5m UK Homes - Energy Live News', 2018 <https://www.energylivenews.com/2018/04/04/smart-thermostat-usage-hots-up-across-1-5m-uk-homes/> [accessed 23 January 2020].

to interpolate , and interpret the weather further away from the stations, an example of this technology, Accuweather claims to accurately predict and log the conditions to a postcode level [14]

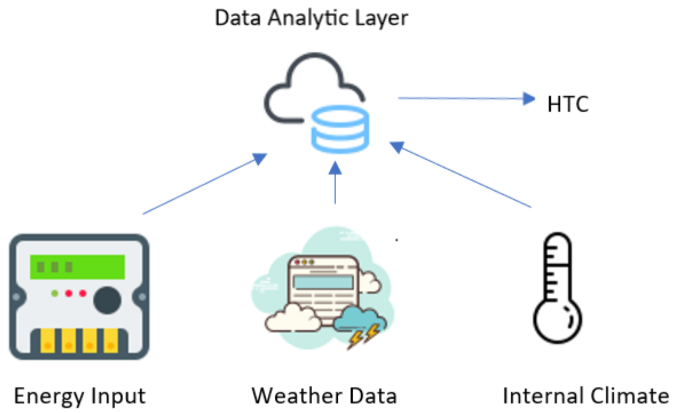

Figure 5 Diagram of inputs to the HTC process using IOT devices.

Research of Methods in a Controlled Laboratory

As with many research projects it makes sense to prove the theory before carrying out significant and expensive field trials. Fundamental research was carried out by the Applied Buildings and Energy Research Group (ABERG) at the University of Salford's Energy House. This work was funded Chameleon Technology UK Ltd, who supply smart meter in home displays in the UK.

The Energy House facility is a full-scale pre-1919 Victorian end-terrace house. It was built using reclaimed materials inside a climate-controlled chamber capable of reproducing a wide variety of weather conditions; this includes temperature variations between -12°C and 30°C, and the application of rain, solar irradiance, wind, and snow. The house, within the chamber, is shown in Figure 6. The construction of the house was completed to standards of the time, complete with solid external walls, single glazing, suspended timber floors, and a cold roof with 100mm of insulation. The adjacent building houses control facilities for the house and chamber and is heated to a constant 21°C.

[14] AccuWeather, 'AccuWeather APIs | API Reference', 2018, p. 2020 <https://developer.accuweather.com/locations-information#PostalCode> [accessed 23 January 2020].

Figure 6 The Salford Energy House: A full scale end-terrace dwelling inside a climate-controlled chamber.

A series of experiments were mapped out including the following scenarios:

1. A series of different weather profiles (autumn, winter and spring profiles; this type of work needs a heating load so the summer period is not effective).
2. Occupancy was simulated in the building using heat loads that switch off and on and set times, as well as window and door opening schedules and drawing off water from the hot water. The experiment was also run with no occupancy to simulate a holiday period, or a weekend away.

The unique aspect of the Energy House is the researchers know the actual HTC of the house, and have researched this aspect for over 9 years. So, the HTC "answer" is known with a high degree of confidence. Using this figure, we were able to process the experimental data through a variety of different data analytics methods and produce our results alongside the answer to quantify the accuracy of our methods. The spread of these results is shown in Figure 7 below. It can be seen some methods performed better than others with the most accurate method under these conditions being the method with an error of around 10% for some methods. Following on from this controlled study work has begun on a field trial of occupied homes with the initial results expected in Summer 2020

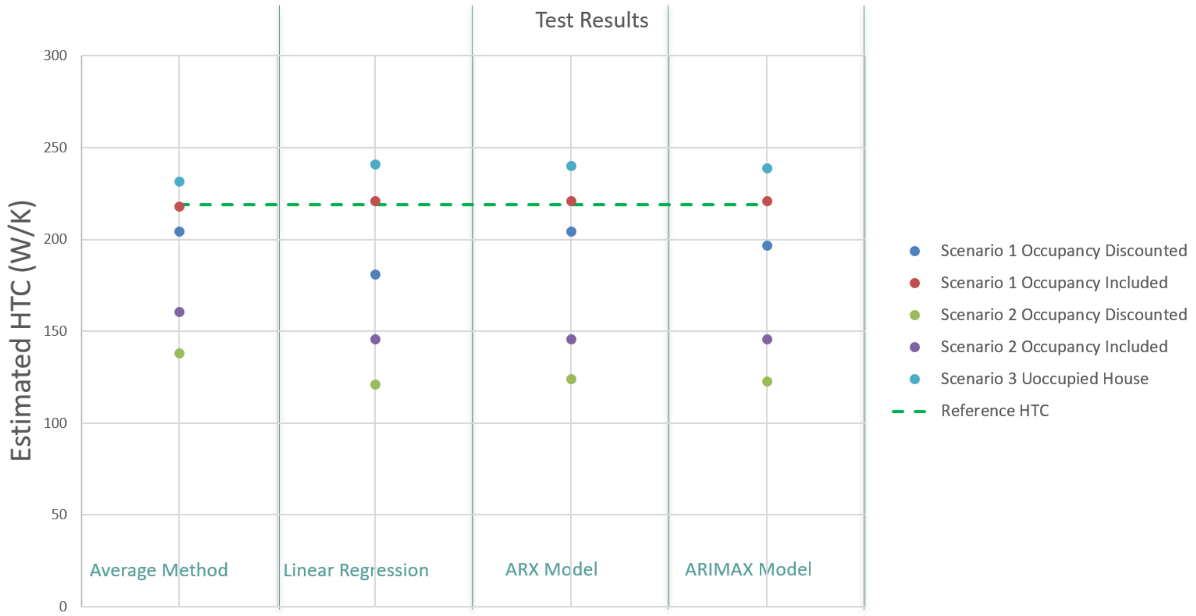

Figure 7 Range of results found during Energy House research project. Actual HTC is green dashed line.

In-Situ Research:

Controlled testing seen in the previous section, whilst accurate and reputable, and very suitable for the research of fundamental principles, does lack the nuance of variables found in the field, effects such as wind, solar gain and occupancy are very difficult to reproduce in the lab. It is for this purpose that when dealing with the building physics research field testing is crucial. The highlights of the recent in-site work on this topic is presented below.

Farmer carried out a series of test using a home's central heating system to estimate the HTC, he found that variance between this method and a reference Coheating test of between 2.5% and 8.7% the measurements taken were more detailed than simply using smart meters and on board devices, but could be rationalised If developed further [15].

Jack presents a methodology which can also use the heating system in a home (gas fired boiler) he found that in a case study of several homes that he was able to measure the HTC of a home within a 15% variance from a Coheating test this is known as the Loughborough In-Use Heat Balance (LIUHB) [16]

This work is continuing to be developed by both of these researchers, this topic has also developed significant interest in the UK, given the release of a £5 million funding pot by BEIS in 2018 to look at this exact issue [17]. This work is at the data gathering stage and has not been published, but with 8

---

[15] (Farmer et al, 2016)

[16] Richard Jack, 'Building Diagnostics : Practical Measurement of the Fabric Thermal Performance of Houses' (Loughborough, 2015) <http://www.lolo.ac.uk/wp-content/uploads/2015/09/RJack-Thesis.pdf>.

[17] BEIS, 'Smart Meter Enabled Thermal Efficiency Ratings (SMETER) Innovation Programme', 2018 <www.nationalarchives.gov.uk/doc/open-government-licence/> [accessed 28 January 2020].

large cohorts, some being led by world class organisations one would expect some significant shifts in the knowledge around this area. All projects are expected to be completed and to disseminate learnings by January 2021

International Research

As referenced above the UK is very active in the development of work around Coheating, and the ideas around HTC from metering and on-board data. However, work is progressing rapidly on the topic globally with the EU states carryon out much work:

Much of this work is being developed in a group overseen by the International Energy Agency, known as Annex 71 [18]. This is a collection of researchers from academia industry that have come together to form and validate methods to measure the HTC with smart meters and on-board data. Work in this group has been carried out since 2016 and will continue to run until 2021. The group has worked on all aspects of HTC including;

- Working with industry to understand their needs and requirements,
- understanding the data that is currently available in each country, from smart meters and other sources,
- the methods of processing and analysing the data,
- accuracy of the data analytics used,
- how the HTC metric can used and presented in industry.

This work is now a mid-point stage where researchers are working to assemble final report and the like, but the initial findings are interesting.

Researchers within Annex 71 are currently publishing results which show promise in terms of accuracy, and some interesting findings, as follows:

Senave for instance makes the following findings I some of the most recent and in depth work in this area [19].

I. Internal temperature is critical to collect, anticipating or estimating the internal temperature can lead to errors in the HTC of up to 26.9% compared to when estimated using data from the living room alone
II. Internal temperatures should be measured in more than one location, two is suggested. There appears to be a law of diminishing returns occurring, as adding seven room temperature sensors compared to only two sensors the HTC estimate is only changed by only 0.5%. This illustrates that the measurement of temperature is important but can be cost effective.
III. The measurement of the internal temperature should be measured at, at least each occupied/heated floor of the property.

[18] Staf Roels, 'EBC Annex 71 Building Energy Performance Assessment Based on In-Situ Measurements', 2017 <http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-71/> [accessed 11 October 2017].
[19] Marieline Senave, 'Characterization of the Heat Loss Coefficient of Residential Buildings Based on In-Use Monitoring Data', 2019.

IV. Ground heat loss is often not factored in to HTC analysis, it was found that when this was only modelled that an underestimation of some 59% was introduced to the HTC, this is very significant, it was found that if this heat loss were to be physically measured (using equipment costing around £3000) then this underestimation was eradicated and the HTC in that property was characterised to within 2% of the reference value. This requires that the ground floor heat loss should be considered by researchers in this field and understood further.

Work in this area continues at pace to develop a tool that can form an HTC in building with minimal data output. A complicating issue of this latest phase of research is to isolate the effects of occupancy on the HTC, this helps to identify only the building fabric performance. This is required as the HTC is concerned only with the building and not the occupant. Methods have been developed to split these two conflicting issues. This has the additional benefit of being able to denote whether a building is affected more by the occupant or by the poor quality of the fabric. This can be done simply with data analytics or by using solutions such as humidity detection in rooms, which can act as a proxy of the occupancy level of a room [20].

HTC Uses and Alternative Metrics

The HTC of a building is useful, as it can act as a global energy efficiency indicator for heat loss, and heat gain in countries where cooling is more prevalent that heating. However a single figure, for some may not be so useful. Take the Energy Performance Certificate (EPC) process in the UK: This is generated using a computer model of a home, this model does contain an HTC figure that is calculated using a series of assumptions about the fabric and geometry of the home, it is then used to run a series of calculations to estimate annual heating bills, CO_2 produced by the building and finally the A-G rating that we see used frequently in energy performance. So, the HTC could be a step in a calculation, when the HTC is measured and correct, the calculation becomes more accurate and ultimately more useful. The HTC is not a weighted metric, it makes no provision for the shape/size/age of a building, it does not allow buildings to be compared on a level playing field. Treatments that could be added to the HTC process to make it more usable and consumer friendly are as follows:

I. Spatial Weighting: A building that is bigger will generally take more energy input to raise the temperature against a smaller building of identical construction. So taking into account a measure such as Gross Internal Area (GIA), may provide a more relatable figure for property experts for example: $W/K/m^2$
II. Volume Metrics: When considering the airtightness of a building the volume is frequently used as a metric, which arguably may be more informative than GIA, as high ceilings etc have a significant effect on the HTC, which may be unaccounted for when GIA is used. For example: $W/K/m^3$
III. Annualised consumption/CO_2/Running costs; using the correct HTC for a building in tandem with energy modelling, a typical occupancy and weather data an annual figure can be built up, this may be more helpful than the HTC for public consumption.

[20] Luis M. Candanedo and Véronique Feldheim, 'Accurate Occupancy Detection of an Office Room from Light, Temperature, Humidity and CO2 Measurements Using Statistical Learning Models', *Energy and Buildings*, 112 (2016), 28–39 <https://doi.org/10.1016/j.enbuild.2015.11.071>.

Discussion and Conclusion

We are at a stage in time where there is stage now where it is readily accepted that climate change is taking place and there is strong evidence to support this [21]. The UK and many other states have in place legally binding commitments to address this situation. Many of these commitments consider the energy use and greenhouse gas emissions from the countries' housing stock. The UK for instance is currently consulting on a Future Housing Standard which aims to increase the energy efficiency requirements for new homes in 2020. The Future Homes Standard will require new build homes to be future-proofed with low carbon heating and world-leading levels of energy efficiency; it will be introduced by 2025.

Whilst this may be a challenge and one that other countries are following suit on, some challenges exist. As we have seen in the early part of this paper we are presented with a performance gap for our new build properties and this could increase with more modern and non-traditional method of construction, this may be also be true of deep retrofits (which will certainly be needed to hit carbon targets in the UK). It is essential therefore that to realise the carbon and energy savings that these new policies bring about that a method is engaged to validate the actual performance of these homes. With the increase in connected controls and the rollout of smart meters, the HTC could estimate in a cost effective, accurate and non-intrusive way. On the proviso that the current rate of research and development continues.

AccuWeather, 'AccuWeather APIs | API Reference', 2018, p. 2020 <https://developer.accuweather.com/locations-information#PostalCode> [accessed 23 January 2020]

Bauwens, Geert, and Staf Roels, 'Co-Heating Test: A State-of-the-Art', *Energy and Buildings*, 82 (2014), 163–72 <https://doi.org/10.1016/j.enbuild.2014.04.039>

BEIS, 'Smart Meter Enabled Thermal Efficiency Ratings (SMETER) Innovation Programme', 2018 <www.nationalarchives.gov.uk/doc/open-government-licence/> [accessed 28 January 2020]

———, *Smart Meter Statistics in Great Britain: Quarterly Report to End September 2019*, 2019 <https://www.gov.uk/guidance/smart-meters-how-they-work> [accessed 21 January 2020]

BSI, 'BSEN ISO 13789:2017 - Thermal Performance of Buildings - Transmission and Ventilation Heat Transfer Coefficients - Calculation Method', *October*, 2017 <https://doi.org/10.1016/j.ijar.2006.06.024>

Candanedo, Luis M., and Véronique Feldheim, 'Accurate Occupancy Detection of an Office Room from Light, Temperature, Humidity and CO2 Measurements Using Statistical Learning Models', *Energy and Buildings*, 112 (2016), 28–39 <https://doi.org/10.1016/j.enbuild.2015.11.071>

Energy Live News, 'Smart Thermostat Usage Hots up across 1.5m UK Homes - Energy Live News', 2018 <https://www.energylivenews.com/2018/04/04/smart-thermostat-usage-hots-up-across-1-5m-uk-homes/> [accessed 23 January 2020]

European Commision, 'Benchmarking Smart Metering Deployment in the EU-27 with a Focus on Electricity', *European Commision*, 2014, 1–10 <https://doi.org/10.1017/CBO9781107415324.004>

[21] IPCC, 'Climate Change 2014 Synthesis Report Summary Chapter for Policymakers', *Ipcc*, 2014 <https://doi.org/10.1017/CBO9781107415324>.

Farmer, David, David Johnston, and Dominic Miles-Shenton, ‘Obtaining the Heat Loss Coefficient of a Dwelling Using Its Heating System (Integrated Coheating)’, *Energy and Buildings*, 117 (2016), 1–10 <https://doi.org/10.1016/j.enbuild.2016.02.013>

Fitton, Richard, ‘Energy Monitoring in Retrofit Projects’, in *Retrofitting the Built Environment* (Wiley, 2013), p. 256

IPCC, ‘Climate Change 2014 Synthesis Report Summary Chapter for Policymakers’, *Ipcc*, 2014 <https://doi.org/10.1017/CBO9781107415324>

Jack, Richard, ‘Building Diagnostics : Practical Measurement of the Fabric Thermal Performance of Houses’ (Loughborough, 2015) <http://www.lolo.ac.uk/wp-content/uploads/2015/09/RJack-Thesis.pdf>

Jack, Richard, Dennis Loveday, David Allinson, and Kevin Lomas, ‘First Evidence for the Reliability of Building Co-Heating Tests’, *Building Research & Information*, 46 (2018), 383–401 <https://doi.org/10.1080/09613218.2017.1299523>

Johnston, David, Dominic Miles-Shenton, Jez Wingfield, David Farmer, and Malcolm Bell, *Whole House Heat Loss Test Method (Coheating)* (Leeds: CEBE, 2010)

Miles-Shenton, Dominic, *Energy Efficient Renovation of an Exisiting Dwelling: Evaluation of Design and Construction and Measurement of Fabric Performance* (Leeds: CEBE, 2011)

Roels, Staf, ‘EBC Annex 71 Building Energy Performance Assessment Based on In-Situ Measurements’, 2017 <http://www.iea-ebc.org/projects/ongoing-projects/ebc-annex-71/> [accessed 11 October 2017]

Senave, Marieline, ‘Characterization of the Heat Loss Coefficient of Residential Buildings Based on In-Use Monitoring Data’, 2019

Zero Carbon Hub, *Closing the Gap between Design and as Built Performance* (London, 2014) <http://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf> [accessed 23 September 2015]