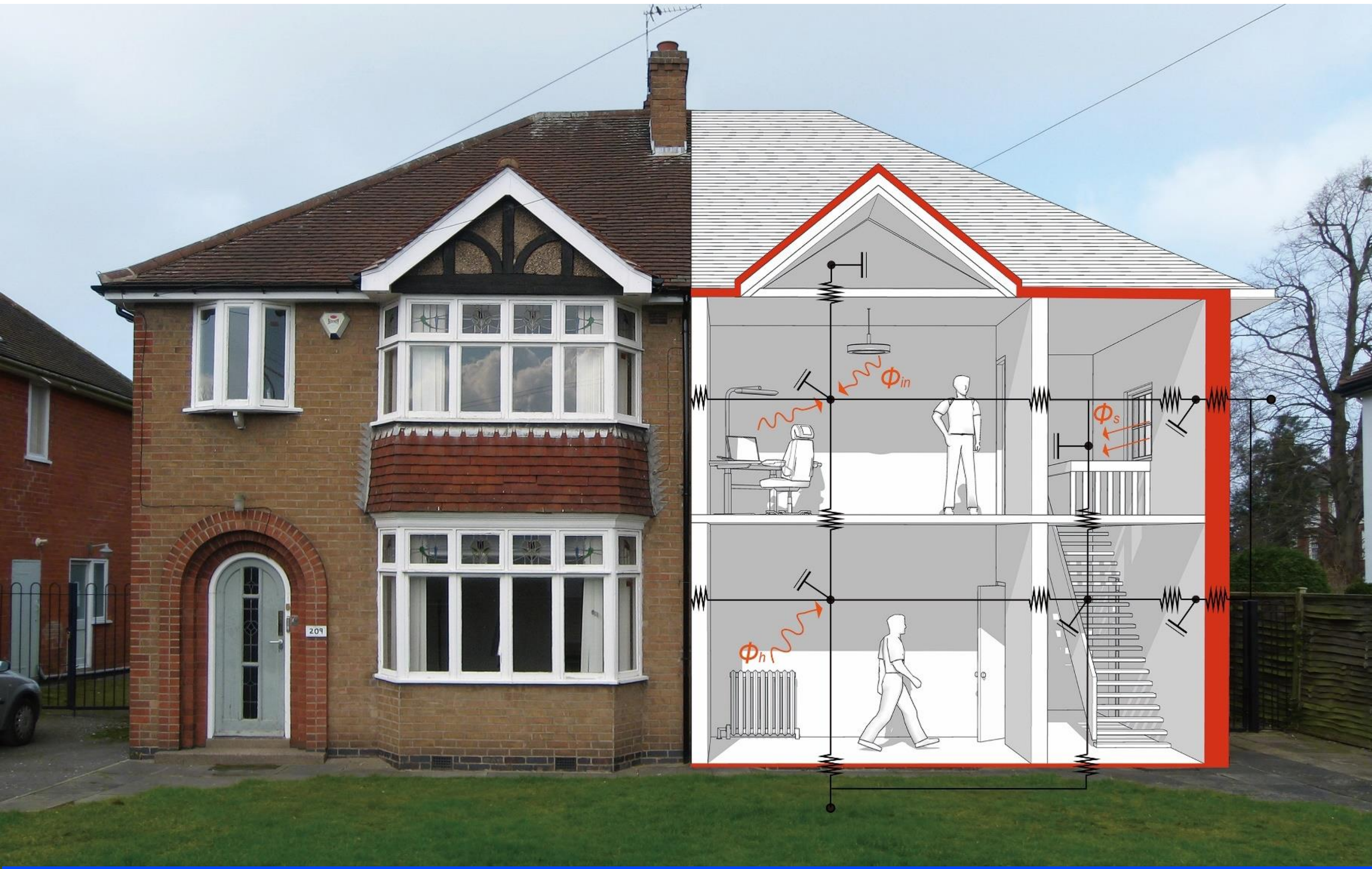
ANNEX 71

EBC
Energy in Building and Communities Programme

Building energy performance assessment based on in-situ measurements

Challenges and general framework

August 2021



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Cover picture: drawing of Xiang Zhang (KU Leuven, Belgium) on a picture of the Loughborough test houses (Loughborough University, UK)

ANNEX 71

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August 2021

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international cooperation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)

Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)

Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)

Working Group - Cities and Communities

Working Group – Building Energy Codes

IEA EBC Annex 71: Building energy performance assessment based on in-situ measurements

Annex 71 in general

Decreasing the energy use in buildings can only be achieved by an accurate characterization of the as-built energy performance of buildings. This is mainly for two reasons. First of all, despite the ever more stringent energy legislation for new and renovated buildings, monitoring the actual energy performances reveals in many cases a significant performance gap compared to the theoretically designed targets. Secondly, the increasing need for integration of renewable energy stresses on the existing energy systems. This can be remedied by using intelligent systems and energy grids that are aware of the actual status of the buildings.

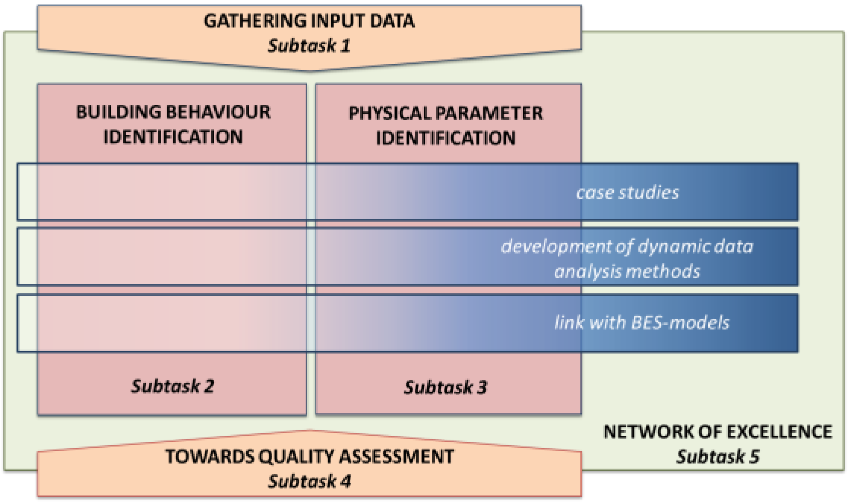
Within IEA EBC Annex 58, a first step was taken to characterize the actual energy performance of buildings based on full scale dynamic measurements. The onsite assessment methods applied within this project mainly focused on the thermal performance of the building fabric. By investigating the possibilities and limitations of black and grey box system identification models, guidelines were developed on how to assess the overall heat transfer coefficient of a building starting from dynamic measured data instead of static co-heating tests. Notwithstanding Annex 58 showed that onsite quality checks are feasible, the project highlighted at the same time the need of non-intrusive methods. Annex 71 progressed with the achievements of IEA EBC Annex 58, but aimed to make the step towards monitoring in-use buildings. The IEA EBC Annex 71 project focused on the **development of replicable**

methodologies embedded in a statistical and building physical framework to characterize and assess the actual energy performance of buildings starting from on board monitored data of in-use buildings.

Structure of the project

The IEA EBC Annex 71-project was limited to residential buildings, for which the development of characterisation methods as well as of quality assurance methods have been explored. Characterisation methods aim to translate the (dynamic) behaviour of a building into a simplified model that can inform predictive control, fault detection, optimisation of district energy systems,… Within Annex 71 we refered to this as building behaviour identification. Quality assurance methods aim to pinpoint some of the most relevant actual building performance metrics. This part is referred to as physical parameter identification.

A reliable characterisation and quality assurance is strongly dependent on the availability and quality of the input data. At the same time, the expected quality and reliability of the outcome will be determined by the required accuracy to perform a quality assurance. As a result, the analysis of potential methods was steered by both the possibilities and limitations of the available input data as well as by the requested outcome to perform real quality checks. Therefore, the research project was organised as illustrated in the figure below and five subtasks were defined:



Subtask 1 investigated the possibilities and limitations of common data bases and monitoring systems. This subtask is strongly related to subtasks 2 and 3 by linking the available input data – as much as possible based on existing (non-intrusive) monitoring systems and data bases – to the accuracy of the predicted outcome. A state of the art survey of existing methods, their costs, timeframe and typical accuracy was made. In a second part the step from monitoring to current on board measuring methods was reviewed. Finally, the application of an on-site measured heat transfer coefficient within the global energy efficiency framework was proposed.

Subtask 2 focused on the development of dynamic data analysis methods suitable for describing the energy dynamics of buildings. Based on in-situ monitored data, prediction models were applied and optimised that can be used in model predictive control, fault detection, and design, control and optimisation of district energy systems,… Necessary data acquisition, development of methodologies and accuracy and reliability of the building behaviour identification models was investigated.

The focus of **Subtask 3** was on development of dynamic data analysis methods suitable for physical parameter identification of buildings. Contrary to Subtask 2, in which the identified parameters do not necessarily have a physical meaning (or do not correspond to the actual value), parameter identification aims to characterize the actual physical parameter. Subtask 3 hence investigated which methodologies are most suitable to determine the actual energy performance indicators of buildings, such as the overall heat loss coefficient, solar aperture,… As in subtask 2, the focus was on methodologies that can be used on occupied buildings, making use of (limited) monitored data.

Subtask 4 investigated to what extent the methodologies developed in ST2 and ST3 can be used in a quality assessment framework. A large survey was performed amongst possible stakeholders on interest and expectations of quality assessment methods based on in-situ measured data. The main focus was on the determination of the actual heat loss coefficient of a building in an easy, cheap and reliable way, so that it can replace the calculated design value in energy performance certifications. That way, subtask 4 made the link between the annex-participants and certification bodies, government, practitioners in the field. At the same time, subtask 4 gave the necessary boundary conditions (reliability, accuracy, cost,…) the methodologies have to fulfil to be applicable in real life quality checks.

Subtask 5 continued the collaboration with DYNASTEE (www.dynastee.info), started within Annex 58. This collaboration showed to be extremely fruitful in dissemination of the results, collecting and distributing research outcomes, and organizing conferences, workshops and training courses.

The **BES-validation exercise i**nvestigated the reliability of common building energy simulation programs. There has been significant work undertaken in past IEA EBC Annexes on validation, particularly inter-program comparisons (e.g BESTEST) and empirical validation on test cells. In Annex 58, empirical validation was extended to full-scale buildings, namely the Twin Houses at Fraunhofer IBP's test site in Holzkirchen, Germany. In this research, the focus was on fabric performance with simple internal heat gain schedules. The empirical validation undertaken in IEA Annex 71 extended the scope of the experiments in the Twin Houses by including underfloor heating systems and realistic occupancy schedules.

Overview of the working meetings

The preparation and working phase of the project encompassed nine working meetings:

Meeting	Place, date	Attended by
Kick off meeting	Leuven, Belgium, October 2016	49 participants
Second preparation meeting	Loughborough, UK, April 2017	61 participants
First working meeting	Chambéry, France, October 2017	62 participants
Second working meeting	Brussels, Belgium, April 2018	56 participants
Third working meeting	Innsbruck, Austria, October 2018	55 participants
Fourth working meeting	Bilbao, Spain, April 2019	59 participants
Fifth working meeting	Rosenheim, Germany, October 2019	56 participants
Sixth working meeting	On-line meeting, April 2020	50 participants
Seventh working meeting	On-line meeting, October 2020	50 participants
Eighth working meeting	On-line meeting, April 2021	56 participants
Closing event	Salford, UK, September 2021	

During these meetings, working papers on different subjects related to full scale testing and data analysis were presented and discussed. Over the course of the Annex, different experiments on characterisation and quality assessment were undertaken, and several common exercises on data analysis methods were introduced and solved.

Outcome of the project

The IEA EBC Annex 71-project worked closely together with the Dynastee-network (www.dynastee.info). One of the deliverables of the Annex project was the enhancement of this network and promoting of actual building performance characterization based on full scale measurements and the appropriate data analysis techniques. This network of excellence on full scale testing and dynamic data analysis organizes on a regular basis events such as international workshops, annual training, with outputs that support organisations interested in full scale testing campaigns.

In addition to the network of excellence, the outcome of the Annex 71-project has been described in a set of reports, including:

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: challenges and general framework (joint report of Subtasks 1 and 4)

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: building behaviour identification (report of Subtask 2)

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: physical parameter identification (report of Subtask 3)

IEA EBC Annex 71 – Building energy performance assessment based on in-situ measurements: design, description and results of the validation of building energy simulation programs (report of the BES-validation exercise)

IEA EBC Annex 71- Building energy performance assessment based on in-situ measurements: project summary report

List of participants and coregroup

In total 42 institutes from 11 countries participated in the IEA EBC Annex 71-project. The different participants are listed below:

Austria:	Max Blöchle, Austrian Institute of Technology
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	Gabriel Rojas, University of Innsbruck

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Ross Holleron, Knauf Insulation

Frances Hollick, UCL

Richard Jack, Build Test Solutions (subtask 4 co-leader)

Matthew Li, Loughborough University

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Behzad Sodagar, University of Lincoln

Paul Strachan, University of Strathclyde (BES validation co-leader)

Summary

Assembling the knowledge, tools, and skills to reliably determine the (Heat Transfer Coefficient) HTC of a dwelling was a main driver for Annex 71. However, research has been carried out in this area for several years. What set this work apart was the idea of measurement of the HTC using cost effective data, such as smart meters and on-board devices such as thermostats, using complex analyses.

The purpose of this report was to look at what goes into these analyses and what comes out. We carried out work thus on the data inputs and data outputs.

An introduction to the HTC was presented with its simple uses and benefits presented.

A review of the industry views and opinions across the member countries of this Annex. From here we assembled a large piece of research around the current methods used to do this work (the established and more modern ways of measuring the HTC).

We examined the current data inputs available in this area, such as smart controls and a complete review of smart meter data across the EU. This included a state-of-the-art review of Building Automation Solutions (BAS)

A series of use cases are presented with several international case studies, alongside some suggested future use cases for the metric.

Table of content

Abbreviations

Abbreviations	Meaning
DHW	Domestic hot water
EN	European Norm
EPG	Energy Performance Gap
EPBD	Energy Performance of Buildings Directive
HLP	Heat Loss Parameter
HTC	Heat Transfer Coefficient
IEA EBC	Energy in Buildings and Communities Programme of the International Energy Agency
kWh	Kilowatt hours: 1 kWh = 3.6 MJ
NZEB	Nearly zero energy building or nearly zero emissions building
PE	Primary energy
U value	Thermal transmittance of a building element

Definitions

Building Energy Simulation (BES): Computer modelling based on building physics, used in the evaluation of energy and environmental aspects of building performance.

Building thermal envelope: Defined in ISO EN 52016 as ”total area of all elements of a building that enclose thermally conditioned spaces through which thermal energy is transferred, directly or indirectly, to or from the external environment”.

Coheating: A test to measure the total heat transfer through the fabric of buildings and to calculate the heat-transfer coefficient (Jack et al., 2018)

Energy Pathology: The systematic investigation of the energy performance of buildings, with the aim of detecting any elements whose performance in energy terms is not as intended

Energy performance gap (EPG): The difference between modelled energy performance and the measured energy performance.

HTC (Heat Transfer Coefficient): 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) (BSI, 2017).

U value: The heat flow rate in the steady state divided by area and by the temperature difference between the surroundings of each side of the system (BSI, 1996).

1. Introduction

This chapter will provide context, background and justification for this work contained within this annex. It will introduce the theory and practicalities of the energy performance gap (EPG). It will also provide details about some current methods that we use to explore this issue. Current thinking around the causes and the makeup of the EPG are also given.

1.1. Energy performance gap

The energy performance gap (EPG) is a simple term with a complex background, the causes for it are often unknown. The definition of the energy performance gap is the difference between modelled energy performance and the measured energy performance.

This report will, given the context of Annex 71, consider the EPG for domestic type buildings, and generally take a view on individual homes. We will also focus on the fabric performance of the building, rather than the effect of heating/cooling and other building services. We do not intend to deal with the occupancy of buildings, although research will be presented to provide information around decoupling the occupancy driven energy consumption from the fabric performance of the dwelling.

Global research has found that it is not unusual to find a gap between the modelled or predicted value for a property and the actual as built energy performance in the field, a collection of these results can be found in Table 1. Mathematically, this figure is often represented in percentage terms and is calculated as shown in Equation 1. It is important to note that these values can be positive or negative, i.e., the building can perform better than the model or the model better than the building.

$$Performance\ Gap = \frac{Actual\ consumption - Theoretical\ consumption}{Theoretical\ consumption} \cdot 100 \qquad \text{(Eq. 1)}$$

Table 1. Global examples of recent EPG studies with sample sizes and levels of performance gap included

Country	Sample size (N)	Average Performance Gap	Reference
Canada	1	74%	(Rouleau et al., 2018)
Germany	3400	30%	(Galvin, 2014)
United Kingdom	25	50%	(D Johnston et al., 2015)
Switzerland	50000	11%	(Cozza et al., 2020)
Italy	6	45%	(Ballarini and Corrado, 2009)

Some results from research in the EPG area are quite stark, Figure 1 illustrates the range in the EPG when Heat Transfer Coefficient (HTC) measurements (an indicator of energy efficiency, to be covered in full in the next section of this report) were taken over a sample of new built properties in the UK with EPG falling between around 5% up-to 140% of the predicted HTC of the dwelling.

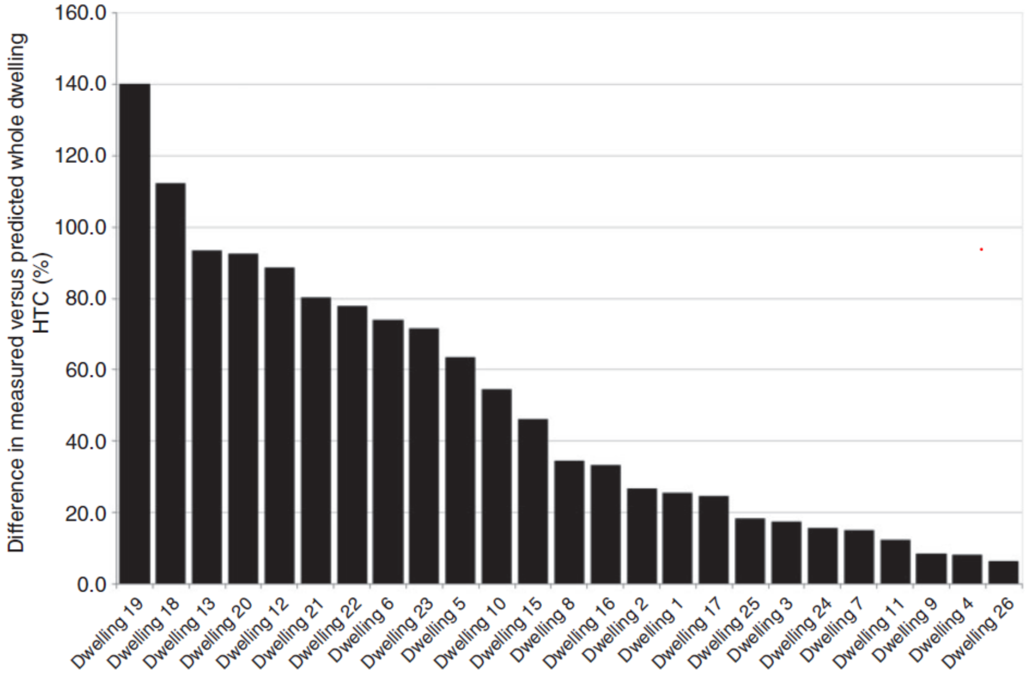

Figure 1. Results from a campaign of HTC (Heat Transfer Coefficient) measurement, illustrating the EPG in a sample of new build homes in the UK (D Johnston et al., 2015).

There are however some modes of design and construction that have been found to have significantly less performance gap issues such as Passivhaus. This uses a model that is unique and also building methods that are more robust than other types of building, a medium size study (n=97) revealed a mean performance gap of around 8% (Mitchel and Natarajan, 2020). A larger study carried out by Johnston found that over a sample of over 2000 Passivhaus and 130 Enerphit standard (retrofit) homes, all of them had an "extraordinary low" EPG with all buildings performing better than the minimum prescribed standard (Johnston et al., 2020). This shows us that the EPG is not a "wicked" problem, it can be overcome with the correct models and construction. However, Passivhuas is not a significant contributor to the number of new homes built globally. We should also consider the vital requirement to consider the EPG in any retrofit or refurbishment work, which is high on many countries' agenda.

It is clear to see that the evidence of EPG is building in the academic world, from the figures presented above, the construction industry is also realising this issue. An industry backed piece of research carried out in the UK saw a large group of experts coming together to study the problem. The findings were published by the Zero Carbon Hub in a report " Closing the gap between design and as built performance" (Zero Carbon Hub, 2014). One of the key findings of this study was the clear need to develop tools to accurately and cost effectively measure the performance of the building.

There are many causes of the EPG, some of which are well known and some of which are not. To help investigate the causes of the EPG, an area of research known as "*energy pathology*" (Mclean and Fitton, 2017) has been developing worldwide since the 1960's which has seen researchers and industry develop new methods for measuring energy flows in a building, work around modelling assumptions and commissioning etc. This has seen the fabric, building services and occupants studied in detail to develop an understanding of the EPG. In the next portion of this section, we will examine some of the possible causes of the EPG, examining the building fabric performance.

1.2. Building fabric

The enveloping structure is the component which separates the indoor (conditioned) environment from the outdoors, the methods by which we examine the performance of this generally have three measurement metrics, U values, thermal bridging and airtightness (given that thermal bridges are very infrequently measured they will not be covered here, although evidence does exist to state that they are often forgotten about and a cause of issues (CEREMA, 2017).

1.2.1. U values:

Definition of U Value: The history of the term "U value" first appeared in the late 19th century (Box, 1868). This publication covered many physical aspects of heat transfer in buildings and engineering works. The author presents a list of building materials of given thicknesses and prescribed internal and external temperatures. From here Box goes on to define a figure known as U. "The loss of heat in units per square foot per hour by a building exposed on all sides to air" (Box, 1868).

In more modern terms, the International Standards Organisation define a U value as such: The heat flow rate in the steady state divided by area and by the temperature difference between the surroundings of each side of the system (BSI, 2018). The term "between the surroundings" is vague; this is defined by a further international standard as a value that "represents the proper weighting of air and radiant temperatures for the purpose of determining the heat flow to the surface" (BSI, 1996).

When a purely physics-based approach is taken of this metric, one may feel that this is a very straightforward figure with little dispute, however in the real world this is not so: There are several mechanisms at play when it comes to the actual U value measured in a completed element, these include variations in; workmanship, porosity and density, moisture levels and material makeup. When we add to this the fact that the overall heat transfer coefficient of a wall for instance is constantly varying due to internal and external boundary conditions such as wind, rain, and solar radiation then in actuality this U value is constantly changing as part of a dynamic system. This system must be simplified to provide a sensible metric. However, this simplification has led to models being created in some circumstances that do not match the building elements found in the field.

An example of this oversimplification lead to a significant under estimation of the U value in solid walls in the UK: the BRE (Building Research Establishment) lead a field study examining the as build performance of solid walls (defined as: masonry walls with no significant cavity) (Hulme and Doran, 2015). The default modelled value for this type of wall using the regulatory tool RdSAP was 2.1 W/m^2K. This was doubted by some researchers. The field trials (N=85) measured the U values using a standard method ISO9689 (ISO, 2014), and the median value was found to be 1.59 W/m^2K, over 32% different to the standard value which has been used by energy assessors in the UK for over 10 years. The reasoning for this difference was largely due to the calculated U values overestimating the moisture content of the wall. The standard U value for solid walls in the regulatory model has now been changed to 1.7 W/m^2K which according to field trial is a more accurate reflection of reality. This mismatch between the calculated and real-world figure, has now been amended, however this figure has been used for well over a decade in the UK, and its lack of accuracy will inevitably have led to some consumers and policy decisions to have been skewed, with decision makers believing that the performance of these walls is poorer than they are.

1.2.2. Air permeability:

The air permeability of a building is an important metric and one that is a key component of the HTC. The airtightness of a building is intrinsically linked to the building's energy performance, as a building with a higher degree of airtightness will not only prevent warm air leaving a heated building, but also minimise the entry of cool air inward through infiltration. This metric does not deal with designed or intended ventilation, only un-designed gaps in the structure which may arise from poor workmanship of products expanding and contracting. Some decisions made in the design process can often affect the performance the building such as poor detailing. This figure is generally denoted at the design stage by an architect or engineer. An example of a typical design figure in the UK is <10 m^3/m^2h, This is the maximum figure allowed by the legislative process for new homes in the UK, although 5 m^3/m^2h is typical (Crawley et al., 2019b). This figure is measured using a pressure test process, a fan is used to create a pressure differential across the fabric form inside to outside of 50 Pascals. Over many years researchers have found issues with airtightness in new build and existing homes. This issue has been cited as one of the significant contributors to the EPG (D. Johnston et al., 2015; Marshall et al., 2017). This is confounded by the issue of suspected poor-quality control in the measurement process behind the certification process of buildings. An example of this is where a limit to comply is set and measurements are carried out to prove this figure. Researchers have postured that these measurements may be subject to last minute "patching" of the fabric to reach the required or even results amended nefariously (Love et al., 2017), although no proof of these issues exist, the patterns found by researchers a large sample of airtightness results in the UK are said to correlate to the design targets, rather than form a normal or Gaussian distribution, as one may expect from a large array of results this distribution is shown in Figure 2.

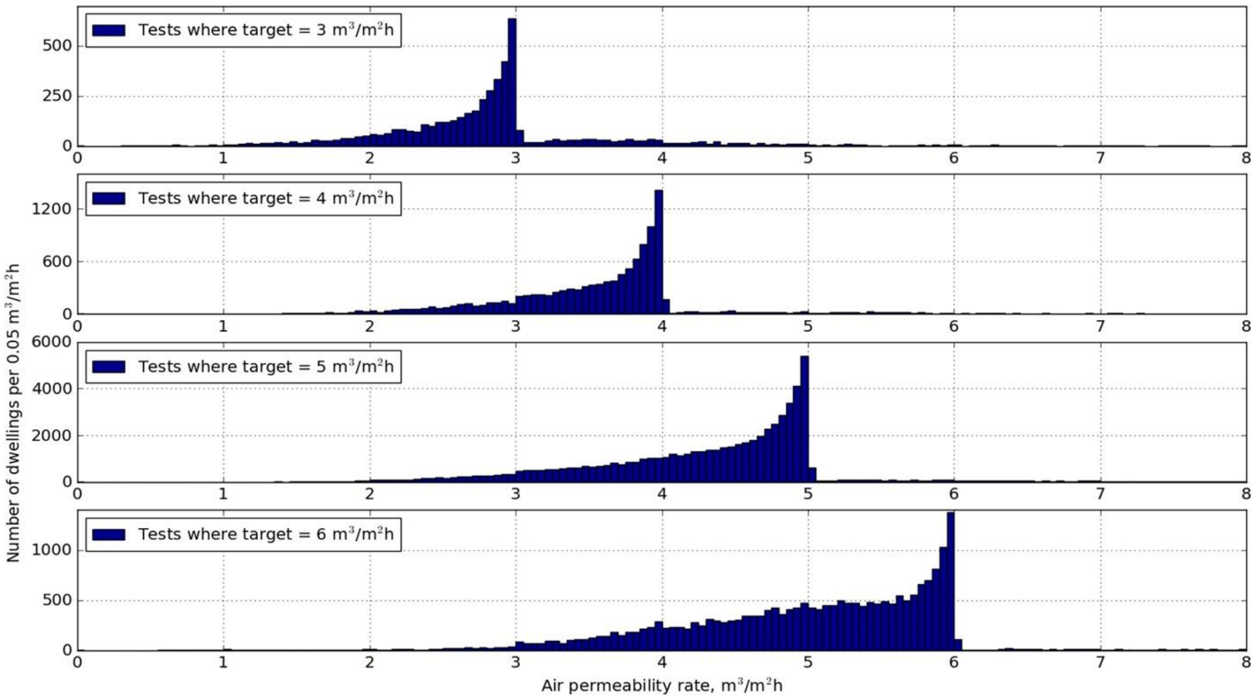

Figure 2. Results for sites with design targets of 3,4 5 and 6 m3/m2h.The design targets are the four most frequent in the dataset, representing 69% of the air permeability tests (Love et al., 2017).

What these results tell us is that the way that airtightness testing is being carried out within the observed data set may not truly reflect the actual performance of the home in the field. This element of "patching" leads to short terms fixes, these will not give the building the long-term airtightness that is required. It also reminds us that the way a buildings performance is measured can sometimes be the cause of or at least a contributing factor to the EPG, we refer to this as the measurement gap and is the topic of the next section.

1.3. Measurement gap

It is all too easy to consider the way a buildings performance is measure is perfect. Given that for many of the metrics, U values, HTC, or air permeability, a standard or agreed method is available. However, when we examine the way that some of these methods are used in practice then issues around accuracy and repeatability can be found. There are a number of examples of this to be found in the literature around this area.

1.3.1. HTC

Firstly, the HTC (the main component of this report) has measurement techniques that have been brought into question. A recent report by the National House Builders Council Foundation (NHBCF) in the UK used a standard test house, to assess the differences in approaches used by researchers using the coheating method to provide an HTC. This was carried out by six teams, the range found between the measured value was 20.4 W/K or around 30% across the results of the team (Butler and Dengel, 2013). The experimental work by each team was also supplemented by some work to minimise the solar gains into the property during testing. The results are shown in Figure 3.

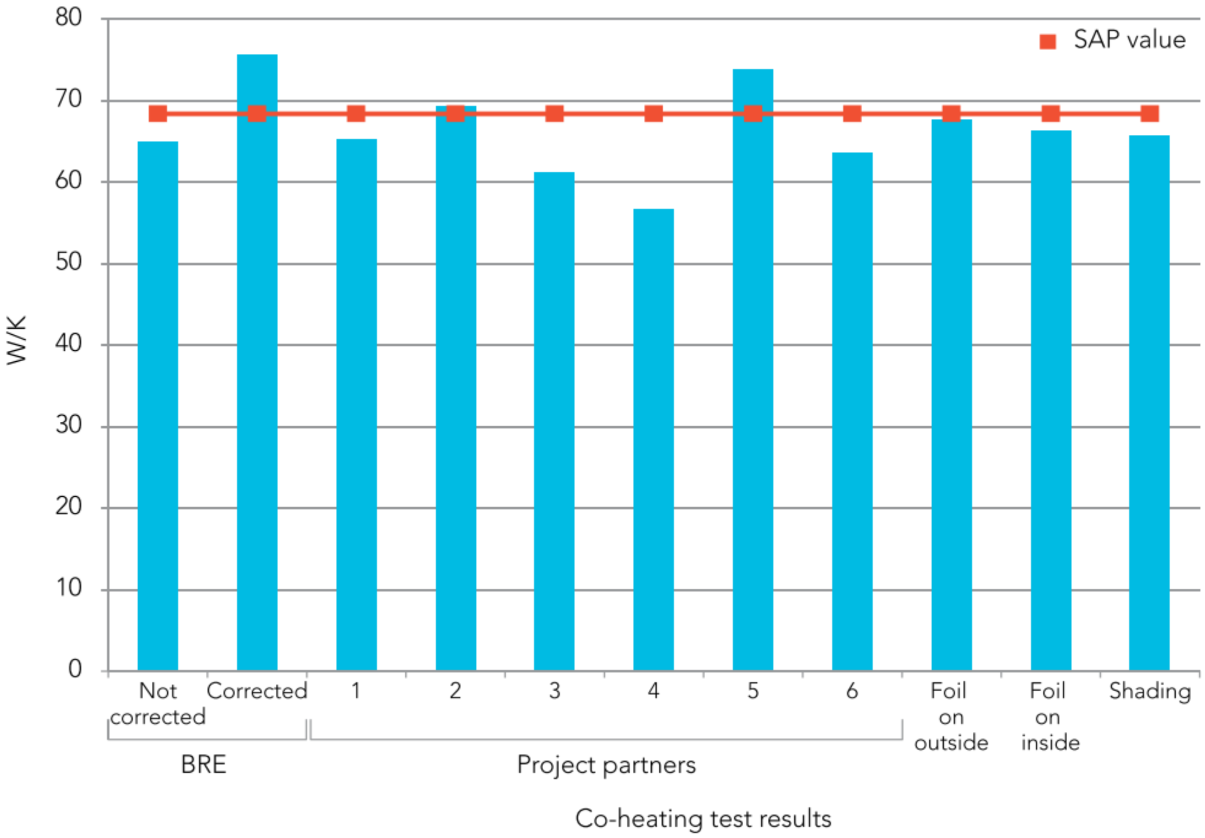

Figure 3. Results of a campaign of coheating test carried out on the same property by different researchers (Butler & Dengel, 2013)

Aside from variances concerned with experimental setup as highlighted above, Stamp, in his thesis around the uncertainties involved with the coheating tests, demonstrates 21 mechanisms that may affect the uncertainty within the coheating protocol (Stamp, 2016). We will not describe these in detail here, but they range from moisture effects in the drying out process of a new building and the effects of wind on a building, right the way through to the measurement periods involved and the data analytics behind forming the final HTC figure. In brief this presents us with the fact that the coheating test leaves room for improvement and standardisation. However work is progressing on a CEN standard for the coheating test (CEN/TC89, 2020)

1.3.2. U values:

If we review the recent literature in U value measurement there are several internationally accepted methods of measuring U values in building elements, here we will focus only on the measurement of walls for the sake of brevity and simplicity. There is a method from the USA (ASTM, 2014) known as ASTM C1155, there is an Internal Standard ISO 9869 (ISO, 2018a), and some researchers have even used a draft EU (Dutch) standard that was never even finalised or published (NEN, 1996). All this leads us to the fact that some measurements have been carried out in a different manner than others, as all of these standards have different nuances involved.

The way that we measure our variables and then carry out our calculations/analysis can have a significant effect. If we take for example a simple U value measurement carried out on an uninsulated solid brick wall under steady state conditions at three points on the wall (21°C indoor and 5°C in the chamber) carried out recently at the University of Salford Energy House Test Facility, we can see a significant variation in the actual estimate U values, even though the wall remains the same the way in which the measurements are taken, and the analysis is put through a series of permutations in Figure 4.

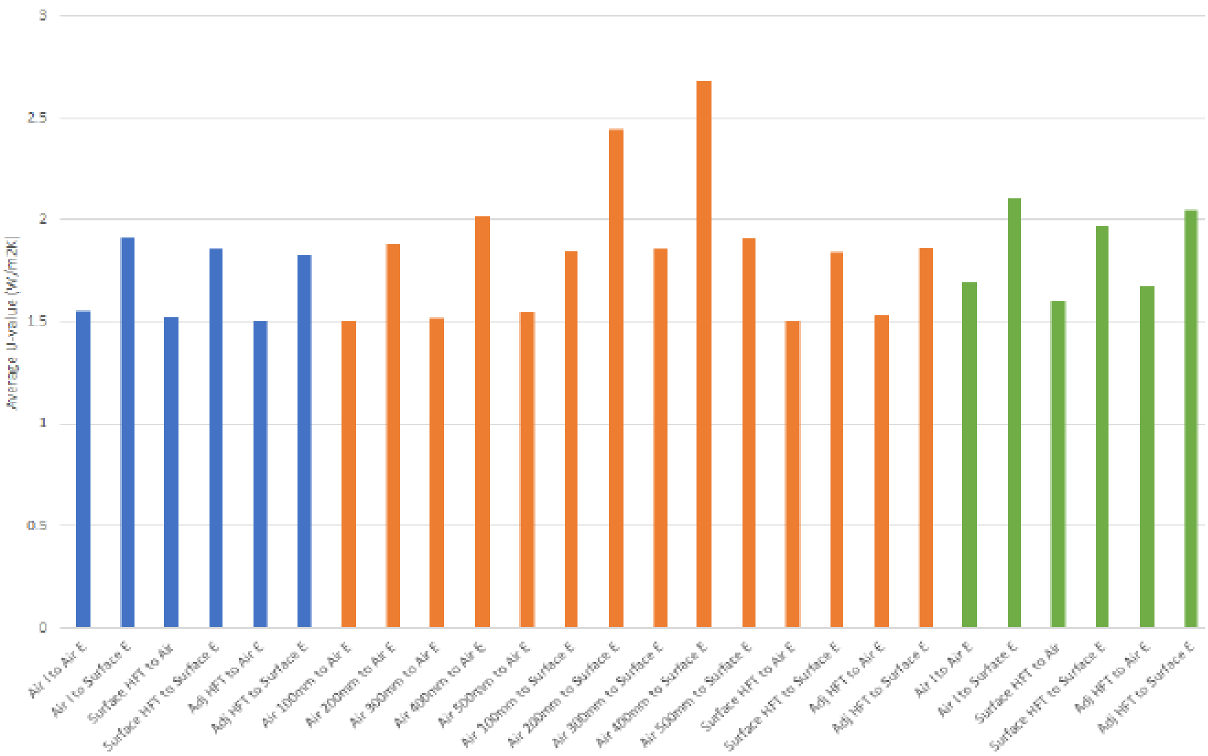

Figure 4. Illustrating the variation of U values across a simple wall. All measurements carried out on same wall area, with different temperature sensors placements and data analytics. Lowest U value = 1.5 W/m^2K – Highest U Value = 2.6 W/m^2K

When we consider Figure 4 and range of around 1.1 W/m2K which can be found when working with U value measurements even using a standardised approach (all comply with at least one of the U value measurement standards) then this presents a significant issue. If we extend this work further and transform these figures into a whole house figure, then this can cause large differences in the calculation of the HTC.

Also, as we are measuring quite small amounts of heat flux in most cases, especially in well insulated buildings we can find that even the smallest measurement changes can make a difference to the outcome of the measurement, this can be affected a large range of variables such as surface contact with sensors, heating patterns in the building, wind, rain and snow, also the effects of moisture in the fabric of the wall form climatic effects of the drying out of moisture in newly built homes.

In conclusion, such a simple measurement can have significant error margins due to the sheer number of issues which may arise during the test. This also explains the large uncertainty figures for these measurements denoted in the standards, right the way up to +/- 28%

1.3.3. Air permeability

Air permeability testing is a readily accepted and intrinsic part of many countries testing regime for newly completed buildings, as well as some retrofit projects. It is not a new area of testing and has an internationally recognised methodology, ISO 9972 (BSI, 2015) and a USA standard (ASTM, 2010). However, we should not consider that a standardised approach produces a perfect measurement. Researchers have been investigating the uncertainty behind these testing methods for some time. One of the significant causes for a higher uncertainty level is the wind speed around the building at the time of test, researchers have found that the level of uncertainty increases with wind speed. This uncertainty is more pronounced at lower test pressures (testing is often carried out at 10 Pascals and 50 Pascals) (Carrié and Leprince, 2016) . This effect is illustrated in Figure 6. The same authors found that a combined uncertainty of between 6-12% should be used for wind speeds between 6-10m/s.

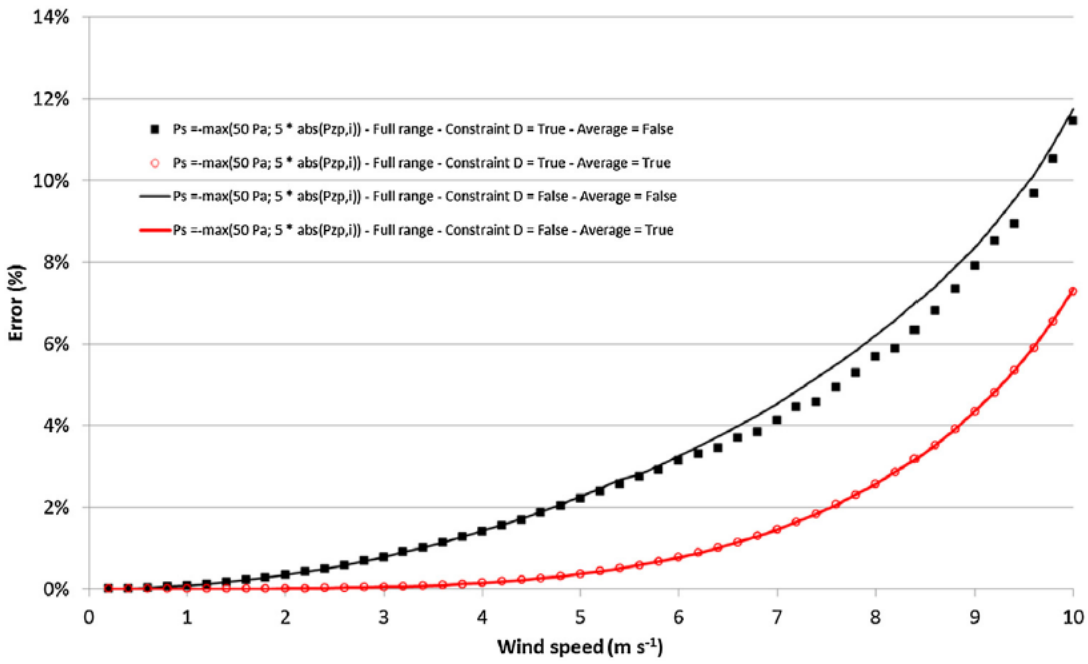

Figure 5. An example of the maximum error found due to wind speed. (Carrié & Leprince, 2016)

Air tightness measurements have also been shown to have issues surrounding the repeatability and reproducibility of their results. When we talk about repeatability in this area of testing it is defined by ISO 5725 (ISO, 1994) as the precision under identical lab conditions, by the same operator using the same equipment within short intervals of time. Delmotte found in his study that the standardised 50 Pascal method had a repeatability of 3.7%. When we examine reproducibility**,** declared by ISO 5725 (ISO, 1994) as the same identical method but in different laboratories with different operators using different equipment. The same study found that this had at 50 Pascals of 2.7%.

These two factors indicate that, coupled with inherent variability owing to factors such as wind etc seen in the first part of this section, give rise to a considerable error, and these three errors (repeatability, reproducibility and wind driven error) by no means form all the errors that can be present in an air permeability measurement.

In conclusion, we have examined a sample of three well practiced building performance measurement techniques in this section, and found that they all have in built errors, some are allowed for in the standards and some are not. What this does tell us is that these measurement techniques are not perfect, open to interpretation, and are not guaranteed to be totally accurate when characterising buildings.

1.4. Modelling gap

With the EPG consisting of a simple calculation of two components (model value and measured value) the modelled values are clearly important. Errors in the calculations, and the interpretation of the outcome of a model should be kept in mind. Over recent years, several pieces of work have highlighted areas of concern in terms of energy modelling of buildings, these range from user errors, (incorrect inputs, oversimplification, inconsistent inputs of areas, and misidentification of HVAC systems) through to the way that energy models can handle physical parameters such as solar gain. Strachan used a well measured case study building to carry out a process of model validation. The data was passed to 21 modelling teams from around the globe, he points to several mechanisms that can be the cause of modelling error; largely the error are down to user error, however some models do cope with the following physical parameters in different ways which lead to differences in the simulations; thermal bridging, long wave transmission of heat to the sky, internal convection model differences, and transmission of heat gain through glazed surfaces (Strachan et al., 2016).

In earlier work Lomas used the test cell infrastructure (simplified models of buildings, that are well controlled and measured, but not full-scale buildings) to attempt to identify errors in building energy simulations, a large group of modellers were in involved (25 combinations of individuals and models). Significant discrepancies were found between the results of the modelling teams, with some software packages reporting different outcomes with different users

(Lomas et al., 1997). This again seems to support the hypothesis that user error is a considerable source of the modelling errors.

A smaller study by Roberts, carried out recently using more modern software than those studies mentioned above, used a case study approach in an attempt to identify issues when dealing with overheating in homes. Whereas this is linked to the energy performance of a building, we can draw parallels in the buildings physical parameters which contribute to overheating. This study used a well measured case study building, to provide data to compare against the simulation outputs. The models were built by four parties, each using a separate modelling software. The aim of this research was to try and predict the level of overheating in each room, so temperature prediction was a key indicator. The models showed a failure to predict this accurately with variation between the modelled and actual measured value differing by up to 4.6 °C in one room (Roberts et al., 2019). Roberts reports the same issues as Strachan and Lomas in terms of user error, however issues around the incorrect calculation of the U value components that make up the model were also raised. A large range of U values were proposed by the teams with a range for some elements being 133% for even simple elements such as external doors, when compared against the mean value presented by the modelling teams.

The work outlined above does not present a firm explanation of why models sometimes perform as well as we expect but it does indicate that user errors are a significant reason, but also some models appear to be also lacking in the areas around building physics and heat transfer. We should therefore assume that the modelling gap is often caused by a combination of these two factors and possibly others.

1.5. Evolution to quality guarantee

In order to take steps to close the gap, some pioneer projects have been carried out in Western Europe. These show that awareness is growing to evolve towards a quality guarantee rather than just a calculated design value. This section describes the evolution in the Netherlands, the UK and France.

1.5.1. Zero on the meter housing in the Netherlands

Experience with performance guarantees based on monitoring data started in the Netherlands with the initiative to realize zero-on-the-meter houses in 2013. The definition of zero-on-the-meter house *"house in which the yearly energy use is lower than the yearly energy production"* (Harmka, 2020). This initiative was called the "Stroomversnelling" which can be translated as "Speeding-Up". The principle behind the guarantee was the need for a business case due to the high costs of renovation to zero-on-the meter of €50,000 to €70,000 and high extra costs for new zero-on the meter houses of €20,000 to €35,000. The ambition was to start with 10,000 zero-on-the meter houses and scale up to 100,000 houses rapidly. In the beginning the uptake went slow because there was a lack of a formal framework. This started to change in 2016 with the introduction of the Energy Performance Fee (EPV) and the initiative of the so called NOM-keur, a zero-on-the-meter certification (Harmka, 2020).

Energy Performance Fee

The Energy Performance Fee is a national regulation for social housing. It was created to solve the problem of the split incentive. The social housing corporation invests in renovation to the level of zero-on-the meter or builds new zero-on-the-meter houses. The performance of the houses is guaranteed for 20 years. In return, the tenant pays an Energy Performance Fee (EPV), which is a fixed amount per month for these 20 years. For a house of 100m^2 this amount will be in the order of €140 per month or less. For the tenant this should be covered by the lower or lack of energy bill. For the housing company this fee of €140 per month is a capitalised capital over 20 years of €33,600, making a budget available for a new zero-on-the-meter house of €33,600. For renovation a budget of around €35,000 that normally is reserved for maintenance is included, leading to a total budget for the zero-on-the-meter renovation of €68,600. Housing corporations often leave the responsibility, including the gains, of the performance guarantee to the building corporation that builds or renovates the houses.

The exact conditions of the EPV are embedded in national regulation. This regulation provides the maximum Energy Performance Fee that a tenant pays, which is linked to the maximum energy need for heating of the house (which can be either less than 50 kWh/m^2 or less than 30 kWh/m^2). In addition, it states that the minimum sustainable energy production of the house should cover: the heating needs, 15 kWh/m^2 for domestic hot water use, the energy needs for auxiliary energy and 26 kWh/m^2 for the energy needs for household equipment. The regulation stipulates that an accredited company determines if the requirements are met. It will check the energy production, energy use for heating and domestic hot water use and the energy use for household equipment and auxiliary energy. The costs for monitoring are €1250 initially, plus €15 per month. The tenant is obliged to pay the Energy Performance Fee only if the house meets the requirements. If the sustainable energy production of the house is less than the energy usage due to less solar hours or due to user behaviour, the tenant has to pay the fee. Only when the energy use is higher than the production due to malfunctioning of the systems or construction flaws the tenant doesn't need to pay the fee.

However, at this moment there are no conclusive methods yet to check compliance. There is no uniform way of data handling, data analyses and reporting. The repair of poor data quality costs over 50% of the analysis time. And in addition, there are issues with data security, such as data leaks. Current research focusses on the development of open-source API's and secured databases. And it is clear that there is an increased demand for ways to check the performance, for instance with models linked to data.

NOM-keur, a zero-on-the-meter certification

In parallel to the Energy Performance Fee (EPV), the Stroomversnelling ("Speeding-Up") initiated the so called NOM-keur, which is a voluntary zero-on-the-meter certification (Stroomversnelling, 2021). There are no formal regulations and there is no fee involved. The focus of the NOM-keur is on building quality, in terms of comfort and indoor environmental quality. In that sense, the NOM-keur goes a step further than the EPV. Also, the monitoring is intensified: in addition to the EPV monitoring also the temperature in the living room is measured, and optional are measurements of the CO_2 level, the level of fine dust, relative humidity and the setpoint temperature in the living room. Also, here there is a lack of a conclusive method to validate the thermal performance of the dwelling.

Numbers of zero-on-the-meter houses

The development of the EPV and NOM-keur has had a positive influence on the numbers of zero-on-the-meter houses. The initial ambition of increasing to 100,000 houses has not yet been met, but from the start until and including 2019 11,225 zero-on-the-meter houses have been realized, see Figure 6. For several reasons the market for new zero-on-the-meter houses is growing much harder than the market for zero-on-the-meter renovation. (Harmka, 2020)

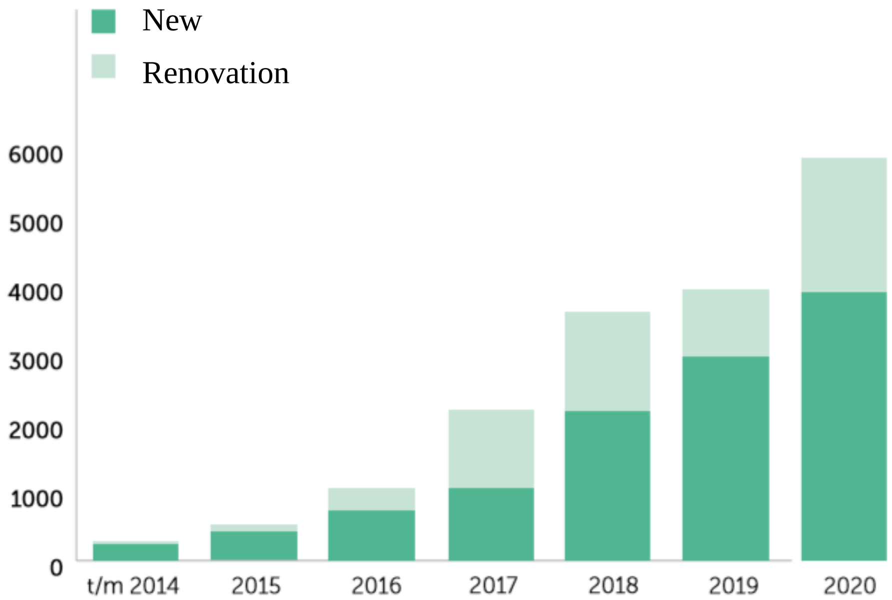

Figure 6. Realisation of zero-on-the-meter houses per year and planning for 2020 (Harmka, 2020)

Summary

The initiatives of the Stroomversnelling ("Speeding-Up") increased the market for zero-on-the-meter houses and therefore more attention has been paid to the assessment of the actual performance of houses and the monitoring thereof. At this moment a practical approach is used to check the actual performance. There are still many questions to resolve, like: how can we standardise the compliance check, how can we reduce the number of sensors used for that, how can we assess the actual user behaviour, how can we standardise data handling? However it does bring to the fore that all of these initiatives lack a methodology to measure fabric performance cost effectively.

1.5.2. Development of whole building HTC measurement in the UK

The ability of the building fabric to provide an effective thermal enclosure has been under scrutiny since the oil crisis of the 1970's when the UK government introduced regulations for the conservation of energy. With the 1976 Building Regulations introducing minimum standards for insulations questions over quality of build and the actual energy efficiency of buildings were raised. Notably the International Energy Agency was established in 1974 and subsequently

Annex's 32 and 41 focused on the building fabric.

In the UK, to better quantify thermal performance, during the latter part of the twentieth century, Bell and Lowe undertook studies to interrogate and measure the building fabric in the field (Lowe et al., 2007; Wingfield et al., 2011). The Elm Tree Mews and Stamford Brook projects were seminal in their attempt to explore the issues for house building related to the zero-carbon trajectory set out by the UK Government in 2006. The projects measured significant underperformance in fabric and services resulting in dwelling heat loss which were 54% higher than designed (Bell and Lowe, 1998). To measure the real performance, the methodologies for obtaining a building's heat transfer coefficient (HTC) were refined and later a guide to coheating was published by the group based at Leeds Beckett University (LBU) (Johnston et al., 2013).

The testing of unoccupied buildings, at the time, proved the only reliable way of capturing a buildings HTC. Thus, through an artificial heating regime, using electric heaters, heat loss through the building fabric was measured. A summary of a studies on 25 new homes, based on a meta-study published by the Leeds Beckett research group, indicated that the different types of buildings consumed on average over 1.6 times their designed values (Johnston et. al., 2015). Based on the work of the group, the coheating methodology, supported with heat flux measurements and blower door tests, became the established method of determining whole house building performance.

Coheating tests were first used in late 1970s, where (Sonderegger and Madera, 1979) and (Sonderegger et al., 1980) used electric heaters and the buildings own heating system to determine the on-site efficiency of duct heating and cooling systems under actual boundary conditions. The term coheating originated from the multiple use of the dwellings on heating provisions and additional heating devices. The main principle from the early coheating tests continued to be used to estimate the thermal characteristics of the building envelope, notwithstanding that the methods to heat the building are now undertaken with independent electrical heaters, which are more easily metered and measured. The principle of obtaining a HTC through the electric coheating test has been applied extensively to evaluate the fabric building performance (Bauwens and Roels, 2014; Bell and Lowe, 1998; Francisco et al., 2006; Glew, 2021; Jack, 2015; Jack et al., 2018; Lowe et al., 2007; Palmer and Pane, 2011; Roels et al., 2017; Stamp et al., 2017; Stamp, 2016)

With questions over the accuracy of coheating being raised an evaluation of coheating was undertaken by the NHBC in the UK through a series of tests by different groups on the same building (Butler and Dengel, 2013). The tests, which were undertaken between December and May 2011 reported a maximum uncertainty in the HTC of 17%. Most notably, weather conditions during the tests affected the accuracy of results, with solar radiation having the greatest impact. The tests were undertaken at different times and the length of the test period varied, with test periods ranging from 12-18 days. However, the spread of results was largely attributed due to the different methods of analysis, as opposed to variations test set up (Butler and Dengel, 2013). Subsequently Jack, reviewed the sensitivity and reproducibility of the method using those data from the study and found that when data collection and analysis methods are more precisely followed the HTC can be obtained with an uncertainty of ±10% (Jack et al., 2018).

The coheating methodology has evolved from the early studies (Sonderegger and Madera, 1979) into guidance provided by Leeds Beckett University (LBU) (Wingfield, 2010) and then a more elaborate method with experimental procedures to limit measurement uncertainty (Johnston et al., 2013) Measures to limit the impact of solar and wind, latent heat from materials that may be drying out, party wall heat exchanges and the thermal capacity of major element are all considered. While variations in coheating methods do exist, as captured by the NHBC study (Butler and Dengel, 2013), the estimates of the HTC, using the LBU method, were considered sufficiently robust and widely used. More recently, as part of the Smart Meter Enabled Thermal Efficiency Rating (SMETER) (BEIS, 2020) project funded by the UK Government's Department for Business, Environment and Industrial Strategy (BEIS) the approach has been revised, specifically for use as a method for comparison to in-use HTC measurements using Smart meter technologies.

Using the Electric Coheating method as an in-use HTC reference value

The LBU electric coheating test method requires that all purpose provided ventilation openings are sealed when undertaking a test. Thus, the coheating metric quantifies the aggregate fabric and unintended air infiltration heat loss rates and does not provide for heat loss rate through purpose provided ventilation. However, the UK's standard energy assessment metric (SAP) assumes that purpose provided ventilation to be open when calculating HTCs and Smart meter technologies collect data from occupied buildings with the purpose provided ventilation in various states of operation. Thus, the HTC's from the electric coheating test protocol may need to be modified to include the heat loss rate through those ventilation openings that have been designed to support healthy air exchanges. Where extract fans, air bricks, flues, fireplaces, trickle vents and other passive vents are present they should be accounted for within the HTC.

Adjustment to the electric coheating test results can be performed experimentally, to allow for ventilation that might be encountered under habitation. However, leaving purpose-built ventilation open during coheating is a problem as wind effects can introduce too much uncertainty into the coheating measurements, especially for less airtight dwellings. Therefore, the electric coheating test can be undertaken in the standard manner (with all vents closed), and multiple air pressurisation tests used to calculate differences in heat loss due to ventilation. Using air pressurisation tests in accordance with ATTMA TS1 (ATTMA, 2010) with all-purpose provided ventilation sealed and ISO9972:2015 (BSI, 2015) the uncertainty in the infiltration can be calculated.

The results of the air pressurisation tests can then be used to disaggregate the HTC obtained from the electric coheating test into its fabric and air infiltration heat loss components. In addition to the air pressurisation test with all ventilation sealed, a pressurisation test can be carried out with the purpose provided ventilation open. This new pressurisation test provides a value that could be used to approximate an average background ventilation heat loss term under more typical, lived-in conditions. The average lived-in ventilation can then be added back to the fabric heat loss term to give an estimate of the HTC of the lived-in property. For these calculations the air permeability measurement at 50 Pa by a blower door or at 4 Pa using a Pulse test (Cooper and Etheridge, 2004) must be converted to an air infiltration at typical in-use conditions. The conversion for measurements at 50 Pa was done by dividing the air leakage (in air changes per hour) by 20 using the 1/20 *rule of thumb* (Sherman, 1987) but there is debate over the suitability of this approach (Jones et al., 2016; Pasos et al., 2019).

Rather than typically considering just one value, it is more appropriate to take the in-use HTC to occur, somewhere between the condition reported with all ventilation closed and that with all of the purpose provided ventilation open. Under habitation, occupants would be expected to use the building with a level of ventilation between the two different conditions. The procedure of using the upper and lower ranges, together with the uncertainty of the test, was adopted by UK's recent SMETER project, where different in-use monitoring devises and algorithms for assessing in-use HTC were evaluated in the field (BEIS, 2020)

The (SMETER) Innovation programme, is a BEIS project, where 8 smart meter technologies are undergoing trials to determine their ability to establish a reliable estimate of HTC. As a baseline assessment the programme is using coheating, supported with blower door tests and heat flux measurement. QUB and Pulse tests are also used for comparison across the 30+ test dwellings. The research is running in parallel with Annex 71, with results to be released in 2021.

UK Energy Company Obligation

The Energy Company Obligation (ECO) is the UK Government energy efficiency scheme first introduced in 2013. Under the ECO the largest energy suppliers in the UK are obligated to promote measures to improve the energy efficiency of homes that help fuel poor and vulnerable households pay for their fuel bills. Energy suppliers are obligated to install energy efficiency measures that will result in a reduction in home heating costs, each obligated company is designated an amount (in £s) of home heating cost reduction based on their percentage of the total energy market in the UK (OFGEM, 2020). The ECO has been through several iterations, with the latest revision, called ECO3, commencing in 2018.

Under ECO3 new provisions were launched which provided incentives to measure the effect of measures installed. By demonstrating the performance of installed retrofit in-situ, obligated suppliers receive an incentivised credit towards their total home heating cost reduction obligation. The incentives are available either to measure the effect of a retrofit directly, or to demonstrate the performance of a new technology through a field trial (BEIS, 2019). This again further reiterates the requirements to develop cost effective measurement methods.

1.5.3. Development of whole building HTC measurement in France

In France, the energy performance measurement market has experienced strong development since airtightness tests were imposed on building professionals. While the French Thermal Regulations of 2005 introduced the concept of airtightness, the updated version in 2012 (Ministère de la Transition écologique, 2012) imposed the so-called "blower door" test, at the end of the work, in individual and collective housing.

This test introduced a real breakthrough in the building sector by shifting it from the obligation of models to the provision of measured results to inform performance.

In addition, several companies have been created and have developed their activity around the measurement of airtightness. While the tests during construction can be carried out by design or control offices, project management or even self-checking companies, the final test before acceptance is carried out by an approved operator (around a thousand operators are approved in the country).

In addition, RT 2012 placed the issue of energy performance at the heart of many debates. One of the main questions which animated the legal sphere was to know if the ten-year guarantee could be engaged for a fault of energy performance. Even if the calculation allowing to lead to a consumption of more or less 50 kWhep /m² /year (ep = FR Énergie primaire = EN primary energy) depending on the reference climatic zone is conventional and not forecast, according to many legal experts this is part of the sales contract and as such, it makes part of the ten-year guarantee. This guarantee could apply in the event of impropriety for destination resulting from a lack of energy performance. The work carried out within the framework of the Sustainable Building Plan (Jouvent et al., 2012) considered that impropriety for destination could be invoked "*in the case of a difference in conventional consumption greater than a certain threshold and in presence of damage materially affecting the structure or its components"*. A decree in the Council of State would have defined the threshold that conventional consumption should not exceed at the end of the work.

However, the Law on Energy Transition for Green Growth limits the implementation of the concept of impropriety for destination in the event of a lack of energy performance and introduces several grey areas (Ajaccio and Caston, 2015). The new article of the Construction and Housing Code (CCH) indicates that "in terms of energy performance, the impropriety for destination, mentioned in article L.111-13, can only be retained in case of damage resulting from a defect related to the products, the design or the implementation of the work, of one of its constituent elements or of one of its leading equipment items, any condition of use and maintenance taken into account and deemed appropriate, to an excess energy consumption allowing the use of the structure only at an exorbitant cost." This article is open for interpretation by not specifying any threshold and by mentioning "an exorbitant cost " which will be left to the subjective assessment of the courts. The triggering of the ten-year guarantee therefore becomes uncertain. Case law will allow us to appreciate how this text can be interpreted.

This debate necessitates the distinction between guarantee of intrinsic energy performance (GPEI) and guarantee of energy result on use (GRE).

The GPEI is a contractual commitment established between a building project owner and a service provider or a user beneficiary and a professional owner-builder. It concerns work carried out on new or existing buildings. The construction operation provider then undertakes:

- "On a maximum level of theoretical or conventional or standardised "energy consumption
- "while respecting a usage scenario and specified comfort parameters (temperature, ventilation, air quality, etc.) " (Jouvent et al., 2012).

This GPEI is above all a measure of compliance with the commitments delivered at the reception stage of the construction phase indicates, "*GPEI is close to a quality assurance or commissioning mission"* (Jouvent et al., 2012). If deviations are notified during the inspection, the guarantor undertakes to correct them by taking appropriate measures. Within the framework of RT 2012, this GPEI would be limited to the five regulatory usages.

With GRE, the contractual commitment is established between a client-owner or tenant and a specialized service provider. It also follows on from work on new or existing but can be signed without any work. The service provider then undertakes:

- "On a maximum level of real and measurable energy consumption, or on a percentage reduction in real energy consumption compared to a baseline situation before contract;
- while respecting specified comfort parameters (temperature, ventilation, air quality, etc.);
- and this for a period of contractual coverage." (Jouvent et al., 2012).

Paradoxically, while performance requirements have never been so high, claims have grown exponentially. In a statement, the SMABTP (Insurance specialised in construction insurances) revealed that claims in terms of costs had increased by 71% between 2008 and 2016. The charge had increased from 194 million to 332 million euros in terms of risk in the course of work while the claims had fallen by 14% over the same period (23,575 to 20,400). In the stock of claims, the increase in the number of incidents was even more substantial (increase from 28,400 to 38,900, i.e. + 41%) for amounts multiplied by 1.75 (from 911 million to 1.6 billion euros). The relative increase is even greater since this period of crisis was characterized by a decrease in the number of construction sites. Finally, the risks after reception stage, concerning the ten-year period, followed the same trend: the claim charge rose from 222 to 316 million euros (+ 42%) and the stock grew by 69% (847 million euros in 2008 and 1.4 billion in 2016).

For all these reasons, the need of envelope thermal performance measurement has been pointed out recently by State bodies, such as:

- Note from the Parliament Observatory for scientific choices assessment (OPECST, 2019): *"Envelope performance measurement and real energy consumption of buildings is an essential precondition for the energy retrofit management"*

- Report from Renovation Plan (Ministère de la Transition écologique, 2021) *“another major challenge for energy retrofit is building’s real performance measurement. Specific measurement tools, beyond thermal calculations and audits, will be necessary in order to warranty the workmanship quality and the level of performance obtained”*

In this context, the need to verify the quality of work related to the envelope becomes more and more pressing. Nevertheless, the generalization of procedures for measuring intrinsic energy performance at the reception stage needs to face several challenges:

- the development of a system that certifies the intrinsic performance of the work;
- an inexpensive procedure to implement which does not radically disrupt the organization of the site;
- the distribution of equipment that allows the test to be carried out;
- training of a workforce capable of performing tests;
- the development of a certification market in connection with the test that sends a signal to the market and certifies the quality of the building delivered.

Energy performance measurements in France

Airtightness measurements are carried out in large number in France, this measurement is mandatory for newly constructed buildings.

Regarding all other aspect of energy performance measurements, several approaches have been successfully adopted, such as:

- Highly instrumented demonstrator buildings: essentially based on the PREBAT program (CEREMA, 2017) these “proofs of concept” aim to provide “best-practice guidelines” to stakeholders. Nevertheless, the huge cost of instruments and data analysis limit this approach to few buildings.
- Energy Performance Contracts (EPC): the aim is to warranty, under specific conditions, the “real” energy consumption of the building. Mainly concerning tertiary buildings and collective dwellings, they do not penetrate massively the construction market (less then 50 contracts a year), even if the trend is increasing.

Several other global energy performance measurements protocols, from fault detections on energy equipment to envelope thermal performance measurements, are also under development or experimented on the field (Ziour and Calleberg-Ellen, 2020).

Concerning the envelope thermal performance measurement, such as intrinsic thermal performance indicators measurements (HTC and U values etc), a lot of national R&D projects implying both researchers and stakeholders have been achieved or are still going on. These projects is detailed in Figure 7.

A crucial step for stakeholder adoption has been taken by training and letting professional operators, generally qualified for airtightness measurement, perform the thermal envelope performance measurements (SEREINE, 2021; Thébault and Bouchié, 2018).

- For CERQUAL project, aiming to benchmark three methods on few new constructed individual dwellings (QUB, ISABELE and EPILOG)
- For DIANE project, aiming to measure new constructed individual dwellings based on ISABELE method in large volumes
- For SEREINE project, aiming to merge, adapt and improve both ISABELE and EPILOG method for retrofitted housings.

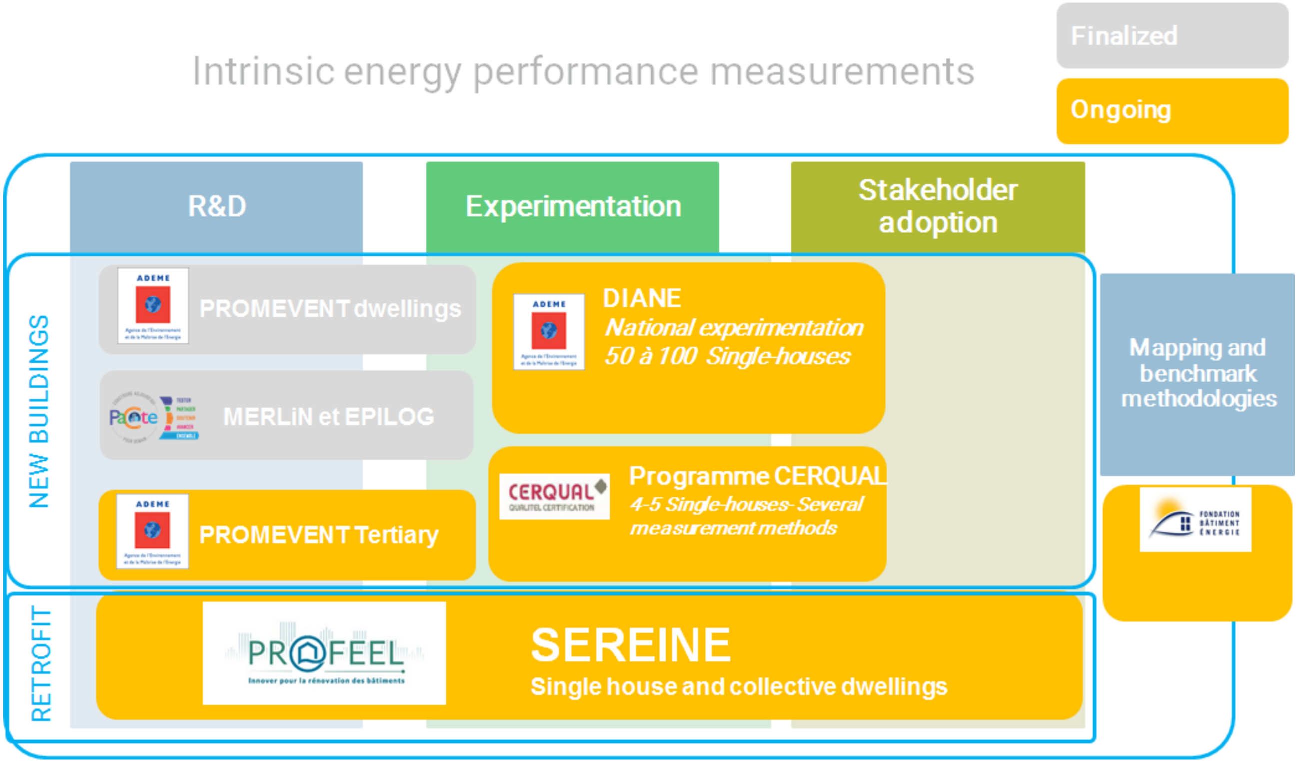

Figure 7. Major research programs dealing with intrinsic energy performance measurements in France

A first market study on energy performance measurement needs and opportunities in France has been produced by the Building and Energy Foundation (Ziour and Calleberg-Ellen, 2020) The study deals with a large scale of energy performance measurement indicators, from fault detection to intrinsic energy performance indicators.

Expert analysis shows that motivations and needs for building energy performance measurement vary widely depending on stakeholder category. Concerning building owner's needs, three major motivations for using building energy performance measurement have been identified:

1. Fault detection and diagnostic of in use buildings, quoted by more than 90% of responders
2. Validate building's performance (envelope and/or systems) at the reception phase or in-use, quoted by 30% of the responders
3. Feedback for improving future works, quoted by less than 10% of the responders

HTC measurements correspond to the second item and is interesting to 30% of the building owners in France. It is important to know that this figure was produced in 2016 and just correspond to a specific part of stakeholders.

Another analysis was then conducted to estimate the market potential (Ziour and Calleberg-Ellen, 2020) Firstly, main building energy performance measurements needs have been categories in three market parts:

- "Works": the need implies major building works, such as fabric retrofitting
- "Operation": the need is linked with operation phase, in order to improve user comfort or contain energy consumption and operation costs
- "Works + operation": the need is generic, not specifically linked with works or operation phase

Previous identified needs have than been classified.

Table 2. Classification of energy performance measurement needs regarding to construction phases (Works, Operation and both).

Energy performance measurement needs	Market part
Diagnostic, make future works more reliable	Works
Check building performance (envelop, energy systems...) at the acceptance stage , without occupancy ("as built")	Works
Get a grant	Works
Ask for a third-party financing process	Works
Self-check	Works
Check buliding performance in operation (with occupancy)	Operation
Fault detection in operation	Operation
Optimize energy contracts	Operation
Optimize performance day by day	Operation
Consumption interupting solutions during energy demand peak periods	Operation
Optimize electrical grid management	Operation
Inform occupants	Operation
Manage Energy Performance Contracts	Works & Operation
Feedbacks	Works & Operation
Communication / increase confidence	Works & Operation
Regulation / quality label	Works & Operation

The potential market size for both “works” and “operation” has been estimated, using several hypotheses described in the report is shown in Figure 8.

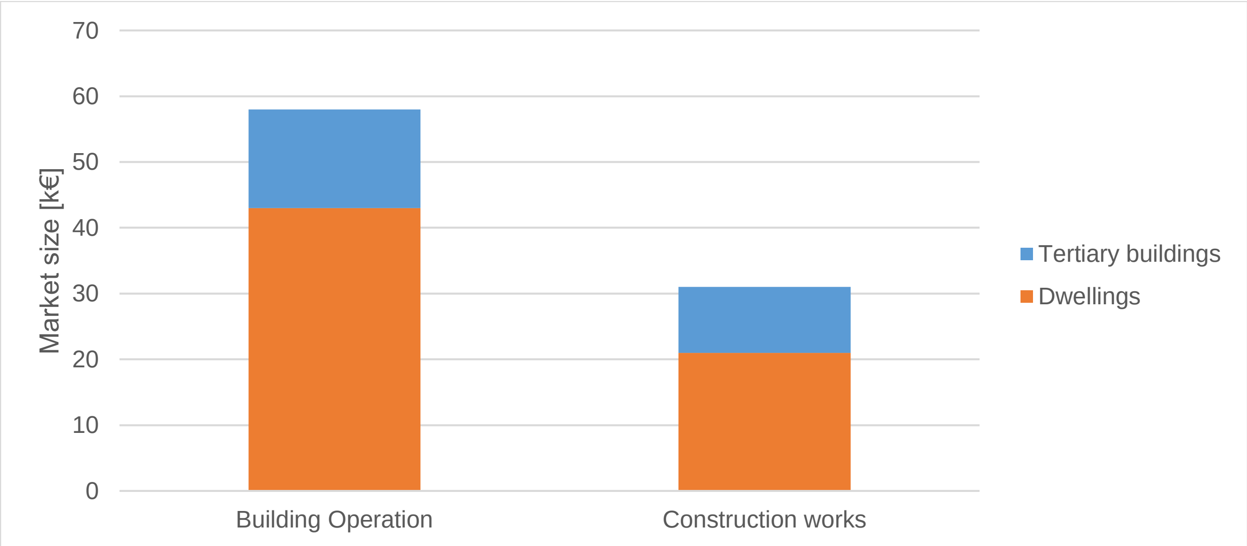

Figure 8. Market size for energy performance measurement in France depending on construction phase (works / operation) and building destinations (tertiary / dwellings)

Three major facts, related to HTC measurement indirectly, have to be pointed out:

- The French “operation” market is two times larger than the “works” market. Indeed, new constructed or retrofitted buildings is quite small (less than 3% of the overall existing buildings in France): the potential for methods applicable in operation phase is than important. Thus, the Annex 71 strategy aiming to measure HTC for in-use building seems correct.
- The actual existing market for building energy performance measurement, i.e. buildings in which energy performance contracts and measurement and verification protocols are quite common (school, health, offices, sport, collective dwellings with collective heating system), represent only 25% of the overall market. Hence it is important to address innovative methods for the other 75%, of the market, mainly composed of individual dwellings or collective dwellings with individual heating system.

- Dwelling market is widely dominant (70% of the market); individual dwelling is a key point of the market (50%).

This information, especially the two last items, highlights the importance of individual dwellings that will be our first case study for assessing the practical possibility for massively measure HTC on the field.

Individual dwellings in France: a case study

The single-family home market represents 100,000 to 200,000 new homes constructed per year in France, with an average cost is 150 k€ (220 k€ including the land) for an average floor surface of 120 m² (2013 figures, see (d'Auzon and Vergne, 2016). The market is very segmented in quality (INSEE, 2017):

- 40% of the market represents "low cost" (less than 1000€/m²) single house for low-income households.
- 60% of the market represents "premium" single house (cost between 1300-3000 €/m²).

Although, certifications are quite rare on the market: 10 % for NF Habitat and less than 0,5 % for the more complete certificates such as NF Habitat HQE and EFFINERGIE (i.e. including energy, environmental and quality targets and representing around 500 houses / year (Observatoire BBC, 2015).

Today, French households generally don't know the general principles attached to French thermal regulation (Ministère de la Transition écologique, 2012). The final clients lack the knowledge and skills to accurately assess the quality of their building, and the impact of certain defects on their future energy consumption, especially when it comes to barely visible elements, which are part of the structure (such as wall insulation).

In the case of the second-hand car market, (Akerlof, 1970) had shown that in an economy where information is imperfect, equilibrium cannot be achieved. In such a market, the buyer does not distinguish good quality cars from bad ones. Only the sellers have information on the quality of the product. Faced with this uncertainty that could lead him to buy a poor-quality car, the buyer only goes for the products with the lowest prices. Quality car sellers then withdraw from the market. Through this anti-selection mechanism, bad products drive out good ones.

The single-family home market remains different as it is clearly segmented and the best single-family home builders have managed to build a quality image for themselves. Nevertheless, opportunistic behaviour and unfair competition may harm serious companies.

Thus, the single-family home market, which is very constrained, does not appear firstly to be very suitable for the development of this type of test. However, this market has evolved with the introduction of new regulatory instruments. The implementation of airtightness tests was a first breakthrough for all of the players involved. It has led to increased professionalization of stakeholders and an improvement in the overall energy performance of the buildings delivered.

As a first step, the introduction of a new test of envelope performance measures could only concern a small part of the market, that is dominated by pioneers who want to meet a need that the majority of the market will express in the future. These pioneers are to be found among builders of single-family homes, but also practitioners who can rely on this test to distinguish themselves from the low-end services offered by some of their competitors. From an organizational standpoint, this test could follow on from the steps already taken to measure the airtightness of buildings

The implementation of a test to measure the performance of the envelope can initially give rise to a certification / labelling so that the actors who embark on this path benefit from a sign of quality that they will be able to enhance later. In the past, the BBC label, launched in anticipation of the future RT2012, guaranteed that the house would not be discounted when switching to RT2012. This certification / labelling must relate to the work and the skills of the players:

- For individuals to buy into the discourse of performance measurement, they must be able to expect a gain in euros when the building is operated or when it is resold. Only a label or certification attached to the work will allow the building, once constructed, to differentiate itself from a building that would not have benefited from this test.
- Professionals (builders and design offices) aim above all to highlight their know-how and skills and show their customers that they offer a better-quality service than those who are not labelled. A label / certification will give them this distinctive sign of quality.

What is at stake is above all that non-professional (householders) and professional (donors, promoters) owners who will be the main beneficiaries of this test, agree to pay for this new service. The problem results from the time lag between costs which are immediate and not insignificant and occur before the occupation of the house and the gains which are spread over the entire life of the building and whose valuation is uncertain. Well-proportioned and temporary aid systems could remove this barrier during the market launch phase.

Finally, the long-term dissemination of the envelope performance measurement test assumes that corrective actions are taken if the initially defined performance values are not reached. Indeed, if no action is taken to correct the observed defects, the test will provide no added value and it will fall into disuse. This risk of having to bear an immediate cost in the event of poor workmanship observed upon receipt, is essential to make the test credible and send out a strong signal to all the actors involved in the act of building.

Finally, a partially public funded support, based for instance on voluntary certification, would allow pioneer using this kind of new methodologies. The emergence of these new measured indicators such as HTC, even for a small part of the market (less than 10% of the constructed houses are certified) will hopefully lead in several years to a better construction quality of the overall market. This evolution has been proven for the airtightness tests: when these tests start on the market, certified houses were much better than all other houses, but after several years the skill improvement of the builders and combined with regulation to make airtightness of the overall market very close to the modelled value (Observatoire BBC, 2015) , as shown in Figure 9.

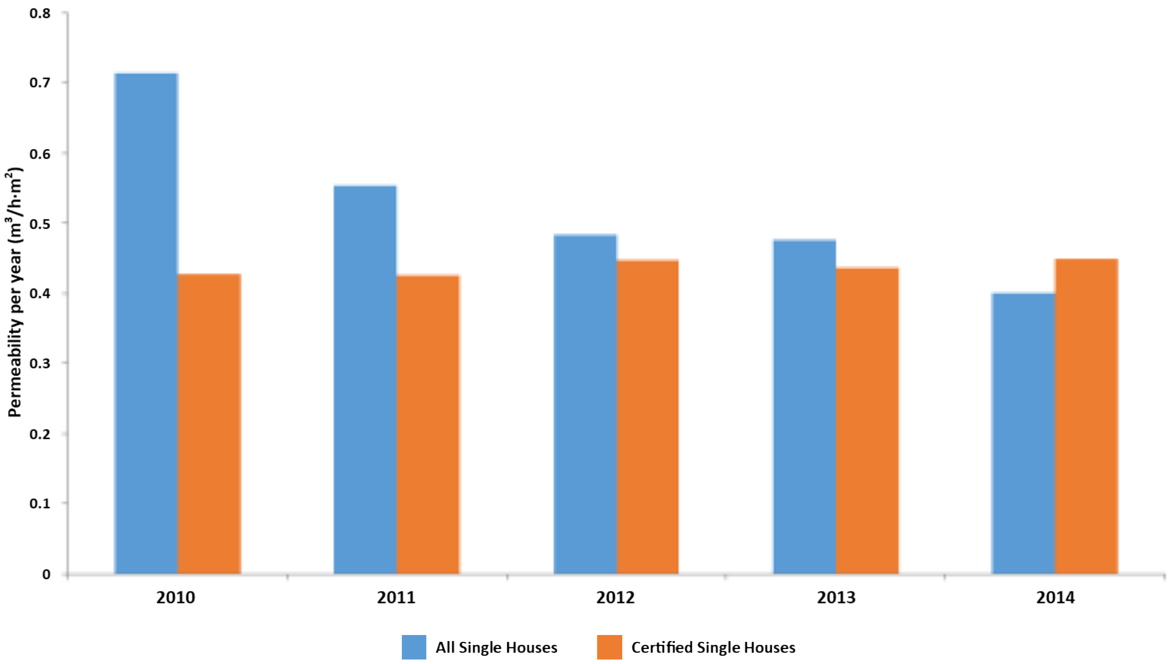

Figure 9. Average measured airtightness tendances from 2010 to 2014 in France, for two samples of single-houses: a certified sample of single-houses and a control sample (not certified) (Observatoire BBC, 2015)

1.6. Stakeholder survey

In order to investigate to what extent developed methods for characterization and assessment of the actual energy performance of buildings based on on-site measured data of in-use buildings can be used in a quality assessment and guarantee framework, an online survey was launched by Annex 71 in January 2019. Between January and December 2019, the survey, which focused mainly on the measured HTC in buildings, has been widely disseminated in the participating countries in several languages including English, Dutch, French and German. A total of 243 responses were collected that are complete in all aspects. It took respondents about 20 minutes to complete the survey. All the responses are translated into English in order to prepare the results for the analysis. A full report with a presentation of the results can be found in Annex 1. Here, we only summarise the main results to better understand what the stakeholders expect.

Stakeholders from a total of 14 countries participated in the survey. These include Austria, Belgium, Denmark, Estonia, France, Germany, Ireland, Italy, Norway, Spain, Sweden, Switzerland, The Netherlands and the UK. Based on the description the stakeholders gave themselves, we broadly identified 13 stakeholder categories, as seen in Figure 11. It should be mentioned that there might be some overlap among these groups. The highest participation is by the Consulting engineers in the building industry, although in making the classification the distinction between Consulting engineer and Engineers specialising in building physics was not always clear. It is followed by Architects, Building contractors and Energy service companies. Together with research and certification bodies, these form more than 70% of the total participation by stakeholder-type. Overall, there is a fair distribution of the stakeholders that participated in the survey. Figure 12 shows the types of buildings that the company or the organization of the stakeholders operate for. We see that the majority of the stakeholders are involved in all types of buildings. Therefore, the responses of the survey will reflect the experiences that pertain to a majority of the building types.

The survey shows that the stakeholders find the existing methods of calculated energy performances quite reliable with over 75% participants supporting this (Figure 13). However, it is interesting to note that over 90% of the stakeholders are still interested in a method that can measure the actual energy performance using the on-site HTC measurements (Figure 14). This indicates that there is a good opportunity to introduce a reliable method based on measurements. The stakeholders also feel that their customers will be interested in such a method with over 85% participants supporting this.

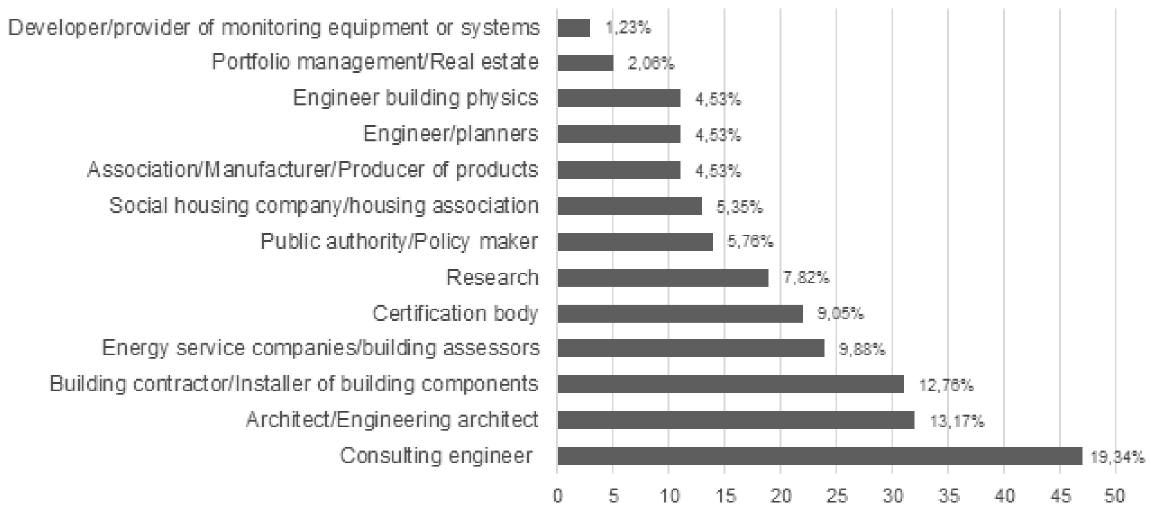

Figure 10. Professions of the various stakeholders that participated in the survey

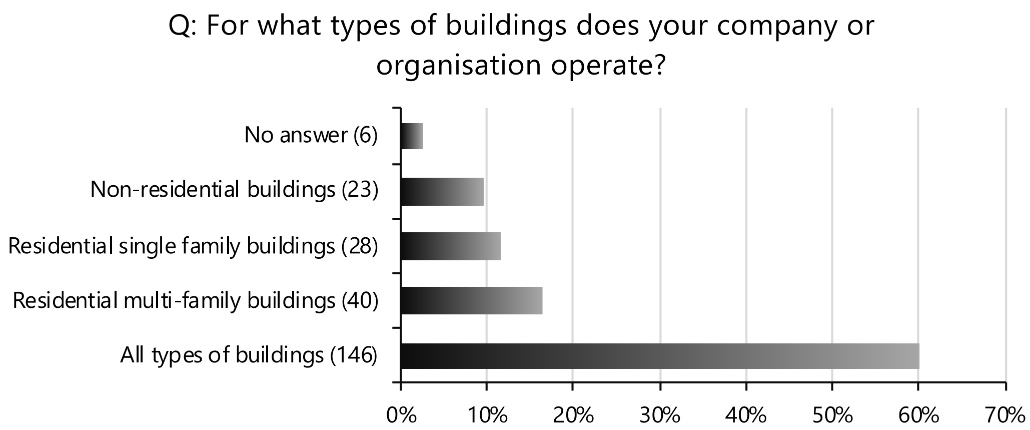

Figure 11. Scope of the building types operated by the stakeholders

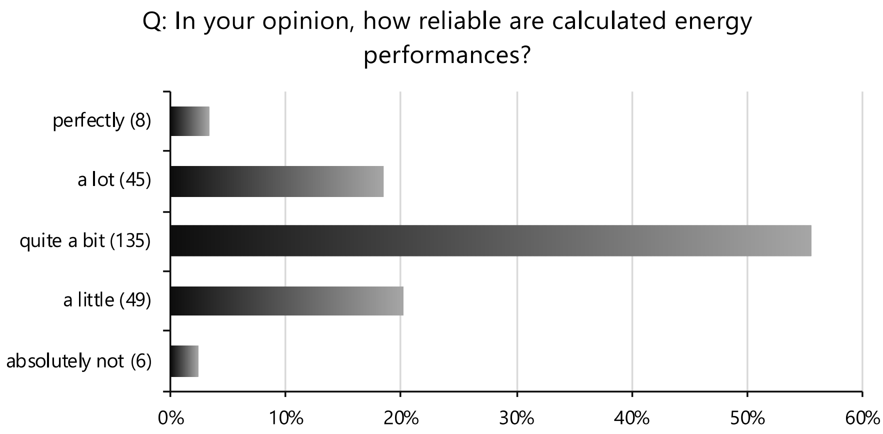

Figure 12. Stakeholder's opinion on reliability of calculated energy performance

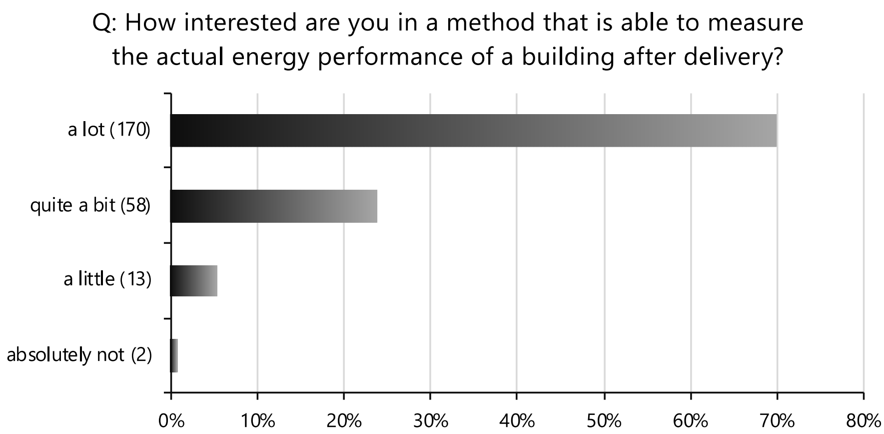

Figure 13. Stakeholder's interest in measured energy performance

1.6.1. Section Summary

An introduction to the theory and practice of HTC measurement was given, the EPG was presented with some possible explanations, helping to prove the requirement for the HTC itself. The issue of "gaps" arising in other areas such as measurement and modelling are also examined, helping to provide context to the issue. A series of use cases were demonstrated which demonstrated the need for the metric, alongside a stakeholder survey which clearly stated across a large sample the interest in the measured performance of a building.

2. Global framework for HTC-measurement

The previous chapter showed the shift towards quality guarantee and the interest of stakeholders to assess and characterise the actual energy performance of buildings based on on-site measured data. To respond to this evolution, the Annex 71 project evaluated and improved identification methods that can be used for this purpose on in use residential buildings. Characterisation and performance assessment of buildings serves many purposes, such as identifying the air tightness of the building fabric, the efficiency of systems, operational use by inhabitants, etc. In the current project we focussed on two topics:

1 **Building behaviour characterisation to predict heat demand / indoor temperature for a given time horizon**

2 **Quality assessment to pinpoint the most relevant building performance indicators, such as the actual overall heat transfer coefficient of the building fabric**

Both topics can serve different applications. Within the Annex 71 Sub Task 2 report building behaviour characterisation has been used for fault detection and model predictive control. The Annex 71 Sub Task 2 report focusses on quality assessment by exploring and optimising identification techniques to determine the overall heat transfer coefficient of individual dwellings based on on-board monitored data. The main objective of the project was to develop a decision matrix that compares and optimises for the different applications, identification techniques in terms of costs and obtained accuracy.

2.1. Basic idea of the decision matrix

As shown by the survey in the previous chapter, stakeholders have different motivations to resort to building performance characterisation or assessment. A construction company may want to guarantee their quality, a social housing company may seek the most effective retrofit strategy, an engineering office may need actual information on the thermal response of buildings to design or optimise a thermal network or to embed the building behaviour in model predictive control (MPC) or fault detection and diagnostics (FDD) strategies, ESCO's and policy makers may want actual performance indicators to optimise their strategies to reduce carbon emissions, etc. Each of these applications seek different information on the actual building performance, such as the overall heat transfer coefficient of a building, the efficiency of heat recovery system, the capacity and response of the building to solar gains. Over recent decades, a wide range of identification methods have been developed that can be used for these purposes. They range from simple linear regression models to advanced dynamic system identification techniques. The methods not only differ in ease of use (some are rather straight forward while others demand advanced statistical expertise), but also vary in required input data, both in amount, duration and frequency.

An important aspect in evaluating those methods is outweighing cost of the measurement set-up and the analysing technique against the achieved accuracy. The accuracy depends amongst others on the analysis technique, the measurement time and the input data including measurement error. To map all these interactions, an evaluation matrix has been developed that links the accuracy of the outcome, expected for a specific application, to the requirements of the measurements and best suited statistical data analysis technique. For instance, determining the HTC of a building from smart meter data will have a different cost and accuracy than performing a dedicated coheating test. And where for some applications the accuracy of the first will do (for instance quick estimate of the insulation quality for renovation purposes), a quality assessment might require a higher accuracy and hence a more dedicated test. Figure 14 presents the basic idea of the matrix. Starting from a level of accuracy (y-axis) as required by the application, a certain method and corresponding cost of data acquisition (x-axis) can be determined. Or the other way around, knowing the data acquisition technique (cost and accuracy of the available data) the most interesting method and maximum attainable level of accuracy of the outcome can be determined. This allows stakeholders that want to do a characterisation or quality assessment of a building to make a well-informed choice depending on the application and the available budget.

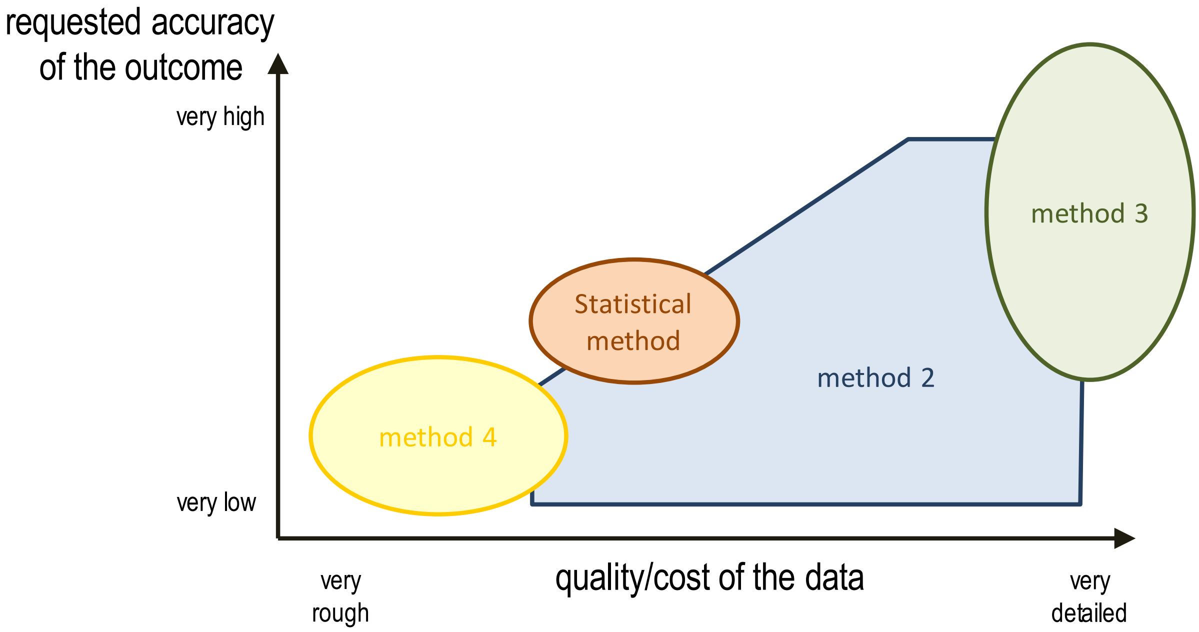

Figure 14. Basic idea of the decision matrix, linking the statistical methods to the quality of the input data and achievable accuracy of the outcome.

Based on case studies on both topics the necessary input data and obtained accuracy was evaluated for different data analysis methods and for different applications. Improvements of the identification techniques can be obtained by reducing the cost (shift to the left on the x-axis) or enhancing the accuracy (shift to the top on the y-axis). As such, the evaluation framework was refined in the course of the project for specific applications. Of course, the project had no intention to optimise all possible methods for all possible applications, but rather to develop the global framework and to explore and optimise it for some specific applications. The Annex 71 Sub Task 2 report explored the framework for model predictive control and fault detection. In the Annex 71 Sub Task 3, report different identification methods have been tested and optimised to assess the actual heat loss coefficient of a building.

2.2. Towards a 3D-decision matrix

Mapping the interaction at play between envisaged application, corresponding performance indicator, expected accuracy, statistical method, available input data, etc. is the main purpose of the decision matrix. Supported by the decision matrix, stakeholders should be able to decide for a specific application on data to be monitored, how to analyse the data (which statistical method) and the corresponding accuracy that can be achieved. The idea of an x-axis providing cost of the data acquisition (see Figure 15) is tempting and definitely appreciated by the stakeholders, but in the course of the project, it became clear that it is very hard to attribute a certain cost to an (on-board) measuring campaign. First of all, some sensors anyway will be available in the building, so it appears more correct to only account for additional sensors needed for a certain application. But even then, sensor costs were found highly dependent on type, accuracy, installation cost, reusability, etc. Furthermore, the cost of sensors is time and sometimes even location-bound. Therefore, a shift was made from specific costs of the data collection, towards an x-axis showing possible sets of prescribed data packages for a specific application. The simplest (and hence cheapest) data package for a HTC-characterisation could for instance be a smart meter and room thermostat providing global energy use and (living room) indoor temperature. Using only this data will require several assumptions on building use, actual (averaged) indoor temperature, solar and internal heat gains, etc. to estimate the HTC of the building. One can therefore expect the accuracy on the HTC-estimate to be low, but maybe precise enough to get a first estimate of the renovation potential of the building. If a more precise assessment is needed, additional measurement points, such as additional room temperatures, flow meters to split energy use for space heating and domestic hot water, a local weather station can be added to define additional data packages that can reduce the uncertainty on the HTC-estimate. Table 3 shows an example of possible data packages for HTC-estimation.

Table 3. Possible Data Packages

Examples of Packages	Equipment	Variables available	Notes
Package A	Existing Home with Smart Meters and Smart Thermostat	• Gas consumption • Aggregate Electric consumption • Internal temperature • Occupancy patterns • Heating setpoints	External weather can be sourced from online sources
Package B	New build home with air source heat pump and. Smart meters	• Aggregate Electric Consumption • ASHP consumption • Internal temperature at several zones • External temperature • Setpoint/occupancy pattern	
Package C	New build highly efficient home with localised and communicative controls.	• Global Electric Consumption • Heat pump (separated consumption) • Internal temperature • External temperature • Setpoint/occupancy pattern • Ventilation system energy consumption • Input from solar PV system	PV invertor data can provide radiation input into the dwelling

In addition, the survey work carried out by ST4 revealed time factors to be crucial for many stakeholders. Often short measurement campaigns are desired. But explorative studies indicated a strong correlation between time span (and frequency) of the available data and practicable accuracy. In a way that a simple data package collecting data over a long time span might result in the same accuracy as a monitoring campaign with a very extensive data package running over a few days. So also, time issues, in a sense, are related to cost.

To respond to those concerns the x-axis of the decision matrix of Figure 15 was transformed in a x-plane, providing on the one hand a choice between different data packages and on the other hand the time span of the monitoring campaign. Figure 15 shows the basic principle of this 3D-decision matrix. If a certain accuracy is a prerequisite for a certain application, e.g. quality guarantee of the HTC of a newly built dwelling, a horizontal cut off plane will reveal all statistical methods in combination with required data packages and monitoring time qualifying the acceptable uncertainty on the outcome. Similarly, if monitoring duration is the main concern of a stakeholder, a vertical intersection can be made revealing all methods and data packages that can be applied within the given time horizon and the corresponding accuracy that can be expected. Note that different use cases, such as fault detection, HTC-assessment, model predictive control, estimations of solar aperture and the like will likely result in different decision matrices. In the next section we show as an example the development of the decision matrix for HTC assessment as was performed on one of the case study dwellings in ST3 of the IEA EBC Annex 71-project

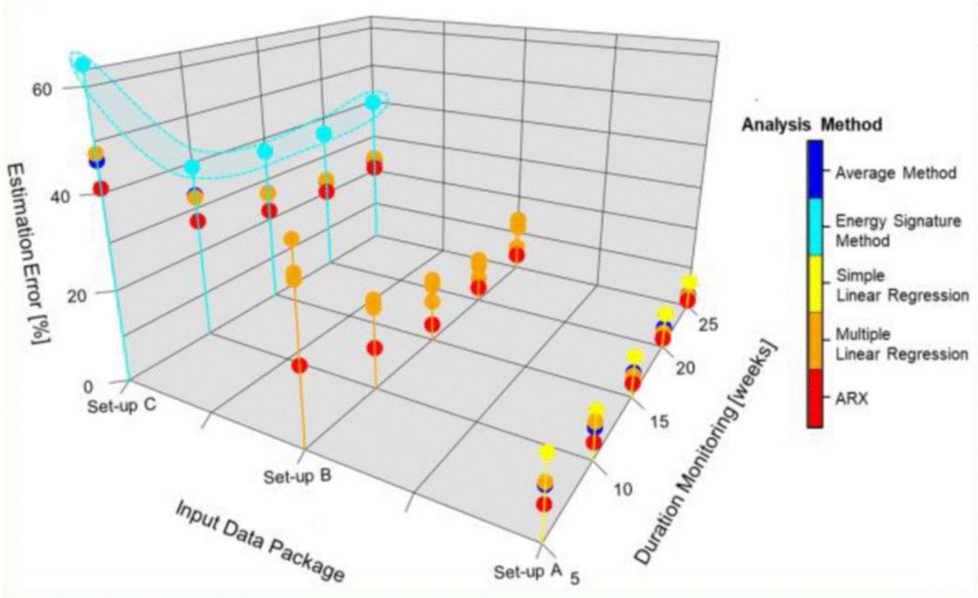

Figure 15. 3-dimensional decision matrix, presenting expected estimation error for different statistical methods, considering (predefined) data packages and monitoring time.

2.3. Explorative application for HTC-assessment

Subtask 3 of Annex 71 investigated methodologies to identify, in a way that is reproducible and repeatable, the performance of the fabric of residential buildings that are in use, and for which we have limited monitoring data available. Starting from a building physical framework, the impact of different input parameters and corresponding statistical modelling approaches to identify the HTC from on-site measured data has been investigated for different case studies. As an example, we show here some of the results for an end-of-terrace social housing dwelling in Gainsborough, UK. Figure 16 shows the building. Details on the Gainsborough case and other examples can be found in the Sub Task 3 report.

In a first step the impact of the different input parameters was investigated. This study dealt amongst others with assumptions on how to take solar and internal heat gains into account, how to split the energy consumption between use for domestic hot water production and space heating, the impact of indoor temperature averaging on the obtained HTC, etc. Based on this and taking into account the available on-site measured data an optimal approach was defined, and different statistical methods applied. Figure 17 compares the results for the different static (averaging and linear regression methods) and dynamic (ARX and state space models) statistical methods with the reference value. Note that for this case study, the reference value is calculated based on designed parameters. The actual estimated result is likely to be higher, among others due to workmanship issues. This is indeed confirmed in Figure 17 all methods show a significantly higher HTC-estimate than the design value, in line with the performance gap identified in Chapter 1. Furthermore, all results are consistent around 80 W/K (double the design value), only the state space modelling results in a lower estimate.

The current analysis in Subtask 3 was rather explorative to investigate to what extent different statistical methods can be used to determine the building's HTC based on limited on-site monitored data. The methods clearly showed promise, but also that care has to be taken on the assumptions made with regard to the input parameters in the underlying heat balance equation. As such, Subtask 3 did not reach its final goal to come to a fully developed 3D-matrix as presented above. A further in-depth analysis on more case studies is advisable to develop the matrix and to turn the methods into reliable tools to be used in actual performance assessment. In doing so, specific attention should go to an in-depth analysis of the uncertainty and repeatability before moving to large scale applications.

Figure 16. Gainsborough Test House: view from the South (Sodagar and Starkey, 2016)

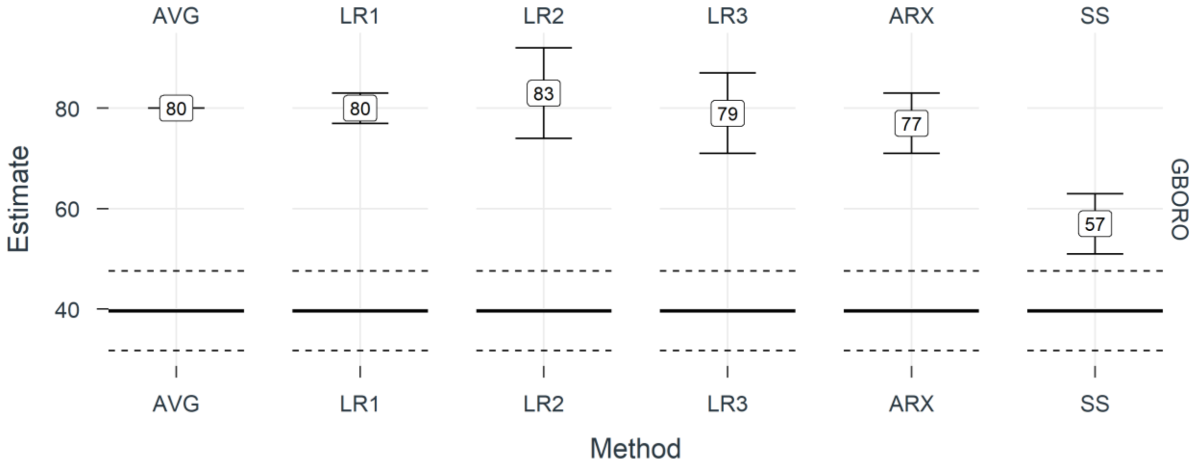

Figure 17. Results for optimal combination of approaches for Gainsborough. The calculated reference value for HTC is indicated as a horizontal thick line, and a 20% deviation above and below as dashed lines.

2.3.1. Section summary

The global framework is a key component of the Annex 71 work, it was first developed in a 2D manner to allow for quality/cost to be compared/linked in a graphical way, during the earlier parts of the Annex work this method did suffice. However, when considering important metrics such as duration of measurement and complexity an alternative was needed, bring about the 3D version. An example of the possible data packages that that could be available was presented, alongside an example presented by the ST3 group.

3. Focus on HTC

This section will provide current information around the issue of the HTC. This will include current industry opinion, current testing methods, including some long standing and complex methods involving some great upheaval for the homeowners, through to more simplified and passive measurement methods.

3.1. Requirements for measured HTC

The stakeholder survey, as introduced in section 5 of this report (found in full in Annex 1), focused mainly on the measured HTC. The instructions of the survey suggested that the measured HTC could be used:

To evaluate energy use/saving calculations and to prove the actual energy use/savings of a new building or after retrofitting

- To assess the quality of workmanship
- To provide a guarantee of quality to the building owner
- To provide an innovative certification label
- To conduct compliance checks in EPBD regulation
- To quantify the efficiency of costly retrofit operations
- To replace the calculated design value in energy performance certification.

87% of the stakeholders answered positively to the question whether they are interested in such a determination of the HTC on-site if tools and methods would be available. On closer examination we see that there are multiple reasons for this:

- It would be possible to have certification based on the measured HTC
- Building constructors would be able to differentiate from competitors
- There can be quality assurance and validation of the works
- It can imply administrative simplification if it can substitute the theoretical calculation, and hence save time
- HTC is a very comprehensive parameter and includes thermal bridging, real product performance and quality of workmanship
- It can be used for fault detection
- It can be beneficial for defining retrofit measures as it allows to have a baseline
- User influence could be determined
- The performance gap can be identified
- It will result in knowledge enhancement for future projects
- It can be used in energy consulting
- It can imply a more accurate forecasting (e.g. consumption)
- It will facilitate to gain a better understanding of the building performance and identify possible shortcomings.

Stakeholders that are not interested in such a determination give following arguments:

- There is no time and budget for such a metric
- The HTC is too technical or theoretical, as it is not a real value (as e.g. the actual energy use and savings)
- There are only a few quality problems with respect to the building envelope. The impact of technical systems can be considered as more important
- It is not relevant in the design phase
- This is only necessary when there are disputes
- Some good tools/approaches are already available, such as thermography for construction defects
- Pinpointing the cause(s) of higher energy consumption is more interesting.

3.2. HTC as metric for energy quality of building envelope

The HTC (Heat Transfer Coefficient), this is defined in ISO 13789 as the "*heat flow rate divided by temperature difference between two environments*" (BSI, 2017). 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) (BSI, 2017b). In straightforward terms this is a **Whole House Heat Loss** figure for a building. The work of Annex 71 focussed on this estimating this figure for single dwellings.

The characterisation of the performance of a building is crucial for many reasons. And it uses for many different purposes. The HTC metric is a global metric and as such is used by many different organisations to assess the performance of an entire building. Many other metrics are available in the building sector which align to building performance. These ranges from U values of elements, linear thermal bridges for junctions, air tightness metrics etc. A document which incorporates and helps to explain these metrics was produced by Annex 58, which was a precursor to Annex 71. (Erkoreka et al., 2016).

3.3. Current methods

Researchers have been active in this area since the late 1970's, motivated by the desire to validate energy savings measures such as insulation and low energy heating system. This has brought about a large range of techniques developed by researchers and industry, and often partnerships between the two. This section will overview the main methods in this area from older methods to the current state of the art.

This section contains a short description of several state-of-the-art methods for measuring an HTC. For each method, the necessary equipment, recommended experience, required time and effort, and achievable accuracy are presented along with corresponding literature.

3.3.1. Coheating

One of the oldest methods of estimating an HTC is the Coheating test. First and foremost this method has a somewhat confusing title and is not entirely descriptive of what is carried out. The name is derived from the original format of the test which was developed to carry out testing on HVAC systems for energy performance and efficiency. The creators of the test, Sondregger and Modera developed a system whereby a building was heated with a temporary electrical heating system, then compared with the test that heated only with the installed HVAC system. The two results were then compared. (Modera et al., 1983),(Sonderegger and Madera, 1979b). The Coheating test is used in a different way in the current day, however the outcomes are the same; the use of the HVAC system in the dwelling has now been removed and only a temporary electrical heating system is used.

The current day Coheating test does not have a formal or approved methodology, although one is being developed (CEN, 2016). However, a guide published by Leeds Beckett University, has been used by many researchers and practitioners and is believed by many to be the nearest document to a formal standard (Johnston et al., 2012). This document outlines the principles of the set up of the test and some basics behind the data analysis used on the collected data. The strength of this document is that it has been used many different times on different housing types, so a portfolio of evidence exists (D. Johnston et al., 2015b). This method has also been compared to other method of estimating an HTC such as the QUB method (detailed later in this report) and has been found to produce similar results under controlled conditions, with a building going through six stages of retrofit (Alzetto et al., 2018). For these reasons it is seen as the standard to which other HTC methods are validated.

The test method is also sympathetic to other measurements that can be accommodated at the same time, given the building is completely heated, empty and at a steady state in terms of thermal capacity. These tests include U value measurement, air tightness testing,

Prerequisites and equipment

The equipment required for a Coheating test is extensive and requires a significant financial investment. The list of equipment includes monitoring systems for internal conditions, heaters, fans, controllers, power measurement equipment and a weather station. Add to this a range of fire protection equipment required for the heaters and a significant cost arises of approximately € 5000. An example of the setup is shown in Figure 18.

Figure 18. Coheating apparatus during a test

Experience

An estimated figure for the amount of Coheating tests carried out in the last 20 years numbers less than 300 in total globally (this data was provided by the members of Annex 71 in 2021) and whilst guidance exists this is still a niche topic area, carried out more in research and industrial development far more than part of the construction process. As such there is only a limited number of individuals who have the knowledge to set up this test and correctly interpret the raw data and analyse this to provide HTC figure.

Time Effort

From of all of the in-situ HTC estimation methods the Coheating test takes the greatest number of days, usually between 7-14, dependant on a number of variables including, but not limited to, weather, type of building, moisture content of building materials and thermal performance of the building (Stamp et al., 2017b). These all affect the amount of time that the building takes to reach a quasi-steady state. This must be achieved for the test to be deemed a success High performing buildings however can take much longer measure, Alexander finds that a testing period of up to 6 weeks can be required for a Passivhaus type of building (Alexander and Jenkins, 2015), results were not also found to be valid for buildings constructed to UK regulatory standards between 2010 and 2012 unless a test length of 6 weeks in typical heating period, or a 3 week test period in only a 6 week period in the middle of winter was allowed for. This is illustrated in Figure 20.

Accuracy

According to Jack the accuracy of a Coheating test is between +/- 8-10% (Jack et al., 2018) on a series of tests carried out on a traditionally constructed building (brick and block). This is confirmed by other authors such as Alexander who state that the accuracy for highly insulated buildings to be greater than 10% (Alexander and Jenkins, 2015).

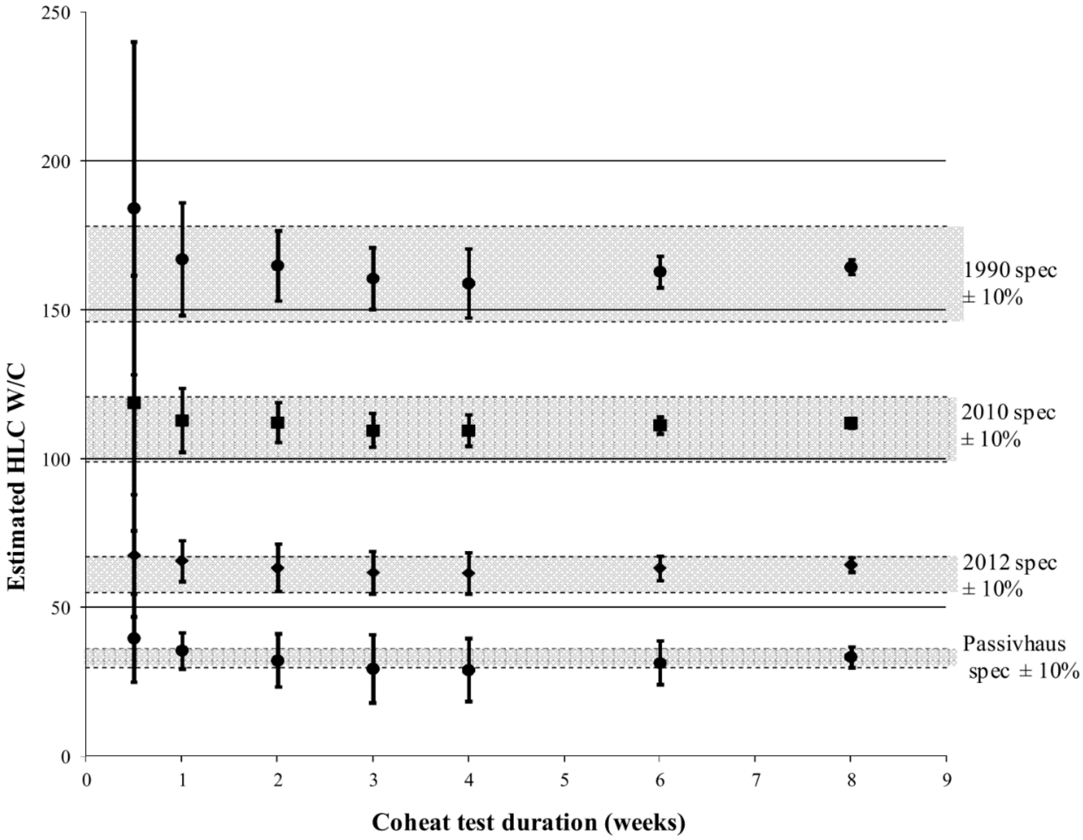

Figure 19. Coheating durations for different types of construction (Alexander and Jenkins, 2015)

3.3.2. QUB

Background

QUB (acronym for Quick U value of Buildings) as presented by Alzetto et al (Alzetto et al., 2016) is a methodology aimed at measuring the HTC of a building in 48 hours or less. For this purpose, the building's thermal response to two stages of internal heat input (for practical purposes 0 % and 100 % of installed power) is measured and the parameters of a single-node RC model are fitted to the recorded temperatures. Preferably, the building should remain in approximately steady state during the first stage and cool down freely during the second. The two stages are applied either in the same or in two consecutive nights. This profile is shown in Figure 21. A complementary blower door test or another technique (such as tracer-gas method) is needed to quantify the air change rate and how it impacts the building's HTC.

Prerequisites and equipment

This method requires multiple electric heaters to ensure homogeneous temperature distribution throughout the testing period as well as the equipment for air change rate measurement. With a similar setup as for a Coheating test, indoor and outdoor temperatures have to be recorded. Given the number of heaters, cables and motoring equipment the building cannot be occupied during the period of testing. The heating equipment is illustrated in Figure 20.

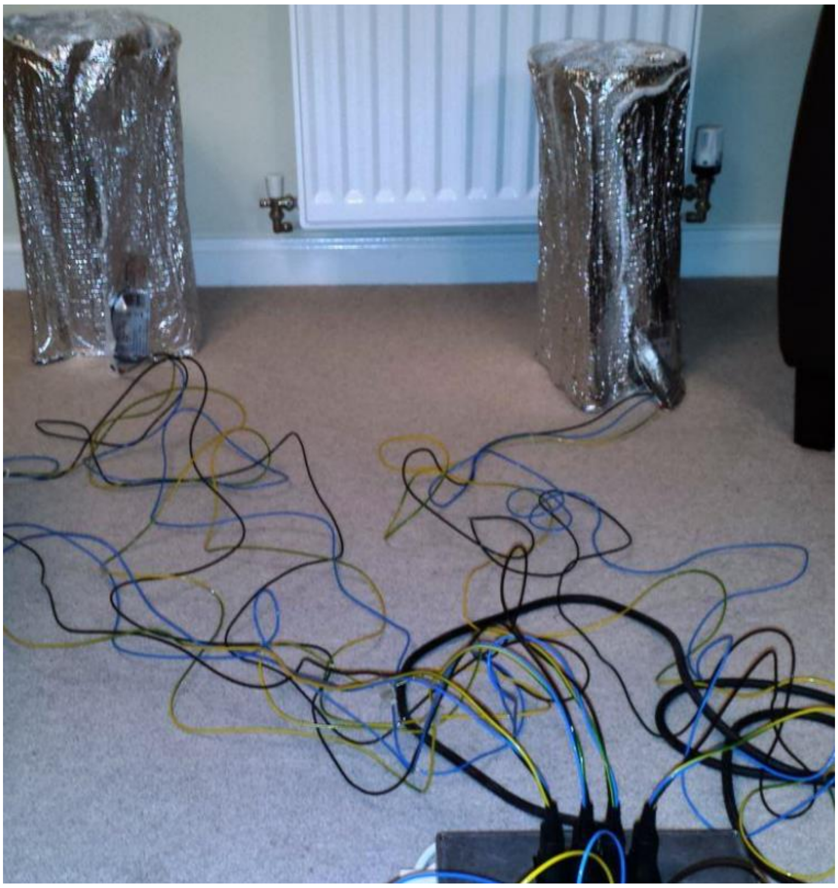

Figure 20. Heating equipment (foil mats) used in QUB Test

Experience

To carry out a QUB measurement, experience in how to place the heating system to keep the temperature in each area as homogeneous as possible as well as in calculating the heating power is needed for steady state during the first stage is beneficial. The QUB test will also need a level of data handling expertise in terms of acquiring, analytics and validation of results

Time Effort

The time taken for a QUB test can vary, however it is practical to complete the test in under 48 hours and less in some cases, according to the authors (Alzetto et al., 2016) (Pandraud and Fitton, 2014). The process should be completed overnight to allow a cooling period without solar gains. A typical test pattern is illustrated in Figure 22. Researchers have also carried out airtightness testing at the end of the test and this can still be managed within 48 hours.

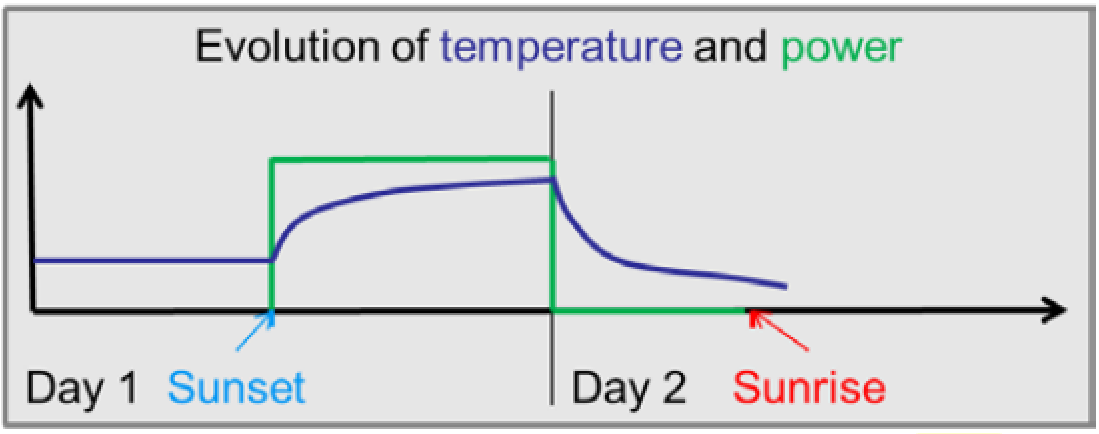

Figure 21. Time series chart of power input and internal temperature for a typical QUB test

Accuracy

As with other test methods this can vary given the amount of measurement time, however a typical measurement was carried out on a series of 6 retrofit scenarios were studied under controlled conditions using the QUB method these were measured against a reference value measured using a Coheating test. The average variance between the two values was found to be 13% with a maximum deviation of 15% (Alzetto et al., 2018)

3.3.3. ISABELE

Background

The purpose of ISABELE (In-Situ Assessment of the Building EnveLope pErformance) is to compare design and as-built performance. An ISABELE test consists of three steps: Initially, the building's conditions with no heating power applied are measured to assess initial thermal energy stored. It is then heated to a set point 10 K above the average outdoor temperature (generally between 25°C and 35°C, setpoints above 35°C are not implemented in practice to avoid damage to the building). Finally, the temperature decreases freely. Steps 1 and 3 are optional but can provide further information on the building's thermal dynamics. Throughout the test, shading devices such as window blinds, are shut, ventilation is turned off and any air outlets are blocked. Temperatures, heating power, air infiltration rate and external climatic conditions are recorded. This method is laid out in an experimental paper which also includes a comparison to the aforementioned QUB method. (Thébault and Bouchié, 2018). A typical testing cycle is shown in Figure 22.

The ISABELE method is currently used for a French national program called "DIANE" (2019-2021). The objective is to compare the HTC measurement in a statistically significant sample of new build homes (around 100) with the theoretical values calculated at the conception phase.

Another program called SEREINE (2019-2021) is aiming to create a new method (partly based on ISABELE) adapted to the HTC measurement of refurbished houses and apartment style buildings, with an optimisation of the experiment setup and measurement time.

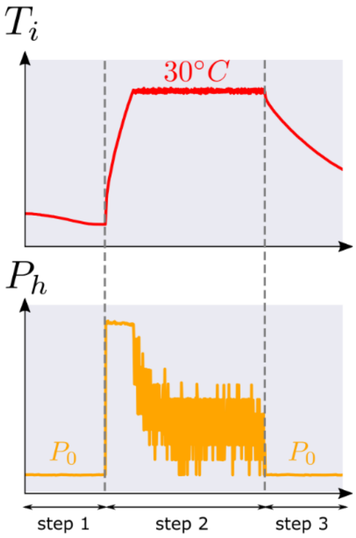

Figure 22. A typical testing cycle for the ISABELE protocol (Thébault & Bouchié, 2018)

Prerequisites and equipment

Small electrical heaters and fans are used to ensure an elevated and homogeneous temperature distribution throughout the testing period. With a similar setup as for a coheating test, indoor temperatures and power consumption are recorded. Specific outdoor sensors, called SENS (for Solar and ENvironment Sensors, see Figure 23 below) record the equivalent temperature limit condition for each facade (including solar gains, longwave radiation, and other climate related phenomenon (Bouchié et al., 2014))

Figure 23. External SENS sensor used for the ISABELE protocol

A local weather station can be used to record wind speed measurement, external temperature, and relative humidity, in order to estimate the infiltration heat losses (Thébault and Millet, 2017). These data can also be loaded from the nearest weather station. As the coheating test, a blower door test can be performed to provide the air flow rate estimation. The building needs to be empty during the test.

Experience

Expertise is required to place the heating and air fans, and also to select the correct number. Some knowledge is also required on the placement of the sensors used. An automated process is used to process and analyse the data but requires specific data analytics skills in R & Python.

Time Effort

As with other test methods the building and weather characteristics can have a significant effect on the timescale to produce an acceptable result. In terms of number of testing days; 2 is seen as acceptable for buildings insulated from the inside, however a building with substantial thermal mass and insulated from the outside can take longer.

Accuracy

When compared to a reference HTC the ISABELE method is between 5% and 20% accurate in most cases, depending on the building, climatic conditions and measurement time. The uncertainty is estimated for each test, considering both model error, measurement uncertainties, and potential error on conventional data – such as pressure coefficients, surface heat transfer coefficients of elements etc (Thébault and Bouchié, 2018).

3.3.4. PSTAR/STEM

Background

The PSTAR (Primary and Secondary Term Analysis and Renormalisation) is an older method that is seldom seen in published works or used in industry currently, that is not to say that it should be discounted. The method was introduced in the USA in the 1970's by the National Renewable Energy Laboratory (formerly the Solar Energy Research Institute) of the US Department of Energy, with developments continuing throughout the 1990's. Whilst there have been many attempts to quantify the accuracy and benefits of the PSTAR method. However, as we often use the Coheating test as a quantifiable baseline for HTC methods, the author has selected to use a paper carried out by Leeds Metropolitan University in 2011, where a direct comparison between Coheating and PSTAR (Palmer and Pane, 2011) is described.

The PSTAR method is similar in many ways to the Coheating test, in as much as heating equipment is installed alongside fans, and temperatures elevated, the significant difference is that a period of not only heating, but cooling (i.e., lack of heating) will be present in the test property. This is illustrated in Figure 24.

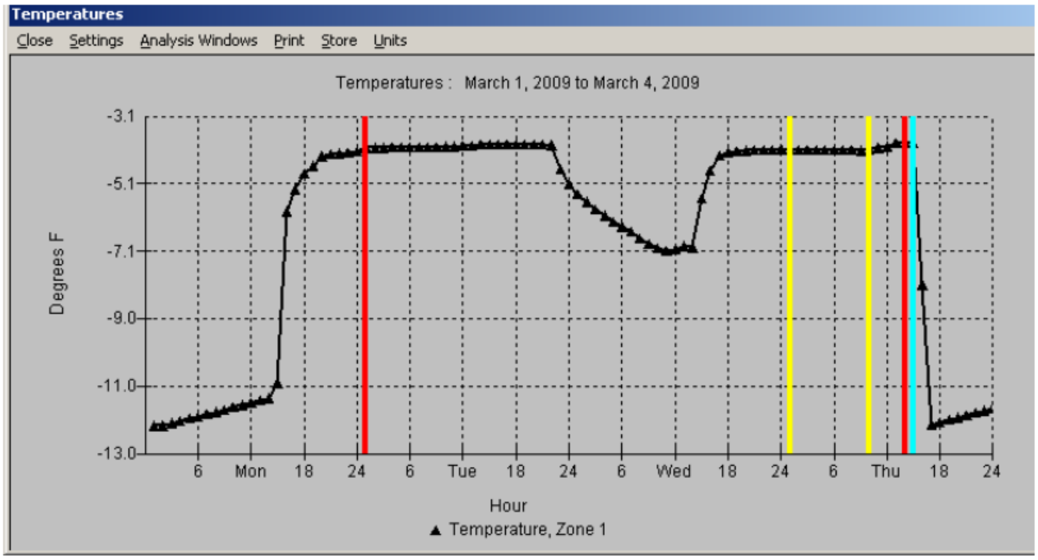

Figure 24. Evolution of temperatures during a PSTAR test

Prerequisites and equipment

The equipment required for the PSTAR method is identical to the Coheating method. The only difference is the control of the equipment and data analysis is carried out by custom built piece of software designed to carry out PSTAR tests. This software is currently difficult to obtain and may be in need of updates for modern technology.

Experience

The level of experience required for PSTAR is directly comparable to that required of coheating. This may vary or even become slightly less burdensome given that a portion of the data analytics work is aided by the software.

Time Effort

The setup and data analytics component of the PSTAR is comparable to the Coheating methodology (several days in total). The length of the data collection required for the test method is a lot shorter with the dwelling only being required for 2-4 days, compared with Coheating which can take 7-14 days.

Accuracy

The method of PSTAR is dynamic and it is difficult to draw comparisons, but when compared directly to the Coheating method, a deviation of 30% was found however it should be noted that the paper around this method by Palmer et al places caveats on this figure (Palmer and Pane, 2011)

3.3.5. Integrated Coheating Method

Background

This testing methodology was developed by researchers from Leeds Beckett University (UK) where the Coheating method was also developed. This method differs from the original one in that it uses the heating appliances already installed in the home, such as a gas central heating system. This has significant advantages, although the house does still need to be empty for a period of time and some equipment needs to be added to the heating apparatus (Farmer et al., 2016)

Prerequisites and equipment

The equipment needed to carry out this test is limited compared to a standard coheating test but is still obtrusive. A heat meter installed onto the heating circuit is necessary for this test. These are costly and should be installed by a suitably qualified engineer. Sensors to measure internal environments in each heated room area also required, as well as a weather station capable of measuring solar radiation. The building must be empty during the test. The building must be heated up to around 25 °C, which is costly and can lead to disturbance in the fabric. The method allows for the researcher to use fans or not, to maintain a homogenous temperature across the building.

Experience

The method does require some setup in terms of ensuring the building is heated to correct levels, layout of sensors and collection of data is carried out properly. This method also needs reasonable assessments of such things as boiler efficiency. The data analytics involved with this method are based on linear regression, thus requiring some knowledge of mathematical analysis.

Time Effort

The setup for this test is relatively straightforward taking approximately half a day, to install sensors and to setup the heating system, around another half day is required to drain down the heating system and install the heat meters. The length of data collection should be between 14-21 days dependant on a number of variables such as building type and weather during test period.

Accuracy

According to the paper by Farmer on this topic the accuracy when compared to a coheating test as a baseline is found to be between +/- 2-8% (Farmer et al., 2016) however the figure may be nearer 10% according to yet to be published data, of studies carried out over a larger sample. As with all of the methods this accuracy figure is dependent on a number of variables, duration of test, weather, type of building and accuracy of data collection.

3.3.6. Loughborough In-Use Heat Balance (LIUHB)

Background

This method was developed by researchers at Loughborough University (UK) The principles are similar to the Integrated Coheating Method in as much as the heating system in the property is used to heat the building rather than supplementary equipment. The significant difference between the two methods is that the building can be occupied and heated to “normal” levels rather than overheating. The building can be occupied for the duration of the test (Jack, 2015).

Prerequisites and equipment

The setup for the test requires addition of accurate temperature sensors to each room of the building and continuous logging of energy supplies to the building. Weather data can be recorded either on site or from a local weather station. The building can remain occupied, but heating must be used as normal by the occupants. The humidity at a central point in the buildings should be recorded during the test to isolate any effects of the building drying out, this is particularly necessary in new build properties where this can have a significant effect on the energy performance.

Experience

The setup for the test in terms of equipment is less onerous than other methods, placing of sensors in each room and logging of energy data. However, the data analytics are as complex as the coheating methods, this may be automated in the future, which will lessen the expertise required for this method. Acquiring of data from weather stations can also be complex, and should be checked for data quality etc.

Time Effort

The sensing equipment and energy logging can be added in half a day. The duration of the monitoring is a minimum of three weeks. This test must take place in the heating season and a Delta T of 10K should be achieved during a significant proportion of the testing period.

Accuracy

This is a method that like others, has been tested against a Coheating test. This was carried out in three homes under simulated occupancy and normal occupancy conditions, the accuracy was found to be around ±15% when compared to a Coheating baseline. This can change depending on variables such as solar radiation input, delta T achieved, type of building, duration of testing and accuracy of measurement equipment.

3.3.7. CAM(B)BRIDGE

Background

CAM(B)BRIDGE (Calculation and Measurements in Buildings: Bridging the Gap) is a methodology based on experiments (Masy and Hinque, 2018) and aimed at measuring the HTC of a building façade in collective buildings where the testing of a unit has to be done without accessing the adjoining zones. The measurement process originally intended to be carried out in 9 days, but experiments showed that a 4-day period is sufficient when the measurement is performed during summer in units that are sun exposed and benefit from significant solar heat gains. For this purpose, a temporary insulated wall is installed at 60 cm from the façade on its internal side (Figure 26). It is made of wooden “legos” filled with insulation. The temperature is measured in the cavity and at the surface of the temporary wall, at the room side. A pyranometer facing the window on its internal side, measures the solar irradiation.

Prerequisites and equipment

This method requires a set of wooden “legos” that can be reused for several experiments and a set of insulation panels that need to be installed on the floor and at the ceiling of the cavity. The installation of the cavity is performed in one day by one person. An electric heater ensures an homogeneous temperature in the cavity and a sufficient temperature difference with the outdoor. With a similar setup as for a Coheating test, indoor and outdoor temperatures have to be recorded, temperature at the surface of the temporary walls are also recorded as well as solar heat gains and radiators heating powers. The tested unit could be occupied during the period of testing, provided its dimensions are large enough. The temporary wall material, heating and monitoring equipment is illustrated in Figure 25.

Figure 25. Temporary wall, Heating equipment and sensors used in CAM(B)BRIDGE Test

Experience

To carry out a CAM(B)BRIDGE measurement, no specific experience is required in how to place sensors and loggers because that equipment is already integrated into specific wooden "lego" pieces. The CAM(B)BRIDGE test will also need a level of data handling expertise in terms of acquiring, analytics and validation of results. Results need to be analysed in a dynamic way.

Time Effort

When the tested unit benefits from sufficient solar heat gains in summer, a CAM(B)BRIDGE test can be performed within 4 days. The measurement period should be increased until 9 or 10 days when the unit is not exposed to the sun. A typical test pattern in illustrated in Figure 26. Researchers have also carried out airtightness testing at the end of the test and this can still be managed within 4 days.

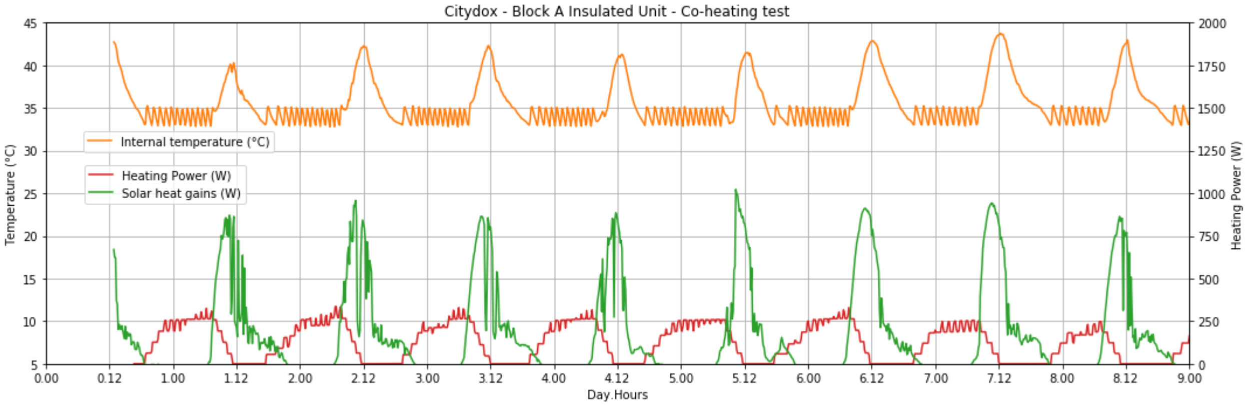

Figure 26. Time series chart of power input, solar heat gains and internal temperature for a typical CAM(B)BRIDGE test

Accuracy

Statistical confidence intervals within 3% have been observed on 5 measurement sites but this result should be considered with caution as confidence intervals are obtained from an implicit good fit assumption related to the statistical analysis method; They do not rely on the physical uncertainties associated to the measured data.

3.3.8. Average Method

Background

The average method is an accumulated averaging method for the Heat Transfer Coefficient (HTC) estimation of in-use whole buildings. The method has been developed in detail in (Erkoreka et al., 2016) and (Uriarte et al., 2019), where it has been used to estimate the HTC of an in-use office building before and after its energy improvement retrofit. The average method is based on the energy balance to the conditioned area of the building (see Figure 27) of a whole in-use building (Uriarte et al., 2019) during cooler and cloudy winter periods. For such periods, of at least three days, with low solar radiation and high space heating demand, it is possible to ensure that the solar heat gains compared to the rest of the heat gains within the building (space heating plus all other internal gains excluding solar radiation) are less than 10%.

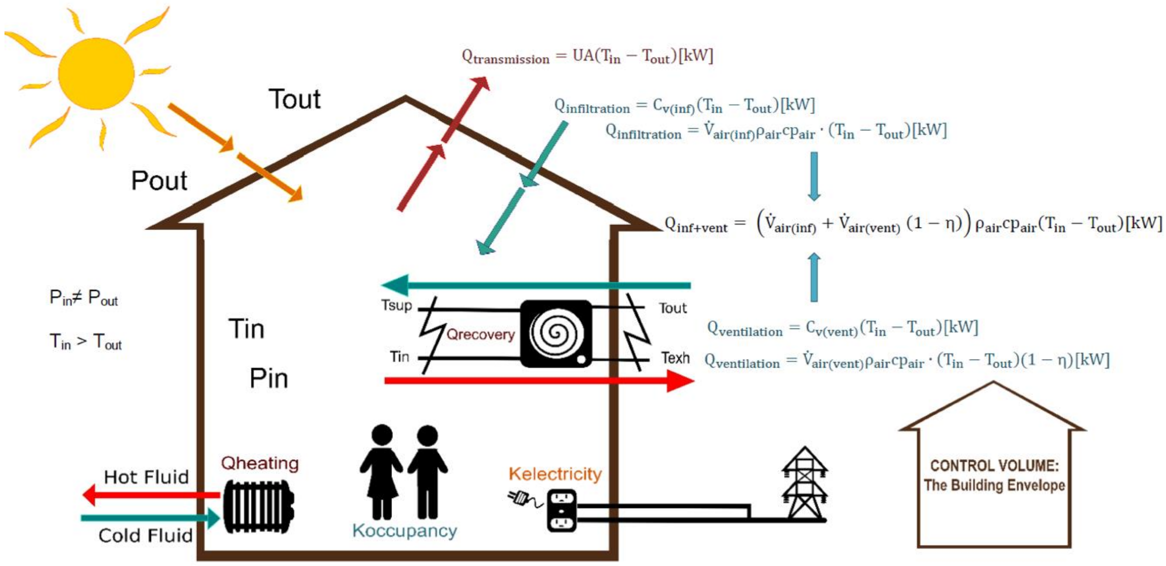

Figure 27. Schematic of all energy and mass exchanges through the control volume defined by the building envelope (Uriarte et al., 2019).

The average temperature difference between the indoor and outdoor air during the testing period must be high (values close to or higher than 15°C are recommended). Thus, measuring errors in temperature difference calculations will be minimized and high heating demands will also permit the heating supply to be accurately measured.

According to (Uriarte et al., 2019) the in-use HTC of the building must be estimated by plotting the accumulated average of the HTC, until the estimate is stabilized within a ± 10% band of the final HTC estimate over the last 24 testing hours (see an example of an accumulated HTC average plot in Figure 28).

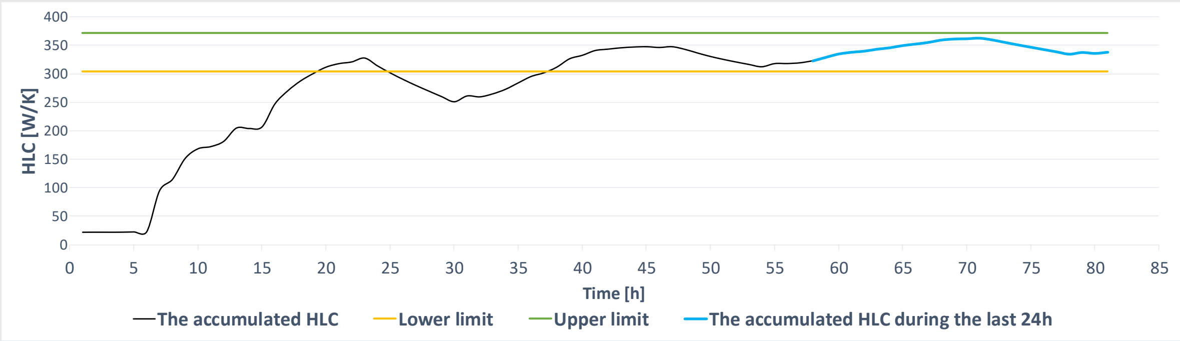

Figure 28. Example of the evolution of the accumulated Heat Loss Coefficient for a cold and cloudy 82 hour period for a whole building.

Finally, it is mandatory to have the same average building temperature at the beginning and end of the analysed periods for estimating the HTC. This temperature will be the average temperature between the indoor and outdoor temperatures. If this is fulfilled, it can be assumed that there will be no accumulated heat in the building in the analysed periods, since the start and end points of the analysis will have the same thermal level.

Prerequisites and equipment:

This method has been developed with the aim of being deployed in Building Automation Systems (BAS), where the outdoor air temperature, horizontal or south vertical global solar radiation, indoor air temperature, heating system heat input and electrical consumption within the building are available with a frequency of at least 1 hour. Thus, during the normal operation of the building, when the BAS system detects cold and cloudy periods of at least three days, the requirements of the method would be tested in the monitored data and if the method requirements are fulfilled, the BAS system would automatically estimate the HTC of each valid period.

Experience

The deployment of the average method within a new or existing building BAS system would require the precise monitoring of representative indoor air temperatures, heating system heat input and electrical consumption within the building. The weather variables could be measured or could be obtained from the internet from the nearest weather station (if available). During the deployment of the average method in the BAS system, the window area of the building should be introduced to be able to approximately estimate the solar gains during the cold and cloudy periods. Note that, for cloudy periods, the solar radiation could be considered completely diffuse and similar in all orientations of the building.

Time Effort

Once the method is implemented in the BAS system, the latter would provide some independent HTC values each winter (depending on the weather conditions). If something is wrong with the building envelope insulation layer or with the building infiltration/ventilation rates, variations between those independent HTC estimates would be found.

Accuracy

As with other test methods, this can vary given the amount of measurement time and weather conditions. However, during the Annex71 common exercise (found in Sub Task 2 report), the method was applied to the Loughborough case study data set and the obtained HTC results were compared against a reference value measured using a Coheating test. The average variance between the two values was found to be 4% with a maximum deviation of 11.5%.

3.3.9. Dynamic Integrated Method

Background

This method is intended to be an interpretation of the Coheating test to be applicable to any weather conditions of buildings in-use. It is named as “Dynamic integrated method” because the analysis is in essence fully dynamic but using energy balance equations in integral form. First, the air volume confined by the building envelope to be characterised is considered. A dynamic energy balance is written for this air in the form of differential equation. Afterwards this equation is transformed into an integral equation. Finally, this integral equation is easily manipulated to obtain HTC from linear regressions based on averages of the measured variables. This method has been applied to several case studies.(Naveros et al., 2012) report an exploratory work applying this method to an opaque wall, (Castillo et al., 2014) describes the application of this method to a room of an in use office building, (Chávez et al., 2019) report an in depth analysis of the method and its validity based on data from the Round Robin Test Box constructed and tested in the framework of Annex 58 EBC IEA.

Prerequisites and equipment

This method requires measurement of a set of driving variables representing all the relevant contribution to the energy balance in the air volume confined by the building envelope to be characterised. The indoor air temperature must be homogeneous. As the method is in essence dynamic, measurements must guarantee the correct representation of the measured variables with a sampling frequency at least twice the frequency of the measured variables

Experience

Installation of all the measurement devices guaranteeing that each relevant measurand is properly represented by the corresponding recorded variable. It is important to keep the indoor air temperature as homogeneous as possible. If the test is conducted in an empty building with electrical heaters their placement must be done to keep the temperature in each area as homogeneous as possible. Additionally, if the test is conducted in an in-use building the measurement system must guarantee accurate measurement of the heating power and occupancy patterns. The method requires certain level of expertise on building physics, behaviour of sensors, and data analysis.

Time Effort

The minimum test period is twenty days, using ten points for each linear regression, considering that the method requires at least one day for each point, and using at least two estimates to check the validity of the results and to calculate uncertainties. However, larger periods could be necessary. Depending on the weather and test conditions integration periods larger than one day could be necessary to obtain accurate results. For example: if the integration period required to obtain accurate results is 2, 3, 4, 5, or 6 days, then the test period to obtain an estimate of the HTC would be 40, 60, 80, 100 or 120 days respectively as seen in Figure 29.

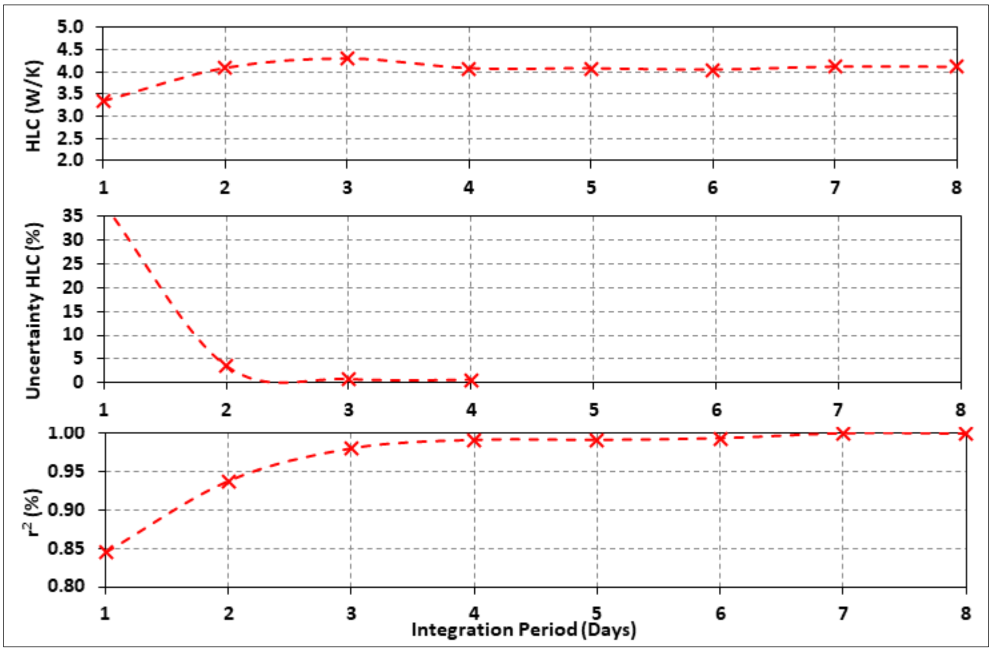

Figure 29. Dynamic Integrated Method. HTC and validity indicators for different integration periods.

Accuracy

The identified HTC for the RRTB applying this method considering a four-day integration period was 4.08±0.6%, while the HTC obtained using the Coheating test and Siviour analysis reported by Baker is 4.06±2.5% which indicate a 0.5% of deviation between the results applying both methods (Baker, 2019). The uncertainty given by the Dynamic Integrated Method itself depends a lot on the integration period used for the linear regression. It also depends on the weather and test conditions, and on the characteristics of the building envelope. The HTC value was obtained with accuracies of 37.5%, 3.5% 0.8% and 0.6% for integration periods of 1, 2, 3, and 4 days respectively (testing periods of 20, 40, 60, 80 days respectively) considering the RRTB as simplified reference building (Chávez et al., 2019). The analysis carried out to obtain these estimated values for the uncertainty included data from experiments conducted in summer and winter in the southeast of Spain.

3.3.10. RC Dynamic Method

Background

This method uses an electrical analogy using resistors and capacitors (RC) to represent the building as a thermal system. The RC model must incorporate all the relevant contributions to the energy balance in the air volume confined by the building envelope to be characterised(Jiménez, 2016). Typically, two parallel branches are necessary to represent the building. One branch is representing the heat transfer through the opaque walls. Different number of nodes connected to thermal capacities depending on the thermal mass of the building envelope may be necessary in this branch. Another branch without accumulation is typically used to represent the fast heat transmission through the building envelope (windows, air leakage, thermal bridges). LORD has been used as software tool to identify the parameters of the model. The solar gains are modelled as an unknown constant gA value multiplied by the measured global vertical solar radiation (Gutschker, 2008). This approach requires dynamic character on the variables used for the analysis and large enough amplitude regarding the uncertainty in the corresponding measurements. This method has been applied to the Round Robin Test Box (RRTB) (Figure 30) constructed and tested in the framework of Annex 58 EBC IEA .(Jiménez, 2018a) It was also applied to the Gainsborough (Díaz-Hernández et al., 2020) and Loughborough buildings considered as case studies in Annex 71 EBC IEA (Jiménez, 2018b)

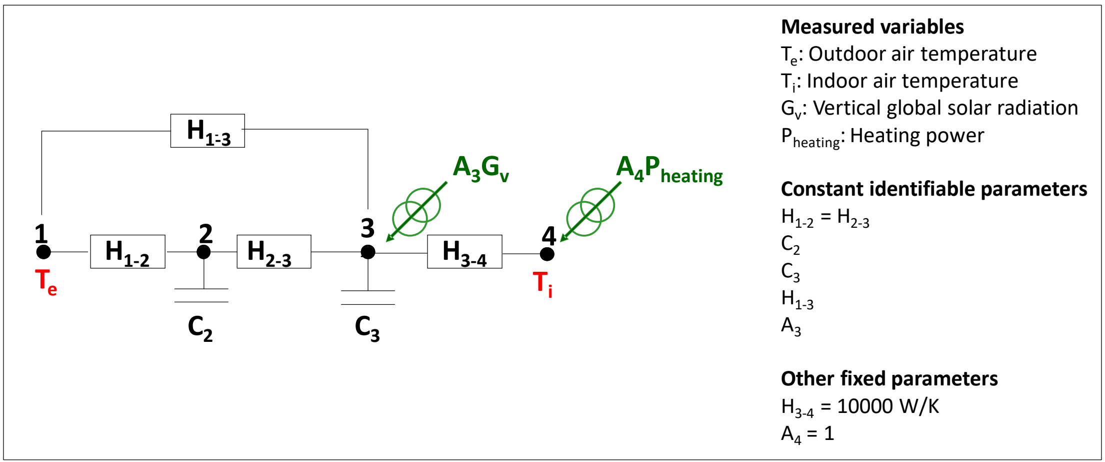

Figure 30. Model used to obtain the HTC of the RRTB.

Prerequisites and equipment

This method requires measurement of a set of driving variables representing all the relevant contribution to the energy balance in the air volume confined by the building envelope to be characterised. The indoor air temperature must be homogeneous. The test campaign must be conducted under clearly dynamic conditions. The main driving variables must present a large amplitude regarding the uncertainty in their measurements. Sampling frequency must be at least twice the frequency of the measured variables to guarantee the correct representation of these variables.

Experience

The careful installation of all the measurement devices to ensure that each relevant measurand is properly represented by the corresponding recorded variable. It is important to keep the indoor air temperature as homogeneous as possible. If the test is conducted in an empty building with electrical heaters their placement shall be done to keep the temperature in each area as homogeneous as possible. Additionally, if the test is conducted in an in-use building, the measurement system must guarantee accurate measurement of the heating power and occupancy patterns. The method requires certain level of expertise on building physics, behaviour of sensors, and experience using system identification tools.

Time Effort

The minimum test period depends on conditions (weather, heating or cooling schedule, whether it is empty or in use, occupancy patterns in case of being in-use, etc.) Typically, one month is enough to estimate the HTC. At least two values of the HTC must be obtained in order to validate the results. Consequently, a testing period of two months is typically required in this approach. However, shorter testing periods could be valid or longer experimental campaigns could be necessary.

Accuracy

The accuracy that can be achieved depends on the test conditions and on characteristics of the building envelope. The identified HTC for the RRTB applying this method was 4.14±1.4% (Jiménez, 2018a) while the HTC obtained using the Coheating test and Siviour analysis reported by (Baker, 2019) is 4.06±2.5% which indicate a 2% of deviation between the results applying both methods. The identified HTC for the Loughborough buildings applying this method was 300W/K±2% (Jiménez, 2018b) while the HTC obtained using the Coheating test reported by (Beizaee et al., 2015) was 382W/K±10%, which indicate a 21% of deviation between the results applying both methods.

3.3.11. CoDY

Background

The CoDY (acronym for Coheating Dynamic) test is a methodology aimed at measuring the HTC of a building in 5 days (Deltour et al., 2020). For this purpose, the building is heated according to a specific on/off cycles, with the help of a dedicated electric heaters. The main differences with a classical Coheating test are that the stationary conditions are not necessary/expected, then the test can be shortened to 5 days instead of around 7-14.

However, as in the classical coheating test, the CoDY test must be carried out in an empty building over the five days period, during the heating season, i.e. when there are low levels of solar radiation.

Due to dynamic signal controlling the heating system an advanced data analysis method is used, based on a so-called RC model.

In building physics, RC models link the thermal variables of the building by a network composed of resistances and capacitances (e.g., multi-zone model). This implies that, usually, the parameters have a direct physical interpretation. This allows the use of prior physical knowledge of the building to be incorporated into the model.

Simple RC models are used (Figure 31). Depending on the building typology and the climatic conditions encountered, different RC models should be used.

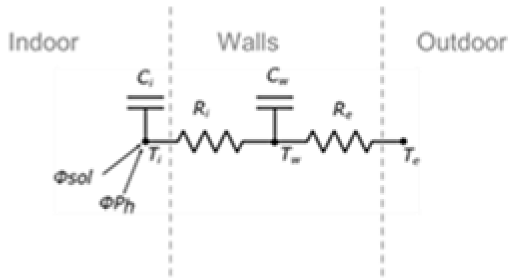

Figure 31. RC model example for adapted coheating

In the model depicted in Figure 32 Ri and Re represent, respectively, the thermal resistances of the walls and the losses through infiltration. Ci and Cw are, respectively, the heat capacity inside the building and of the external walls. T_i, T_w and T_e are, respectively, the indoor temperature, the temperature of the wall and the outdoor temperature.

Thus, the HTC is the inverse of the sum of both resistances.

$$HTC = \frac{1}{R_i + R_e} \quad \text{(Eq. 2)}$$

Prerequisites and equipment:

This method requires the following measurements:

- Heating power in each heated room – Ph (W)
- Internal temperature and possibly relative humidity in each room – T_i (°C) and RH (%)
- Electric consumption of the circulation fans (kWh)
- External temperature – T_e (°C)
- Solar radiation – I_{sol} (W/m²)
- Wind speed (m/s)

Relative humidity is only necessary when building is not sufficiently dried-out prior to the commencement of the test. And wind speed is, e.g., necessary to separate heat loss due to the air infiltration from heat loss due to transmission.

Moreover, the building cannot be occupied during the five-days period of testing. An example of the equipment used for a CoDY test is illustrated in Figure 32.

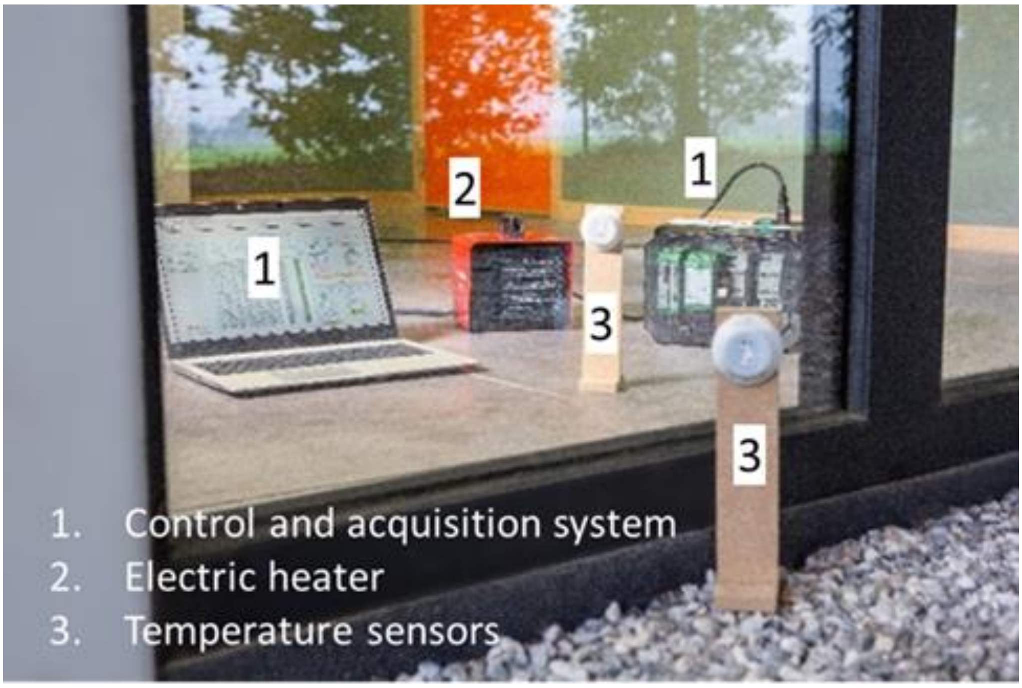

Figure 32. Equipment used in CoDY Test

Experience

To carry out a CoDY test, experience in how to place the heating system to keep the temperature in each area as homogeneous as possible is beneficial. The CoDY test will also need a level of data handling expertise in terms of acquiring, analytics, and validation of results.

Time Effort

The time taken for a CoDY test can vary, however in general a period of over five days is required for a newly built single-family home, that is well insulated. A typical test pattern in illustrated in Figure 33. In addition, an airtightness test is also recommended at the beginning of the test.

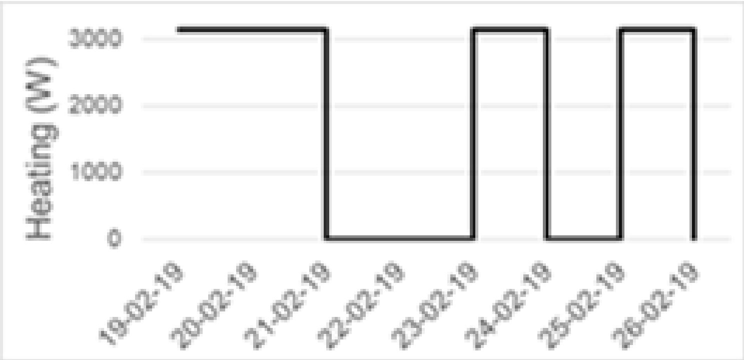

Figure 33. Time series chart of power input for a typical CoDY test

Accuracy

As for other test methods this can vary given the duration of the measurement, typologies, climatic conditions during the test. In average, the uncertainty varies between 10 - 15%.

3.3.12. Veritherm (Not Peer Reviewed)

It should be noted that 2 weeks before draft publication, the authors were approached by Veritherm (UK) to present their HTC measurement process. This process is documented in a publicly available report (Baxter et al., 2021), but this has not been peer reviewed, or extensively reviewed by the authors. As such this method is presented here only for information, with a peer reviewed methodology due to be published later in 2021

Background

The Veritherm method is used to assess if a building has the thermal insulation properties that are specified in its design data. The approach is different to existing products, in that it is aimed at validation rather than measurement. The thermal validation process consists of applying heating power to the building over a short period of time, measuring its thermal response, and comparing to the response to what would be expected to be seen on the basis of the design data (Baxter et al., 2021).

The methodology can be split into three main stages: preparation, measurement, and validation calculations:

- Preparation: The preparation stage consists of preliminary heat loss calculations, (may be found in energy certificate data or building information model)
- Measurement: The measurement stage consists of measuring the temperature inside and outside the building while it is heated, and then left to cool passively
- Validation calculations: The validation calculations produce a range of heat transfer coefficients for the building that are consistent with the measured data. This range is compared with the building's design data.

The main aim of this is to ensure compliance with design at hand-over between construction and management of a building, although it can be used at other times, e.g. checking the effect of a major re-fit or for accurately sizing a heat pump.

Prerequisites and Equipment

The method uses a network of simple sensors and loads, and heat is evenly spread by using fans to mix the air in the building, keeping the air temperature approximately homogenous. Indoor and outdoor temperatures are recorded with wireless data loggers and the Veritherm cloud platform allows remote control and reporting. Due to the nature of the test the building must be unoccupied.

Experience

The Veritherm computer software is designed so that validation calculations are automated, requiring minimal input from the user. Results and test reports are published immediately with no requirement for manual data handling. Some practical experience is required to understand equipment positioning and the test process.

Time Effort

Veritherm returns a confidence level following a single night of testing, 12 hours or less. Measurements are collected over a single night, to remove the effects of solar load from the power balance equations. During the test, heating is on at a constant power for the first 30-50% of the period

Accuracy

In typical scenarios deviations of 15% in the heat loss coefficient can be expected. It is worth noting that sensitivity of the measurement is improved by increasing the maximum temperature difference between the interior and exterior of the building. A peak difference of at least 10K should be obtained, 20K or more is preferable.

3.3.13. Overview and Summary of Existing Methods

This section has highlighted eleven methods that can measure the whole house heat loss of a building. Some have been used extensively over a number of years and some are more juvenile methods. In terms of number tests undertaken globally, Table 4 collates this.

Table 4. Review of variables by method. From the data passed to the author of this report, collated January 2021 from the authors of each given methodology.

Method	Typical Duration of Measurement (Days)	Typical Expected Error %	Cost per Test (€)	Equipment purchase Cost(€)	Number of variables	Number of buildings tested to current	Level of complexity (1 easy 10 difficult)
Coheating	14	10.0	€ 1,400.00	€ 4,500.00	12	112	8
QUB	2	13.0	€ 1,000.00	€ 2,500.00	7	105	7
ISABELE	10	8.0	€ 1,000.00	€ 3,000.00	7	20	7
CoDY Method	5	12.5	€ 1,000.00	€ 8,500.00	18	10	8
Dynamic Integrated Method	60	4.0	€ 1,000.00	€ 500.00	5	8	6
Loughborough In-Use Heat Balance (LIUHB)	21	15.0	€ 1,000.00	€ 500.00	5	6	6
RC Dynamic Method	30	4.0	€ 1,000.00	€ 500.00	5	6	6
CAM(B)BRIDGE	7	3.0	€ 1,500.00	€ 16,098.75	12	5	7
Integrated Coheating Method	17	6.0	€ 820.00	€ 4,000.00	10	4	6
Average Method	5	8.0	€ 1,000.00	€ 500.00	5	4	6
PSTAR	3	30.0	€ 1,000.00	€ 4,500.00	10	2	6

If we view these methods through the lens of the 3d graph metric mentioned earlier in this report then we can see that there is a wide range of variance in these methods (Figure 34).

These methods have been validated in some way against a reference case, thus giving a level of confidence. However, the analysis of these methods to find the “best one” is a complex proposal. It does not follow that the more complex the method is or the longer the duration of the less the errors in output may be, this is represented in Figures 35 and 36. This may be a function of several factors some methods will work far better in different properties than others, for instances heavyweight buildings are more suited to longer duration tests, the figure presented here in terms of accuracies may also only reflect validation on certain types of buildings. Another factor may be the conditions under which the testing has been carried out, some tests are more sensitive to solar radiation than others for instance.

It is however clear to see thought that there appears to be little agreement on a perfect (low error), quick and low complexity test method. Also, some of these methods are further developed than others, so more experience and detail is added to the data collection and analysis, this may lead to more accurate methods. There is also one important note to make; the errors for these methods are all deduced by a comparison with a coheating test, this is to say that the coheating test is in effect the perfect reference. It has been criticised for several things in the past including repeatability the way that solar radiation is accounted for in the measurement and analysis (Butler and Dengel, 2013) but given it’s prevalence and the fact that most researchers choose to adopt this method for whole house heat loss measurement we must give it credit.

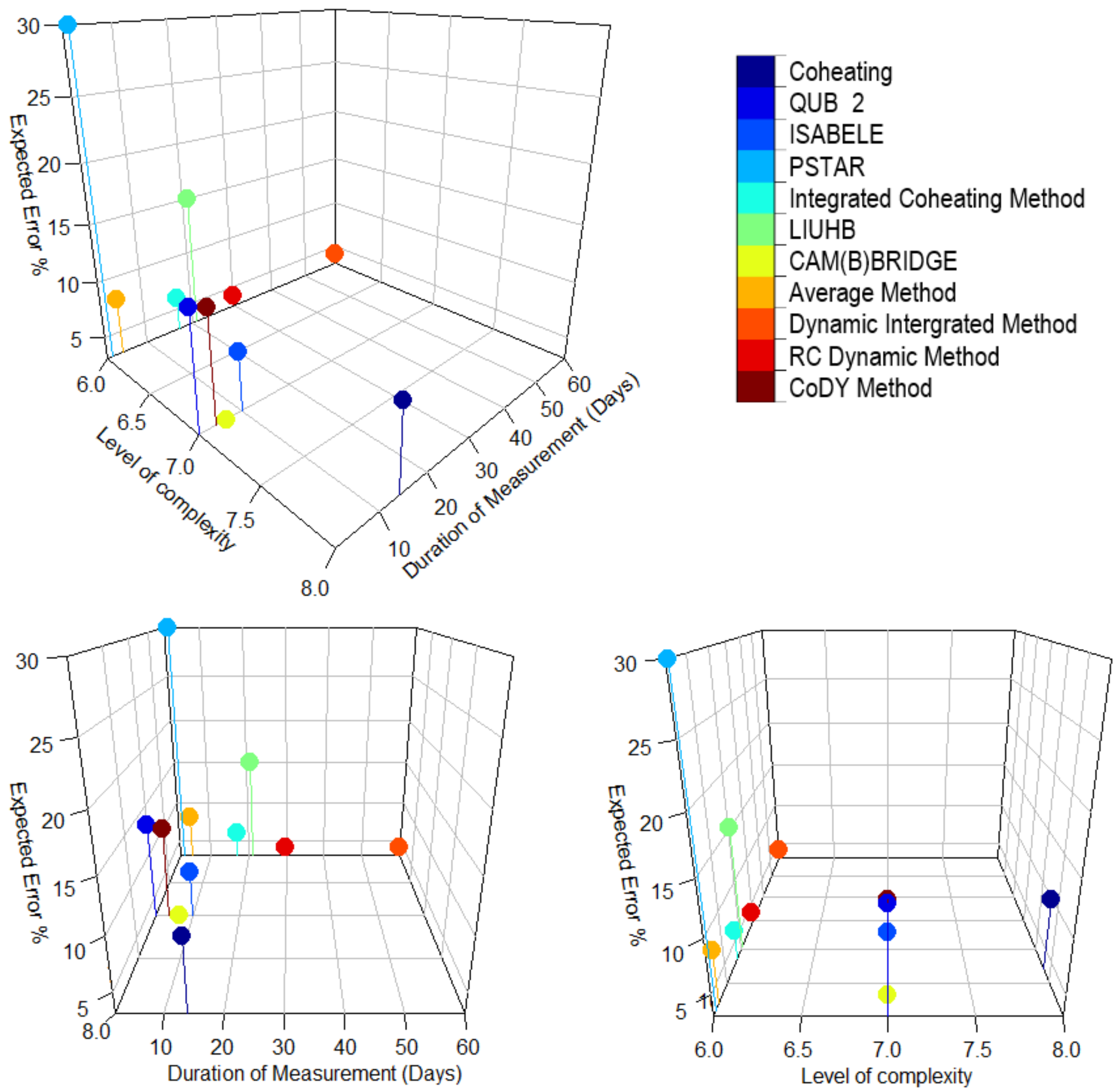

Figure 34. Current methods of HTC measurement presented on the 3d graph mechanism.

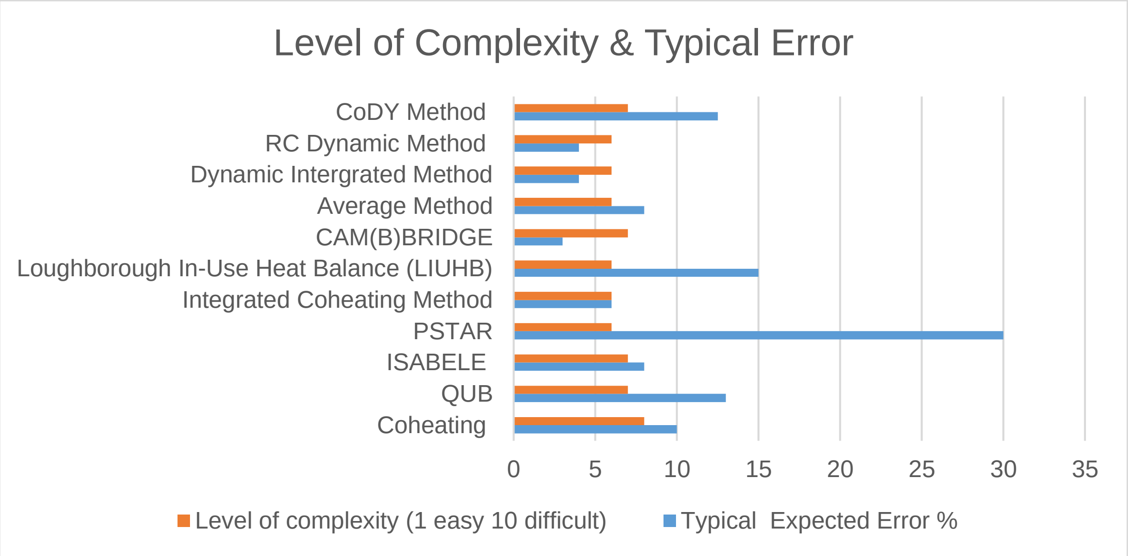

Figure 35. Illustration of the level of complexity and typical error. No correlation is found between these two variables.

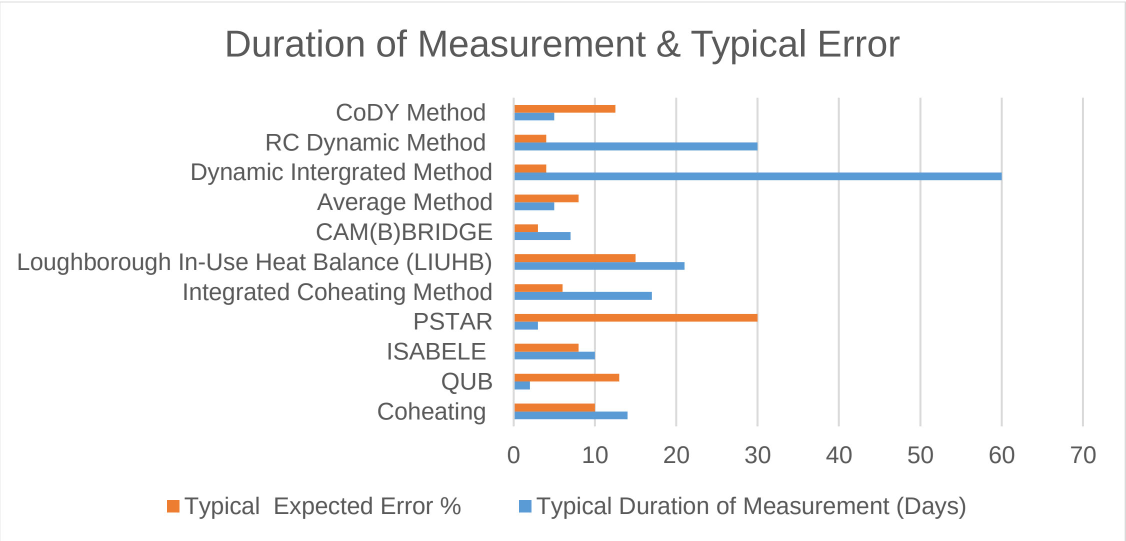

Figure 36. Illustration of the level of duration of measurement and typical error. No correlation is found between these two variables.

3.3.14. Section Summary

This section focusses on and goes into depth on the topic of HTC measurement; existing and established methods are reviewed and compared. It is interesting to note that none of the methods at the time of writing have had a significant number of tests. However more importantly we can see clearly that these methods are constantly developing with several new methods presented that appear to be performing well

4. Current monitoring situation

This section of the report will discuss how buildings are currently measured by researchers and industry experts for the purpose of examining the energy performance of a dwelling. These are intrusive measurements that will be required to be added to a typical dwelling, a typical example would be temperature monitoring equipment, such as small wireless sensors. This differs from “on board” data which will be covered in a later section of this report in that this would be part of an installed system, such data coming from a sensor in a boiler or thermostat.

4.1. (Intrusive) current monitoring campaigns

Building performance measurement is often seen as being split into two camps, testing (short measurement campaigns, on small samples sometimes under controlled conditions) and monitoring (longer-term measurement campaigns over larger number of properties, with in-situ conditions).

4.2. State-of-the-art survey

To get a better view on the current state-of-the-art regarding monitoring, a limited survey amongst the Annex 71 participants was performed in which current testing techniques and related costs were examined. The survey was closed with 21 responses distributed over the participating countries (Figure 37). Since the responses are not necessarily representative for the countries – participants could give their personal view – the presented results should be treated in a qualitative rather than quantitative way. Nevertheless, these results give an interesting view on the use of several testing techniques. Since creating this report this work has now been peer reviewed and published (Deb et al., 2021)

Figure 37. Number of participants per country

Figure 38 shows how common the four most known building acceptance tests are in the participating countries in the opinion of the respondents. Blower door tests are rather common whereas coheating tests are more exceptional.

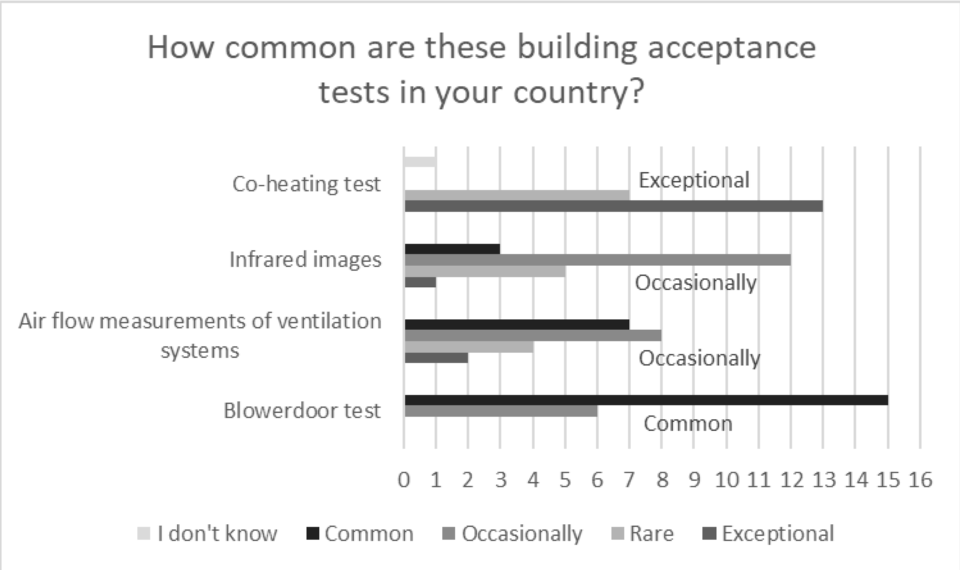

Figure 38. Prevalence of building acceptance tests. Average answers are given next to the bars.

Figure 39 shows how common gas and electricity smart meters are in the participating countries in the opinion of the respondents. It seems that electricity meters are more common than gas meters. Furthermore, the resolution of the data is often limited to yearly data. The smart meter rollout is still ongoing in Europe, potentially explaining these results.

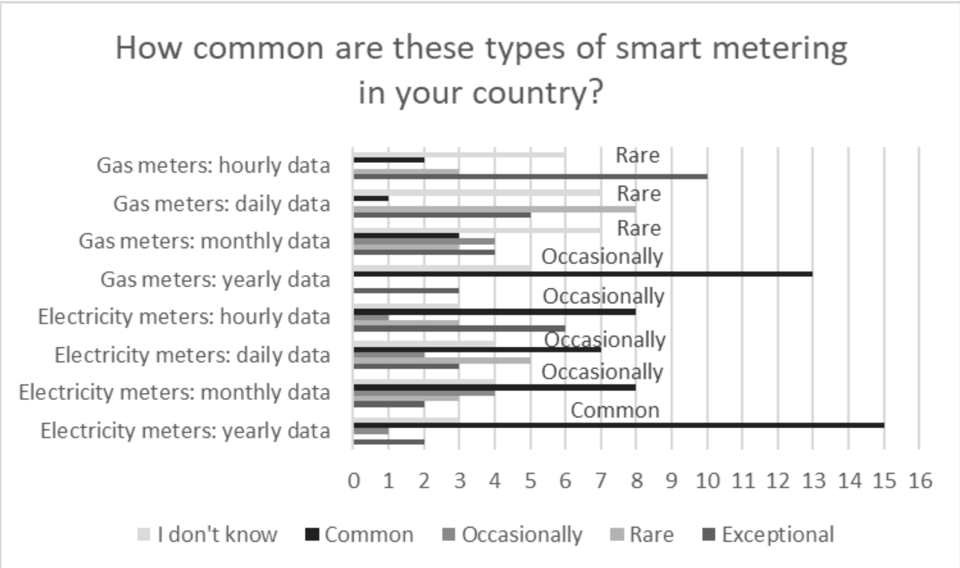

Figure 39. Prevalence of smart metering types. Average answers are given next to the bars.

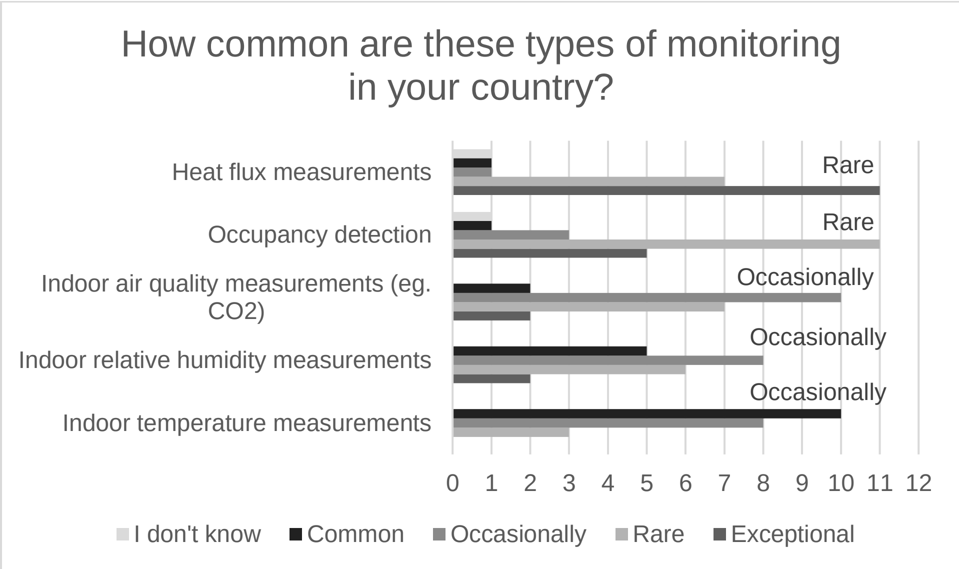

Figure 40. Prevalence of monitoring types. Average answers are given next to the bars.

Figure 40 shows how common five other types of monitoring are in the participating countries in the opinion of the respondents. In this figure, the monitoring types are ranked from least to more common. One can see that, in general, these techniques are only rarely or occasionally used. However, in some countries these are common in some specific cases, for example sensors integrated in new ventilation or heating control systems. Most of the advanced monitoring and testing of building performance is still limited to research or expert assignments.

Besides the techniques that were examined in the first part of this survey, the participants could provide other types of measurements that are commonly or occasionally used in their countries. This list is not exhaustive.

- Acoustic tests in general (UK)
- Acoustic tests of noise of the ventilation system (the Netherlands)
- Airtightness tests of ventilation network (France)
- Illuminance measurements in offices for control of artificial light (Austria)
- QUB testing (very limited) (UK)
- Smoke / fire detection systems (Austria)
- Yearly check on the exhaust systems of all combustion heating systems (Germany)
- Water counters (often not smart technology) (Spain)

The second part of the survey examined costs and application cases for building acceptance tests and assessments. Figure 41 shows the indicated costs for widely known tests and assessments. Also, the average costs, based on the indication the participants gave, are calculated to give an indication of order of magnitude. Please note that these costs contain both costs for single and multifamily buildings. One can see that the costs for blower door test and control of ventilation system are similar to the costs for an EPBD certificate or an energy label, however there are some differences indicated by the participants. The cost for a coheating test is clearly much higher. This might explain why these tests are only exceptionally used, as was seen in Figure 40

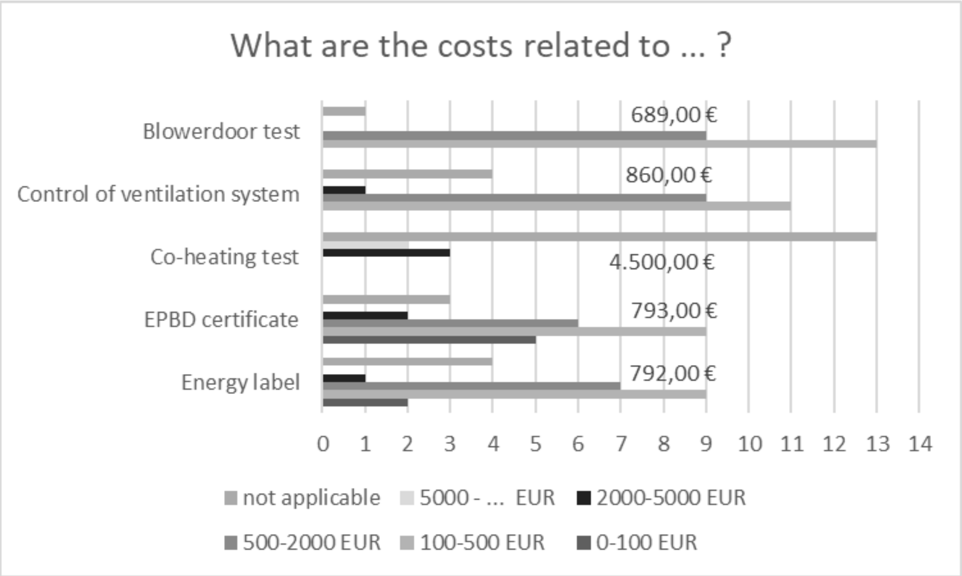

Figure 41. Costs related to building acceptance tests and assessments. More answers were possible. Average answers are given next to the bars.

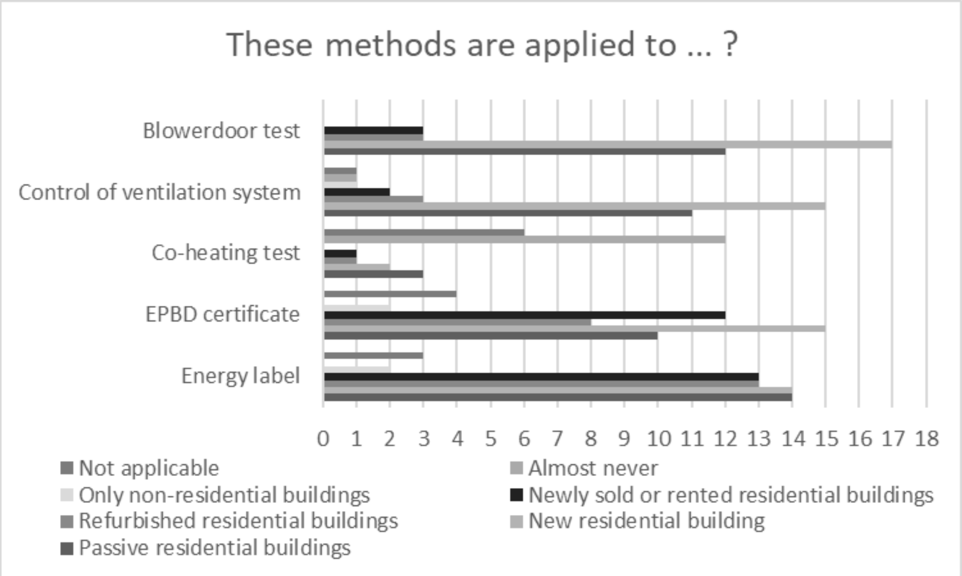

Figure 42. Application area of building acceptance tests and assessments. More answers were possible.

As presented in Figure 42, these building acceptance tests and assessments are mostly used for new residential buildings, including passive residential buildings. An EPBD certificate and energy label are also used for newly sold or rented residential buildings and refurbished residential buildings. Coheating tests are often only used in research including government commissioned research.

4.2.1. Section Summary

This type of stakeholder survey concerning the HTC and surrounding work has not been carried out on this scale beforehand. The survey sheds some light on the demand for measured energy performance of a building, however it does also show that many parties are also carrying out complimentary techniques and have a good knowledge of them, such as airtightness testing. Also, it highlights the high reported costs of methods such as coheating.

5. Evolution towards quantification based on on-board data

This chapter will examine the current situation in terms of input data for the HTC analyses, including energy and environmental inputs, key components of any HTC estimate. We will also examine how the outputs of the analyses can be best put to use, including use cases and also some issues that may stop the HTC being used in some use cases.

5.1. Stakeholder's demand

The survey (Annex 1) (Deb et al., 2021) set out to test the demand for a thermal performance measurement method amongst stakeholders and found that this was very high in general. 70% of all respondents ranked their level of interest in a measurement method as 'a lot', which was the highest category available (a detailed description and full results of the survey are given in Annex 1). Furthermore, when asked directly whether they would be interested in an HTC measurement 87% answered yes. It is clear from the survey that there was a consistently high level of interest across a group that included engineers, architects, product manufacturers, social housing providers, policy makers and researchers.

The survey then went into detail to understand the characteristics of a testing method that would be suitable for the stakeholders use. Unsurprisingly, when given multiple options for how expensive, long and accurate an HTC test should be the stakeholders most desired a cheap, quick and accurate measurement. There was, however, a general understanding of the practicalities of performance measurement, particularly in the length and cost of the measurement. Over a quarter of the respondents felt that a cost of more than 500EUR would be practical, which is significantly more than is typically spent on building performance measurement at present. Although more than 50% of responses were that a test should be less than a few days in length, several responses highlighted that testing could be longer if it allowed the building to be occupied during the test.

The most challenging demand of the stakeholders appears to be the required accuracy of an HTC test, with more than 75% of responses demanding a confidence interval of less than 10%. This may indicate a lack of general appreciation of typical measurement uncertainties in in-situ testing, and perhaps an overconfidence in the accuracy of building performance *calculations* at present. Despite the prevalence of the performance gap demonstrated by the research projects described in this report, more than 80% of stakeholders ranked their confidence in the reliability of building performance calculations as 'quite a bit', 'a lot' or 'perfectly' (the other options were 'a little' and 'not at all').

5.2. From monitoring to on board measuring

5.2.1. Monitoring Equipment

This section explores the numerous sensors used in data acquisition through the use of a survey distributed among Annex 71 members in order to review the general perception of data acquisition criteria, from which a directory is generated.

Survey Summary

A survey was initially distributed among members of Annex 71 to gauge the perception of measurement data criteria with regards to sensors and equipment typically used in the assessment of building energy performance. The definition of a building's thermal performance using the HTC requires the identification of all sources, transmissions and losses of heat. Assuming all transmissions within the building result in a net flow of zero, the HTC is then dependent on only sources and losses of heat – specifically through the outermost envelope of the building – given there is a difference in temperature across that envelope.

Sensors used in building energy performance assessment identify the sources of heat (gains) to the system, the temperature difference across the building envelope, and other environmental conditions that might impact heat loss. The HTC is to be defined in detail using a heat balance equation within ST3 of Annex 71, however it can be loosely outlined as:

$$HTC = \frac{\sum Q_i}{\sum \Delta T_i} \quad \text{(Eq. 3)}$$

Where Q_i represents thermal gains within the system and ΔT_i represents the differences in temperature between the building's internal spaces and the outside. Thermal gains within simple building systems can be regarded as anything from space heating, solar gains, occupancy gains, equipment gains, catering gains, and lighting gains. In more complex systems, this can be extended to include factors such as cooling and heat recovery.

Measurement of these gains and environmental conditions can be summarised for the following sensors.

Internal Air Temperature Sensor: These sensors measure the air temperature of individual thermal zones – i.e. the living room, kitchen, and bedrooms – and are a crucial component of the HTC calculation. The number of sensors and the placement of those sensors is an important decision in capturing the best representation of air temperature. Thermal zones can often differ in temperature throughout the day and are dependent on the heat gains and losses within those spaces. Stratification of air can also occur, so placement of sensors within individual zones can also impact the collected data.

External Air Temperature Sensor: These sensors measure the air temperature outside of the building and together with the internal air temperature sensors determine the difference in temperature across the building envelope. The variable is often measured along with other environmental conditions using a weather station, where a single local station is considered. On-site measurement of the variable can also be conducted, though significant variations can occur at each of the building's facades due to air flow, shading, solar incidence etc. On-site measurement of this variable may then require the consideration of multiple sensors and careful placement.

Surface Temperature: As with internal and external air temperature sensors, however these sensors can give an indication of the heat flow into the surface of the building's envelope. This can be an important factor in identifying surfaces impacted by solar incidence, high air velocities, rain and moisture etc.

Ground Temperature: This sensor can provide an indication of the heat lost to the ground. Caution must be taken when using these sensors however, as the ground floors of buildings can vary considerably, for example solid concrete floors, ventilated spaces beneath suspended timber floors and even buildings with basement levels.

Absolute / Relative Humidity: This variable is typically used to determine thermal comfort and does not directly contribute to the calculation of HTC. It can be used to infer occupancy and potentially quantify that occupancy in combination with other sensors. It can also help to determine to what extent a newly built dwelling has dried out which can affect the HTC outcome.

Heat Meter: Heat meters can be used to quantify the inflow of heat into the system. Depending on the heating system installed in the building, a varying proportion of this heat can be considered as flowing directly into the building – the remainder is considered as waste heat. For gas-based heating systems, additional measurements of heat are recorded during the provision of domestic hot water, which can be difficult to disaggregate.

CO_2: The concentration of CO_2 indoors can be used as a proxy for occupancy and therefore as an indication of internal gains due to occupancy. Distribution and number of sensors could play an important role in identifying the number of occupants within thermal zones, space usage and type of activity. Measurement of CO_2 can also be used to estimate air leakage through measurements of decay in unoccupied rooms.

Passive Infrared: These sensors are triggered by movement within rooms and so are used to detect occupancy and occupant activity. These sensors are limited in their capability however, as they are only able to produce a binary signal indicative of that occupancy and are unable to relay information on number of occupants, space usage or type of activity.

Window Opening Trigger: This sensor detects when windows are opened or closed. The sensor is limited to this binary detection and cannot detect the extent to which the window has been opened. While acting as a proxy for ventilation and cooling, direct measurement is not possible without combining with other sensors.

Pyranometer: These sensors are typically contained within a weather station array, however may be deployed individually. External mounting of these sensors allows the measurement of solar irradiation for the calculation of solar gains within the building – depending on the solar aperture of that building. Solar gains can be comparable in magnitude to the space heating provided by the building's systems and heavily impacts on the charging of a building's thermal mass. Measurement of solar gains is therefore extremely important in determining the HTC. A lone sensor is typically used on-site due to its cost – although data from local weather stations may also be sourced.

Wind Speed and Direction: Air flow across the surface of a building causes an increase in the heat lost from that surface. This effect can be different for each of a building's facades, and so it is important to be able to detect both speed of that air flow, and the direction in which it flows. These variables are often measured using either an on-site or local weather station.

Rain Level: As with air flow, the presence of moisture on the surface of and within the building's envelope causes an increase in heat loss. By measuring the rate of rainfall, it is possible to infer periods of increased heat flow during the collection of data for filtering.

Barometric Pressure: The measurement of barometric pressure is not considered as a crucial variable when calculating the HTC of a building. For some buildings however, pressure differences between thermal zones could be used to infer occupancy.

Survey Results

Within the survey, members were asked to populate the following criteria for each sensor / equipment:

- Typical Cost
- Installation Time
- Level of Intrusion
- Accuracy
- Benefit to Annex 71

Results from this survey were collected and used to form the basis of a directory to act as a reference point when quantifying methodologies along the x-axis of the matrix. A summary of these results is given in Table 5, which displays the most popular answer for each criterion.

Table 5. Summary of responses from the Annex 71 survey.

Measurement Group	Sensor / Variable	Typical Sensor Cost (€)	Time of Installation (Hours)	Level of Intrusion (1-3)	Accuracy (±%)	Benefit to Annex 71 (1-10)
Environmental Conditions	Internal Air Temperature	100	1	1	3*	10
	External Air Temperature	100	1	1	3*	10
	External Surface Temperature	100	2	1	4*	8
	Relative Humidity	100	1	1	3*	8
	Wind Speed	300**	2	2	3*	8
	Ground Temperature	200*	2	1	4*	5
	Wind Direction	300**	2	2	3*	5*
	Absolute Humidity	100	1	1	2*	5
	Lux Level	300	1	1	3*	5*
	VOC Level	200	1	1	0.1	5*
	Barometric Pressure	200	1	1	2*	4
	Rain Level	300	2	2	4*	4*

Internal Heating Gains	Heat Meter	300	3	2	5	10
	Solar Radiation	1500*	2	2	5	10
Cooling Losses	Window Open Trigger	50	2*	2*	1	8
Occupancy	Indoor CO_2	500	1	2	4*	8
	Passive Infra-Red	150*	1	1	1	5*
	Noise Level	50	1	1	0.1	4

**Significantly different responses were noted, criteria were averaged.*
***Sensors typically coupled i.e. within a weather station.*

It should be noted that in addition to these sensors, on-site energy consumption is measured as standard. This gives an indication of internal gains due to gas consumption for space heating, and due to convection from electrical equipment. Consumption of water is can also be measured for the disaggregation of gas consumption for space heating and domestic hot water. It should also be noted that auxiliary systems (data loggers, computers etc.) should also be considered in the quantification of data acquisition techniques.

5.2.2. Smart meters

Introduction

The purpose of this section is to identify the status and progress of the smart meter rollout in the EU states. The timescales and anticipated number of installations will be presented; this will allow a view to be taken on the likely impact of data analysis works being carried out as part of Annex 71.

Background

Smart meters are difficult to define, and have no set definition; however, they are generally considered as an electronic device that provides information about energy consumption in a more advanced way than a standard energy meter. The European Smart Meter Association however do advice that smart meters should have the following characteristics (ESMA, 2014):

- Automatic processing, transfer, management and utilisation of metering data
- Automatic management of meters
- way data communication with meters
- Provides meaningful and timely consumption information to the relevant actors and their systems, including the energy consumer
- Supports services that improve the energy efficiency of the energy consumption and the energy system (generation, transmission, distribution and especially end use)
- Can be used on multiple utilities, such as water, gas and electric, generally one meter for each.

It is an aim of the European Union (EU) to introduce smart meters across the union at a rapid rate with the aim of 72% coverage for electric and 40% for gas metering. (European Commision, 2014) This reflects an anticipated injection of some €45billion in the metering infrastructure across the EU. It is also proposed that every consumer in the EU should be able to request a smart meter from their supplier. The reasons for the installations are many in number, but the significant ones are to address the complex billing issues that exist with reading manual meters, to allow for the introduction of more flexible tariffs, and to drive energy efficiency with savings achieved simply form the installation of smart meters leading to 3% savings in energy consumption (European Commission, 2014).

This section will focus on the EU marketplace, given the current membership of the Annexe, however this can be expanded at a future date. It will also focus on the domestic marketplace. The data available for smart meters rollouts is sometimes commercially sensitive and updated infrequently. An attempt has been made to use the latest up to date source for each country where possible.

A view will be taken on the technical capabilities of the smart meters in each country; in terms of the number of readings taken per period (frequency of reads) this is critical information for the data analysis/modelling process. A review of the progress of the rollout of smart metering system will be presented along with an impact summary.

Rollout Timetable

The EU has mandated to rollout smart meters, but the implementation method and timescale of this mandate has been left to each member country. This has led to countries taking radically different approaches to technical and programming. ESMA (European Smart Metering Association) see five emerging types of rollout arrangements (ESMA, 2016). The data is taken from the 2016 data collection. This is shown graphically in Figure 43.

Front runners: These countries have finished their rollout >95% installed. Clear regulation, policy support and consumer information are all in place. Finland, Spain, Sweden Estonia and Malta make up this category.

Dynamic movers: These are countries on a path to full implementation mandatory rollout is agreed or under serious consideration with large trials in place. Smart metering solutions are currently being offered to customers these countries consist of Austria, Denmark, France, Ireland, Italy, Luxembourg, The Netherlands, Norway, Poland, Portugal, Slovenia and the UK.

Market drivers: These countries have no legal requirement for the introduction of smart meters but the suppliers are installing them anyway due to positive aspects for the suppliers and customer demand. Poland and Cyprus make up this group.

Ambiguous movers: A policy and framework is in place, the issue is high on the countries agenda, but suppliers are not making rapid implementation. Germany, Greece, Hungary and Romania form this group.

Waverers: These are the countries who have just started the implementation process without yet achieving a full regulatory framework to deliver a legislative push to the rollout, the countries making up this group are Bulgaria, Croatia, Czech Republic, Latvia, Lithuania and the Slovak Republic.

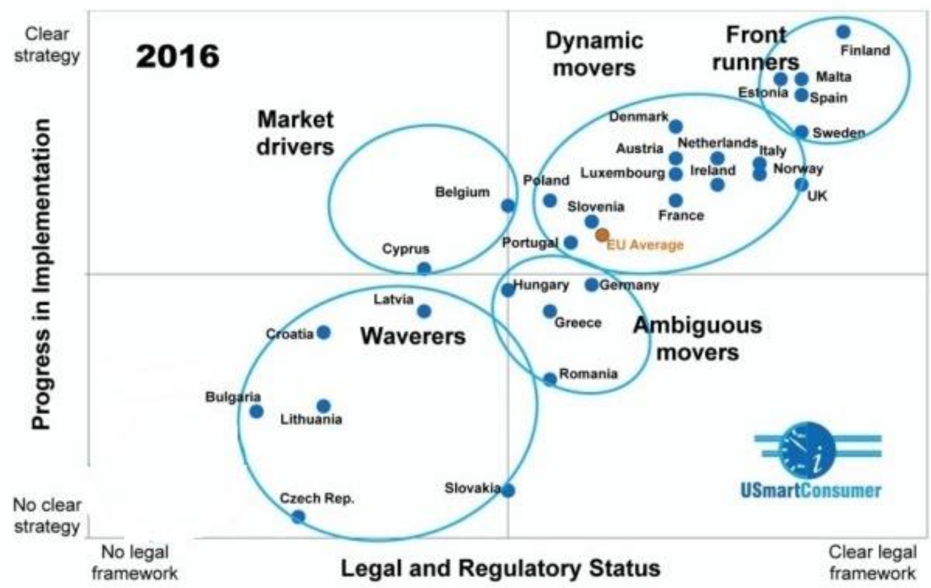

Figure 43. Chart showing the legal, regulatory and market situation in the EU.

Electricity Smart Meters: Detailed Analysis:

What follows in this section is a breakdown on a country by country basis, as it can be seen from the high level data presented above, each country is installing meters at a different rate, and also of differing types. The data presented here is devolved from the recent (2014) EU study on the rollout of smart meters in the member states "Benchmarking smart metering deployment in the EU-27 with a focus on electricity" (European Commision, 2014). As the title states the document focusses on electric meters but gas is also covered.

Progress

The rollout process of each type of meter is unique to each country; some countries took an early lead whilst others had trial stages and the like. Figure 44 illustrates the process of the rollout in each country where data is available:

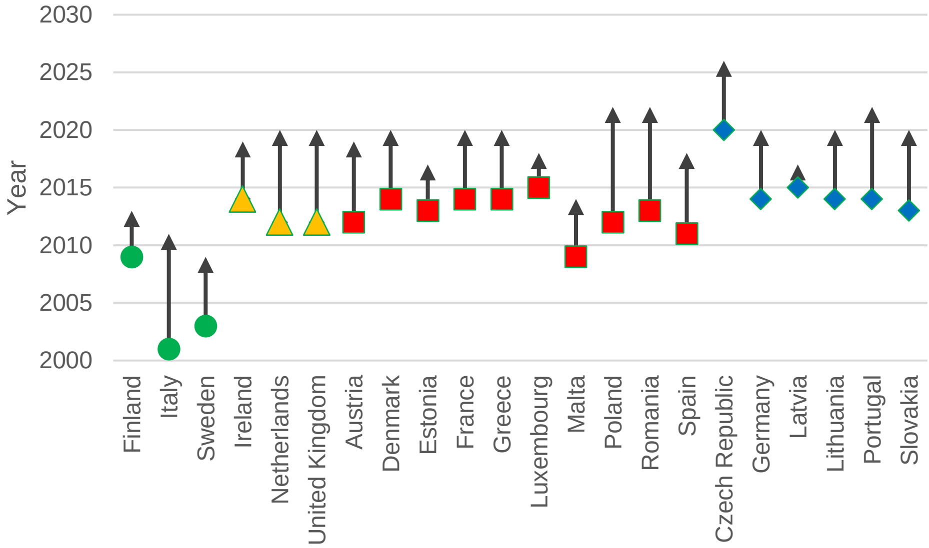

Figure 44. EU Electric Smart Metering Timescales

- Green circles are the three member states that have already completed the electric smart-metering roll-out,
- Orange triangles are the three member states rolling out joint electric and gas smart metering
- Red squares are the 10 member states rolling out electricity-only smart metering by 2020
- Blue diamonds are the six member states NOT rolling out large-scale electricity smart metering by 2020

This data tells us that there is significant distribution in the rollout periods for smart meters, with some countries already completing the task and others such as the Czech Republic not making a start until much later on. It is fair to say though however that the vast majority of smart meter rollouts will be completed by 2020 according to the data gathered.

Rollout Data

Table 6 gives a breakdown of the landscape of the electrical smart meter rollout progress across the EU. This is shown in a visual format in Figure 45. As illustrated, each country is considering hugely different approaches in terms of both rollouts, and penetration rates and technical capability such as frequency of reads to the consumer and the supplier. Some countries are currently undecided on the approach to the rollout, and some countries such as Germany are taking a selective rollout to the consumers with a lower penetration rate. It is important that these figures be viewed in absolute terms with reference to the level of populations and number of metering points taken into account.

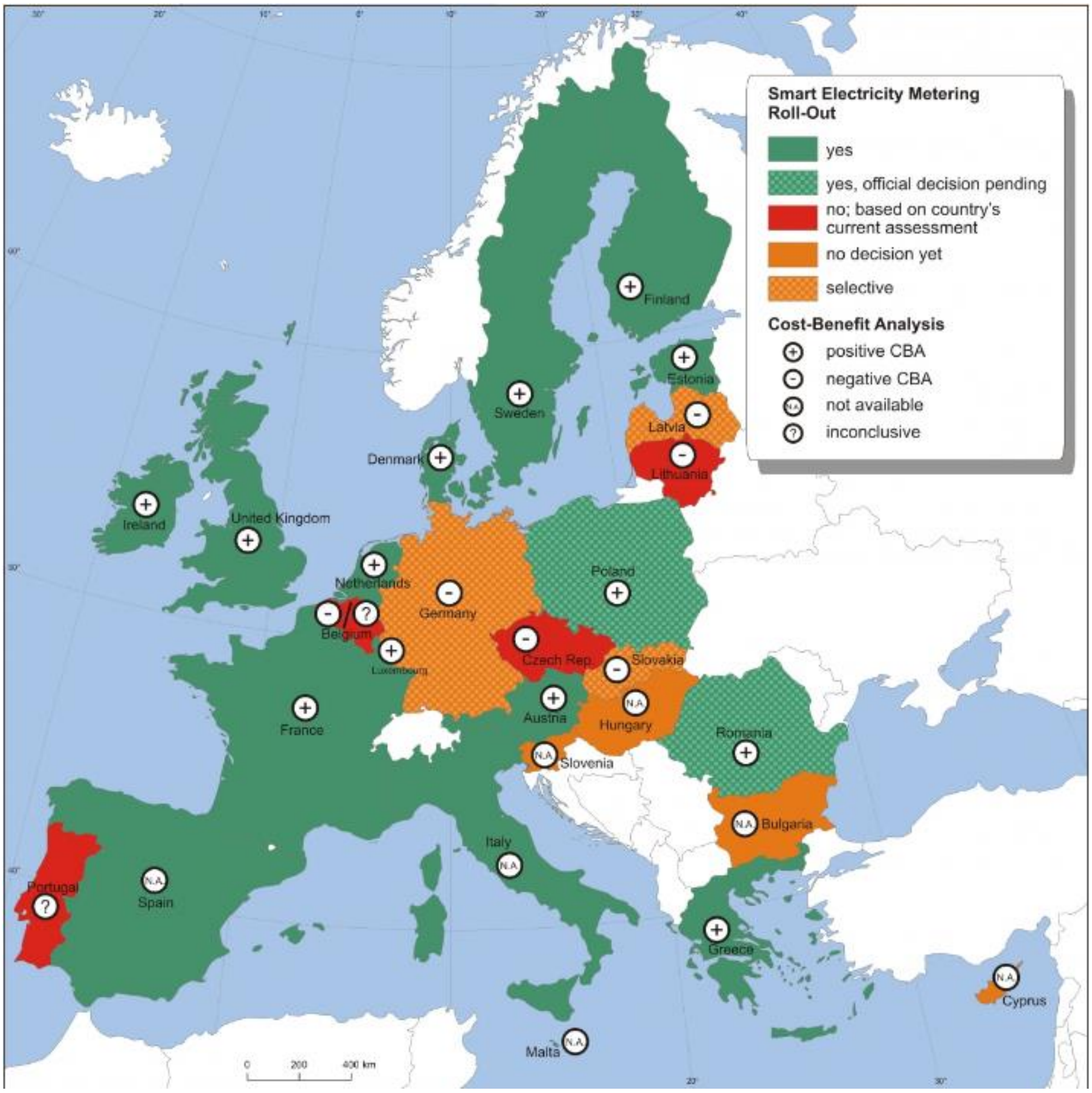

Figure 45. Geographical representation of electricity smart meter rollout (European Commission, 2014)

Table 6. EU Electric Smart Meter Programme (European Commission, 2014)

		EU Electric Smart Meter Programmes					
Country	Population 2015 Millions (Eurostat 2017)	Metering points by 2020	Planning Wide-scale Smart meter rollout? (80% by 2020)*	Expected diffusion rate by 2020 (%)	Number of Smart Metering Points to be installed up to 2020	Frequency of reads to customer (minutes)	Frequency of reads to supplier
Austria	8.6	5700000	Y	95	5415000	15	15
Belgium	11.2	5975000	N	-		varies	varies
Bulgaria	7.2		Undecided				
Croatia	4.2		No Data				
Cyprus	0.8		Undecided				
Czech Republic	10.5	5700000	N	1	57000		
Denmark	5.7	3280000	Y	100	3280000	15	15
Estonia	1.3	709000	Y	100	709000	60	60
Finland	5.5	3300000	Y	100	3300000	60 (real time optional)	60
France	66.5	35000000	Y	95	33250000	10	30
Germany	81.2	47900000	Selective Rollout	23	11017000	15	15
Greece	10.9	7000000	Y	80	5600000		
Hungary	9.9		Undecided				
Ireland	4.6	2200000	Y	100	2200000	real-time	30
Italy	60.8	36700000	Y	99	36333000	10	
Latvia	2	1089109	Selective Rollout	23	250495		
Lithuania	3	1600000	N	-			
Luxembourg	0.6	260000	Y	95	247000		
Malta	0.4	260000	Y	100	260000		
Netherlands	16.9	7600000	Y	100	7600000		
Poland	38	16500000	Y	80	13200000		
Portugal	10.4	6500000	N	-		1	15
Romania	19.9	9000000	Y	80	7200000		
Slovakia	5.4	2625000	Selective Rollout	23	603750	15	15
Slovenia	2		U				
Spain	46.4	27768258	Y	100	27768258		
Sweden	9.7	5200000	Y	100	5200000		60
United Kingdom	64.9	31992000	Y	99.5	31832040	10 seconds	30

Gas Smart Meters: Detailed Analysis

The gas meter rollout in the EU is a much smaller project than electricity, where coverage of over 70% is expected for electricity metering, gas is only expected to reach 40%. This is also reflected by the lack of available data on the technical capabilities and detailed rollout information in the public domain. In addition, two countries; Greece and Cyprus, have no gas distribution network, and thus no need for smart metering, and at least seven countries are unsure as to whether they will complete a full rollout of gas metering.

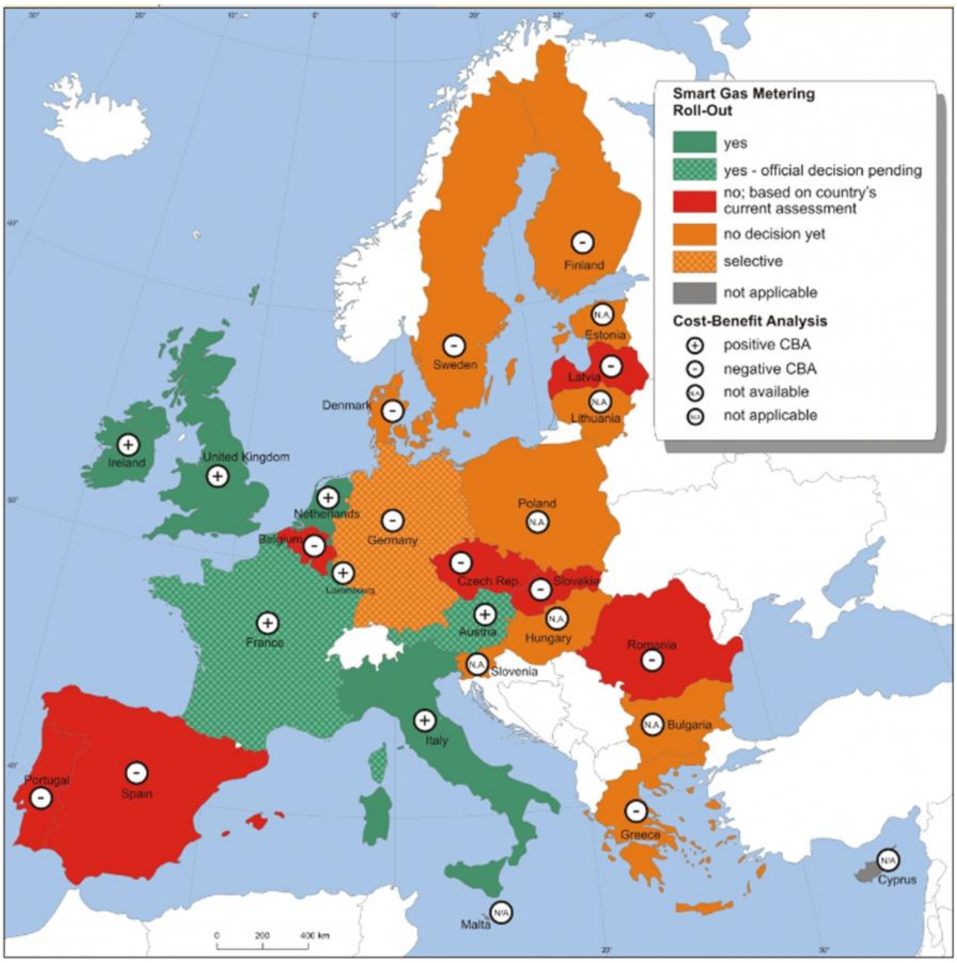

Figure 46. Geographical representation of gas smart meter rollout (European Commission, 2014)

Table 7. EU Gas Smart Meter Programme

		EU Gas Smart Meter Programmes		
Country	Population 2015 Millions (Eurostat 2017)	Metering points by 2020	Planning Wide-scale Smart meter rollout?*	Expected Penetration rate by 2020 (%)
Austria	8.6	1470000	Y	95
Belgium	11.2		N	
Bulgaria	7.2		Undecided	
Croatia	4.2	No data		
Cyprus	0.8	No gas grid in Cyprus		

Czech Republic	10.5	2870000	N	100
Denmark	5.7	410000	Undecided	
Estonia	1.3		Undecided	
Finland	5.5	37000	Undecided	14
France	66.5	11000000	Y	100
Germany	81.2	14000000	Selective Rollout	
Greece	10.9		Undecided	
Hungary	9.9		Undecided	
Ireland	4.6	600000	Y	100
Italy	60.8	22200000	Y	60
Latvia	2	2200	N	
Lithuania	3		Undecided	
Luxembourg	0.6	80000	Y	95
Malta	0.4	No gas grid in Malta		
Netherlands	16.9	7600000	Y	80
Poland	38		Undecided	
Portugal	10.4		N	
Romania	19.9	2800000	N	100
Slovakia	5.4	805000	N	
Slovenia	2		Undecided	
Spain	46.4	7500000	N	100
Sweden	9.7	37000	Undecided	
United Kingdom	64.9	25663000	Y	99.5

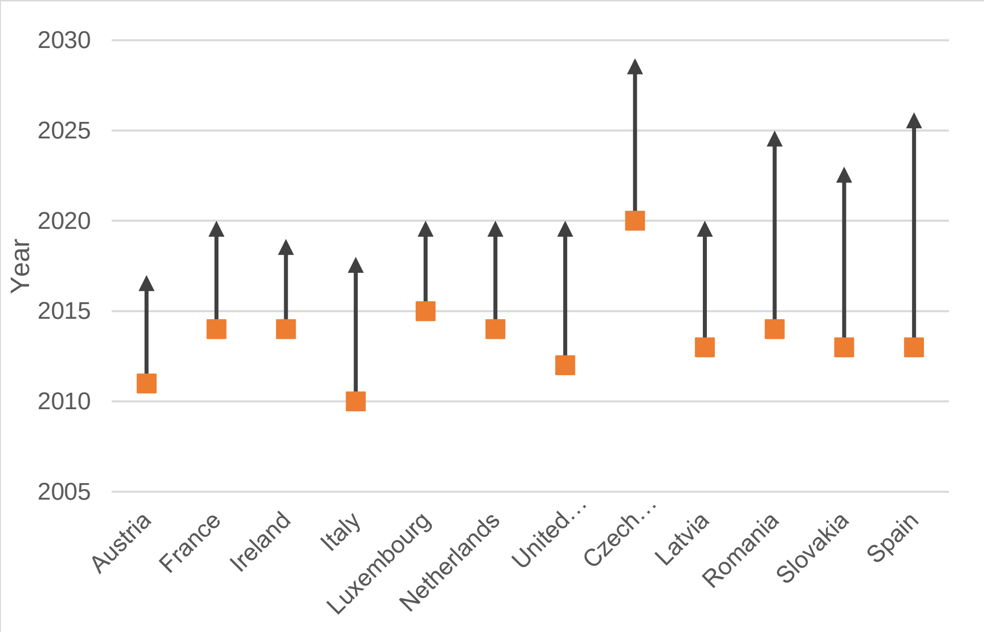

Figure 47. Chart of the EU Gas Smart Metering Programme Timescales

Technical Notes

The data provided by smart meters is grouped into two categories, that available to the supplier and that available to the consumer. In general, the work of this annex is concerned with only one deliverable, the energy consumed by a particular utility, be it electricity or gas. An important variable however is that of frequency, how often the metered fuel consumption rate is reported. For electricity meters, this varies between 10 seconds and 60 minutes - shown in Table 7. In general, the higher frequency data is delivered to the consumer only rather than the supplier. Unfortunately, this data has not been made available at an EU level for gas meters, but in general the frequency of reads form gas meters are lower than electric, at around 15-30 minutes.

Work in the annexe should take this wide variation in the frequency into account with models and analyses being developed that can handle such a wide distribution of frequencies.

Accuracies of meters in general are required to be (using UK an example)(OFGEM, 2016) in the order of:

- Electricity (+2.5% and -3.5%)
- Gas ±2%

However, these figures are widely disputed for older non-smart meters. In addition, recent electricity smart meters have come under intense scrutiny for their accuracy in particular when resistive loads are being used in the property (Leferink et al., 2016).

Summary

It appears the rollout is well developed with the majority of countries intending to have their rollout period completed by or during 2020. This means that countries are committed to rolling out close to **200 million smart meters for electricity** and **45 million for gas** by 2020. In terms of coverage, it is foreseen that 72% of EU consumers with have electricity smart meters, whilst 40% will have a gas smart meter. Currently (in 2016) around 80 million smart meters were installed across the EU and Norway (these figures have not been separated in the source data).

5.2.3. On board data

The fundamental idea behind the Annex 71 proposition is to gain energy performance characteristics for dwellings using on-board data. On board data sources can take many forms, often known as smart home, building automation or home energy management systems. Even some objects that are not often seen as being "smart" such as boilers, air conditioning units and district heating systems can be sources of on-board data. The defining characteristics of "on board” therefore is something that is already in the dwelling with no additions needed.

The sector for smart homes (which are seen by many to be the main source of on-board data) is growing rapidly. Actual sales figures are difficult to come by as these are commercially sensitive, but the trend is clear: Shin et al estimated that smart home technologies are currently present in 7.5% of homes globally with an annual market of $44.2 million in 2018 (Shin et al., 2018). The EU is a strong leader in this market place with a recent Berg Insight market research report claiming that at the end of 2017 the EU had around 22.5 million smart homes or 9.9% of households with France, Germany and the UK leading the market (Berg, 2018).

Examples of on-board data

Smart thermostat data will be a large portion of the data that can be used to help with HTC estimation. There is no generally accepted for smart thermostats, but Sanguinetti et al put together some generic capabilities of a smart thermostat, which are highlighted in Figure 48 (Sanguinetti et al., 2018). One important capability present on large proportion of the smart thermostats on the market is the ability to extract data remotely from the device, over the web or cloud-based infrastructure, typically this can be data such as; occupancy profiles/patterns, internal temperatures, external climates and setpoints for the heating system. All of this data is extremely useful for the areas of HTC estimation research.

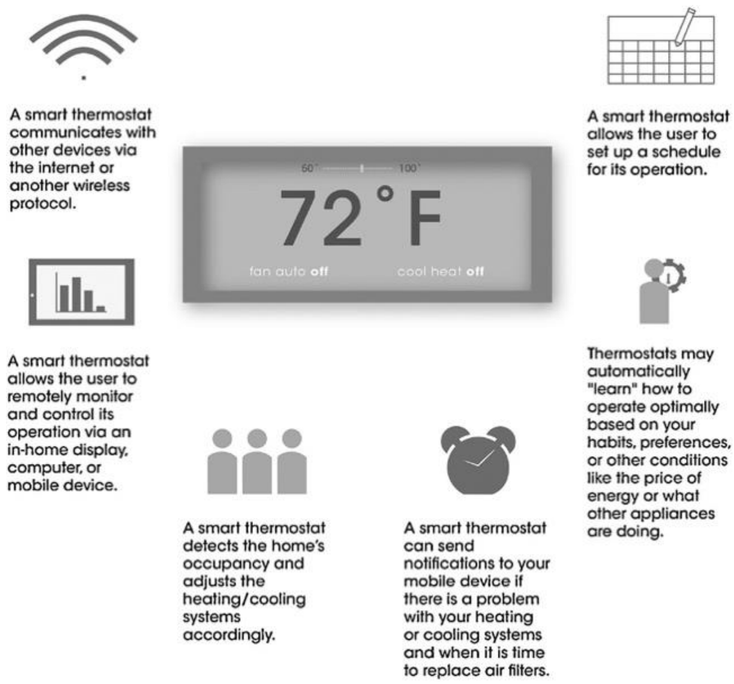

Figure 48. Typical facets of a smart thermostat (Sanguinetti et al., 2018)

Other devices, often defined as IOT or Internet of Things devices, can also provide a wealth of data to this involved in this area or research. Examples of this are as follows, alongside typical examples of the data that can be accessed:

- Amazon Echo Internal temperature sensor
- Appliances (Tumble dryers, fridges etc) can offer occupancy patterns and energy usage
- Smart boilers/Air source heat pumps
- Heat meters for energy billing
- Weather stations
- Home energy management systems

Building Information Modelling: A building goes through various life cycle phases, such as design, planning, construction, operation (use), renovation and demolition / recycling. In each phase, the architects, construction engineers and planners involved generate documents that depict the status of the building. Information is exchanged using proprietary or open data exchange standards. Powerful modelling software has made it possible to generate so-called Building Information Models (BIMs). According to ÖNORM A 6241-1(Austrian Standards, 2015), BIM is an intelligent digital building model that enables all project participants - from architects and building owners to facility managers - to work together on a unified model. The realized models are three-dimensional. Based on 3D-BIMs, enhanced BIM applications include cost estimates, energy simulation, daylight simulation and air flow modelling. While BIM is used in the planning phase, the operational phase with its runtime values of sensors and actuators of building automation systems is still insufficiently covered.

Two current open data exchange standards for BIMs are the Industry Foundation Classes (IFC), found in ISO16739 (ISO, 2018b) and Green Building XML (gbXMl) (GBXML, 2017). Although IFCs take a holistic approach, i.e. should cover all life cycle phases of a building, data that are relevant in the operation phase are still insufficiently represented. For example, a sensor (data point) of a building automation system can only be modelled rudimentarily in IFC. This also applies to the gbXML scheme which enables data exchange between architecture and energy simulation programs.

BIMs differ not only in terms of data structures, but also in terms of modelling environments. IFCs are defined in the STEP-EXPRESS (ISO, 2004) data modelling language. For IFC as well as for gbXML there is an encoding in the Extensible Markup Language (XML) (WC3, 2008). Also, a Web Ontology Language (OWL (WC3, 2012) representation of the Industry Foundation Classes (IFC) schema has been proposed. The data exchange between BIM applications takes place either via files or model servers. IFC-based model servers were developed to support collaborative design workflows. These model servers can be accessed with specific queries. The definition of model views is helpful for the development of data interfaces between BIM software. These define a sub-scheme of IFC, which covers information requirements in certain life cycle phases. One example is the IFC Coordination View for the coordination of architecture, HVAC and supporting structure in the planning phase.

5.2.4. Data from Building Automation Software (A review from An Austrian Apartment Viewpoint)

What makes the idea of on-board data complicated is the complexity of quality requirements involved. Residential buildings can be sensor-starved, and if information sources are present, the question of the potential quality of data series arises since the HTC estimation methods can be very sensitive to faults in the data. Since it is not known in advance which sources are present in any existing building, preparation delays the start of the field methods. Finally, an approach is needed that is in sound alignment with the engineering methods in the fields of control systems and automation.

In the following, within a structured approach, a set of feasible data sources for the use case of an Austrian apartment building respectively one-family home is presented. For this purpose, the case of integrated control of individual systems is included, such as electrical lighting, daylighting, radiators, or remote access to the building systems. These could be implemented with a mix of automation solutions, but for simplicity, data sources were validated with the KNX standard. (ISO, 2016)

Apartment / Residential Room Level Data: Electronic devices have multiple functions, which are selectively configured for a specific use in a building. These functions vary by manufacturer and device. If interesting for data logging, additional, not yet used functions can be activated using an engineering tool.

Temperature sensors are installed in heating systems with thermostatic control, and as separate devices in rooms with automated control functions. Compact ventilation systems, individual devices for air quality in apartments, and can have a relative humidity sensor installed.

There are several sensors installed in window systems that have been automated for central control. They may be more prevalent in roof window systems but can also be found on windows in walls. Sensors for wind and rain are integrated in the windows themselves and will cause an alarm with the automated closing of the window. More advanced control systems for window systems have carbon dioxide and relative humidity sensors as separate devices installed.

Smart meters cannot be integrated as a device into residential automation in Austria, but through a customer interface (optical/IR in any case, sometimes additionally RJ12 depending on the devices the energy providers install), raw data on energy consumption can be logged in 1-second intervals. Alternatively, there are automation devices for smart metering or sub-metering of apartments, which would have to be installed separately, or in case the monitoring takes place before occupancy of the building, where smart meters are not yet in service.

Information that might be also useful for logging are the status of system functions and local time. The messages in some automation networks have a timestamp that can be logged. Functionalities of devices that have been integrated produce status values that can be logged, either continuously or in the event of change. That way, not only information about the systems operation (on/off) can be logged, but for instance with blinds, their position can be known, which is an important indicator if there is no illuminance sensor installed. An overview of the sensors in an apartment or home is presented in Table 8.

Table 8. Apartment / residential room level data

Parameter	Comments
air temperature	heating system
carbon dioxide	windows / natural ventilation system
relative humidity	windows, compact ventilation system
wind	alarm / windows
rain	alarm / windows
system status	on, off, open, closed, percentage (blinds)
time	local, synchronized
energy consumption	electricity, gas, water

Residential Building Level Data: Information sources on the building level cover the building as a whole, and refer to requirements from outside, such as for compliance with building codes or interaction with energy providers. These are increasingly stored in electronic data formats that can be accessed for use in simulations or calculations.

Real-time building level information: On a whole building level, primarily smart meters and outdoor air temperature sensors are available. In apartment buildings, there should be one smart meter for the building installed, in addition to the smart meters for the individual apartments.

Concerning outdoor air temperature sensors, they are part of the spatial operations, but within a single automation standard, particularly in the presence of open protocols, one sensor is sufficient. For advanced building services, weather stations are on the market for integration into the building automation networks. Typical values they provide are wind, temperature, and relative humidity of outdoor air. Table 9 contains a summary of building level real-time parameters for logging.

Table 9. Real-time building level data

Parameter	Comments
outdoor air temperature	single device
energy consumption	electricity, gas, water

Occupant Level Data Sensors in mobile phones in recent commercially available smart phones, a lot of sensors are installed to provide functionalities for geolocation of the devices and improved performance qualities. Depending on the model, they may include - besides cameras and microphones – an accelerometer, a gyroscope, a pressure sensor, a magnetometer, and a lighting sensor. While it is possible to use some of these sensors for physical experiments in citizen science type projects [9], the ambient light sensor, for instance, can only be accessed on a low level, which is not permitted in commercially distributed apps (Phypbox, 2020).

Weather Data There are many commercial providers of weather data offering historic data at a cost. Sometimes, smaller volumes, such as data for up to 4 days or larger time intervals, e.g., 4 hours, are provided for free.

ZAMG (Austrian Central Institute for Meteorology and Geodynamics) (ZAMG, 2021) takes part in the Austrian Open Data Project (Open Data Austria, 2021) , and through this platform shares online hourly weather data from 21 weather stations across Austria. Their parameters are:

1 Temperature

2 Dew point

3 Relative humidity

4 Wind direction

5 Wind speed

6 Peak wind direction

7 Peak wind speed

8 Precipitation

9 Atmospheric pressure

10 Sunshine percentage

A visualisation of the hourly data set from 21 weather stations is shown in Figure 49.

Station	Name	Höhe m	Datum	Zeit	T °C	TP °C	RF %	WR °	WG km/h	WSR °	WSG km/h	N l/m²	LDred hPa	LDstat hPa	SO %
11010	Linz/Hörsching	298	01.02.2021	17:00:00	0,3	-2,5	82	120	11,2		16,6	0	1000,8	962,6	8
11012	Kremsmünster	383	01.02.2021	17:00:00	-1,1	-3,7	84	7	11,9	360	22	0	1001,1	953,5	3
11022	Retz	320	01.02.2021	17:00:00	0,3	-3,8	74	125	7,2	74	22	0	1001,4	962,4	37
11035	Wien/Hohe Warte	203	01.02.2021	17:00:00	1,7	-3,5	69	114	10,4	142	23,4	0	1001,3	975,8	37
11036	Wien/Schwechat	183	01.02.2021	17:00:00	1	-3,3	73	120	16,6		27,7	0	1001,5	979	22
11101	Bregenz	424	01.02.2021	17:00:00	5,8	5	95	114	9,7	114	18,7	3,5	999,4	947,7	0
11121	Innsbruck	579	01.02.2021	17:00:00	4,1	1	81	277	5,8	285	20,2	0	998,8	930	0
11126	Patscherkofel	2247	01.02.2021	17:00:00	-5,1	-6,2	92	190	13,3	179	23,4	0		756,5	0
11130	Kufstein	495	01.02.2021	17:00:00	5,3	2,2	80	146	1,4	227	6,1	0	998,4	940,4	0
11150	Salzburg	430	01.02.2021	17:00:00	3,7	2	89	320	7,6		11,2	0	998,8	945,8	10
11155	Feuerkogel	1618	01.02.2021	17:00:00	0,3	-5,1	68	280	4,7	212	22,7	0		818,4	0
11157	Aigen im Ennstal	640	01.02.2021	17:00:00	2,2	-1,2	79	183	3,2	180	8,3	0	1000,5	923,5	7
11171	Mariazell	866	01.02.2021	17:00:00	1,4	-2,3	77	147	10,8	148	19,8	0	999,2	898,4	16
11190	Eisenstadt	184	01.02.2021	17:00:00	2,2	-4,7	61	90	15,5	117	32	0	1000,9	978,6	45
11204	Lienz	659	01.02.2021	17:00:00	-0,2	-2,5	84	89	1,8	89	4,7	0	1002,9	923,2	39
11240	Graz/Flughafen	340	01.02.2021	17:00:00	-0,9	-2,9	86	160	7,6		11,2	0	1002,3	957,9	11
11244	Bad Gleichenberg	280	01.02.2021	17:00:00	-0,1	-2,9	83	111	2,9	153	7,9	0	1002,5	969,2	17
11265	Villacher Alpe	2140	01.02.2021	17:00:00	-5,3	-6,6	92	291	4	269	12,2	0		765,8	68
11331	Klagenfurt/Flughafen	447	01.02.2021	17:00:00	1,1	-2,5	77	265	4	291	9,4	0	1002,7	948,2	0
11343	Sonnblick	3105	01.02.2021	17:00:00	-8,8	-10,8	86	275	21,6	277	28,8			677,7	55
11389	St. Pölten	270	01.02.2021	17:00:00	1	-2,1	80	344	5,4	339	13,7	0	1000,8	968	0

Figure 49. Example of an hourly weather data set for 21 weather stations in Austria (in German). (data.gv.at, 2021)

Geographical information systems, sources used in regional and city planning are sometimes used for download in Open Data and Open Government projects. Since these trends are more recent, those resources are rather available on occasion, organized by topics, such as landmark buildings (e.g. in Vienna, Austria (data.gv.at, 2021a), or climate data (e.g. for past 3 years in Vienna, Austria (data.gv.at, 2021b)). They provide descriptive information on the buildings, such as architects, number of stories, etc., or heating degree days in the case of the climate data, but are not always well maintained and regularly updated, and have to evaluated on a case-by-case basis.

Data sources in an Austrian apartment building respectively one-family home assuming partial, low complexity automation infrastructure of individual systems, such as electrical lighting, daylighting, heating, or remote access to building systems were identified. These could be implemented with a mix of automation solutions, but for simplicity, data sources were validated with the KNX standard. Associated parameters were reviewed on a room, building, occupant, and world wide web level of infrastructure.

Although residential buildings may be rather sensor-starved, there are trends that more and more data sources will be available in the future useful for logging for in-situ measurements. While there are some open data projects in Austria, which can provide data to a large number of apartments or homes, sensors and information sources in the field remain technology-specific, and the focus should be on finding an approach in the measurement methodology to deal with this complexity. Components emerging with the Internet of Things might change the view in some years, when embedded sensors can be accessed over separate networks which are faster and have fewer physical limitations than with current automation networks. A summary of potentially useful information and parameters discussed here is presented in Table 10.

Table 10. Overview of potential information sources in residential buildings

Parameter	Comments
Apartment / Room Level	
air temperature	heating system
carbon dioxide	windows / natural ventilation system
relative humidity	windows, compact ventilation system
wind	alarm / windows
rain	alarm / windows

system status	on, off, open, closed, percentage (blinds)
time	local, synchronized
energy consumption	electricity, gas, water
Building Level	
outdoor air temperature	single device
energy consumption	electricity, gas, water
World Wide Web Level	
weather data	hourly intervals
geographical information	climate and building data, some open data

5.3. Stakeholders requests and concerns

The survey (Annex 1) included a number of questions designed to understand what services the stakeholders believed that HTC measurements could be used to provide, and what the requirements of a method would be for testing to be practical including cost, test length and uncertainty margin. Interestingly, the stakeholders themselves were most interested in aspects of building performance, such as energy use, change in energy use after retrofit and thermal comfort, while they were most interested in providing their customers with quality assurance and design and retrofit guidance. These responses are understandable considering that the largest percentage of professions amongst the stakeholders were consulting engineers and architects. The split between what the stakeholders themselves were most interested in, and what they believed their customers would find most attractive, highlights that there are several user groups for performance measurement and that the outputs will have to be tailored to each.

The last two questions of the stakeholder survey were open and were about the complications that could arise in the on-site measurement of the HTC, and suggestions about how these measurement methods could be used by their company. The first question showed the most important concern for the stakeholders is about the actions to be taken when measurement results are not as good as expected. Other often mentioned concerns are related to the technical difficulty of the measurement (influence of the weather and the occupants, possible high cost and duration) or are more logistical (accessibility and privacy, damages to the building). Many other different issues are mentioned by a smaller number of stakeholders but are still very legitimate (theft and insurance, electricity availability, incomplete data for example), which shows that many fears will have to be assuaged before such methods can be used with the complete trust of all the stakeholders.

The question about suggestions led to the paradoxical result that the most common answers are usually the least interesting, as they are the most obvious ones: building quality assessment, building element assessment, renovation preparation, certification, construction of a building database etc). On the other hand, some individual suggestions are more original: quantification of the energetic impact of damages, monitoring the use of public subsidies, continuous evaluation of HTC or preventive maintenance, etc.

More information is presented in Annex 1.

5.4. Normalisation of data

The stakeholder survey highlighted some concerns around the ability for end users, be they consumers, energy experts, or policy makers to understand the actual HTC figure. As such we propose below a series of ways in which the HTC can be normalised which may make the figure more usable:

HTC divided by heat loss area: The HTC characterizes the thermal performance of a building envelope. As such it is building specific. Buildings with a larger fabric area will have a higher HTC for the same heat loss per m². Hence, an HTC-value will give no clue on the performance quality of the fabric components itself. If we want to assess the quality of the fabric (transmission and infiltration heat losses through the fabric), it is more relevant to divide the HTC by the total fabric area A (see also Building physical framework in ST3 report). Doing so we get a building envelope averaged assessment of the fabric performance in W/(m²K), which is directly comparable with an averaged design U value. Note though, that, in contrast to a U value, an HTC/A will quantify both the insulation quality as well as the airtightness of the fabric.

HTC divided by total floor area of the building: This is known as the Heat Loss Parameter (HLP), this has recently been examined by a consultancy called BTS in the UK, findings from this work propose a scaled approach to the HLP to make this easier for customers to understand. The division of HTC by floor area also assists in the comparison of buildings of a similar size but a different construction or type.

The team used a typical house of size 5x8x5m with a variety of different constructions/types to illustrate the HLP approach as shown in Figure 50.

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 LIMITING FABRIC PERFORMANCE[1]	Walls	0.3	
	Windows and doors	2	
	Floor	0.25	1.82
	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	
PASSIVHAUS EXAMPLE[2]	Walls	0.13	
	Windows and doors	0.88	
	Floor	0.2	0.93
	Roof	0.14	
	Airtightness	0.6	

Figure 50. A selection of properties subjected to the HLP metric (shown in far-right column)

Simplifying this approach even further an HLP scale was developed to allow for comparison for laypeople/homeowners or buyers. This is shown in Figure 51.

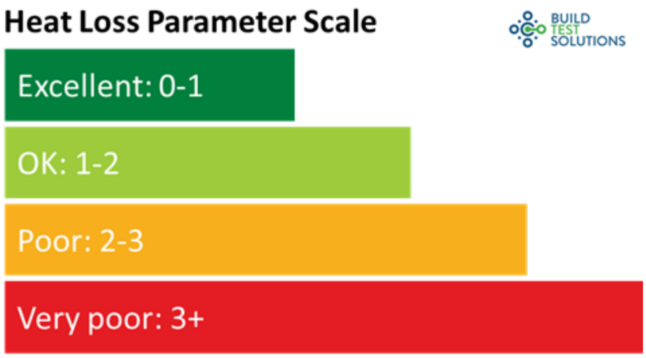

Figure 51. Example of HLP scale, provided by Build Test Solutions. https://buildtestsolutions.com/heat-loss-parameter-a-metric-for-total-fabric-performance

HTC divided by heated volume: Instead of dividing the HTC by the total loss area, one could argue it is more correct to divide the HTC by the total volume of the dwelling. This will result in a metric in W/(m^3K) which will not only take the performance quality of the fabric into account, but also the compactness of the building. Compactness (m^3) defined as total building volume over the total heat loss area. It could be argued that the more compact a building is (smaller heat loss area per volume), the less stringent we must be on the envelope performance. This corresponds to accepting a certain amount of energy to heat (cool) each m³ of a building. This way, an HTC/V incorporates both the performance quality of the fabric as well as the compactness of the design.

Reasons not to normalise: There are situations where normalising the HTC by building geometry is unhelpful. The HTC quantifies the rate of heating energy required to maintain each degree Celsius of temperature difference between indoors and outdoors in a home. As such it is similar in concept to the fuel efficiency of a car expressed in litres/100km. Owners of larger cars expect a larger fuel efficiency value. Similarly, owners of larger homes should expect a larger HTC. To promote energy efficiency to homeowners, the HTC should not be normalised by floor area or façade area, in the same way that fuel efficiency is not normalised by the cylinder capacity of the engine. This 'raw' HTC value is also required for EPBD calculations, and it is recommended that it be reported on EPCs to help with promoting the value and use of this metric.

In promoting the HTC metric into everyday use, it will be important to provide additional education and support to homeowners. While car drivers often know their annual distance travelled (e.g. 10,000km), the owners of homes may not typically know their annual heating degree days (HDD) or how to use them in a calculation. This could be helped by providing bespoke HDD data (expressed as 1000s of K.hours) for households, both historically and for benchmark calculations. This is all helped by the magnitude of typical HTCs (say 40-400W/K) and the average HDD across Europe (c50k.K.hrs), such that a simple multiplication is possible. For example, a home with a HTC of 300W/K and 50k.K.hrs will require 15,000kWh (=300 x 50) of heating energy.

5.5. Application of HTC global energy efficiency framework (Survey of EPBD-models)

A survey was carried out for all EU states that form part of Annex 71, which are as follows, what follows is a review of the way that HTC is calculated, recorded, viewed and edited in the energy model for each member country. This highlights some issues that may need resolving before the HTC can be used effectively in terms of allowing a measured value to be inserted into the software or to allow an HTC to be viewed, and by whom. **The full results of the survey can be found in Annex 2 of this document**.

Survey responses were received from the states below

- Austria
- Belgium (Wallonia and Flanders)
- Denmark
- Estonia
- France
- Germany
- Netherlands
- Norway
- Spain
- Switzerland
- UK

Under the regulations of the EPBD (European Performance of Buildings Directive) each member state should make provision for the energy modelling of its housing stock. As such all of the states approached here that are member states do have their own EPBD compliant models, and even non member states (UK, Switzerland and Norway) have models that meet the standards laid down in the EPBD, generally. However the way that they calculate and deal with the HTC component is quite different across the sample.

The HTC is present in one form or other in all of the energy models reviewed. This is because it is an intrinsic part of the calculation method to predict the annual running cost of a dwelling, without this simple heat transfer metric there is no easy way to model the heating/cooling energy required to maintain the thermal comfort in the building.

The way that the HTC is calculated however does not appear to be harmonised or named across the sample. Most states use a very straightforward method *(where U= U value of the element. A= area of the element, and I = infiltration level of the building):*

$$\text{HTC} = (\text{U.A}) + \text{I} \qquad \text{(Eq. 4)}$$

However, Germany appears to not include infiltration in the HTC calculation opting for:

$$\text{HTC} = (\text{U.A}) \qquad \text{(Eq. 5)}$$

France on the other hand ops for a normalised approach to the HTC, locally known as Ubat, or U bâtiment, meaning in English, U of the building, or whole building U value, however this is normalised using the floor area of the building ($m^{2)}$:

$$\text{U}_{\text{batiment}} = \frac{U{\cdot}A+I}{m^2} \qquad \text{(Eq. 6)}$$

At this moment, no countries allow for a direct input of the HTC to "override" the calculated HTC component, some researchers responded to the survey elaborating on ways the HTC could be amended using more "creative" styles of energy modelling, such as amending the U values of the elements or the infiltration rates, but this is far from official or recommended by any authority.

The HTC although a hugely important component of the energy modelling industry, is not able to be able to be altered in any meaningful way to suit the as built performance of the dwelling. This leaves a quandary; techniques in this annex and indeed outside on global level are being developed to rapidly and cost effectively measure an HTC and yet when it comes to using these figures (in the states identified) it is not actually possible to the use these values for regulatory purposes to provide models/certification for dwellings. There are however many other use cases for the HTC which will be identified in the next section of this report.

5.6. Use Cases for HTC

The HTC is an important building physics metric which can help deem the fabric energy efficiency of a dwelling, however given its simple nature and that fact that it incorporates the entire fabric performance it can also be used for wide range of purposes, these will be examined in turn in this next section.

5.6.1. Quality Assurance for New Dwellings

This section applies to the new building dwelling sector only. Earlier parts of this report have highlighted many cases of the EPG. This evidence is mounting on a global level. Also, problems have been found with data contained in some input data which has led to mislabelling of the energy performance labels in the UK as an example, with errors found in 27% of the EPC data inputs (Crawley et al., 2019a). This coupled with an increase in recent interest around guaranteeing energy performance is likely to prove the requirement for a more robust approach to determining the energy performance of a dwelling rather than relying on modelled values. This is made clear in section 1.5 of this report and also by similar recent work in Norway (Winther and Gurigard, 2017).

5.6.2. Heating and Cooling Commissioning and System Design

The installation of low carbon heating and cooling systems are starting to become more popular, an example of these systems are air source heat pumps, with quoted energy performance statistics convincing many to have these installed, not to mention the associated carbon savings. As such many EU states are considering heat pump options when planning their decarbonisation strategy (Kavvadias et al., 2019). However this type of technology (and other similar ones) only perform as expected when they are correctly to size to the dwelling that they serve. Where this is not the case then the operating efficiency of the heat pump will be less than expected, and such an EPG will likely be formed (Domanski et al., 2014). As such it would be beneficial for those designing, installing, and commissioning these systems to know the characteristics, to better select the sizing and settings on these systems. Another issue with heating apparatus is the sizing of heat emitters rather than the heat pumps themselves, this sizing is done on a room-by-room basis, whereas the current HTC do not declare to be able to measure room by room heat loss this would certainly be a useful development in the future.

5.6.3. Energy certification

Energy certification as mentioned in section 5.6.1 has its issues but projects such as SMETERS (BEIS, 2020) in the UK and others around the EU have alluded to the idea of using the HTC to add to or replace the energy labelling present under the EPBD. However, this work is at very early stages, it does however have a unique advantage in that if a real-world building energy rating can be used rather than a model then it would arguably make the labelling process more accurate and also could be more useful for other critical/sensitive tasks such as energy performance guarantees. However, as section 5.5 in this report examines, this is not always as easy it seems, with practically all countries not allowing this substitution of a modelled value, at the time of writing.

5.6.4. Retrofit pre and post measurement

In many cases of energy efficiency based retrofits, funds are allocated by central or local governments or funders with only a limited time to carry out the works, this is unfortunate as any research or studies are often carried out only on a completed retrofitted dwelling, this does not give the opportunity to carry out investigation on the improvement made by the works, nor the actual performance of the original dwelling (was it better or worse than we believed in its original state and also, did the retrofit make the savings estimated, two vital metrics, especially when trying to attract further funding for projects). We have already seen evidence of performance of solid wall homes performing better than researchers believed for many years, (Hulme and Doran, 2014). This type of fundamental misunderstanding of fabric performance in historic properties (the type most likely to undergo retrofit) should lead to more focus being given to the actual performance of the dwelling before and after retrofit, given that the improvements are often modelled, this will lead to the savings for energy and/or carbon being subject to large errors. If an HTC measurement was taken at the pre and post retrofit stage, then these savings would be much more accurate. Also, a feedback loop can be provided to state which retrofit methods were the most effective for a given archetype of property.

5.6.5. Energy pathology

Energy pathology; is defined as “the systematic investigation of the energy performance of buildings, with the aim of detecting any elements whose performance in energy terms is not as intended” (Fitton, 2020). This technique can be used when a building as not performing as expected by the occupant/designer etc. These complaints can be for many reasons, but often high energy bills or poor levels of thermal comfort are quoted. When high bills are referenced then fabric issues can often be at fault. These are easily examined and rectified using thermal imaging and blower door tests, however a test to determine the whole dwelling heat loss whilst, without removing the occupants from the house, (as may be required with coheating or some other methods) is a powerful capability for energy pathologists, as this HTC can be then compared to the modelled figure. It should be noted that this can been as a “blunt tool” as an HTC alone will not help to diagnose the defects, only to measure the magnitude of them (Fitton, 2013)

5.6.6. Continuous monitoring and predictive maintenance

As we have already seen in earlier stages of this report even something as the thermal performance of a simple masonry wall can be constantly changing as it experiences changes in moisture levels, heat gain etc. This is to be expected. However, when something significant changes in a structure, for example the wall becomes saturated due a leaking gutter, or a flat roof covering fails, then this can lead to a significant increase in the rate of heat transfer int that element and ultimately the HTC will rise. Given that these defects are often invisible to the occupants of the building then this type of defect can go unnoticed; where strategies of HTC measurements are automated and an HTC can be generated at regular periods , say for each day or month, then when significant disturbances to the building fabric occurs then these can be easily identified using basic pattern detection techniques.

5.7. HTC Measurement for Policymakers

One of the intended outcomes of Annex 71 is a consideration of how HTC measurement could be used as a policy instrument. This was addressed broadly in the initial stakeholder survey (Annex 1), but as the survey was designed to be applicable to a wide variety of stakeholders there were few questions aimed directly at understanding the role of HTC measurement in policy. To provide further information, a second survey was carried out more specifically designed for policymakers. The survey was entirely qualitative and carried out with a subsample of three policymakers, with one each from Belgium, France and the UK. This work has also been presented as a journal article (Deb et al., 2021)

5.7.1. Insights from the Stakeholder Survey

In the full sample of 243 stakeholders for the initial survey, of which the results are presented in Annex 1, there is a subsample of 14 from public authority or policy makers. The survey results from that subsample are given below, they show an excellent level of interest and give a good guide to what policy makers are looking for from an HTC measurement: a test with high accuracy (<10%) delivered without significant disruption to builders or occupants at a reasonable price (<500EUR), suitable for use in building energy classification.

These 14 public authorities or policy makers are in 6 countries (Figure 52).

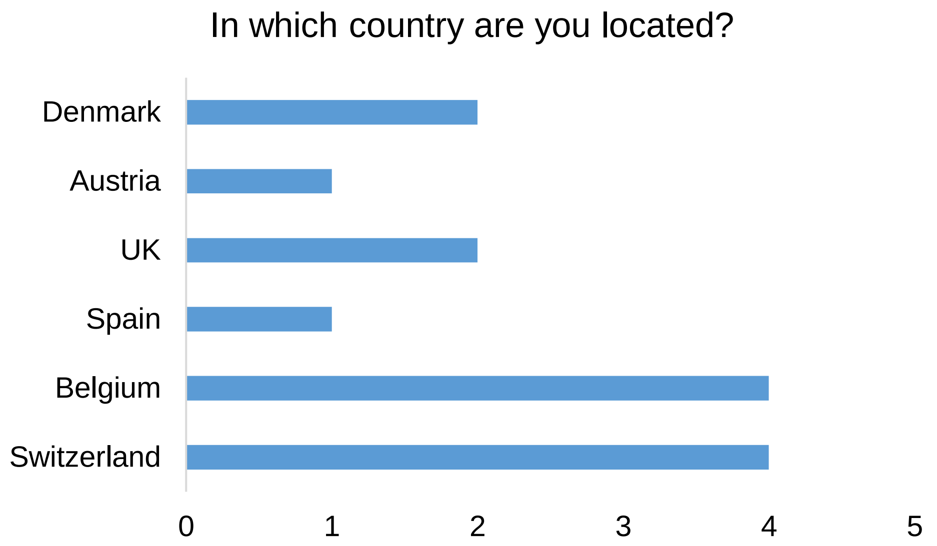

Figure 52. Countries from which the responses from public authorities or policy makers came from.

The survey gives us some good insights into this subsample's interest in HTC calculation and measurement (Figure 53):

- There is good confidence in the accuracy of HTC calculations
- The majority is interested in measurement
- The majority sees HTC measurement as a tool for building energy classification
- The price should be less than 500EUR
- There is split opinion on when a measurement should be carried out
- The majority thinks the measurement should take a few days at most
- The majority feels that the confidence interval of the measurement should be less than 10%

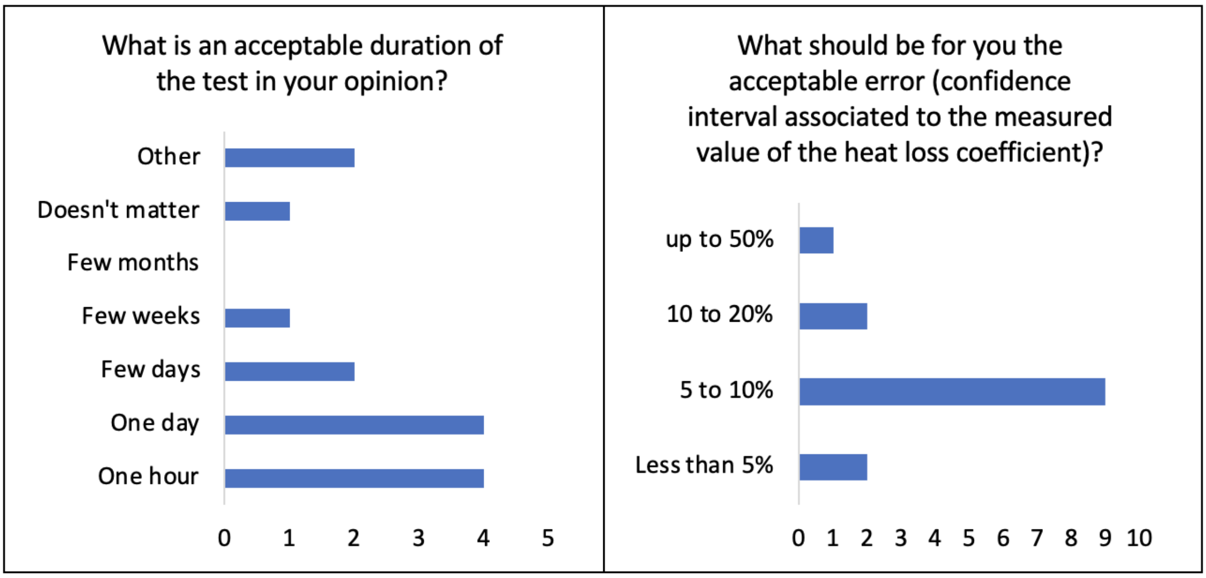

Figure 53. Public authorities and policy makers responses to selected questions from the survey.

5.7.2. Further Detailed Survey

While the stakeholder survey gives a good broad insight into general interest in HTC measurement among policymakers, it does not provide much information about a practical route for the inclusion of HTC measurement in legislation. To further understand this, a second, more detailed and qualitative, survey was carried out with a small subsample of three policymakers from three countries (Belgium, France and the UK). Six questions were asked in total, for each the respondent gave a free text answer.

Question 1: What are the barriers to adopting HTC measurement as a regulated metric?

A range of answers were given here, but one was common across all three respondents, that there weren't sufficiently well validated HTC measurement methods. Therefore, putting a system in place to provide well recognised validation of any testing method is clearly an important barrier to overcome.

The practical constraints that were highlighted as a concern amongst the wider group of stakeholders were also repeated by the subset of policymakers. Two of three responded that additional costs could be problematic, and the Belgian respondent highlighted that it would be difficult to base regulations on a seasonally dependent test (i.e., one that had to be carried out in winter). The French respondent highlighted the difficulty of responding to a failed test, given that the building is already built at that time and remedial measures may be extremely difficult.

The French and UK policymakers both felt that the range of changes required to existing regulations around energy efficiency could be complicated and perhaps unacceptably burdensome to comply with. Related to this, the UK and Belgian respondents highlighted that HTC is not a currently regulated metric and were unsure how this new metric would work with existing targets around energy use or carbon emissions.

All of these points highlight that beyond the technical feasibility of measuring an HTC it is important to further consider the measurement in context. In order to be widely accepted, perhaps there needs to be a standardised validation process? Even once happy with the accuracy and repeatability of the result, how could regulations be shaped to accept a measured HTC? Should the HTC, or a normalised version of it, become a new regulated metric itself, or should the measured HTC be included to better calibrate existing models which produce regulated metrics like energy demand or carbon emissions?

Question 2: In what areas of policy do you think HTC measurement could be applied? E.g. New build building regulations, requirements for social housing, requirements for landlords.

All respondents felt that HTC measurement could be applied across all types of building and policies applied to buildings. The Belgian respondent felt that there could be less time pressure in social housing and new buildings, while the UK respondent replied that application for new buildings could be more technically challenging (but did not expand on why). The French respondent suggested a voluntary certification for buildings that have had their performance assured through measurement, indeed this seems like a practical suggestion to start this process and could provide a standardised route upon which to build further regulation.

Question 3: What should happen if the measured performance is not as expected?

This had already been raised as an issue in the stakeholder and policymaker surveys, and indeed the responses to this question demonstrated that this subject requires careful further consideration.

All respondents relied that the repercussions of unexpected measured performance should be different depending on the context. The UK respondent did not provide specific suggestions, just that the repercussions should be considered in line with existing policy. The French respondent felt that there should be no financial repercussions initially, with the concentration instead of familiarising the industry with the process and learning from the feedback.

Both the Belgian and French respondents felt that potential punishments should be dependent of the contractual agreements in place for the building. For example, if a new building was found to underperform in comparison to expectations there should be a fine applied to the owner, which could be passed onto the builder depending on the contractual relationship between owner and builder.

This will clearly be a highly controversial topic for policymakers in the future, especially as given the few measurements which have been carried out to this time it is not clear how frequently there will be cases of underperformance and to what extent the underperformance will typically be. In the first instance, voluntary certification could be a good route to allow a more open learning process.

Question 4: Could an HTC measurement with a confidence interval of ±15%, ±25% or ±30% be used in legislation?

There was some variation in this answer, with both the Belgian and UK respondents highlighting that the use of confidence intervals themselves would be new and unfamiliar to regulations. The French respondent highlighted that in the first place the reliability of the measurement will be most important, and that even an uncertainty of ±50% would be useful to highlight the worst cases of underperformance. The UK respondent felt that the most important criteria was that the measurement was more accurate than the predictions it could replace, this is somewhat difficult to define but is logical.

Both the Belgian and French respondents felt that in the long term an accuracy of around ±15% would be required in order for the industry to have confidence in the results of the measurement.

Question 5: What evidence would you have to see to be confident enough in an HTC measurement method to include in legislation?

All three respondents highlighted the importance of accurate and particularly reproducible results. Both the French and Belgian responses highlighted the importance of reproducibility, that similar results are gathered for the same building by different testing bodies. The UK and Belgian respondents highlighted that a sufficient number of case studies would need to be carried out In addition, the UK reply highlighted that a sufficient number may not be generated only through pure research. The Belgian respondent suggested that an objective and ideally internationally recognised method for this validation would be ideal.

Question 6: If you think that HTC measurement could be used in legislation, in what time frame? E.g., in the next year, 5 years…

There were two clear opinions in the response to this question. The French respondent said that they expect voluntary certifications to be in use within the next year due to work that they have already carried out, they suggested that use within regulations could begin in the next 5 years depending on the results of the voluntary certification.

Both the UK and Belgian respondents felt that it was unlikely that performance measurement would be in use within the next few years. That could be a question of degree though, as performance measurement is already available as an option through some UK regulation such as the Energy Company Obligation.

5.7.3. Summary and discussion

The initial stakeholder survey showed a good level of interest amongst policymakers in HTC measurement, but with rather demanding requirements for a high level of accuracy, low price and a quick test that are hard to meet with existing HTC measurement methodologies.

In the further detailed survey several items came up repeatedly, the first was an absolute requirement that any measurement method be reproducible, unbiased, and reliable and further that it would be desirable to demonstrate this via a standardised method. This was more important than the absolute accuracy of the measurement, i.e., a smaller confidence interval.

There is value in and demand for a method to validate the accuracy of an HTC measurement method, ideally this would be standardised internationally. There is already some precedent for such a process, for example the EU's Environmental Technology Verification (ETV) (European Commission, 2016). There is a clear practical challenge in this process for HTC measurement, as the possible benchmark HTC values are open to questions about their accuracy in the case of predicted HTC values, or expensive and difficult to apply in the case of existing methods like the coheating test.

The UK Government funded the Smart Meter Enabled Energy Efficiency Ratings (SMETER) project between 2019 and 2021 (BEIS, 2020). In the SMETER project several teams developed a performance measurement method using smart meter data which were then applied by a third-party consortium of universities (including Leeds Beckett University, Loughborough University and University College London) to 30 occupied dwellings. In each of the 30 dwellings a coheating test was also carried out by the consortium of universities, to provide a benchmark value. This process provided a validation of the measurement method developed and could provide a good template and data for the development of a standardised validation method. Carrying out 30 coheating tests is no small undertaking, requiring a large budget and lots of access to buildings. Perhaps the suggestion of the Belgian and French policymakers to validate less invasive tests against each other offers a more practical alternative.

As well as the concern about validation of testing methodologies, the respondents all reported that there needed to be more thought about how HTC measurement could be introduced into a policy area with several existing regulations. For example, should the HTC be a regulated metric itself or should it be included within existing energy models to increase their accuracy in producing metrics that are already regulated, such as energy use or carbon emissions? Further, for a building which has already been built, what is a suitable response to a finding of underperformance? In France, there is a movement towards an initial voluntary certification of measured performance. This seems like a sensible first step towards understanding the practicalities of utilising HTC measurement in policy.

5.7.4. Section Summary

Much has been covered in this section, but in essence a view has been taken on what goes in and what goes out of an HTC analysis. The HTC does indeed have a number of varied use cases that many of the stakeholders appeared to be willing to consider, however that is not to say that this is to be easy. We find that around the energy modelling work, significant blockers are currently in place to stop editing and indeed viewing of the HTC figure, this clearly presents an issue that will need to be resolved before going forward. Of course, the issue of the accuracy and uncertainty clearly needs to be addressed before industry will seize this possible opportunity.

6. Conclusions

This report has two main aims, to examine the inputs and outputs of the analytics which formed the main work of Annex 71. The inputs ranged from smart meters, BIM, weather platforms and on-board data from domestic systems. The current methods of the measuring an HTC on site were also considered and it was noted that this is also a rapidly developing in academic and industry.

Although one of the significant outputs of this Annex was of the course the ability to measure the HTC of a dwelling, it was also important to examine which parties might want this, and how it could also be used for several different purposes, ranging from identification of energy performance gaps, assisting in the accurate certification of dwellings and energy performance guarantees.

A wide-ranging review of the current in situ testing methods that are used for HTC measurement, examining the existing methods and cutting-edge methods, this work was compelling in that it showed that work is accelerating in this area which could grow into an industry.

It was found that there is a significant interest from industry and policy makers to use methods such as the ones that are being developed within this Annex, and some of the current methods reviewed in this document. However, there are some obstacles which are currently making this difficult: There lacks a common approach to the validation of the methods being developed, to provide levels of uncertainty and operating parameters (such as time taken for the test). This is required to allow for a degree of certainty in the methods, especially when we consider that more than one method could be used, and some being more capable with one building type than another. There is also an issue around the ability to ***actually use*** an HTC figure, most of the regulatory energy models around the EU and UK for instance do not allow for the HTC to be directly entered as a measured value. Some states have changed this around the air permeability figure which is now allowed to be manually entered.

Future Work

To address the obstacles that are presented further work is needed. A method of validating the uncertainty and effectiveness of the methods provided in the annexe is required, which may assist in the removal of the second obstacle of the lack of ability to amend regulatory certified values around HTC.

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Annex 1: Results of the stakeholder survey

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A1.1. Description of the survey

Despite regulatory enforcement, monitoring of actual energy performance of buildings reveals a significant gap with theoretically designed targets in many cases. This accentuates the need to develop reliable methods that can be applied on site to assess the actual performance of buildings. The main aim of the international research project '*IEA EBC Annex 71 Building energy performance assessment based on in-situ measurements'* is to (further) develop methods that can be used to characterize and assess the actual energy performance of buildings based on on-site measured data of in-use buildings. Based on on-site measured data (such as smart meter data) and IOT devices and sensors such as connected thermostats, the developed methods would allow characterization of the actual heat transfer coefficient (HTC) of the building. The measured HTC can be used in many ways, such as:

- to evaluate energy use/saving calculations and to prove the actual energy use/savings;
- to assess the quality of workmanship;
- to provide a guarantee of quality to the building owner;
- to provide an innovative certification label;
- for compliance checks in EPBD regulation;
- to quantify the efficiency of costly retrofit operations and
- to replace the calculated design value in energy performance certification, thereby reducing the performance gap.

As one of the goals of the IEA EBC Annex 71 research project is to investigate to what extent the developed methodologies can be used in a quality assessment and guarantee framework, an online survey was launched in January 2019. This survey focused on the measured HTC in buildings and was distributed within the networks of the Annex 71 participant countries in several languages including Dutch, English, French and German. The survey is categorized into four sections. The first section deals with locating the surveyed stakeholders geographically and professionally in order to be able to distinguish the given answers. The second section takes a look at the interests and the opportunities for a method that is able to measure the actual energy performance of a building right after delivery, both for the stakeholders and for their customers. The results of this section should tackle the incentive of developing methods for on-site energy performance characterization and place this in a broader perspective of their interests. The third section tackles the boundary conditions in time, cost, duration, error and results representation, specifically for the on-site determination of the HTC. This will help the researchers in developing methods that answer the needs of the stakeholders. Finally, the last section deals with the concerns and the opportunities that the stakeholders perceive for the application of an on-site determination method.

Between January and December 2019, the survey has been widely disseminated in the participating countries. A total of 243 responses were collected that are complete in all aspects. It takes about 20 minutes to complete the survey. All the responses are translated into English in order to prepare the results for the analysis.

A1.2. Results of the survey

A1.2.1. Country and profession of the stakeholders

A total of 243 stakeholders participated in the survey from the following 14 countries: Austria, Belgium, Denmark, Estonia, France, Germany, Ireland, Italy, Norway, Spain, Sweden, Switzerland, The Netherlands and the UK. As can be seen in Figure 55 almost half of the participants came from Switzerland and almost a fifth from Belgium.

It should be noted that some countries had a small number of responders to this survey. It should therefore be noted that the reader keep this in mind when interpreting these results.

We asked the participants to specify the type of company or organisation they work for and clustered these in the 13 stakeholder categories that are shown in Figure 56. Since stakeholders named their profession themselves, without a given categorisation upfront, there might be some overlap among the stakeholder groups. In particular, making the distinction among the various engineering groups was not always clear. When we look at the distribution of the participants among the categories, we see that the largest group in the survey is the group of consulting engineers in the building industry, although some of the consulting engineers might in fact be better categorised as a building physics engineer or another type of engineer and vice versa. Other large stakeholder groups that participated in the survey are, in order of magnitude, architects, building contractors, energy service companies, certification bodies and researchers. Together, these stakeholders form more than 70% of all participants. Despite some very small groups, the distribution among categories seems reasonable. Most of the stakeholders are involved with residential and non-residential buildings, see Figure 57. The results of the survey therefore cover all building types.

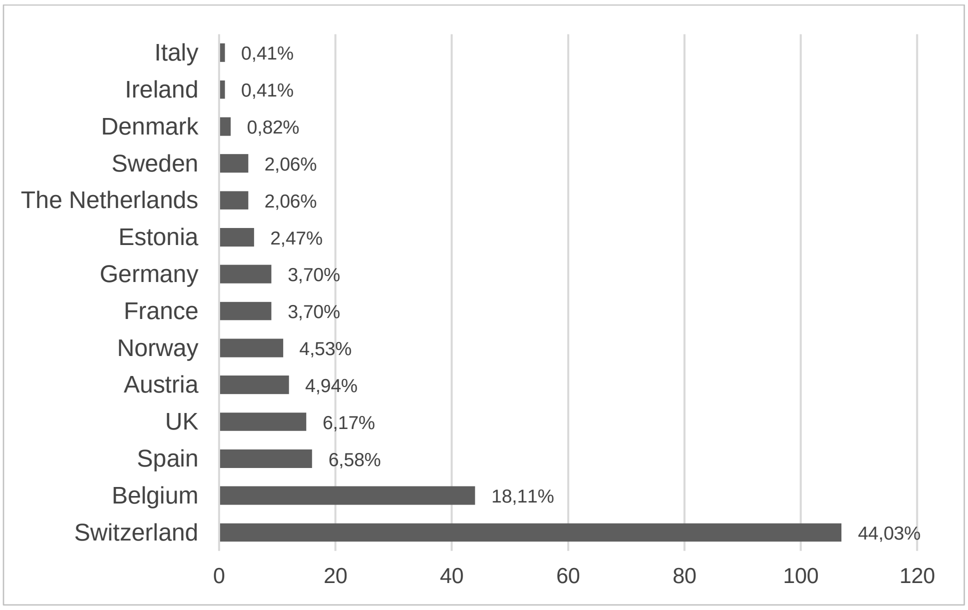


Figure 54. Country of origin of the various stakeholders that participated in the survey.

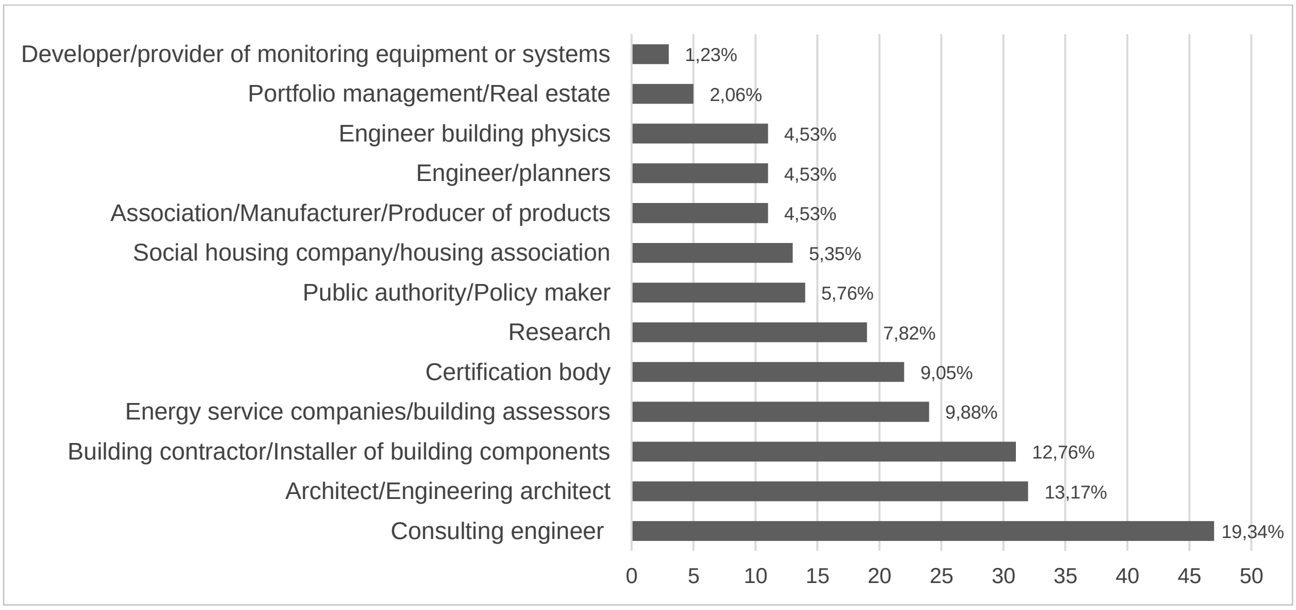


Figure 55. Professions of the various stakeholders that participated in the survey.

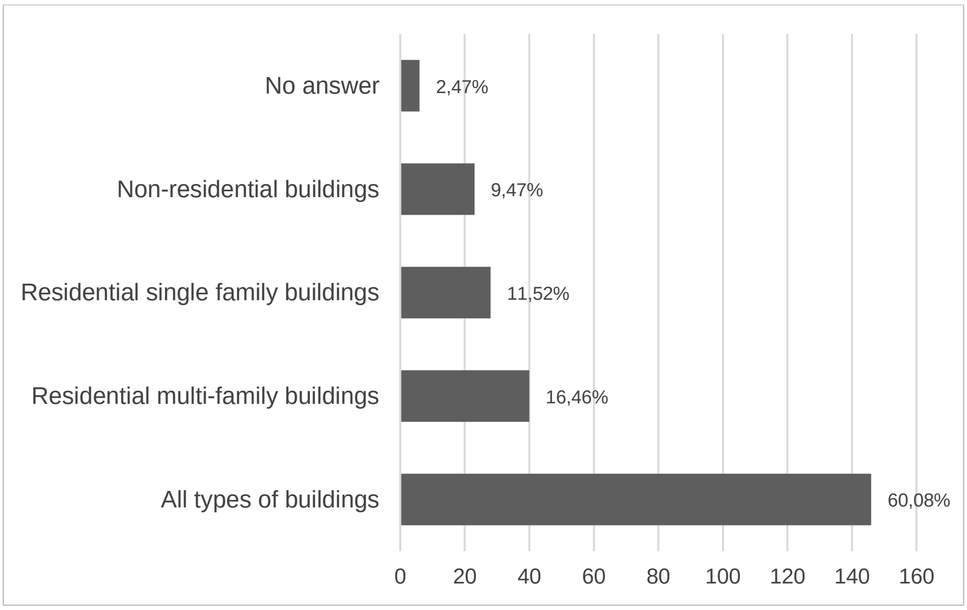


Figure 56. Scope of the building-types operated by the stakeholders.

A1.2.2. Stakeholders interest in measured HTC

A series of questions were asked which were designed to test the level of interest in energy performance measurement amongst the stakeholders interviewed and their customers. Further questions were designed to better understand the products and services which the stakeholders would like to offer using performance measurement.

The results showed a good level of trust in the reliability of existing methods to *calculate* the energy performance of buildings, with over 75% participants supporting this (Figure 58). Despite this level of trust, however, more than 90% of the stakeholders are still interested in a method that can measure the actual energy performance (Figure 59). This indicates that there is a good opportunity to introduce a reliable method based on measurements. The stakeholders also feel that their customers will be interested in such a method with over 80% participants supporting this.

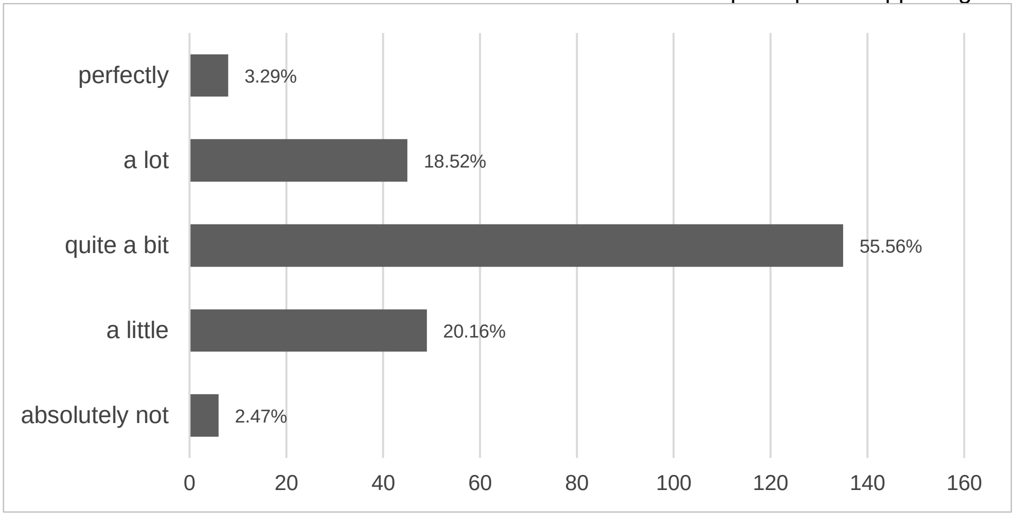


Figure 57. Stakeholder's opinion on reliability of calculated energy performance.

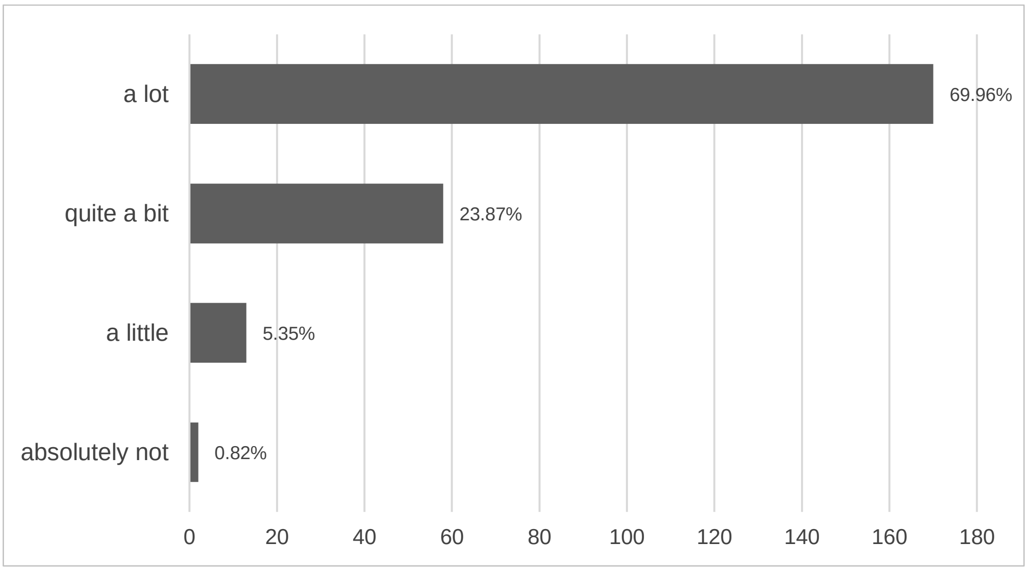
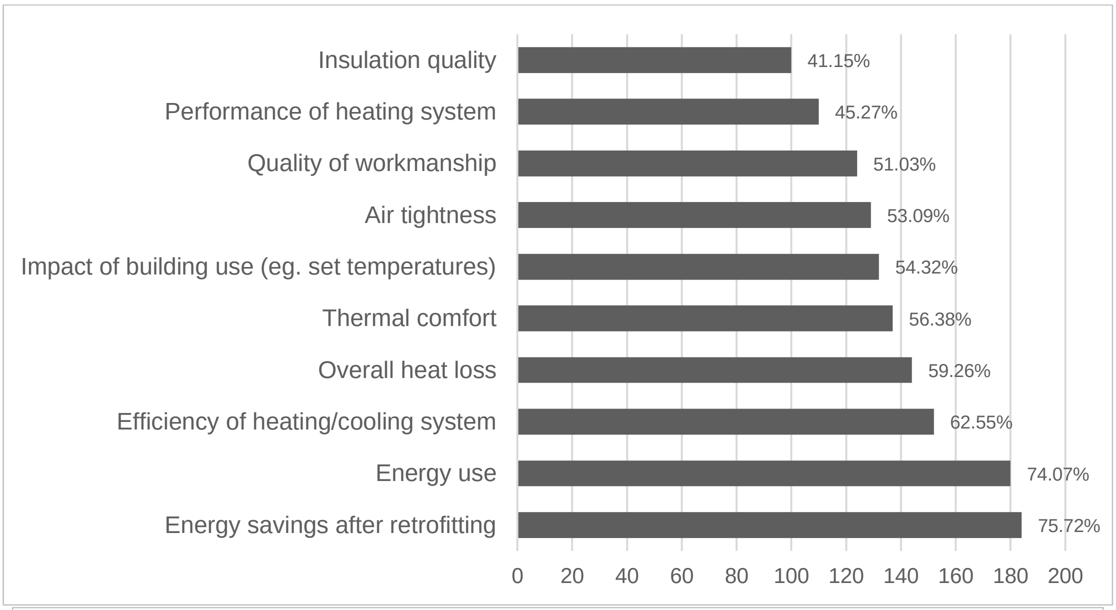


Figure 58. Stakeholder's interest in measured energy performance

The survey continued beyond general interest in energy performance measurement to investigate specific aspects that stakeholders (Figure 60) and their customers (Figure 61) were most interested in. In both cases, we see that energy use and energy savings after retrofitting were the most common responses. This shows the high importance of the final energy consumption in the current and retrofitting stages of a building and stakeholders' concentration on the final use of the measurements, such as an energy certificate rating. The stakeholders feel that from the customers perspective, saving energy is of primary interest since this is directly related to financial savings. These aspects are followed by efficiency of the heating and cooling system and thermal comfort for the stakeholder and the customer respectively. We see that the insulation quality is a less popular choice for both the categories, despite the clear link between insulation quality and HTC. The confidence in existing calculation methods shown in Figure 60 may be significant here, with stakeholders believing that these calculations are sufficient to characterise U values accurately.



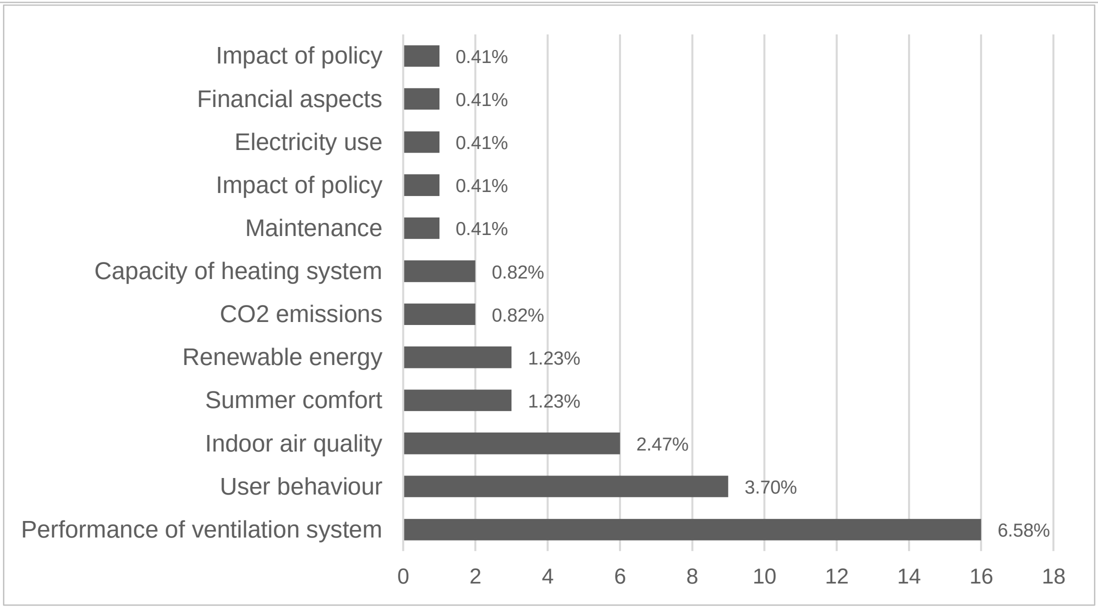
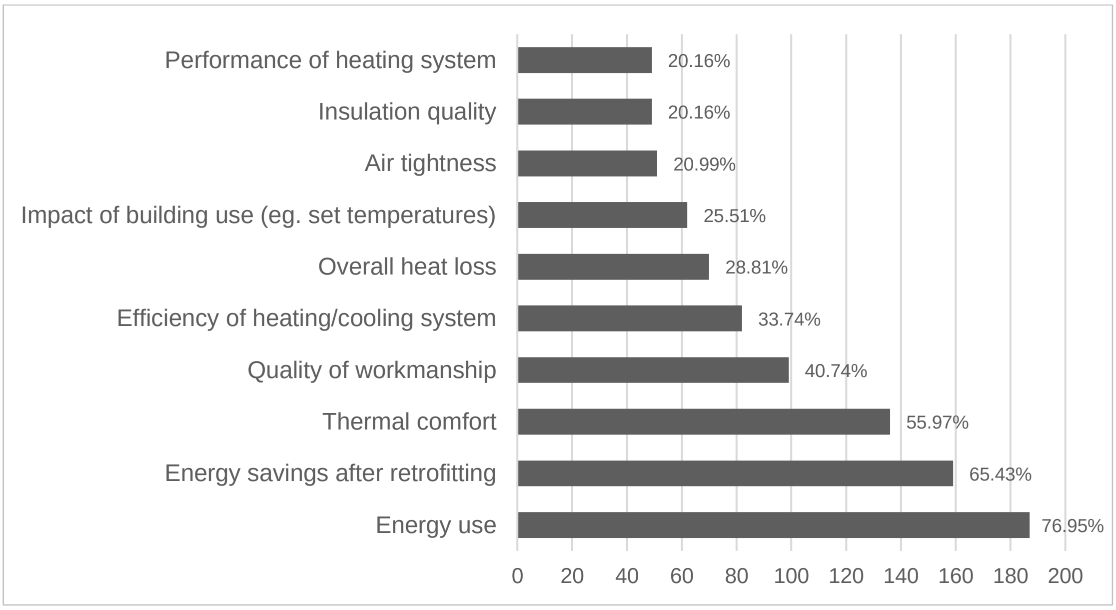


Figure 59. Aspects of energy performance which stakeholders were more interested in. Respondents could pick multiple answers and add some extra.



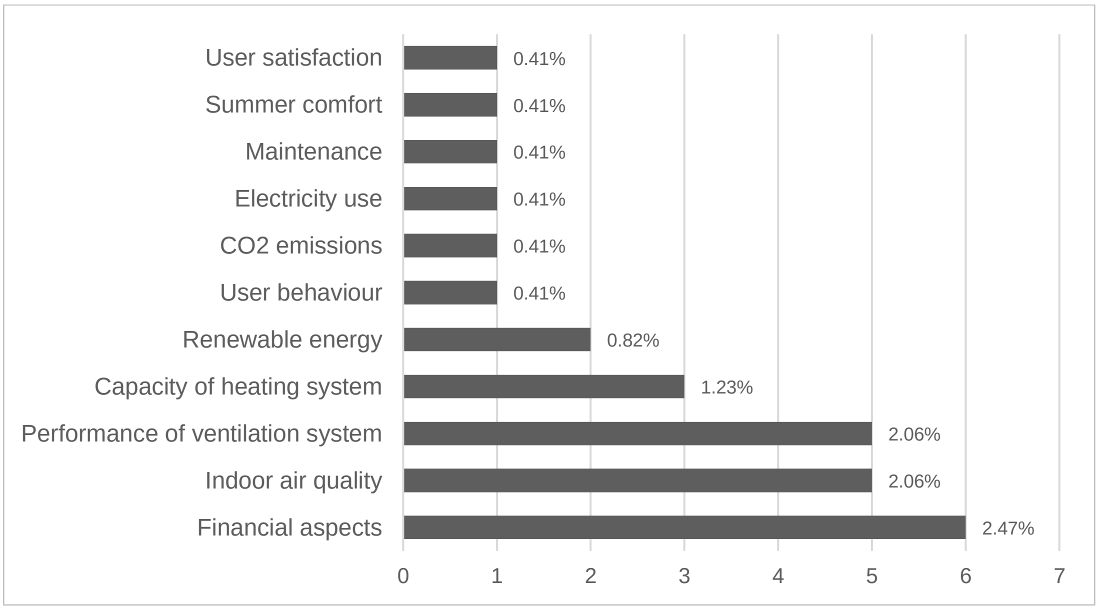


Figure 60. Aspects of energy performance which stakeholders felt their customers would be interested in. Respondents could pick multiple answers and add some extra.

The stakeholders were also asked about the services they could give to their customers based on such on-site measurements (Figure 62), with design and retrofit guidance and quality assurance the most popular responses. These responses seem to demonstrate a desire from the stakeholders to create a feedback loop to improve build quality, both on existing and future projects. Interestingly, there was relatively little interest in using performance measurement for building energy classification (8% of responses) which seems an obvious use for such measurements. Perhaps this reflects that HTC measurement methods are still rather new to the industry, and that there is still progress to be made in understanding how to measure HTC and how to ensure that HTC targets are met before accepting legislative tools for HTCs based on measurement. A free text response given in the survey sums this up well:

“This measure is an indicator. The construction, especially in renovation, is a duty of means (handmade) and not of result. Integrating the coefficient as an "obligation of result" explodes the risks and therefore the costs associated with renovation”.

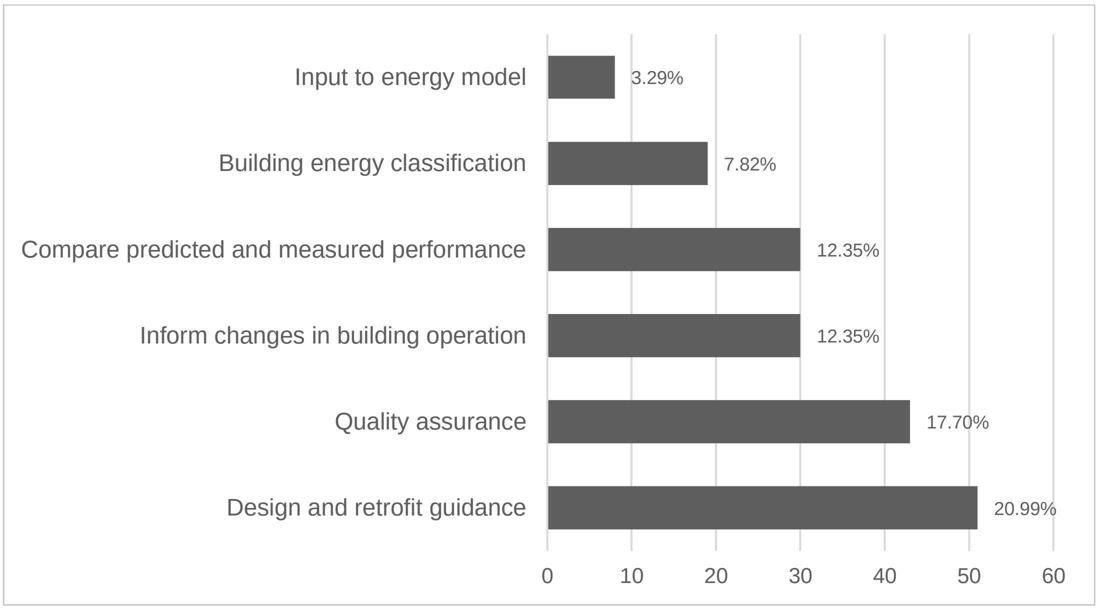


Figure 61. Services which stakeholders would like to provide their customers using energy performance measurement.

A1.2.3. Characteristics of an on-site HTC measurement method

A series of questions was designed to understand the characteristics of a testing method that would be attractive to the respondents: when should a test be carried out, how long could it be, what would be an acceptable cost, what's an acceptable confidence interval? The first question established a clear interest from the stakeholders in using a performance measurement tool, with 87% responding that they would be interested (Figure 63)

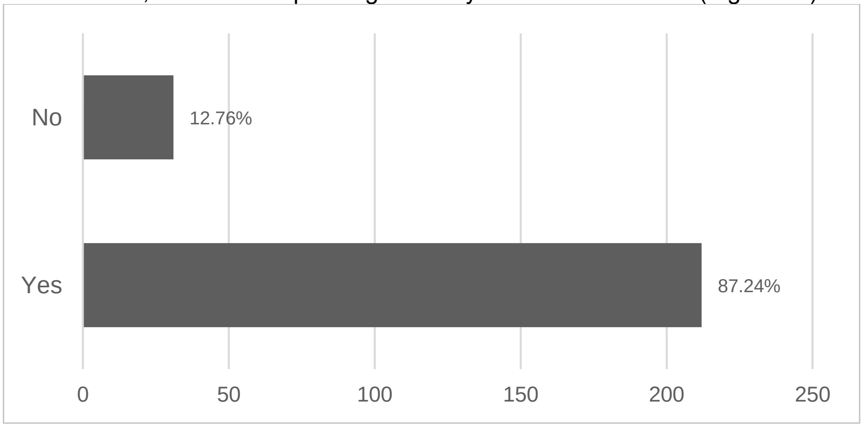


Figure 62. Stakeholders broad interest in using an energy performance measurement test.

An important consideration when considering what sort of performance measurement testing would be acceptable and desirable is when the test could be carried out. This would be important in determining how long the test could be and whether it would be acceptable to require the building to be vacated. There was a wide range of opinions on this matter (Figure 64), with an even split between before delivery of the building and within one year after the delivery.

In addition to the quantitative response to this question a free text response was also allowed to enable stakeholders to explain their choice of when the test should be done. In these free text responses, it was frequently mentioned that the testing should be done before or shortly after delivery in order that defects could be found and remedied while the project was still under warranty and the builder was still closely involved. On the other hand, many respondents were concerned that the measurement could not accurately be undertaken soon after the completion of the build because there could be drying of components at this time which may affect accuracy. Respondents also highlighted that performance measurement could play an important part during building retrofits, and that measurement could be an ongoing process.

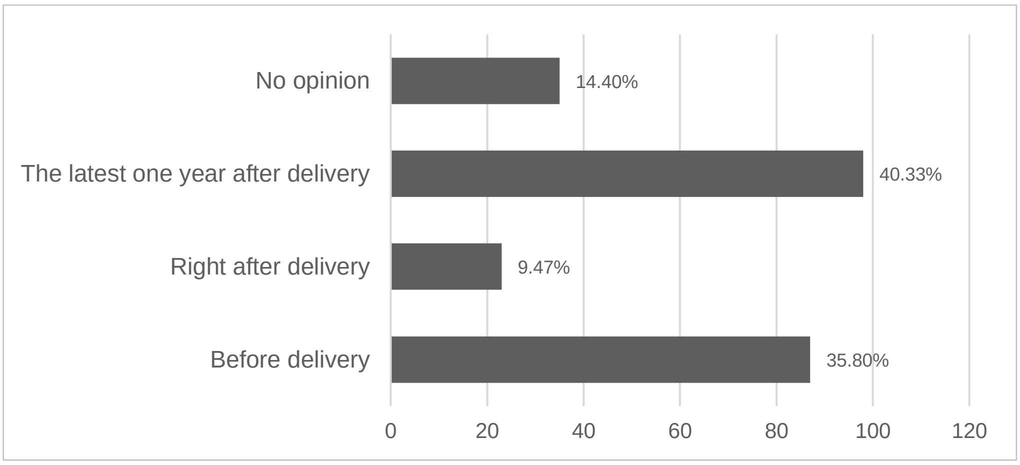


Figure 63. Stakeholder's opinion of when testing should be carried out.

The majority of respondents felt that an acceptable cost for a performance measurement would be either 100-500 EUR or 500-2000 EUR (Figure 65) these were the second and third lowest cost brackets in the survey. 100-500 EUR is in line with the current cost of an airtightness measurement, by far the most common performance measurement method currently in use. The range of responses, with 30% indicating that a cost of over 500 EUR would be acceptable, show that many stakeholders would find a cost slightly higher than that of an airtightness measurement to be acceptable. By comparison, the cost of a coheating test is typically greater than 2000 EUR and would therefore be unacceptable to most stakeholders.

In the free text response, many stakeholders highlighted that the cost of the measurement should be in relation to either to cost of the investment or the cost of the likely energy savings (either for a retrofit or be ensuring there was no performance gap), for example:

"The cost of the assessment must be reasonable in relation to the investment", and *"Costs must be low or in line with the optimisation potential"*.

Many also highlighted that the acceptable cost is very dependent upon the size and complexity of the building, in line with the similar comment above that the cost of measurement should be in line with the cost of investment. Several respondents felt a cost per m^2 would be more suitable, with two providing examples of acceptable costs of 1-3 EUR/m^2 and 3-5 EUR/m^2.

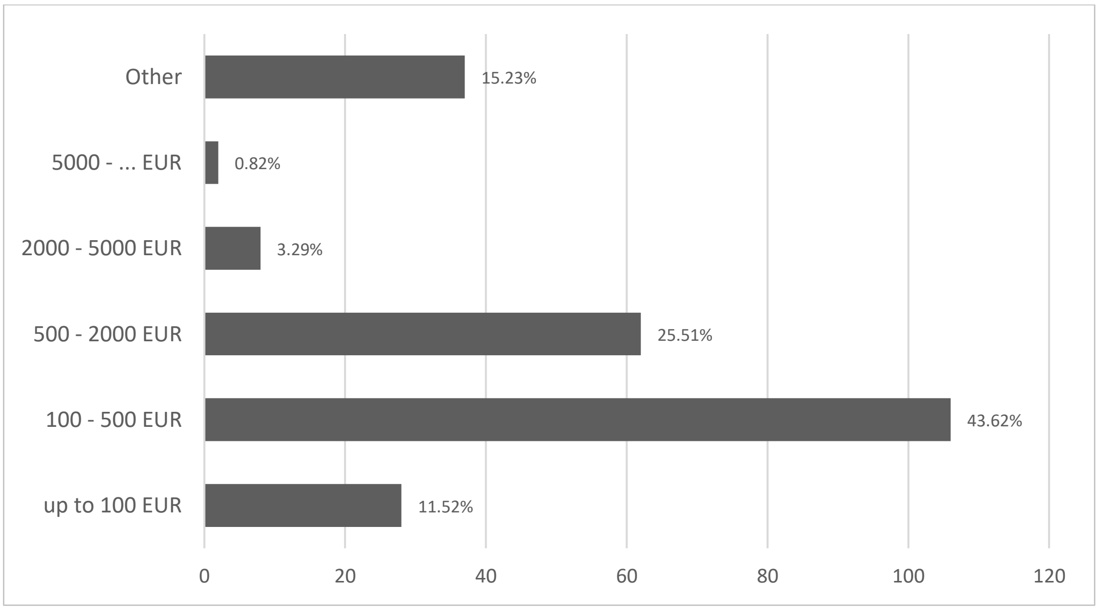


Figure 64. Reponses on what cost is acceptable for a performance measurement.

In terms of the acceptable duration of a test, the majority felt that it must be a few days long at the most (Figure 66). By looking at the free text responses we can see that the justification for requiring a relatively quick test was based upon cost and practicality:

"A matter of cost. If tests last over several days / weeks, the cost may not add up.",

"difficult to fit with the planning of the rest if more than 2 or 3 days (ideally 1 day)", and,

"difficult to occupy the property that is already waiting for delivery".

Several respondents highlighted though that they did not believe an accurate result could be generated in a test of only a few days, while several others highlighted that if the test was not invasive then the length of the test wasn't significant:

"Given that the tests are no-invasive, I don't see a reason why the duration matters."

"With minimally invasive measurement parallel to use, measurement over a complete heating period is possible. If the use is impaired, a weekend would still be feasible in many cases, but not more."

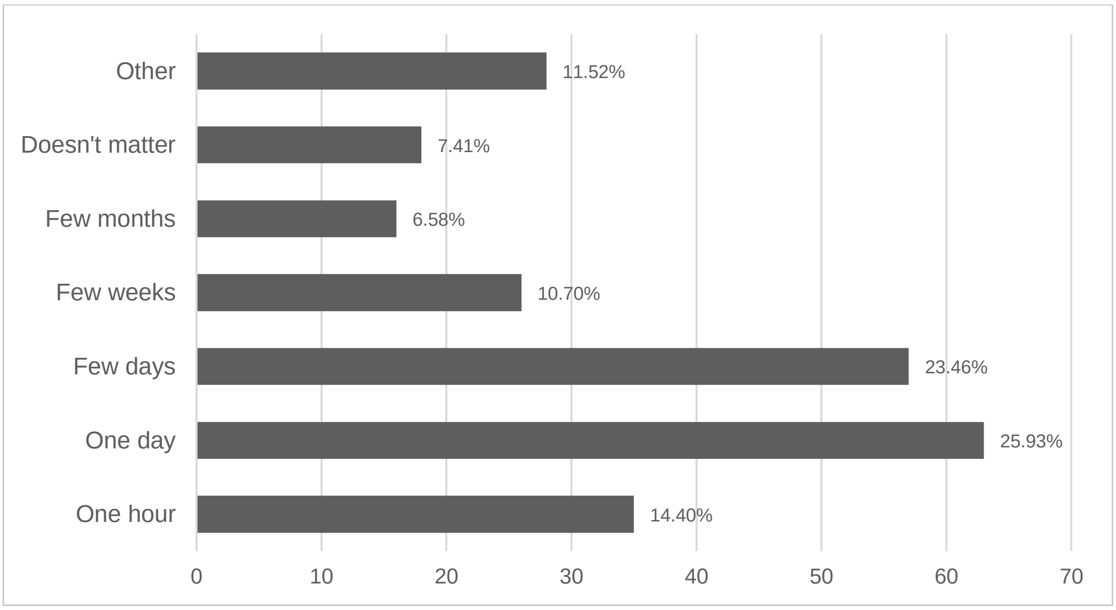


Figure 65. Responses on the acceptable duration for a performance measurement.

More than three quarters of the respondents felt that the uncertainty in the HTC measurement should be less than 10% (Figure 67), this is a very challenging target given the uncertainty of similar tests. For example, in ISO9869 the uncertainty of a U value measurement by heat flux plates is given as between 14 and 28%.

In the free text responses, there was a clear and repeated statement that measurements of less than 10% accuracy would not be useful, with many stating that current estimates are at least this accurate. Some examples are given below, but there were many responses like this:

"because with higher % one can also assume the theoretical calculation / and practical execution that has a larger deviation" (quantitative response, less than 5%)

"If the error margins become very large, it will be of little use to use measured data rather than calculated values that already exist." (quantitative response, less than 5%).

Also, in the free test response stakeholders linked the accuracy to the service they intended to offer using the measurement:

"I appreciate the test cannot be extremely accurate, but the retrofit measures we install may only improve the thermal performance by 25% or so and it's important that we can detect this level of improvement."

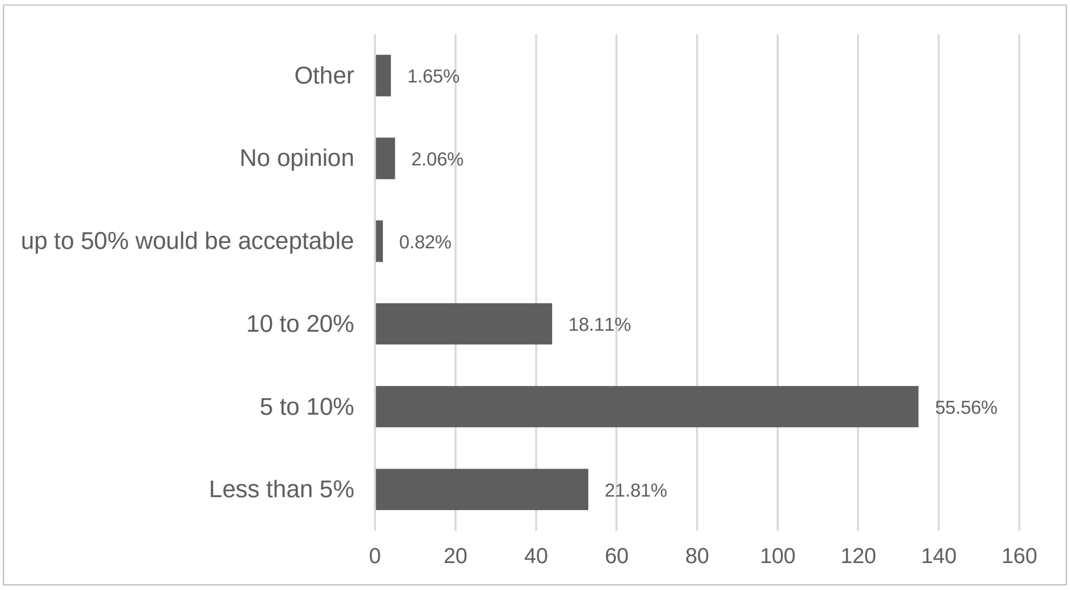


Figure 66. Responses on the acceptable confidence interval of a performance measurement.

It's obvious that people would want a quicker, more accurate and less expensive measurement in general and that trend is apparent in the responses of the stakeholders. For all but the expectation of the accuracy of the measurement, however, there seems to be a realistic expectation. The expected accuracy of the majority of the respondents of at least 10% appears particularly challenging by comparison with existing measurement methods.

A1.2.4. Representation of results

This section of the survey deals with the representation of the results of the on-site HTC determination. It demonstrates that the opinions of the stakeholders are quite scattered on these questions and no clear conclusions can be taken. The representation of the results seems to be highly dependent on the purpose and personal interests of the stakeholders.

Figure 68 shows the stakeholders opinion on the presentation of the HTC resulting from measurements. Of the listed answers, the absolute value is slightly preferred over a colour scale or relative value to predicted value. 24 respondents provided an additional answer. Some examples of these are:

- *Benchmark with limit values for similar buildings in similar climates;*
- *Real value taking into account the gaps related to inaccuracy;*
- *Direct comparison to the calculated value, indicating the uncertainties of both values (error bar);*
- *Relative to similar buildings or legal limits;*
- *Needs careful consideration as HTC is not normalised by property size. May need some comparison to equivalent property sizes from a database approach or simply normalise the value and then represent in a colour scale (like an EPC).*

As shown in Figure 68 the majority of the respondents are in favour of a comparison of the HTC resulting from measurements to a range of minimal and maximal reference values, or to an average reference value, or to the calculated theoretical value. However, their opinion on the kind of reference value varies a lot, as seen in Figure 69. 74 respondents provided an additional answer. Some examples of these are:

- *By occupant satisfaction;*
- *By typology;*
- *By building size;*

- *By occupation;*
- *By location and climate conditions;*
- *By legal requirements.*

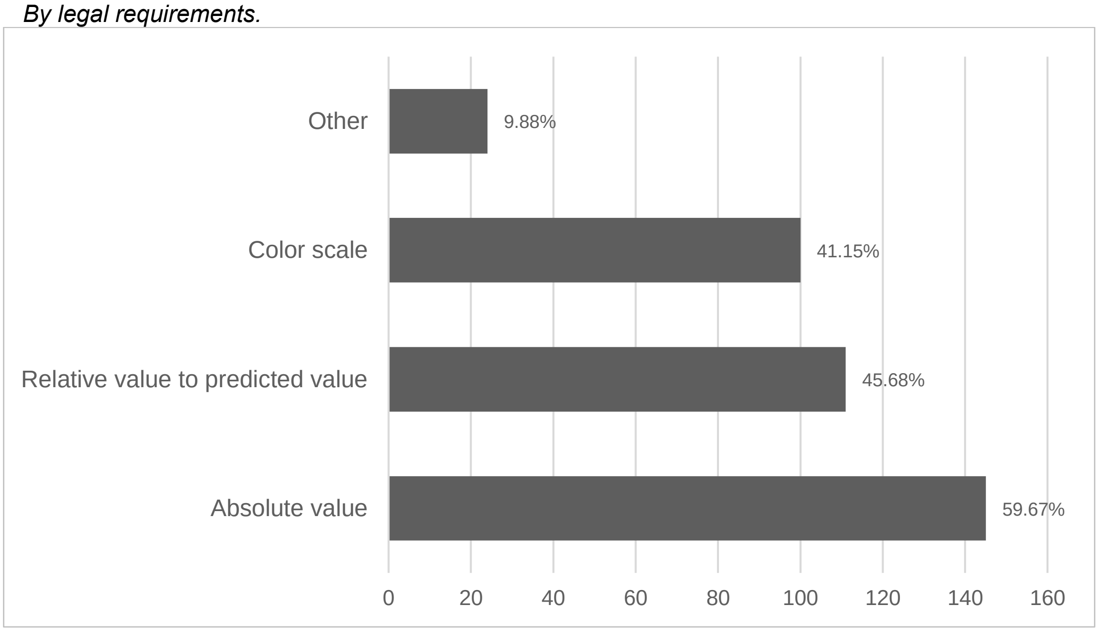


Figure 67. Stakeholder's opinion on presentation of the HTC resulting from measurements. Multiple answers were possible.

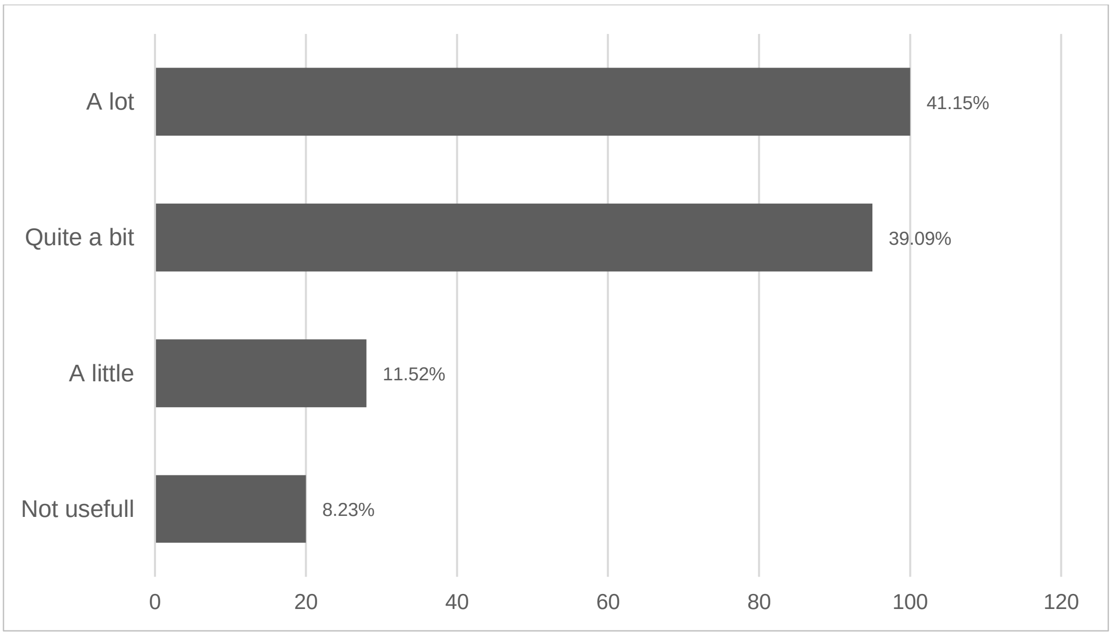


Figure 68. Stakeholder's opinion on usefulness of comparison of the HTC resulting from measurements to a range of minimal and maximal reference values or to an average reference value or to the calculated theoretical value.

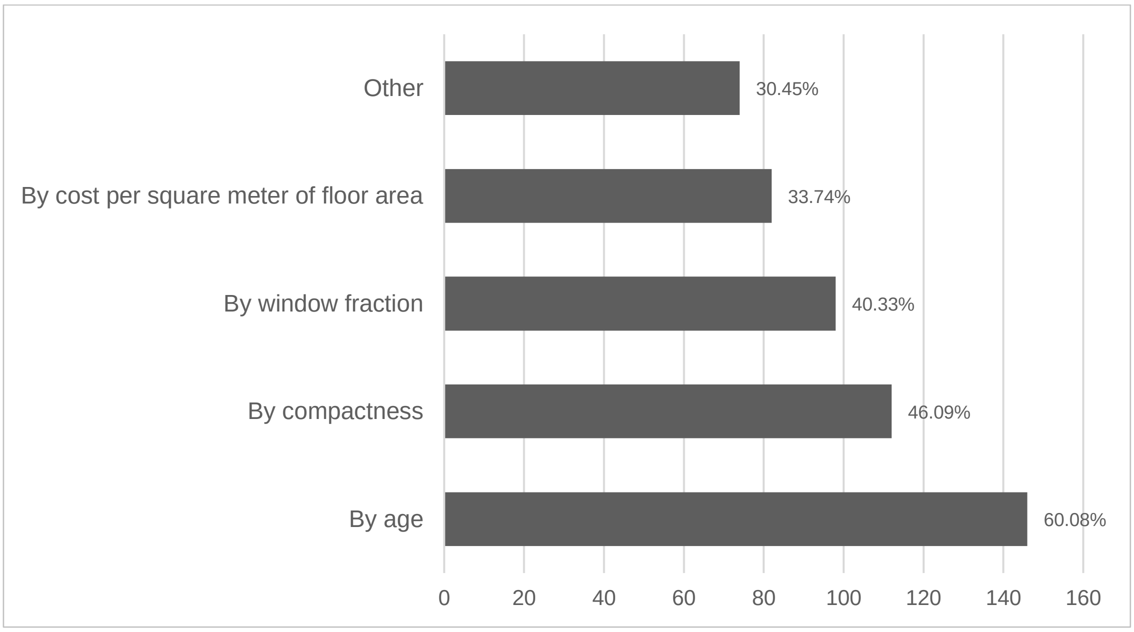


Figure 69. Stakeholder's opinion on the kind of reference values that should be used. Multiple answers were possible.

A1.2.5. Concerns and opportunities

The last two questions of the survey were open-ended: "Do you see any complications that could pop up when going to on site assessment of the HTC?" and "Do you have other suggestions for the application of these methods for your type of company?". Each stakeholder was free to give as many answers as they wanted; 120 answers were given to the first question and 47 to the second.

As each stakeholder was free to choose their wording, the first task was to understand each answer and reformulate it in order to see when two stakeholders used different words to express the same concept. In some cases, this task is easy, as some words do not have many synonyms (e.g., weather) or they are easy to spot (e.g., occupants / user / inhabitants or test duration / time / length). But in some cases, this requires more work of interpretation, and the analysis of the answers gains some uncertainty as it becomes dependant on the analyst. For instance, for the first question, it has been decided by this analyst that "Yes, warranty discussions Tolerances" (sic), "In case of deviations between measured value and calculation, there are discussions", "Yes, the interpretation playroom" or "What do we do if the performance is not there?" were four different ways for the stakeholders to illustrate their concern regarding the interpretation of results not reaching the expected values, leading to complications and an unknown situation. Therefore, they were all counted in the same category called "consequences of bad results". Maybe because of this, this category was the one counting the most answers, all expressed differently. All categories and the number of answers they received are presented in Figure 71.

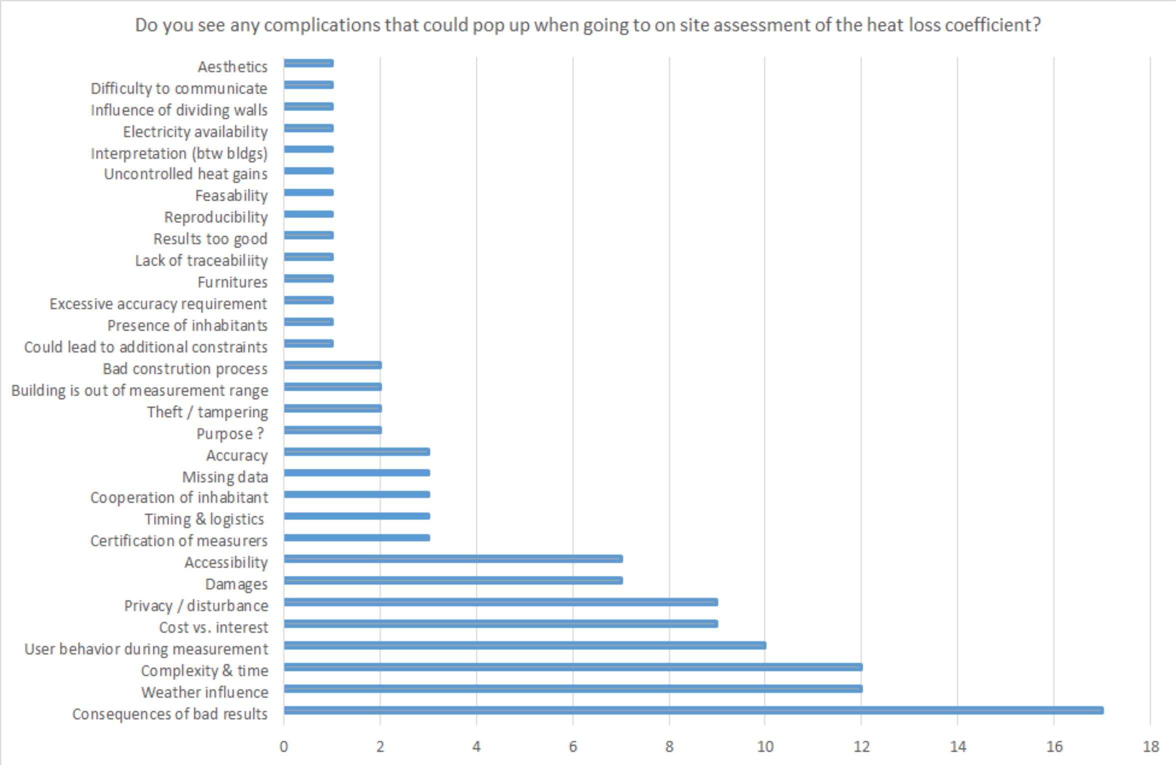


Figure 70. Stakeholder's opinions on the possible complications of the measurements. Multiple answers were possible.

The main takeaway from these results is that the stakeholders have a lot of possible complications in mind. According to this analysis, there are 31 different sources of problems. And while this number could probably be reduced by regrouping some categories, it will stay high as many issues are clear and quite different, from scientific issues (influence of weather, heat gains or inhabitants) or practical ones (accessibility, duration, cost, damages to the building...) to logistical (timing, theft, electricity availability...) or related to the results analysis (missing data, consequences of bad results, bias towards excessively good results, analysis of thermal bridges...).

While most of these answers seem very relevant, only 8 are repeated more than 3 times, and therefore probably represent the problems for which the most communication should be made in order for such measurements to be accepted: the consequences of bad results, the influence of weather and user behaviour, complexity, time & cost of the tests, and the problems more related to the inhabitants: privacy, accessibility and damages to the building.

The analysis of the answers of the second question concerning suggestions is more complicated. First, there were less answers (47), and were more dispersed. Besides, answers having more recurrence might not be more interesting, as they can represent concepts that are already well-known. Furthermore, the differences between concepts are less clear that for the first question, which leads to more "porous" categories, and more difficulty to combine answers (is "before and after renovation" the same as "input for renovation"? Are "Certification", "in legislation instead of calculation", "acceptable in court", "as quality assurance" and "Comparison with energy certificate" similar or different categories?). Finally, answers of different stakeholders are obviously not coordinated and can seem contradictory. For instance, calculation tools are mentioned several times by different persons: one says that an on-site measurement could help develop a numerical tool, another that it could help validate it, a third that it could complement it, and a fourth that it could replace it. While these uses are not fully mutually exclusive, they do not lead to a clear conclusion...

Despite these drawbacks, it seems that a trend emerges: additional services could be rendered using the HTC measurement setup: For example, it could be used for assessing the building envelope's performance while detecting the biggest energy consumers. It could also be used to optimize operations (e.g., heating curve) and to build a database of measured values for a group of buildings.

Because no answer has been proposed more than 4 times, it doesn't seem that the number of occurrences is important in the result analysis. Therefore, the full answers are presented as a sorted list rather than as a histogram (Table 11).

Table 11. Answers to the question regarding suggestions for the application of in situ measurement methods. Multiple answers were possible

Individual components, e.g. facades only	**Quality control as a service**
	As a combination with calculation tool
Envelope official quality control	As a service like acoustics
When assessing buildings	Complex buildings
Certification (e.g. Minergie)	Acceptance as a consultancy service
Acceptable in court	modelling based determination for design/consulting companies
In legislation instead of calculation	
As quality assurance	**Quality control for indirect use**
Comparison with energy certificate	Preventive maintenance
	For energy performance contracting
Quality control for renovation	Continuous evaluation of HLC (via management system)
Input for renovation	
Measurement before renovation	**Other uses of the measured indicators**
Before / after renovation	Optimization of operation (e.g. heating curve)
	Building Database
Scientific uses	Impact on energy flexibility index
For building science	To monitor the use of public subsidies
Study ageing of components, systems, solutions…	Demonstrate inefficiency of expensive specs
Analysis of the energetic effect of damages	Follow the biggest energy consumers
Develop a correct calculation tool	Generalized measurement per use & per important factors
Health	

A1.2.6. Selected stakeholders

To compliment the aggregated view on the results with individual, stakeholder-specific responses, eight individual stakeholders of the most represented stakeholder groups were selected. Their responses are analysed in order to have a deeper view of their personal opinions. The selected stakeholders are (Table 12 & Table 13):

- a consulting engineer;
- an architect/engineering architect;
- a building contractor/installer of building components;
- an energy service company/building assessor;
- a certification body;
- a researcher;
- a public authority/policy maker;
- a social housing company/housing association.

For ease of interpretation, the questions of the survey in Table 12 & Table 13 also refer to the figures in this report. These eight stakeholders were selected because of their overall interesting inputs and point of view, this does not, however, mean that they are an average stakeholder in their group. Due to the limited number of participants in each stakeholder group and the fact that the answers in each group are still quite scattered, a stakeholder with an average opinion in its group would not necessarily be the most interesting stakeholder to look into their individual answers. The average answers per stakeholder group will be elaborated in more detail in section A1.3.2. Therefore, in this section we focus more on those stakeholders with clear and comprehensive explanations of their answers. It can be seen that their views on on-site determination of HTC differ because of their experiences in design and execution.

Of these eight individuals, the consulting engineer has a lot of trust in the reliability of calculated energy performances but might be interested in measurements to even improve these models for future projects. Therefore, they prefer a high-quality assessment which might take some time.

The architect/engineering architect is in favour of HTC determination because they rely less on calculated performances, and this could contribute to a quality control before delivery. It also might be useful to show improvement potential of the building. However, the test should be limited in effort and should have a high accuracy. Therefore, they prefer a measurement on an unoccupied building.

The building contractor/installer of building components wants to prove the quality of their work in comparison with their competitors. The quality assurance would be a differentiator from their competitors. Moreover, this could be a tool for controlling the performance of the sub-contractors and different product options. Because of that, the measurements should be done before delivery and should also be limited in costs for being able to be competitive.

The energy service company/building assessor finds the on-site determination crucial for evaluation of buildings and quality of works. The measurements could run over a longer period when there is low nuisance for the building users. The accuracy should be rather high otherwise an expert appraisal can be used instead. For them, not only the overall HTC would be of interest, but also the heat loss through components.

The certification body indicates that the on-site HTC determination is a useful indicator to analyse which aspects can be improved in design, material selection and workmanship. However, it will only be useful in combination with the identification of most influencing parameters for this HTC.

The researcher relies only a little on calculated energy performances. Therefore, they are very interested in HTC determination, preferably during regular operation of the building. In their opinion, this should be done before delivery of the building. They compare this with delivery tests on products such as cars and electronics.

Although the public authority/policy maker relies a lot on calculated energy performances, they are still in favour of on-site measurements. When these can replace theoretical calculations, this will result in administrative simplification. Therefore, the determination should be done before delivery to allow interventions by the contractor. The reliability of the determination should be sufficient, a precise measurement protocol should be set up and there should be certification of the practitioners.

The main interest of the social housing company/housing association in this methodology is quality assurance of the workmanship. Therefore, the determination should be done before delivery. The cost must be in the same order of magnitude as an airtightness measurement. The duration must be limited in time when carried out in occupied houses.

Quality and quality control is a repeated theme amongst these eight respondents, and also scored highly across the survey. This seems to reflect an awareness of the performance gap and a commercial interest in ensuring in-situ performance as well as satisfying legislated as-designed thermal performance limits.

Table 12. Eight selected individual stakeholders based on their interesting individual answers – part 1

Stakeholder group	**Consulting engineer**	**Architect/Engineering architect**	**Building contractor/Installer of building components**	**Energy service companies/building assessors**
Country (Figure 55)	Switzerland	Switzerland	UK	Germany

Building types (Figure 56)	All types of buildings	All types of buildings	Residential single-family buildings	All types of buildings
Reliability of calculated energy performances (Figure 57)	A lot	A little	A little	A little
Interest in methodology (Figure 58)	Quite a bit	Quite a bit	A lot	A lot
Aspects of this energy performance (Figure 59)	Air tightness; Efficiency of heating/cooling system; Energy savings after retrofitting; Energy use; Impact of building use (eg. set temperatures); Overall heat loss; Quality of workmanship; Thermal comfort.	Energy savings after retrofitting; Energy use; Overall heat loss; Performance of heating system; Thermal comfort.	Air tightness; Efficiency of heating/cooling system; Energy savings after retrofitting; Energy use; Impact of building use (eg. set temperatures); Insulation quality; Overall heat loss; Quality of workmanship.	Efficiency of heating/cooling system; energy savings after retrofitting; energy use; Impact of building use (eg. set temperatures); Insulation quality; Overall heat loss; Quality of workmanship; Thermal comfort.
Aspects of this energy performance for customers (Figure 60)	Efficiency of heating/cooling system; Energy savings after retrofitting; Energy use; Thermal comfort.	Energy savings after retrofitting; Energy use; Thermal comfort.	Energy savings after retrofitting; Energy use; Insulation quality; Quality of workmanship.	Efficiency of heating/cooling system; energy savings after retrofitting; energy use; impact of building use (eg. set temperatures); insulation quality; Quality of workmanship; Thermal comfort.
Services to customers (Figure 61)	Inform changes in building operation; Input to energy model.	Quality assurance	Quality assurance	Retrofit assessment; Design and retrofit guidance; Inform changes in building operation.
Interest in determination of HTC (Figure 62)	Yes	Yes	Yes	Yes
Interest in determination of HTC - Why?	Quality control and knowledge enhancement for other projects.	Quality control on the one hand and to show improvement potential on the other.	We're aware of the performance gap and want to make sure we deliver the best job possible. The quality assurance would be a differentiator from our competitors, we would also like to be able to analyse the performance of our sub-contractors (i.e. workmanship) and different product options.	Crucial for evaluation of buildings and quality of workmanship.
Acceptable time (64)	The latest one year after delivery	Before delivery	Before delivery	The latest one year after delivery
Acceptable time - Why?	Only then does the operation become visible.	The human factor leads to inaccurate measurements.	Really important to have a comparison before and after a retrofit.	A provision would be advantageous before handover, but also during use. Particularly in the case of renovation measures, measurement is only possible with parallel use.
Acceptable cost (EUR) (65)	2000 - 5000	500 – 2000	100 - 500	2000 - 5000

Acceptable cost - Why?	Depending on the size of the building, very different costs can be implemented.	The costs must be dependent on the volume, on the capital employed.	Price is extremely important to winning work and our clients do not yet ask for performance measurement, so this would be an additional cost compared to our competitors. The acceptable price would be different if the measurements were for a sample of dwellings or all dwellings.	Depends strongly on building type and size. Costs of 5 to 10 EUR/sqm (typically well below annual heating energy costs before renovation) should be achievable.
Acceptable duration (Figure 66)	Few months	One day	Few months	Depends strongly on the type of execution
Acceptable duration - Why?	Only then qualified statements possible.	It can also be longer. The question is rather how limited such a test would be. If no large restrictions were to be expected, then the test could last also 5 years.	Time of measurement is not so important if the measurement is not invasive. Our projects are carried out on 10s or 100s of dwellings over an extended period (months or years), so we have lots of time on-site to facilitate measurements.	With minimally invasive measurement parallel to use, measurement over a complete heating period is possible. If the use is impaired, a weekend would still be feasible in many cases, but not more.
Acceptable error (Figure 67)	10 to 20%	Less than 5%	10 to 20%	5 to 10%
Acceptable error - Why?	10 to 20% accuracy is already difficult with a dynamic system.	A survey only makes sense if it is also accurate.	I appreciate the test cannot be extremely accurate, but the retrofit measures we install may only improve the thermal performance by 25% or so and it's important that we can detect this level of improvement.	Up to 10% error should still be acceptable, better significantly less. In the case of larger errors, one is hardly better than an expert appraisal without measurement.
Presentation of measured HTC (Figure 68)	Colour scale; relative value to predicted value	Colour scale	Relative value to predicted value	Absolute value
Comparison for measured HTC? (Figure 68)	A lot	Not useful	A lot	A little
Reference values (Figure 69)	By age; By compactness; By window fraction	Reference values lead to inaccuracies, even in interpretation	By cost per square meter of floor area	Presumably, reference buildings must be defined here which contain all the criteria mentioned. In my view, this is a separate research topic.
Complications (Figure 70)		Yes, there may be disputes between the customer and the executor.	Difficulties with access. Often no access to WiFi if required for sensors. Heat input may be low in social housing.	
Suggestions (Table 11)		It will show very good inputs for improvement and optimization possibilities.	As well as retrofit we also provide maintenance contracts for local authorities and housing providers, we would like to include this in our asset management products so that we can give better recommendations for retrofit measures and possibly contribute to preventative maintenance.	We see a need to estimate the heat transfer coefficient also for individual components such as roofs, basement ceilings, areas of the external facade.

Table 13. Eight selected individual stakeholders based on their interesting individual answers – part 2

Stakeholder group	Certification body	Research	Public authority/Policy maker	Social housing company/housing association
Country (Figure 55)	Spain	Switzerland	Belgium	France
Building types (Figure 57)	Residential single family buildings	Residential single family buildings	All types of buildings	Residential multi-family buildings
Reliability of calculated energy performances (Figure 58)	Quite a bit	A little	A lot	Quite a bit
Interest in methodology (Figure 59)	A lot	A lot	A lot	A lot
Aspects of this energy performance (Figure 60)	Air tightness, Efficiency of heating/cooling system, Energy savings after retrofitting, Energy use, Impact of building use (eg. set temperatures), Insulation quality, Overall heat loss, Performance of heating system, Quality of workmanship, Thermal comfort	Air tightness; Efficiency of heating/cooling system; Energy use; Overall heat loss; Performance of heating system; Thermal comfort	Air tightness; Efficiency of heating/cooling system; Energy use; Overall heat loss; Quality of workmanship	Air tightness; Efficiency of heating/cooling system; Energy use; Impact of building use (eg. set temperatures); Quality of workmanship; Thermal comfort
Aspects of this energy performance for customers (Figure 61)	Air tightness, Efficiency of heating/cooling system, Energy savings after retrofitting, Energy use, Impact of building use (eg. set temperatures), Insulation quality, Overall heat loss, Performance of heating system, Quality of workmanship, Thermal comfort	Energy use; Thermal comfort	Air tightness; Efficiency of heating/cooling system; Energy use; Overall heat loss; Thermal comfort	Energy savings after retrofitting; Impact of building use (eg. set temperatures)
Services to customers (Figure 62)	Design and retrofit guidance		Building energy classification	Quality assurance
Interest in determination of HTC (Figure 63)	Yes	Yes	Yes	Yes
Interest in determination of HTC - Why?	It is a very useful indicator to analyse which aspects to improve both in the design of buildings as in the selection of materials and workmanship. This tool will be useful if it is able to identify which parameters are most influencing the final value of the data. Knowing only the final value of the data can be a limited and unusable information.		Administrative simplification if on-the-spot measure can replace theoretical calculation	This coefficient makes it possible to check the quality of implementation of the work.
Acceptable time (Figure 64)	The latest one year after delivery	The latest one year after delivery	Before delivery	Before delivery
Acceptable time - Why?	Because the use of building occupants, in terms of the use of thermal installations, as the operable elements of	The determination should be done during regular	Allow further intervention by the contractor if a	

	the thermal envelope is fundamental.	operation of the building	problem is detected.	
Acceptable cost (EUR) (Figure 65)	Variable	This cost should be included in the delivery of the building.	100 - 500 EUR	500 - 2000 EUR
Acceptable cost - Why?	Because the use of building occupants, in terms of the use of thermal installations, as the operable elements of the thermal envelope is fundamental.	Most products (cars, consumer electronics, etc) are tested before delivery to the customers. Why should buildings be any different?	Magnitude of reasonable price in my opinion	Must be of the same order of magnitude as the airtightness measurement.
Acceptable duration (Figure 66)	No opinion	Doesn't matter	One day	One day
Acceptable duration - Why?	We do not have information to analyze this data. It will depend on whether it is a single measurement in situ, or if it includes computer modeling	Given that the tests are no-invasive, I don't see a reason why the duration matters.	Estimated duration in relation to the cost estimate (previous question).	As the work is carried out on an occupied site, the dwellings can only be emptied for a very short time. 1 day is really a maximum.
Acceptable error (Figure 67)	No opinion	5 to 10%	5 to 10%	10 to 20%
Acceptable error - Why?		Less than 5% seems fairly ambitious for the construction sector. 50% error margin can be achieved with calculations only.	If greater confidence interval, what would be the reliability of the measurement?	The objective is to obtain a reliable indicator but to facilitate implementation. Accuracy should not be sought at all costs if the measurement can never be achieved in practice.
Presentation of measured HTC (Figure 68)	Color scale, Absolute value, Relative value to predicted value	Absolute value, Relative value to predicted value, Benchmark with limit values of the codes and similar buildings in similar climates.	Absolute value	Relative value to predicted value
Comparison for measured HTC? (Figure 69)	A lot	A lot	A lot	A lot
Reference values (Figure 70)	By age, By compactness, By cost per square meter of floor area, By window fraction	By age, By compactness, By cost per square meter of floor area, By window fraction, occupant satisfaction	By age, By compactness, By window fraction	By compactness, By window fraction
Complications (Figure 71)	We do not have information to evaluate this section, since we do not know how the measurement of this data was made: visual inspection and measurement of dimensions, tests, monitoring, ...?	Privacy issues.	Need to set up a precise measurement protocol, as well as a certification of the measurers.	Generalization performance guarantees.
Suggestions (Table 11)		Since one is already investigating, an occupant survey could be done as well.	Integration in legislation (alternative to theoretical calculation).	

A1.3. Analysis and discussion of the results

This chapter takes a deeper look into the results of the survey and discusses the outcomes both from the country-wise and the stakeholder-wise perspectives. The country-wise analysis will inform us about any geographical bias in the responses. It will also help to capture any similarities between countries about their HTC information and inclination. Such understanding will help to formulate rules for further dissemination of the HTC measurement process. On the other hand, the stakeholder-wise analysis is done to derive practical information mainly focusing on their responses regarding the time of the measurement, setup cost, duration and acceptable error. First, we look into the responses in regard to the different types of stakeholders followed by their reasons for choosing a particular response. This is done to assess whether a particular stakeholder group has specific preferences or if the responses could be generalized.

A1.3.1. Results for different countries

As described in section A1.2.1, the stakeholders that participated in the survey origin from 14 different countries, shows that almost half of the participants come from Switzerland, almost 20% from Belgium and some countries have only 1 or 2 participants in the pool. Therefore, it is hard to compare countries, let alone try to explain differences. On some of the questions in the survey, however, we did see some interesting differences in the trend among the answers from different countries. In the analysis below, we took only the following countries into account, since from other countries only 2 or less stakeholders participated: Austria, Belgium, Estonia, France, Germany, Norway, Spain, Sweden, Switzerland, The Netherlands and the UK.

a. Calculated versus actual energy performance

When we compare how reliable participants think calculated energy performances are, stakeholders from Spain, UK, Austria, France and Germany are a bit more pessimistic than the ones from Switzerland, Belgium, Norway, Estonia, Sweden and the Netherlands. This can be seen in Figure 71, where for the more pessimistic countries almost half or more of the stakeholders answer that they think calculated energy performances are absolutely not or a little reliable, compared to only one third (Estonia) or far less than a third of the other countries (the rest). It’s striking though that from the countries that trust the calculations the least, namely the UK and Austria, around 40% of the stakeholders don’t think their customers are interested (absolutely not or a bit) in the actual energy performance of the building either (see Figure 72). Incidentally, most stakeholders say that they themselves are very interested in actual energy performances (see Figure 72), including all stakeholders from the UK and Austria (quite a bit or a lot).

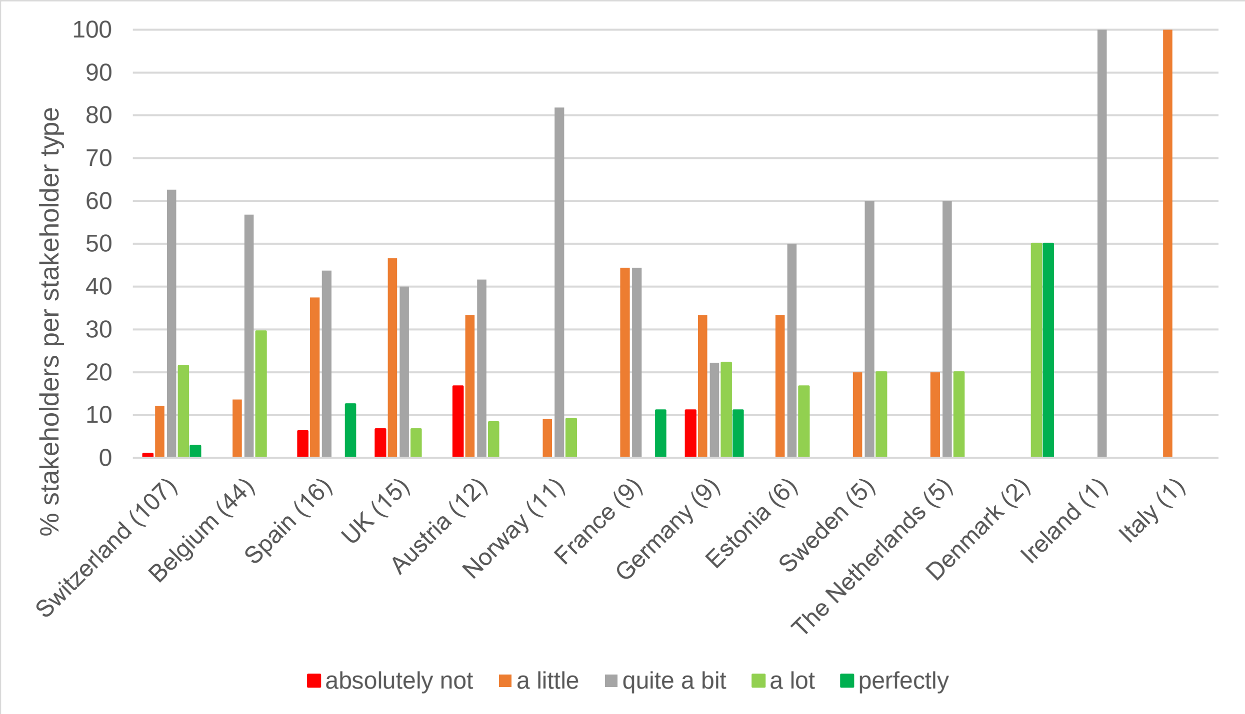


Figure 71. Stakeholders opinion on how reliable calculated energy performances are, per country.

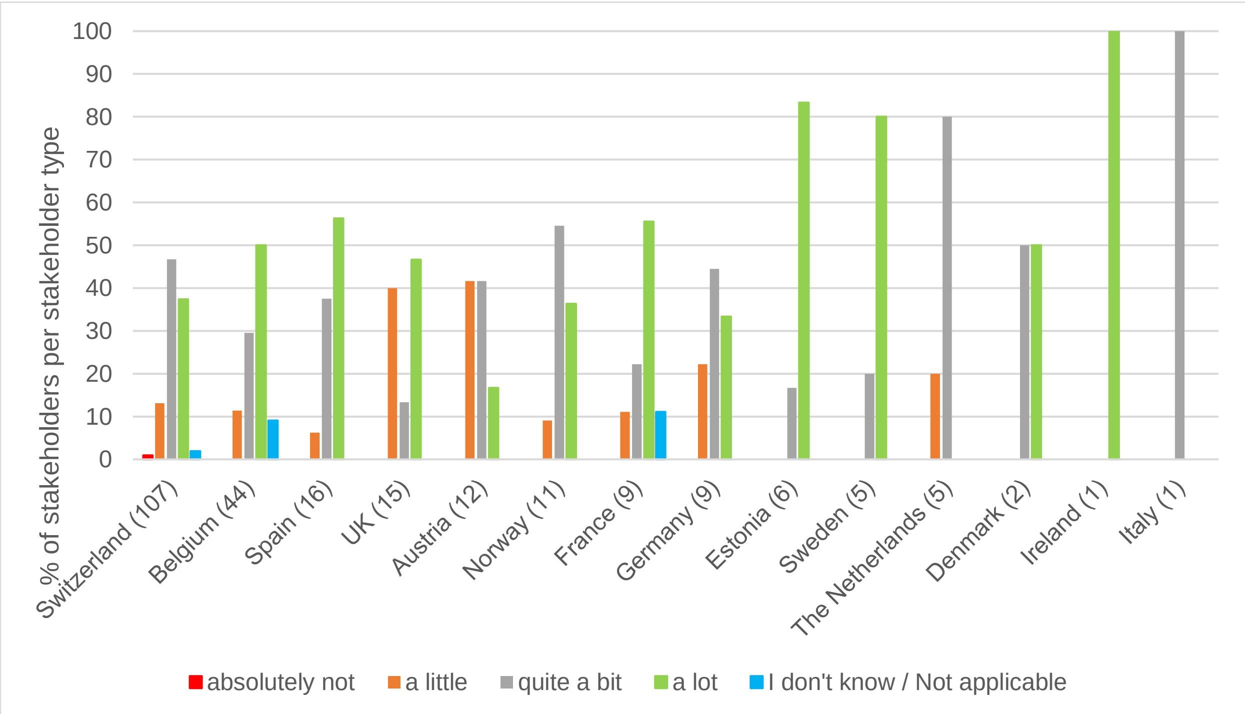


Figure 72. Stakeholder's opinion on how interested their customers might be in the actual energy performance of a building after delivery, per country.

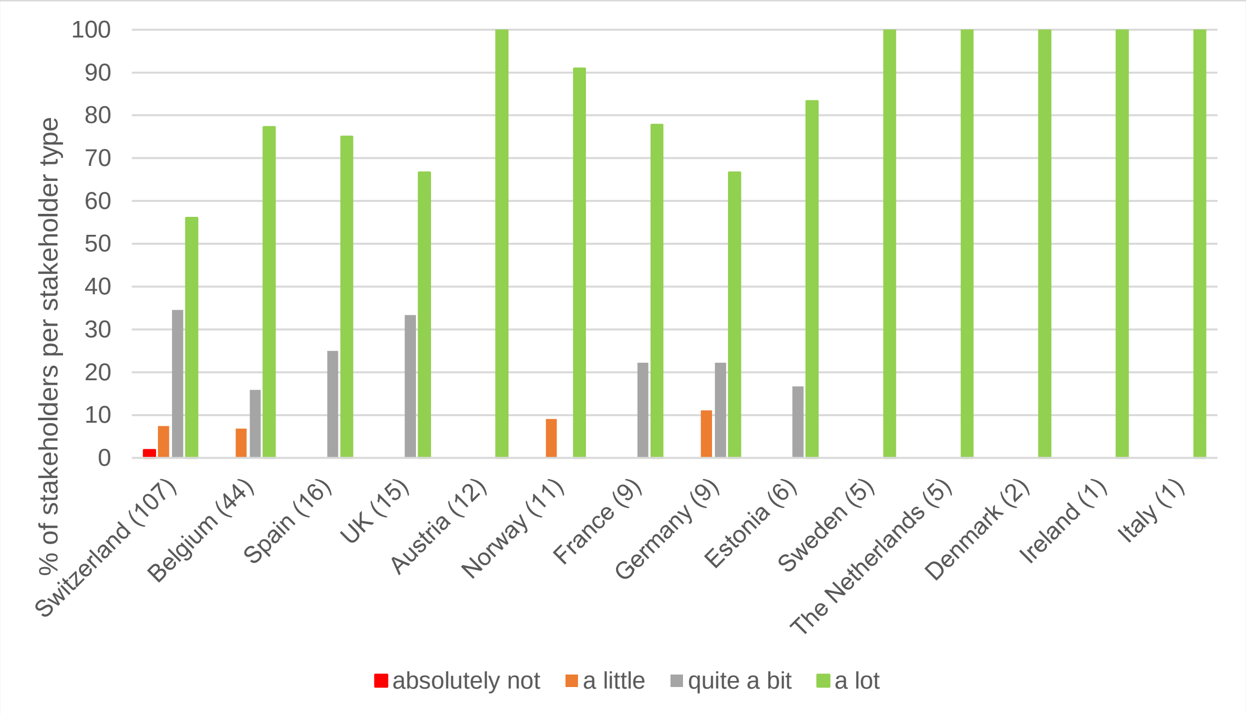


Figure 73. Stakeholder's opinion on how interested they themselves are in the actual energy performance of a building after delivery, per country.

b. Cost and duration of the assessment of the HTC

When we compare what stakeholders, think is an acceptable duration for the HTC assessment (see Figure 74), it is striking that only in France a vast majority think that the assessment should not take more than a day. In contrast, in other countries a third or more of the stakeholders think a few days or more are acceptable and, in the UK, Germany, Sweden and the Netherlands a third even think that a few weeks or more is okay. What stands out is that in Norway and Sweden, almost no stakeholders says that the assessment should not take longer than a day: they almost all find a few days or longer acceptable. In Sweden we find also the most stakeholders that accept higher costs for the assessment (see Figure 75: 80% 500 EUR or higher and 40% 2000 EUR or higher). Also, in France two third of the stakeholders accept costs of 500 EUR or more, which seems in contrast with the finding that most stakeholders in France opt for a short assessment duration.

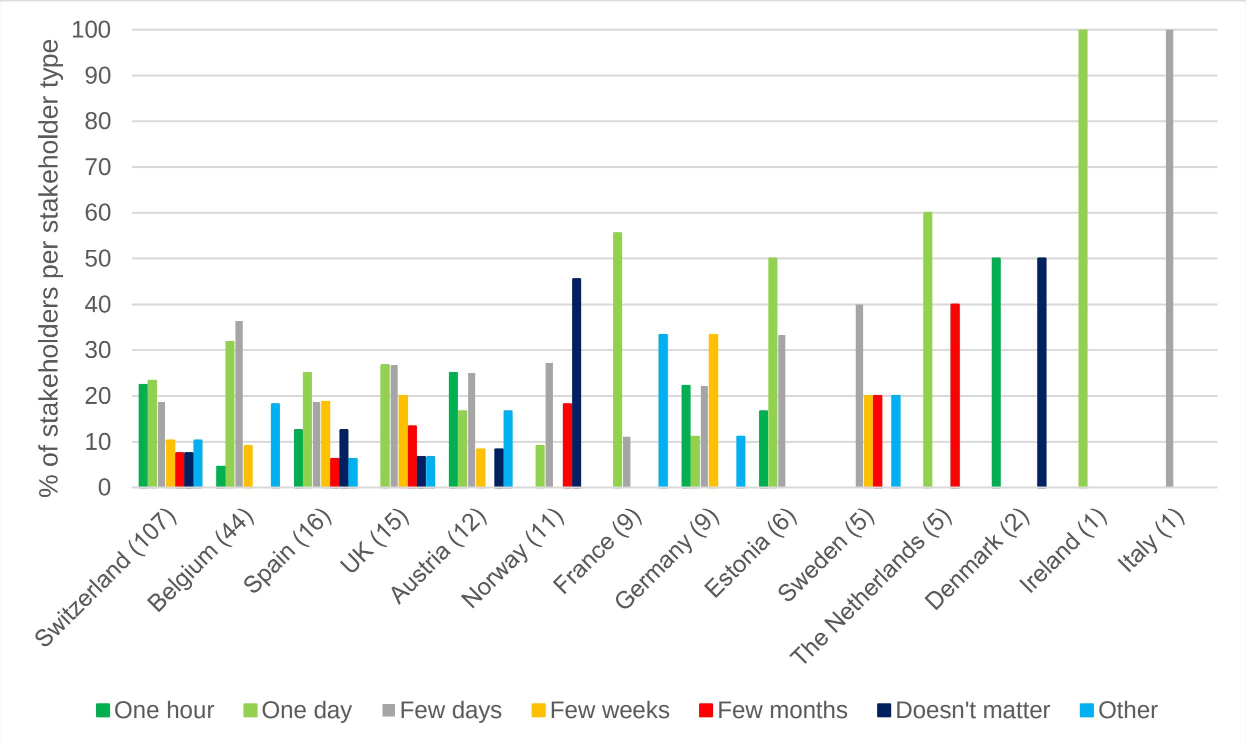


Figure 74. Stakeholders opinion on acceptable duration of a HTC assessment, per country.

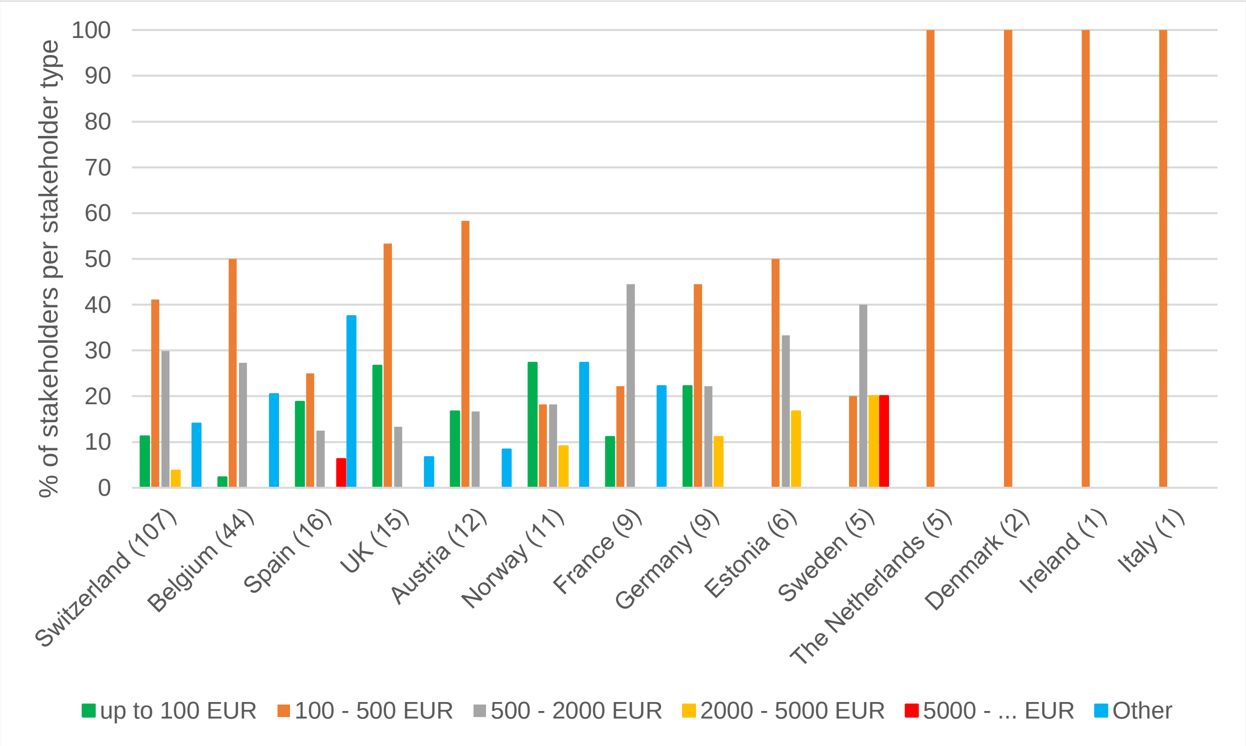


Figure 75. Stakeholders opinion acceptable cost of a HTC assessment, per country.

A1.3.2. Results for stakeholder types

As described in section A1.2.1, we asked the participants to specify the type of company or organisation they work for and clustered these in the 13 stakeholder categories that are shown in Figure 55. We analysed the survey results for differences among stakeholder groups. In this section we will present the trends that we saw.

a. Reliability of the calculated energy performance

Researchers, developers/providers of monitoring equipment and portfolio management/real estate are the most pessimistic about the reliability of the calculated energy performance (see Figure 76: over 40% up to almost 70% say that they do not find the calculation reliable at all or only a little reliable). In contrast, the engineer/planners are the most positive, with 45% of this group say that the calculation is very reliable. From researchers and developers of monitoring equipment we could expect more knowledge of these calculations, which might make them more sceptical.

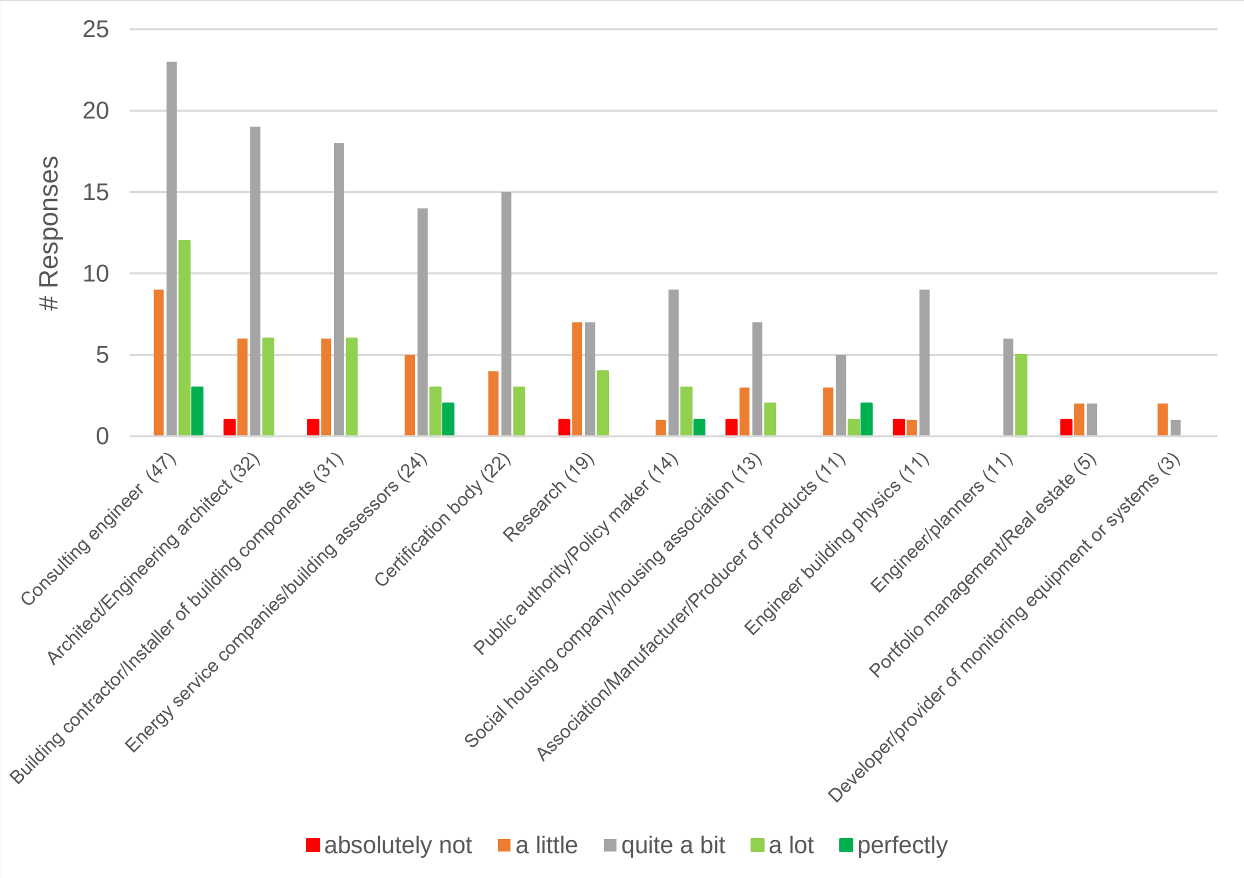


Figure 76. Stakeholders opinion on how reliable calculated energy performances are, per stakeholder group.

b. Timing of a HTC assessment

The energy service companies, certification bodies and real estate agents are relatively more in favour of an assessment of the HTC just after the building is delivered than any other group, followed by the researchers (Figure 77). However, in all groups, even in these four, most stakeholders are in favour either of an assessment before delivery or a year after delivery.

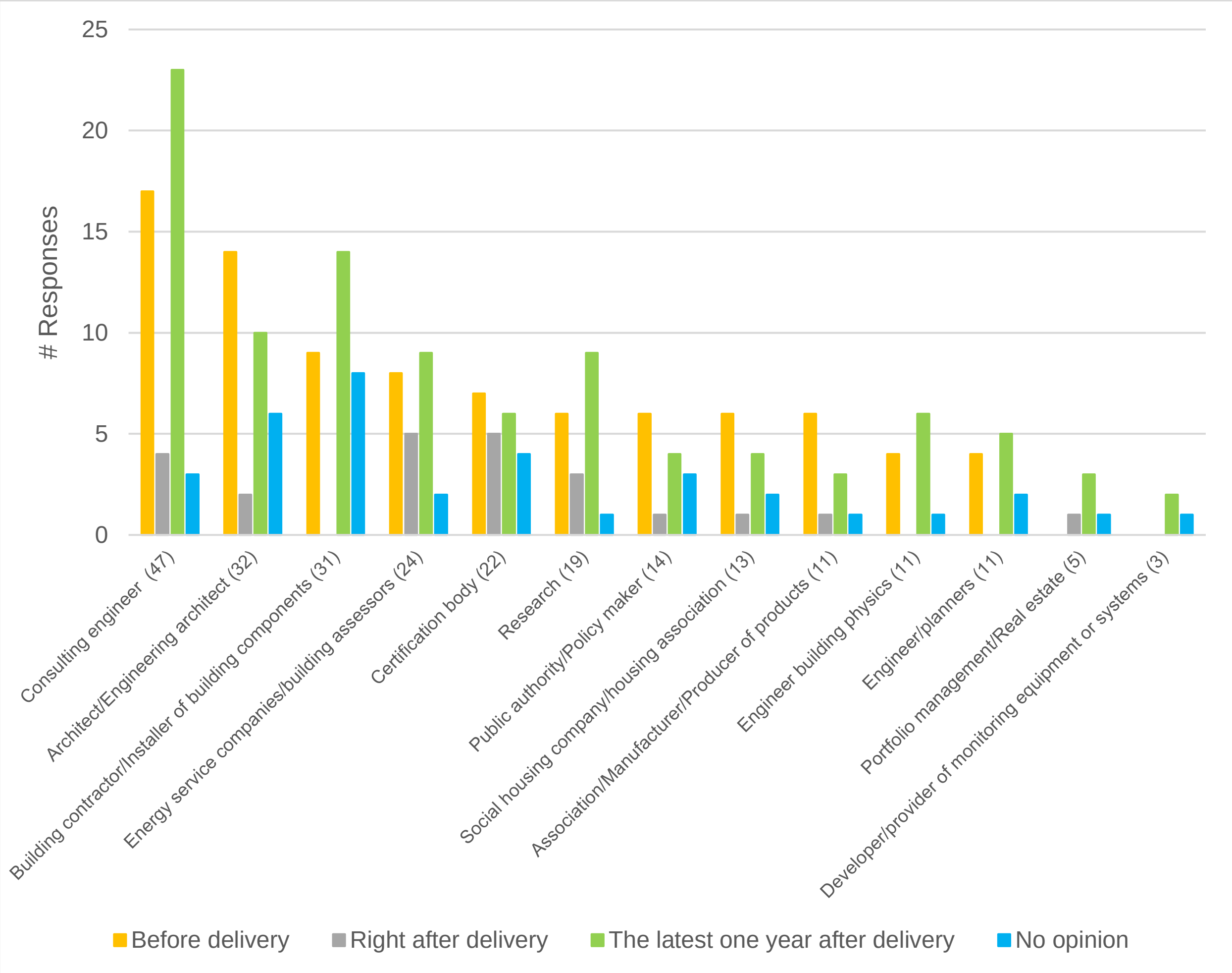


Figure 77. Stakeholder's opinion on when the determination of a HTC assessment should be done, per stakeholder group.

c. Cost and duration of a HTC assessment

While all stakeholder groups are generally in favour of keeping the costs for an assessment under 500 EUR (at least 40% of stakeholders in all groups), the policy makers stand out with over 90% of stakeholders in that group that think that the assessment costs should be 500 EUR of less (Figure 78). When we compare what stakeholder groups think is an acceptable duration for an assessment (Figure 79), we see that most stakeholders in all groups (50% or more) find maximum a few days (or less) an acceptable duration. The only exception to this are the developers/providers of monitoring equipment: in that group all stakeholders think a few weeks or months is acceptable.

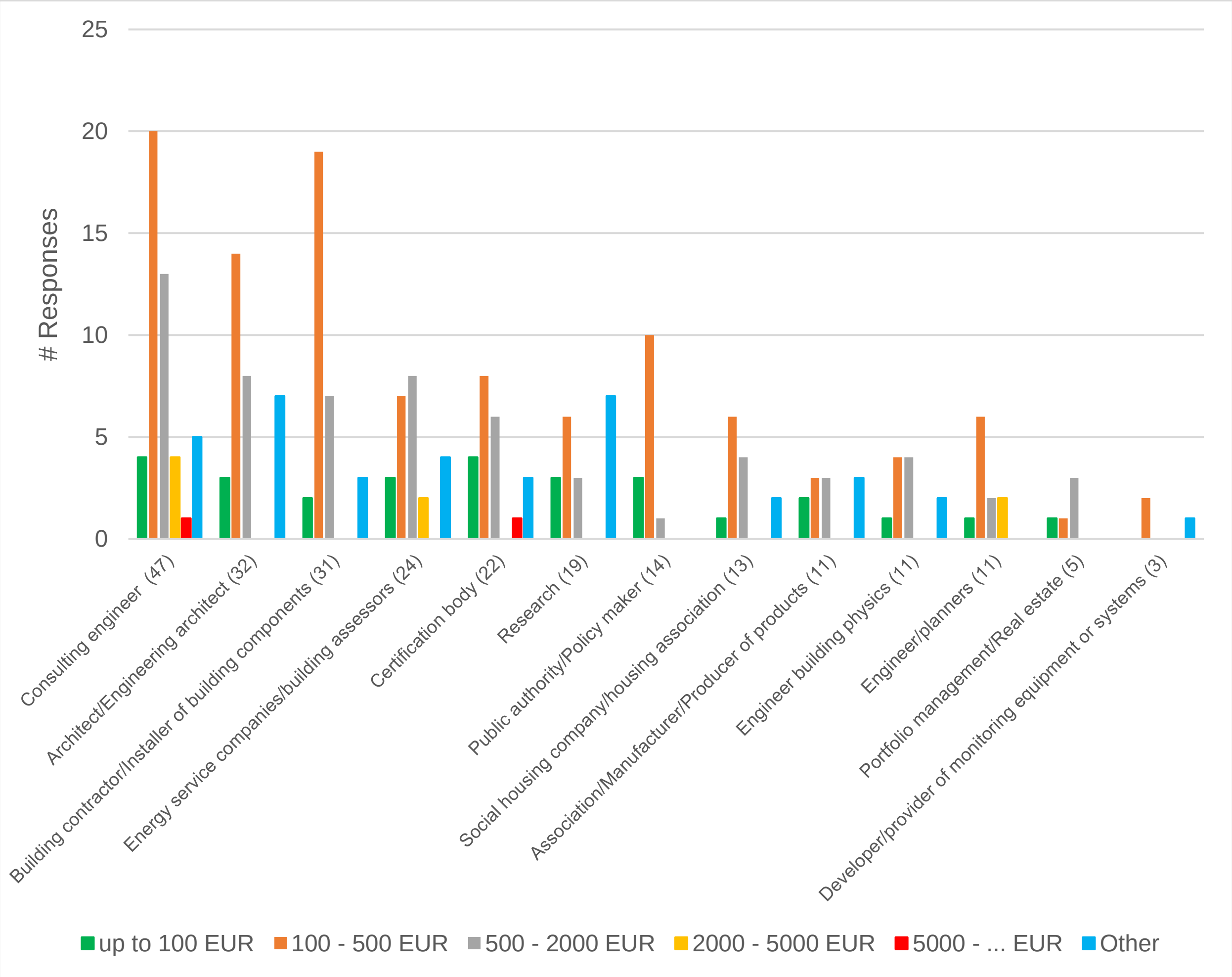


Figure 78. Stakeholder's opinion on acceptable cost of a HTC assessment, per stakeholder group.

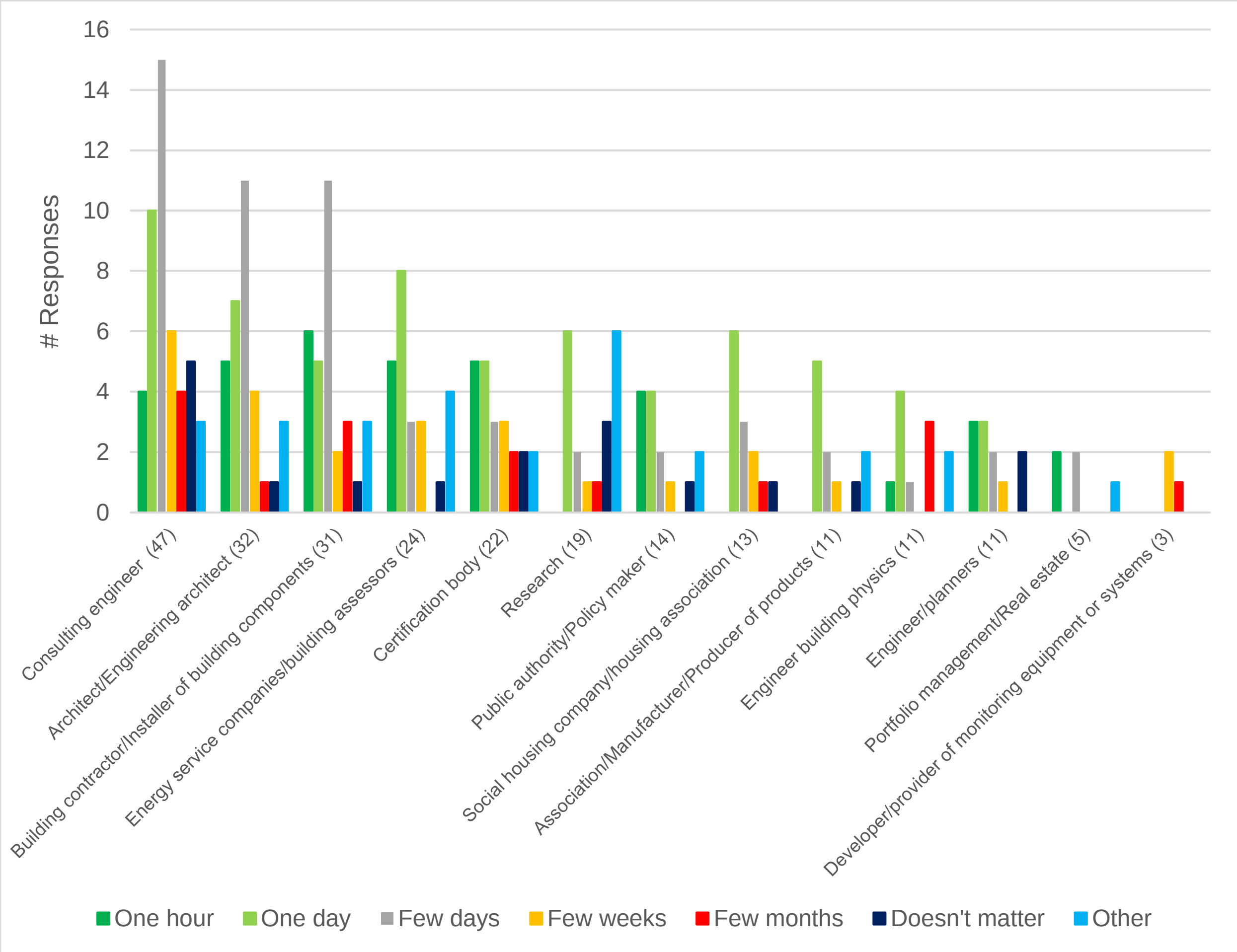


Figure 79. Stakeholder's opinion on acceptable duration of a HTC assessment, per stakeholder group.

A1.4. Conclusions

The stakeholders' perspective and preferences about an on-site measurement and calculation method for the HTC gives us many insights. Stakeholders in the building industry from 14 countries participated in the survey and expressed an almost unanimous interest in such a method. Comparing the country-wise responses, stakeholders from Spain, UK, Austria, France and Germany are a bit more pessimistic than the ones from Switzerland, Belgium, Norway, Estonia, Sweden and the Netherlands in terms of how reliable the present HTC calculations are. Although we did not conclude a strong basis for this difference, a deeper look into the existing methods of calculating HTCs in these countries may tell us more about this distribution. The responses from France show that a vast majority of the stakeholders there think that the HC measurements should not take more than a day to measure, whereas, in Norway and Sweden, almost no stakeholders feel the same. In terms of acceptable costs, we find that stakeholders in Sweden accept higher costs for the assessment (80% 500 EUR or higher and 40% 2000 EUR or higher). Looking into the stakeholder-wise comparison, we see that the impact on the final energy consumption is the most important reason to measure the HTC. This shows that the stakeholders find the final energy consumption more important than other aspects such as occupant comfort. Their responses in regard to the time of the measurement, cost, duration and acceptable error are studied in detail. We see that longer tests that capture the variability of the weather variables and user behaviour are preferred. However, the concern about nuisance caused to the occupants is crucial. Therefore, we conclude that a non-invasive test is a possible solution. However, for newly built and retrofitted properties, it's likely that the measurement will need to be quick due to the cost of vacancy to the developer, while building vacancy would allow a more invasive test. For assessment of existing buildings, the balance could shift the other way, requiring a less invasive test but where the speed of the test is less critical. The preferred acceptable cost of the test is between 100 EUR and 2000 EUR, however largely dependent on the project, while an acceptable error of 5-10% or less is expected. We note that affordability is one of the key factors for upscaling the entire process of measurement and calculation. Practically, costs are likely driven by the expense of the equipment and particularly by the amount of time and expertise required per measurement. Driving down cost, therefore, is likely driven by automation of HTC calculations and perhaps by integration with measurement systems already installed in houses (e.g. heating controls and smart meter devices). The opinions from different stakeholders also tell us that the development of a standard procedure that satisfies the needs of all the stakeholders is rather challenging. Therefore, the process should be flexible and adaptive in meeting their needs.

Annex 2. Results of HTC Review

	Austria	Belgium	Belgium Wallonia	Belguim Flanders	Denmark	Estonia
Does your country have a EPBD compliant domestic energy tool	Yes	Yes	Yes	Yes	Yes	Yes
What is this tool known as in your country?	ÖNORM B 8110-6-1	EPC	PEB	EPB	Be18	Väikeelamu energiatõhususarvu kalkulaator
Provide a link to the home page of this tool	Several tools exist	https://www.energiesparen.be/epc	https://energie.wallonie.be/fr/performance-energetique-des-batiments.html?IDC=6148	https://www.energiesparen.be/EPB-pedia	https://sbi.dk/beregningsprogrammet/Pages/Start.aspx	https://www.mkm.ee/sites/default/files/vaikeelamu_energiatohususarvu_kalkulaator_2019_01_10.xlsx
Is the HTC a calculated value in this energy model?	Yes	Yes	Yes	Yes	Yes	Yes
If so how is it calculated, please show a screenshot of this	(U*A)+V)	(U*A)+I	(U*A)+I	(U*A)+I	(U*A)+I	(U*A)+I
Who can view the part of the data where the HTC is located.	Assessors and Software Providers	Not available	Not available	Not available	Assessors and Software Providers	All stakeholders
How can the HTC be viewed	Only in Software	Not available	Not available	Not available	Part of the output documents	Online via Excel Spreadsheet
Can the HTC be Input	No	Only by inputting incorrect proxy U values/Areas	Only by inputting incorrect proxy U values/Areas	Only by inputting incorrect proxy U values/Areas	Not directly, requires reworking of model	Only by inputting incorrect proxy U values/Areas

	France	Germany	Netherlands	Norway	Spain	Switzerland	UK
Does your country have a EPBD compliant domestic energy tool	Yes	No	Yes	Yes but requires specific EMS module	Yes	Yes	Yes
What is this tool known as in your country?	DPE	Enev -Blitz-Ausweis (example from many different software)	Energy-Index	EMS "Energimerkesystemet"	HULC, CYPETHERM HE Plus, SG SAVE (General certification) CE3, CE3X, CERMA (Simplified certification)	Lesosai	RdSAP/SAP
Provide a link to the home page of this tool	https://www.rt-batiment.fr/batiments-existants/dpe/evaluation-des-logiciels.html	https://www.bmwi.de/Redaktion/DE/Infografiken/energieausweis.html	https://www.energielabelvoorwoningen.nl/	www.energimerking.no	https://energia.gob.es/desarrollo/EficienciaEnergetica/CertificacionEnergetica/DocumentosReconocidos/Paginas/procedimientos-certificacion-proyecto-terminados.aspx https://www.codigotecnico.org/	http://www.lesosai.com/en/	https://www.bregroup.com/sap/standard-assessment-procedure-sap-2012/
Is the HTC a calculated value in this energy model?	*Ubât is generally used rather than HTC (HTC/Floor Area)	Transmission heat loss only	Yes	Yes but requires specific EMS module	Yes	Yes	Yes
If so how is it calculated, please show a screenshot of this	(U*A)+I)/Heat Loss Area	U*A	(U*A)+I	(U*A)+I	(U*A)+I	(U*A)+I	(U*A)+I
Who can view the part of the data where the HTC is located.	Dependant on tool used	Assessor Only	Assessor Only	NA	Assessor only	This can only be viewed by the companies and the assessors who carry out the calculations. Lesosai is a paid software.	Assessor only
How can the HTC be viewed	Dependant on tool used	Only in software/tool	Only in software/tool	NA	In software	The calculations are viewed in their raw format.	In software
Can the HTC be Input	Only by inputting incorrect proxy U values/Areas	No	Only by inputting incorrect proxy U values/Areas	NA	No	No	Only by inputting incorrect proxy U values/Areas

Table 14. Results of the HTC Review Process.

ANNEX **71**

EBC

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