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Are the energy savings of the Passive House standard reliable?

A review of the as-built thermal and space heating performance of Passive House dwellings from 1990 to 2018

Abstract

The Passive House (PH) Standard is a voluntary quality assurance standard focused upon maximising the health and wellbeing of occupants, whilst reducing space heating demand to a very low level. To meet the PH standard well defined criteria have to be met. However, given literature that suggests a '*performance gap'* for energy savings, the question remains, how well do PH dwellings perform *in situ*?

This paper presents results from *in situ* building fabric thermal performance measurements, along with a comparison between the design intent and the measured space heating energy used by over 2000 newly built and retrofitted PH dwellings. The results reveal the *in situ* thermal performance of the building fabric is close to the design predictions. Within space heating measurements, a standard deviation of up to 50 % has to be attributed to the broad spectrum of user behaviour; this is not specific for PH, but a general observation. Despite this, the average values for the PH developments ranged within the uncertainty of the demand calculations. With over 2000 PH dwellings averaging a space heating energy consumption of 14.6 kWh/(m²a), the *in situ* performance is close to the original design intent and extraordinary low compared to the consumption in ordinary buildings.

The results suggest the PH Standard is capable of producing dwellings in a verifiable manner. This means, on average, the *in situ* thermal performance of the building fabric and the energy consumption for space heating match the design intent i.e. there is no significant 'performance gap'.

Keywords:

Passive House
Energy consumption
Heating energy demand
Fabric performance
Coheating
PHPP (Passive House Planning Package)

1 Introduction

The European Energy Performance of Buildings Directive (EPBD), (EPBD 2012) requires all new buildings to be nearly zero energy buildings[1] (NZEB) by the end of 2020. The prerequisite for reaching this ambitious target are highly energy efficient buildings. The Passive House (PH) Standard has been tested and applied for more than 25 years. With its high energy efficiency, it provides a solid foundation for the development of NZEBs, as heat pumps and on-site renewable technologies, such as photovoltaics and solar thermal, can be added in order to cover the small amount of residual primary energy demand that is still required (Grove-Smith et al. 2018).

The PH Standard focuses on maximizing the health and well-being of building occupants by providing excellent indoor thermal comfort and air quality, whilst simultaneously reducing the space heating demand. For certification (PHI 2016) purposes, the PH Standard requires the Space Heating Demand to be < 15 kWh/(m^{2}a) of Treated Floor Area (TFA), which in moderate climates generally corresponds to a heating load of < 10 W/m^2 (often used as alternative criterion). Further requirements are an overheating risk limited to < 10 % per annum and a restricted Primary Energy Demand, which includes all energy use in the building. Since PHPP 9.6 the Primary Energy Demand target is determined on a national basis and is typically reported as < 120 kWh/(m^{2}a) – this is including all energy applications, e.g. the total domestic electricity use. Provided a building meets all of the quality assurance thresholds listed above, it is considered reasonable to certify, or declare, that the building is a PH.

To deliver a successful PH building five basic physical characteristics can be identified. Relative to other building standards these are: very high levels of thermal insulation for both (1) the opaque elements of the building envelope and (2) transparent elements like windows; then in addition, (3) thermal bridge free design and construction (as assessed using external dimensions); (4) high levels of airtightness - meaning pressure test results must have an n_{50} of < 0.6 h^{-1}; and (5) installation of noise dampened mechanical ventilation systems with heat recovery. The result is the highest standard comfort without downdrafts at the windows; good indoor air quality; and, no excessive noise from mechanical ventilation.

Without appropriate performance thresholds and processes to support both design and construction, these physical characteristics could still lead to significant underperformance and result in money being spent with little or no quantifiable benefit. Therefore, regardless of the calculated energy demand, the following quality assurance principles are required to ensure the performance goals are met. First of all, a Passive House Institute (PHI) approved calculation tool, such as the Passivhaus Planning Package (PHPP) (PHPP 2015), must be used to establish appropriate boundary conditions and determine the energy demand, appropriate U-values, ventilation rates, downdraft risks, overheating risk, etc. Secondly, input parameters have to be entered carefully, so the declared conductivity of all materials, products, components and constructions satisfy relevant standards. The certification of components has evolved as a means of helping to ensure the quality of calculations and for these reasons, the use of PH certified components are recommended. Finally, for certification, in addition to PHPP calculations, a comprehensive set of construction drawings and documentation, including commissioning reports (for airtightness and ventilation) and photographic records, must be provided and the contractor must provide a written declaration confirming that the building has been built in accordance with the contract documents (PHI, 2016). This rigour helps to avoid large differences between design and realized constructions. Furthermore, the PH Classes introduced by the PHI, now also include the consideration of renewables (s. contribution by Jessica Grove-Smith (Grove-Smith et al.2015).

1.1 Experiences from the 1st Passive House

The first PH building was built in 1991 in Kranichstein, Darmstadt, Germany and has demonstrated consistent and exceptionally low space heating energy demand over the last quarter of a century

[1] NZEB is a building that has a very high energy performance: The nearly zero or very low amount of energy required should to a very significant extent be covered by energy from renewable sources, including renewable energy produced on-site or nearby.”

(Feist et al. 2019). The measured final energy consumption for gas and electricity, is depicted in Figure 1. The figure shows the first 8 years of operation for all four households that form this terraced building. Included without exception are all forms of energy crossing the property line and being paid for. Furthermore, energy use data is broken down by application (space heating, domestic hot water, household electricity, gas stoves and general electricity e.g. for house bell, basement lighting and heating pumps).

Measurement was carried out using the meters provided by the respective energy suppliers (diaphragm gas meters and electricity meters) and sub-meters were used to disaggregate the energy use into the main end-use categories. The reference area for all specific values is the net living space (156 m² per dwelling unit which is almost equal to the treated floor area defined later).

At the time the Kranichstein PH was constructed, the space heating energy consumption of the average German dwelling was 200 kWh/(m²a). More recently, the current reference values were calculated on the basis of official energy consumption statistics ((Ziesing 2018), (BMWi 2018)) using average values for all households. The results show that in 2017, the final energy required to cover space heating at the Kranichstein PH was still a factor 10 lower than the average German household (Feist/Werner 1993), (Feist/Werner 1994), (Feist 1997a), (Feist 1997b), (Feist 1997c), (Feist 1998). See Figure 1 for a graphic representation of this comparison.

It should be noted that the Kranichstein PH did not just reduce space heating energy consumption. Through the use of very energy-efficient household appliances, other sources of energy demand, such as domestic hot water and household electricity, were significantly reduced (Ebel/Feist 1997), (Feist 1998), (Feist et al. 2016) thus reducing primary energy demand and any related carbon emissions.

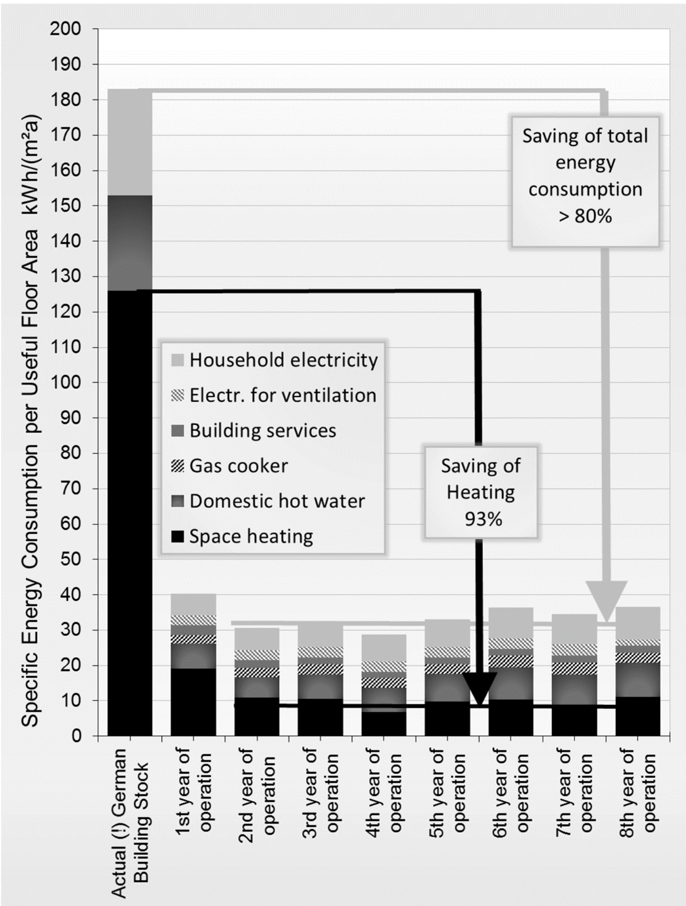

Figure 1: Measured specific final energy consumption values for all four residential units of the Passive House Darmstadt Kranichstein compared with the German building stock in 2017.

1.2 Expectations from demand calculations and measured reality

Since its development in early 1990s, and coupled with a national and international drive to improve the energy efficiency of buildings without undermining the health and wellbeing of occupants, the PH Standard has emerged as a world leading quality assurance standard. As there are no restrictions on how to use the Standard and because the know-how has been made public and available for everybody to use, PH buildings are a solution which can be used throughout the world.

Over the intervening years since its inception, studies have been undertaken to evaluate the *in situ* in-use performance of PH buildings. These studies have been used to validate the PH quality assurance process and inform the ongoing refinement of the Passivhaus Planning Package (PHPP). To compare the calculated energy balance of the PHPP with the measured consumption data, there is a simple guide in (Peper 2014). These wide-ranging international studies have not only allowed the performance of the PH Standard to be assessed, but also demonstrate the transferability of the quality assurance methodology to a wide range of countries, cultures, building techniques and construction technologies (Schnieders et al. 2019).

PHPP is an energy balance calculation tool developed in the 1990s to depict a realistic understanding of the energy performance of energy efficient buildings. Therefore, as far as practically possible, real physical dependencies are calculated within PHPP. For other influences, a number of dynamic building simulation runs were performed in order to derive simplified correlations between data. These correlations are also incorporated within PHPP. However, before a comparison can be made between PHPP based demand predictions and the corresponding *in situ* measured space heating consumption, some preliminary considerations require discussion.

The PHPP demand calculation predicts consumption based upon a detailed collection of parameters associated with the building. Some parameters, specifically the climatic boundary conditions, are given as monthly or general average values, and as such, are not at the high temporal resolution used by dynamic simulations. Consequently, for any single building it has to be expected that there will be a difference between the predicted demand and the actual energy consumption. For instance, the climate data used to calculate the energy balance is based upon a long-term average, yet following construction, any one individual year can be different (warmer or colder, more or less solar radiation, etc.) (Feist 1997a), (Feist/Loga 1997). Another important point relates to the internal temperatures that are used within PHPP. For the purpose of PH certification, the internal winter operative temperature is set to 20 °C, whilst in practical use, the individual comfort temperatures of tenants vary strongly. In fact, in a significant number of monitored buildings, for some of the users, much higher indoor air temperatures prevailed (CEPHEUS project) (Schnieders et al. 2001) (Schnieders 2003), (Feist et al. 2005), (Schnieders/Andreas 2006). Further comprehensive information on the topic of temperature differentiation in energy-efficient buildings can be found in the publication (AkkP 25).

Uncertainties in prediction can be reduced, if the real boundary conditions, such as the monthly indoor and outdoor air temperatures derived from *in situ* measurements, are used for the space heating energy balance calculations. This is of course not possible during design, because neither the weather conditions of individual years nor the behaviour of occupants can be predicted with such accuracy. After the fact, all boundary conditions can be known better and a new calculation run can be undertaken using the actual values (this has also been done in some of the projects (Peper/Feist 2002) but will not be investigated here). However, to keep the comparison transparent, only the original design-value energy balance calculations are referred to in this paper. For example, this form of analysis has been undertaken for a retrofit applying Passive House components. The project "Tevessstraße" in Frankfurt a.M. is an apartment building with 20 dwellings (it is one of the buildings in Figure 13). The PHPP calculation undertaken with standard conditions (20°C indoor air temperature and Frankfurt climate data) results in a space heating demand of 17.3 kWh/(m²a) for the refurbished building. If the measured weather conditions (outside temperature and global radiation) for the year investigated are used (2007/2008), a value of 10.6 kWh/(m²a) results. If the average indoor temperature of 21.8°C measured in winter is applied in the PHPP, the space heating calculation value increases to 15.1 kWh/(m²a). In comparison, the real measured space heating consumption accounted to 18.1 kWh/(m²a) (Peper/Grove-Smith/Feist 2009).

An estimation of the expected errors associated with space heating energy demand calculations will be derived in the next paragraph and will form the basis for the proceeding discussions. The performance of PH buildings will then be discussed step-by-step. Firstly, the characterisation of the aggregate thermal performance of the building fabric will be discussed, based upon an evaluation of electric coheating test data. Secondly, the in-use energy performance of PH dwellings will be discussed, which not only takes into account the thermal performance of the building fabric, but also considers the performance of the installed building services and user influence (occupancy). Whilst the tests that have been undertaken on the fabric are typically short-term measurements, with a maximum length of weeks, the in-use energy performance measurements are typically considered on an annual basis. Finally, conclusions will be made based upon how the measured PH dwellings performed in terms of building fabric and in-use energy performance.

1.3 Expected uncertainties attributable to space heating energy demand calculations

To understand the different factors influencing space heating energy demand and to be able to assess the differences between predicted demand and *in situ* energy use, the uncertainties associated with these factors need to be quantified. Therefore, the uncertainties associated with the parameters that are used as input to the energy balance calculations, and their resultant influence on space heating demand, have been estimated based upon previous work published in Feist (Feist, 2001). The result is an uncertainty estimation that is expected to be attributable to the calculated space heating demand of PH buildings.

Table 1 shows, for the building fabric, the insulation of the opaque envelope can cause differences in the annual space heating demand of ±0.7 kWh/(m^2a) due to uncertainties in the measured average insulation thicknesses and thermal conductivities. The insulating properties of windows and the heat recovery efficiency of the ventilation unit also provide additional uncertainties (±0.6 and ±1.2 kWh/(m^2a), respectively). In addition, uncertainties associated with the pressurization test result can add an additional ±0.24 kWh/(m^2a).

Accumulating all of these (seen to be independent) sources of uncertainties in quadrature, results in a total expected uncertainty associated with the building fabric of ±10 %, which equates to ±1.5 kWh/(m^2a), based on a typical PH space heating demand. Note that the reasons for the uncertainties given here are independent of the calculation method – even with highly sophisticated methods it will still be difficult to reduce these uncertainties. As a second note, these uncertainties are still small enough to allow a reliable significance of the energy savings achieved by the measures taken at the buildings.

Table 1: Collection of uncertainties of the boundary conditions for heating demand calculation that have to considered when compared with a measured heating energy consumption according to (Feist 2001). Note, that these uncertainties are those associated with the average values of the quantities discussed – the individual distribution of the quantities will have far higher standard deviations (for external temperature of the winter period e.g. an individual year can lead to up to 35% lower or higher consumption). For the design process only the average expectation matters.

Category	Influence	Factors	Uncertainty in heating demand (kWh/(m²a))	Uncertainty in heating demand by category (kWh/(m²a))	Total uncertainty in heating demand (kWh/(m²a))
Building fabric	Insulation	Thickness and thermal conductivity	± 0.7	± 1.5	± 3
	Ventilation	Deviation in heat recovery efficiency	± 1.2		
	Infiltration	Pressurisation test accuracy	± 0.24		
	Windows	U-values for glazing, frame and thermal bridges	± 0.6		
User influence	Interior temperature	Standard deviation of the average in large samples	± 1.2	± 2.0	
	Ventilation with windows	Behaviour of tenants opening windows	± 1		
	Internal heat gains	Electricity consumption, occupancy regime, etc.	± 1.3		
Climate	Annually changing climatic conditions	Uncertainties for measurements and standard deviation in heating degree days	± 0.7	± 0.7	

The error associated with user influences, such as variations in internal temperatures, frequency of window opening during the heating period and internal heat gains, which are strongly influenced by the electricity consumption and the presence of people in the building, tend to be much larger. Uncertainties attributable to these factors can, as shown later, account for up to 45% of the space heating demand of individual dwellings. For the energy saving goals, this is not crucial, because the random distribution of the individual users level themselves out with respect to an average condition of user behaviour. From statistics, it is known that the uncertainty of the average is given by the standard deviation of the distribution divided by the square root of the number of individual dwellings. With a minimum of 16 dwellings this will be in the range of ±2 kWh/(m²a). In addition, the climate data used in the energy balance also has an uncertainty in the measurement. Assuming that the temperature could be measured within a small error of ±0.15 K and the global solar radiation with an error of ±5 %, a total deviation in the heating demand of ±0.7 kWh/(m²a) is to be expected.

The resulting total absolute error thus equates to ±3[2] kWh/(m²a). This gives a relative error of some ±20 %, corresponding to a space heating demand of 15 kWh/(m²a). However, although the relative

[2] Since not all effects contributing to the uncertainty of the heating energy demand and the uncertainties themselves do have uncertainties the total uncertainty in heating demand was rounded to 3 kWh/(m²a).

percentage error appears to be large, the absolute error is small enough, particularly compared to the space heating demand of mainstream housing. Considering the differences in space heating energy demand between PH and conventional buildings or even old buildings, which is relevant to savings and economic decisions for retrofits, this uncertainty is only of minor importance i.e. ±3 kWh/(m²a) for the average German home 126 kWh/(m²a) ((Ziesing 2018), (BMWi 2018)) is just ±2.4%. Comparing uncertainties for PHs with the consumption of low energy houses with around 60 kWh/(m²a) they are only 5 %.

At this point, it has to be stated that the estimated uncertainty for the space heating demand is the best possible value. An individual measured space heating energy consumption can have much larger variances than the derived ±3 kWh/(m²a), as will be seen later in this paper.

2 Fabric performance of Passivhaus dwellings

Very few studies exist where the *in situ* performance of the building fabric of PH dwellings has been verified and compared against the theoretical design intent (see (Gupta 2018, Johnston 2014, Johnston 2016)). This lack of comparable empirical data is not just confined to PH dwellings, it is also prevalent in mainstream housing. This is because traditional design assumptions take *in situ* thermal performance for granted. Consequently, the building fabric is very rarely tested or measured in the field. However, in recent years, a growing and well-founded body of evidence has emerged, which indicates that a *'gap'* in performance often exists between the design intent and the *in situ* measured performance of the building fabric (Bagge 2013), (Galvin 2014), (Hens 2007), (Johnston 2015), (Stafford 2012), (Thomsen 2005), (ZCH 2010), (ZCH 2014). This *'gap'* in performance has been observed at both an aggregate and an elemental level and is commonly referred to as the building fabric thermal *'performance gap'*.

In dwellings meeting the PH Standard, it is possible to achieve a number of the performance targets required for certification, without the need for in-depth building fabric testing. For instance, the Space Heating Demand and the Primary Energy Demand, are only verified using PHPP. This practice is not unusual, as the same holds for all known international, national and regional building standards and funding practices independent from a specific standard. For PH certification, these calculations are supported by the MVHR (mechanical ventilation and heat recovery) commissioning report, the contractor's statements of conformance and site reports and photographs to demonstrate build quality. However, the only building fabric performance target requiring mandatory testing is the airtightness of the building envelope.

As the PHs certification process is primarily paper-based, there is a risk the *in situ* performance of the building fabric could significantly exceed the design intent (as calculated within PHPP). Should this be the case, it may not be possible to achieve the Space Heating Demand or Specific Heat Load targets of ≤ 15 kWh/(m^{2}a) and ≤ 10 W/m^2 respectively. Furthermore, optimisation during the design phase would not deliver the intended result. In addition, even if the Space Heating Demand and Heating Load targets are achieved in practice, there is no guarantee the *in situ* thermal performance of the building fabric of individual buildings is performing as the design originally intended. This is because occupant behaviour within individual buildings could mask any discrepancies that exist in the performance of the building fabric.

Despite the PH Standard not requiring in situ thermal performance testing, a literature review reveals a small number of PH dwellings where the thermal performance of the building fabric – excluding all user influences - has been field tested. In total, tests have been undertaken on 21 PH dwellings across 16 separate developments located in four different countries. On four of these developments, more than one dwelling was tested (3 dwellings at Wimbish, and 2 dwellings each at Dungannon Passivhaus, Future Works and the Racecourse Development). Although the size and non-random nature of the sample is statistically insignificant, the learnings gained from testing these dwellings are still important and informative. Details of all of the dwellings that have been tested are detailed within Table 2.

Table 2: **Details of the PH dwellings that have undergone *in situ* building fabric performance testing.**

Dwelling	Form	No. of storeys	Main external wall construction	Gross floor area (m^2)	Electric Coheat-ing test	Heat flux measurement	Thermo-graphy
Camden Passivhaus, UK (CAR 2011), (Stamp 2015)	Detached	2	Pre-fabricated timber-frame	118	Yes	Yes	Yes
Dormont Park Cottage DA2´(GSoA 2015)	Semi-detached	2	Pre-fabricated timber-frame	87	No	Yes	Yes
Dungannon Passivhaus Dwelling 1, UK (Choice Housing 2014)	End terrace	2	Pre-fabricated timber-frame	85	No	Yes	Yes
Dungannon Passivhaus Dwelling 2, UK (Choice Housing 2014)	Mid-terrace	2	Pre-fabricated timber-frame	85	No	Yes	Yes
Ford Close, UK (Randall 2012) ,(Siddall 2013)	Mid-terrace	2	Pre-fabricated timber-frame cassette	91	Yes	No	Yes
Future Works Passivhaus Larch house (CAR 2012 & Guerra-Santin 2013)	Detached	2	Timber-frame	99	Yes	Yes	Yes
Future Works Passivhaus Lime house (CAR 2012 & Guerra-Santin 2013)	Detached	2	Timber-frame	76	No	Yes	Yes
Lancaster Co-housing, UK (Johnston 2013)	End-terrace	2	Full fill masonry cavity	65	Yes	Yes	Yes
Knights Place Plat A (Gale 2014a)	Flat	1	Externally insulated solid block	42	Yes	Yes	Yes
Plummerswood (Gaia Research, 2015)	Detached	2	Brettstapel timber panels	346	Yes	Yes	Yes
Racecourse Development Dwelling 1, UK (Johnston 2013b)	End-terrace bungalow	1 plus mezzanine	Pre-fabricated timber-frame cassette	66	No	Yes	Yes
Racecourse Development Dwelling 2, UK (Johnston 2013b)	Mid-terrace bungalow	1 plus mezzanine	Pre-fabricated timber-frame cassette	66	Yes	Yes	Yes
Rowan House Flat B (Gale 2014b)	Flat	1	Externally insulated solid block	74.1	No	Yes	Yes
Tigh-Na-Cladach Passivhaus, UK	Semi-detached	2	Timber-frame	95	No	Yes	Yes
Wimbish Passivhaus Plot 6, UK (Linktreat 2014)	Flat	1	Externally insulated thin-joint blockwork	-	No	Yes	Yes
Wimbish Passivhaus Plot 9, UK (Linktreat 2014)	Mid-terrace	2	Externally insulated thin-joint blockwork	-	No	Yes	Yes
Wimbish Passivhaus Plot 11, UK (Linktreat 2014)	End-terrace	2	Externally insulated thin-joint blockwork	-	No	Yes	Yes
Darmstadt, Germany (Ottinger 2016)	End-terrace	3	Externally insulated sand-lime brick	196	Yes	No	No
Deinze, Belgium (Manioglu 2007)	Detached	1	Timber-frame	152	Yes	No	Yes
Heusden-Zolder, Belgium (Meulenaer 2005)	Detached	2	Timber-frame	194	Yes	No	No
Passive House Disc, Austria (Ottinger 2016)	Detached	1	Timber-frame	142	Yes	No	No

Table 2 shows that the dwellings not only vary in terms of their size, form and main construction type, but they have also been constructed in a diverse range of geographic locations. Despite the small and non-random nature of the sample size, the majority of the tested dwellings are located in the UK (17 of the 21 dwellings), which may bias the results obtained. The reason for the disproportionately large UK sample can be attributed to a Government funded Building Performance Evaluation (BPE) Programme that was undertaken by the Technology Strategy Board (TSB 2010).

With the exception of an air pressurisation test, the fabric tests that were undertaken on the dwellings comprised either an aggregate test (electric coheating), an elemental fabric test (heat flux density measurements), or a combination of the two. In addition to these quantitative tests, thermography has also been undertaken on a number of the dwellings, which may provide a qualitative insight into the results obtained from the fabric tests. Details of the fabric tests undertaken on each dwelling are contained within Table 2.

2.1 Electric Coheating Tests

As can be seen from Table 2, more than half of the identified dwellings (11 out of 21) have undergone an electric coheating test. An electric coheating test is a quasi-static steady-state test method undertaken on an unoccupied dwelling to quantify the Heat Transfer Coefficient (HTC) of the dwelling in W/K (see (Wingfield 2010) and (Johnson et al. 2013)). It involves electrically heating the building to a constant mean elevated homogeneous internal temperature (commonly 25°C) for a period of between 7 to 21 days and simultaneously measuring various internal and external parameters, such as internal and external temperatures, solar radiation and the total electrical power input to the building (see Figure 2). Thus, the total daily heat input to the building in Watts that is required to obtain a particular ΔT in K can be established. The results of the tests are illustrated in Table 3 and Figure 3.

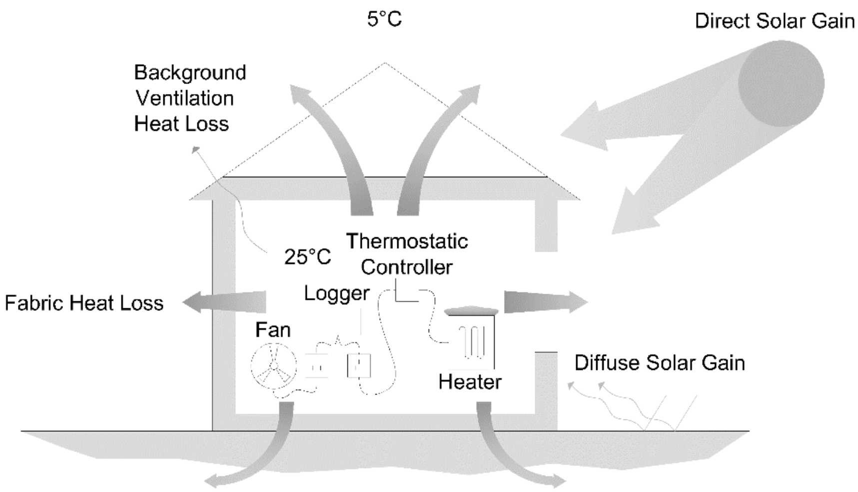

Figure 2: Diagrammatic representation of an electric coheating test (Brooke-Peat 2015).

For comparative purposes, the measured HTC obtained from the electric coheating test has been compared against the original design intent HTC contained within the PHPP assessments that were submitted for certification purposes. Where it has been published, the standard error associated with the regression analysis has also been included within Table 3 to give an estimate of the regression model uncertainty associated with the electric coheating test result.

It should be noted that caution needs to be exercised when interpreting the results contained within Table 3 and Figure 3. For instance, it is not possible from the available published data to determine whether all of the tests have been undertaken using the same test protocol. For those dwellings in the UK that were tested as part of the Technology Strategy Board's BPE Programme, all dwellings were required to undergo an electric coheating test in accordance with the Leeds Beckett University (formerly Leeds Metropolitan University) test method (see Wingfield et al., 2010). For those dwellings located in the UK that did not participate in the programme (Ford Close) or those dwellings constructed abroad (Darmstadt, Heusden-Zolder and Passive House Disc), the adoption of this test method was not compulsory, so an alternative or a variant of this test method may have been used instead. This potential variation between the test methods may lead to some additional uncertainty associated with the test data and the test result obtained.

Further complexity arises because the majority of the tests were undertaken by different testing teams, all with very different levels of testing experience. Consequently, there is a potential risk that this inconsistency in experience may lead to some uncertainty with regard to the results that have been obtained and their interpretation.

It is important to acknowledge that the uncertainty figures stated in Table 3 do not account for any measurement, systematic or random errors associated with undertaking the electric coheating test. Instead, they only account for the error associated with the regression model used to analyse the empirical data obtained from the test. Despite this, a limited amount of work has been undertaken in the UK to investigate the robustness of the electric coheating test method.

Table 3: Electric coheating test results for the Passivhaus dwellings. *The error stated within this column relates to the error associated with the regression model used to analyse the empirical data obtained from the test.

Dwelling	Predicted HTC in W/K	Measured HTC in W/K*	Absolute difference in HTC in W/K (%)	Within total maximum error range (±15.5%[1])
Camden Passivhaus	66.0	56.0 ±5.0	-10.0 (-15.2)	No
Ford Close	45.6	50.4	4.8 (10.5)	Yes
Future Works Passivhaus Larch house	57.6	62.0 ±4.0	4.4 (7.6)	Yes
Future Works Passivhaus Lime house	37.2	45.0 ±2.0	7.8 (21.0)	No
Lancaster Co-housing	40.0	47.3 ±0.5	7.3 (18.3)	Yes
Racecourse Development Dwelling 1	40.3	46.7 ±0.5	6.3 (15.7)	Yes
Racecourse Development Dwelling 2	35.8	38.1 ±0.5	2.2 (6.2)	Yes
Darmstadt, Germany	92.4	94.8 ±2.4	2.4 (2.6)	Yes
Deinze, Belgium	-	-	-	
Heusden-Zolder, Belgium	-	-	-	
Passive House Disc, Austria	60.0	59.9 ±1.2	0.1 (-0.2)	Yes

[1] This figure is based upon the average error observed by Butler (2013).

In a series of round-robin tests funded by the NHBC Foundation (see (Butler 2013)), broadly similar results were obtained by six different teams, when they tested the same dwelling for a different 2-week testing period. This is despite the teams having differing levels of experience, utilising different equipment and utilising different testing and analysis methods. The Heat Transfer Coefficient (HTC) measured by the teams for the test dwelling varied between 56.7 to 78.0 W/K (-11.7 W/K to +9.6W/K, equating to -17% to +14% of the calculated steady-state value of 68.4 W/K), resulting in average difference of 10.6 W/K (±15.5%). These results suggest the electric coheating test method appears to be relatively robust.

In addition, recent work undertaken by Jack *et al. (Jack 2017)*, based upon the same round robin tests, investigated the uncertainty associated with three of the key measurements undertaken during an electric coheating test (internal/external air temperature difference, electrical power consumption and solar radiation), as well as the uncertainty associated with utilizing different regression analysis methods. It was found that if a 'best-practice' coheating test method and properly calibrated sensors were used, then the estimated general uncertainty in the HTC measurement of the test dwelling would be ±8%, equating to 5.5 W/K. Although these results are based upon a series of measurements undertaken on only one dwelling with a calculated HTC of 68.4 W/K, they suggest that the uncertainty associated with the electric coheating test is likely to range from ±8 % to ±15.5 %.

During the electric coheating test periods in both dwellings at Deinze and Heusden-Zolder, Belgium (Manioglu 2007), ((Meulenaer 2005) a number of issues were encountered which could have unduly influenced the results obtained. At both dwellings, the indoor climate was disturbed during the test period due to unexpected internal activity, there was uneven distribution of heat within different rooms of the dwellings, there was temperature stratification within the rooms and both dwellings suffered from experimental overheating caused by solar gains through the windows of the dwellings. Furthermore, as no comparable HTC figures have been published, it has not been possible to insert the results into Table 3 and Figure 3. Consequently, both results have been excluded from any further analysis of the electric coheating data.

Interestingly and for the point of record, the only published figures available relate to a space heating energy use for the Deinze dwelling, which is almost twice the calculation result of 15 kWh/m^2 per annum, and for the Heusden-Zolder dwelling, a whole building average measured U-value that is claimed to be lower than that calculated.

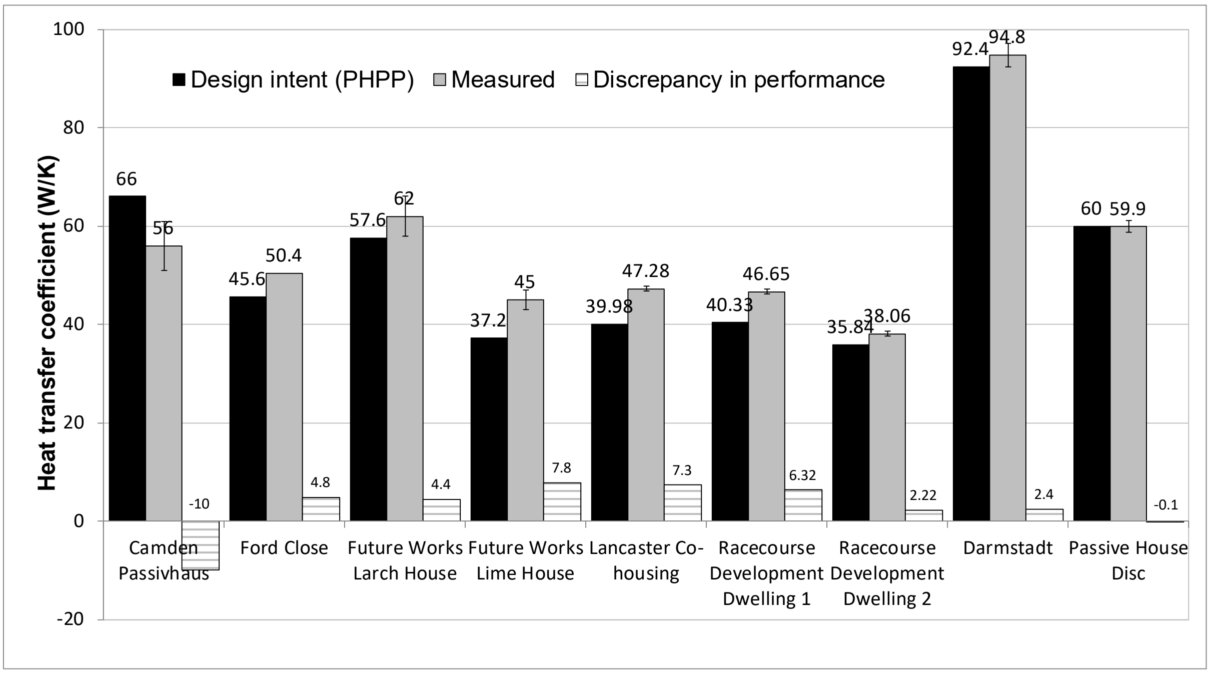

Figure 3: Design intent and measured heat transfer coefficient (HTC) for each of the Passivhaus dwellings. The error incorporated within this figure relates to the error associated with the regression model used to analysis the empirical data obtained from the test.

It is clear from Table 1 and Figure 3 that a wide range of building fabric thermal performance has been measured across the PH dwellings. This is not surprising, given the more than two-fold variation in the size of the dwellings and the differences in form factor. However, one of the most important observations is that the majority of the measurements (6 out of 8) are within the total maximum error margin currently attributed to the electric coheating test method (±15.5%). The performance of the remaining two dwellings, Camden Passivhaus and Future Works Passivhaus Lime House, lie just outside of this range of expected uncertainty (see Figure 4). Therefore, the data suggests that it is possible to construct PH dwellings that, in terms of building fabric thermal performance, perform pretty much as the design originally intended.

Further analysis of the data contained within Table 3 reveals that although there is some variation in the absolute size of the difference between the design intent and the measured *in situ* performance for the PH dwellings, which ranges from -10 W/K (15 %) for the Camden Passivhaus, to just under 8 W/K (just over 20 %) for the Future Works Lime House, the absolute difference in the measured HTC is still very small. On average, the absolute difference in performance is only 3 W/K.

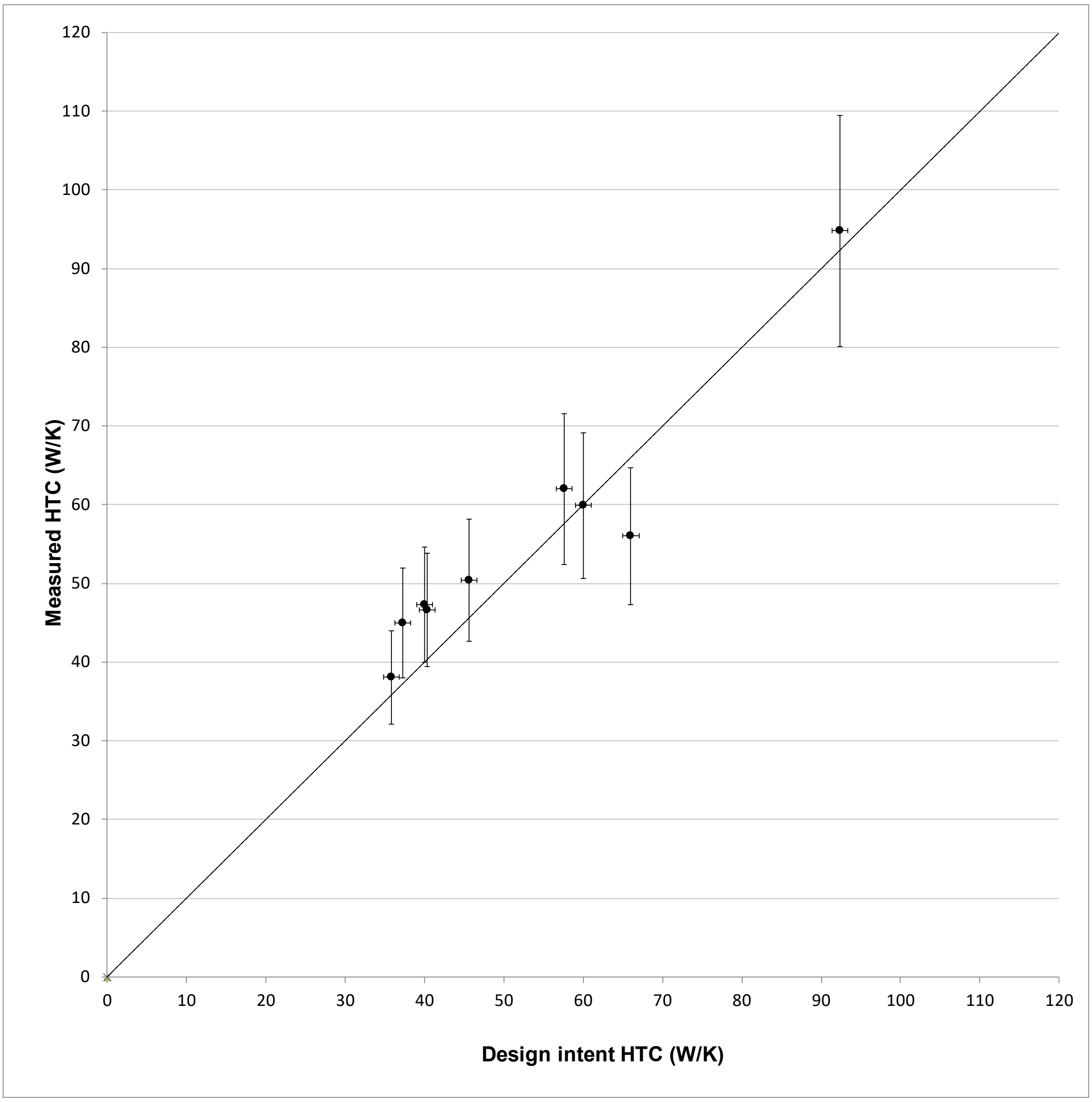

Figure 4: Design intent versus measured heat transfer coefficient (HTC) for each of the Passivhaus dwellings. The solid line assumes a perfect match between design intent and measured performance. The error bars assume a maximum total uncertainty of ±15.5 %.

To put these results in context, Figure 5 compares the electric coheating test results for the PH dwellings against the test results obtained from 27 new build dwellings contained within the Leeds Beckett University Electric Coheating Test Database. For more information see (Johnston 2016), there a similar presentation of the data is shown like in Figure 3. This database, represents one of the most comprehensive and extensive databases of its kind and incorporates a wide range of new build dwellings which vary in terms of size, age, form factor and construction type.

All of the new build dwellings incorporated within Figure 5 were, as a minimum, designed to meet, and in many cases exceed, the fabric requirements of Part L1A of the UK Building Regulations 2006 (NBS 2006). The results illustrate that the Passivhaus dwellings are not only the best performing dwellings in the sample, but they also, in the main, consistently perform as predicted. This cannot be said for their non-PH counterparts. In fact, in a number of cases, a significant *'performance gap'* has been measured in the non-PH dwellings, which is considerably outside the error margins associated with the electric coheating test. In overall terms, the average fabric *'performance gap'* for the non-PH dwellings equates to 47.9 W/K, representing a discrepancy of almost 50%. Reasons for the deviations could be attributable to poorer quality building fabric of the non-PH.

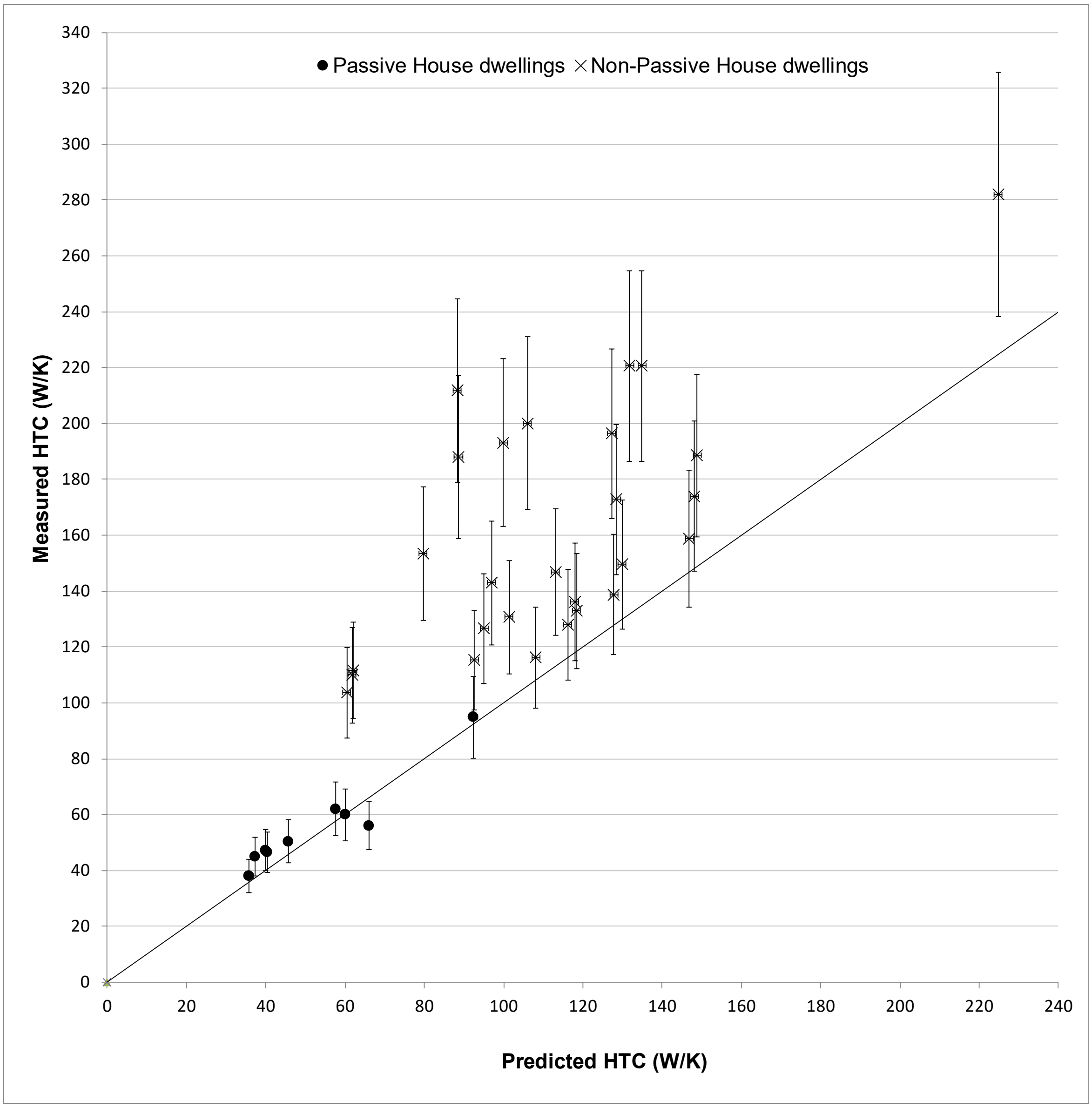

Figure 5: Measured versus steady-state predicted heat transfer coefficient (HTC) for each of the Passivhaus dwellings and the Leeds Beckett new-build coheating database. The solid line assumes a perfect match between design intent and measured performance. The error bars assume a maximum total uncertainty of ±15.5%.

2.2 Measured *in situ* U-values

In addition to the electric coheating tests, the literature review process revealed that a number of heat flux density measurements had also been undertaken on some of the PH dwellings (see Table 4). These measurements were undertaken to determine the *in situ* U-value of various plane elements of the dwellings, primarily the external walls, ground floor and roof. In the majority of cases, the heat flux density measurements comprised a single spot measurement that was undertaken in accordance with ISO 9869-1:2014 (BSI, 2014). Consequently, the total uncertainty associated with the heat flux density measurements is somewhere between the quadrature sum and arithmetic sum of the errors, namely ±14% to 28% (BSI, 2014). It is also important to note that as building elements exhibit heterogeneous heat flow across their surfaces, the spot measurements that were undertaken may not necessarily be representative of the performance of the element as a whole (BRE 2014), (Pelsmakers 2017). Additionally, as ISO 9869-1:2014 was devised to measure one dimensional heat flow, the heat flux density measurements were undertaken, as much as possible.at undisturbed elements of the construction where the heat flux could be seen as one dimensional, as a good approximation.

The results obtained from the heat flux density measurements are detailed within Table 4. As all of the measurements were undertaken in accordance with ISO 9869-1:2014 (BSI, 2014), it has been assumed that the total uncertainty associated with the measurements is at most ±28%. As can be seen from these Tables, the majority of the measurements were undertaken on the external walls of all of the UK dwellings, with a much smaller sample of measurements being undertaken on the ground floor and roofs of the dwellings. In addition, in only one of the developments, the Racecourse Development, measurements were also undertaken on both sides of the party wall between Dwellings 1 and 2. As with the electric coheating tests, all of these measurements were undertaken in the UK as part of the Technology Strategy Board's BPE programme.

Table 4: Heat flux density measurements for the external walls, ground floors and roofs of the Passivhaus dwellings.

Dwelling	Design U-value W/m^{2}K	Measured U-value W/m^{2}K	Difference in U-value W/m^{2}K (%)	Within error range (±28%)
EXTERNAL WALL				
Camden Passivhaus	0.122	0.097 ±0.03	-0.025 (-20.5)	Yes
Dormont Park	0.100	0.120 ±0.03	0.020 (20.0)	Yes
Dungannon Passivhaus Dwelling 1	0.125	0.156 ±0.04	0.031 (24.8)	Yes
Dungannon Passivhaus Dwelling 2	0.125	0.158 ±0.04	0.033 (26.4)	Yes
Future Works Passivhaus Larch house	0.095	0.120 ±0.03	0.025 (26.3)	Yes
Future Works Passivhaus Lime house	0.095	0.108 ±0.03	0.013 (13.7)	Yes
Knights Place Flat A	0.122	0.230 ±0.06	0.108 (88.5)	No
Lancaster Co-housing	0.120	0.180 ±0.05	0.060 (50.0)	No
Plummerswood	0.094	0.140 ±0.04	0.046 (48.9)	No
Racecourse Development mean of Dwelling 1	0.100	0.120 ±0.03	0.020 (20.0)	Yes
Rowan House Flat B	0.122	0.200 ±0.06	0.078 (63.9)	No
Tigh-Na-Cladach Passivhaus	0.095	0.120 ±0.03	0.025 (26.3)	Yes

Wimbish Passivhaus Plot 6	0.090	0.130 ±0.03	0.040 (44.4)	No
Wimbish Passivhaus Plot 9	0.090	0.150 ±0.04	0.060 (66.7)	No
Wimbish Passivhaus Plot 11	0.090	0.162 ±0.05	0.072 (80.0)	No
GROUND FLOOR				
Camden Passivhaus	0.103	0.099 ±0.03	-0.004 (-3.9)	Yes
Future Works Passivhaus Larch house	0.103	0.099 ±0.03	-0.004 (-3.9)	Yes
Lancaster Co-housing	0.110	0.140 ±0.04	0.030 (27.3)	Yes
Plummerswood	0.119	0.300 ±0.08	0.181 (152.1)	No
Racecourse Development mean of Dwelling 1	0.100	0.100 ±0.03	0 (0)	Yes
Tigh-Na-Cladach Passivhaus	0.095	0.120 ±0.03	0.025 (26.3)	Yes
ROOF				
Dormont Park	0.100	0.120 ±0.03	0.020 (20)	Yes
Lancaster Co-housing	0.100	0.090 ±0.03	-0.01 (-10.0)	Yes
Racecourse Development mean of Dwelling 1	0.090	0.130 ±0.04	0.04 (44.4)	No
Tigh-Na-Cladach Passivhaus	0.094	0.160 ±0.05	0.066 (70.2)	No

In the majority of the measurements undertaken on the external walls, ground floors and roofs (15 out of 25), the measured *in situ* U-values were within the total uncertainty associated with the measurement method (±28%). However, ten of the twenty five measurements were outside the uncertainty associated with the measurement method. Although the specific reasons why these measurements lie outside the uncertainty limits are not known, it is recognized that it is very difficult to quantify such differences in *in situ* U-values, when the U-values are so low.

Closer analysis of the data contained within Table 4 reveals that the size and range of the difference between the design intent and measured *in situ* U-values varies in percentage terms, from -20.5% for the external walls at the Camden Passivhaus to 80% for the external walls at Plot 11 of the Wimbish Passivhaus. It is also important to note that considerable caution should be exercised when using such a metric, as this tends to unfairly penalise well insulated dwellings due to the very low design intent U-values that tend to be specified for PH dwellings.

A more appropriate metric for comparative purposes would be to use the absolute difference in U-value between the *in situ* measurement and the design intent. Using such a metric results in a very small absolute difference in U-value for all of the elements tested, ranging from -0.025 W/m^{2}K to 0.072 W/m^{2}K. However, it is also clear from the data that although the absolute differences are small, as the dwellings are all well-insulated, the error margins are comparatively high and range from ±0.03 to ±0.08 W/K. In comparison, recent work published by Gupta and Kotopouleas (Gupta 2018) found a much larger discrepancy in the performance of the external walls of low energy dwellings in the UK. Based upon measurements undertaken on 48 dwellings the discrepancy was 0.07 W/m^{2}K. For roof structures, based upon a smaller subset of measurements undertaken in only 15 low energy dwellings, a deviation of 0.10 W/m^{2}K was found. This suggests that, in the UK at least, PH dwellings are performing better and closer to their design intent than their low energy counterparts.

2.3 Infra-red thermography

As a qualitative measure of performance, infra-red thermography was also undertaken in all of the UK PH dwellings and on one of those constructed abroad (Deinze). Overall, the thermography revealed the dwellings performed very well, with no significant areas of unexpected heat loss being identified. However, there were a number of areas where small amounts of unexpected heat loss had been identified that are only likely to have had a marginal effect on the measured HTC. The most common issue was air leakage or thermal bridging around external windows and doors (Camden, Dormont Park, Dungannon, Knights Place, Plummerswood, Racecourse Development both dwellings, Rowan House (dormers), Tigh-Na-Cladach, and Wimbish).

In a smaller number of dwellings, thermal bridging was observed at the sloping roof section in the kitchen at Camden, the ceiling at Dungannon, Lancaster CoHousing and both Future Works Passivhaus dwellings, the overhead roof section above the balcony at Ford Close and at the external wall/eaves junction at Ford Close and Lancaster Cohousing. At Ford Close, some thermal bridging was also observed at the timber framing of the gable external wall and at a small section of the party wall in the front bedroom (Fox 2012).

A small amount of air leakage was also observed around service penetrations at Dormont Park (Glasgow School of Art, 2015). At Knights Place, a thermal bridge and some possible air leakage was observed at the kitchen cavity wall next to the landlord’s corridor (Gale 2014a). At Deinze, the only area of unexpected heat loss was some air leakage that was observed around steel column next to the window (Manioglu 2007).

It is noted that PH buildings are not required, or expected, to be completely airtight, nor are they expected to completely eliminate localised thermal bridging. This means that the residual exfiltration (n_{50}-values typically between from 0.2 to 0.6 h^{-1}) and localised thermal bridging observed during these comprehensive thermographic surveys can be expected to fall within the expected range and do not constitute a specific failing.

3 In-use space heating energy performance

3.1 Statistical basics

In order to compare design and *in situ* measured space heating energy demand, it is important to understand the accuracy of any measurement undertaken and to be able to calculate the associated margin of error. The accuracy of space heating energy demand calculations in PH buildings, discussed earlier, is expected to be ±3 kWh/(m²a).

Origin of errors

In general, the sources of errors can be separated into statistical and systematic errors. Statistical errors can be reduced if the measurement period is prolonged (e.g. several years instead of one) or the number of measurements is enlarged (e.g. different measurement instruments or lots of values instead of one). Systematic errors, on the other hand, cannot be reduced if the reason for its occurrence is unknown. A short practical guideline for monitoring the energy consumption of buildings was published in the European FP7 project SINFONIA by Peper (Peper 2015). This formed the basis for monitoring approximately 500 dwelling units in the city of Innsbruck and Bolzano. Further literature on measurement accuracy and avoidance of errors can be found e.g. in (Schnieders 2012).

In order to be able to devise generalized statements about the performance of energy standards, it is very important to consider the results from more than one building. Even when the measurement error is small, because it was done very carefully, users can exert considerable influence on the buildings energy consumption. The influence of occupant behaviour on energy consumption was tested in the field during the 1980's by Lundström et al. (Lundström 1986). Lundström's study, where two families were moved between dwellings, demonstrated that the energy consumption of an individual building can change significantly when users move out and other uses move in – all things being equal, the consumption profile is in effect "moved" from one building to another. Therefore, in order to be able to deduce general statements about the space heating performance, the space heating energy consumption of a number of dwellings built to a similar build quality would be expected to be consistent with a normal or Gaussian distribution (see Figure 6). This distribution has then been used to undertake statistical analysis of the data to determine statistical parameters such as the mean value μ and the standard deviation σ associated with the space heating demand.

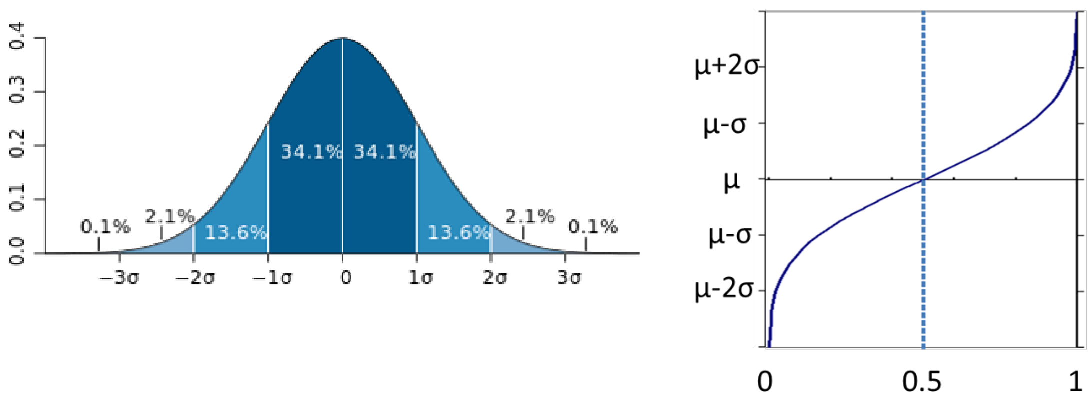

Figure 6: Probability density (left) and distribution function (point reflected, right) for a Gaussian normal distribution with a mean value μ and a standard deviation σ.

In natural science and technology, there are many quantities that have a random distribution. It's also not rare, that such distributions have high standard deviations, sometimes higher than the average values; one example is the velocity distribution in a gas: Although different molecules might have extremely different kinetic energy (ranging from zero to several times of 3/2 *kT*), the average kinetic energy is well defined and can, in any huge sample, be measured very accurately. If there is a high spread in measured results of a quantity, we can use this statistical method to separate out the systemic properties of the sample, given by the average μ of the quantity and the amount of random influences, for which the standard deviation σ is a measure. In our case, considering a sample of buildings with (as far as possible) an equal standard of energy efficiency, the efficiency standard can be checked by measuring the average consumption. All random influences, including those of the occupants, but also possible random distribution of e.g. different n_{50}-values, will contribute to the value of σ. The bigger the sample n, the more accurately the mean value will represent the expected value of energy consumption. The uncertainty in this mean value is not to be mixed up with the standard deviation. The standard deviation is a measure for the broadness of the distribution (random influence) whereas the uncertainty of the mean value depends also on the number n of individual objects in the sample. It is given by $\Delta\mu = \sigma/n^{0.5}$ (for the "1 σ" confidence interval).

3.2 Statistical evaluation of measured space heating data

Long-term occupant experiences and statistically verified in-use energy consumption data are available for a number of PH developments. As with all building standards, it is common to find significant differences in energy use, even in the case of almost identically designed and sized buildings. This has been known for some time (Lundström1986). Although there are a range of occupancy related factors that can influence space heating demand, such as the time and frequency of opening windows, levels of internal heat gains (electrical appliances, etc.), the most important occupant related factor that determines the space heating demand is the indoor temperature. This is important, as a number of assumptions are made in energy calculation tools regarding the indoor operative temperature. This temperature has a high influence on measured results.

As patterns of behaviour are randomly distributed, space heating energy demand calculations undertaken in advance of construction always have to assume boundary conditions. These include factors such as the average set-point temperature for heating and the frequency of window opening by users. At design stage, these assumptions can only make use of average figures according to the available knowledge. For this reason, the PHPP makes considered assumptions about appropriate boundary conditions. In occupied dwellings, because most of the actual boundary conditions will tend toward a "higher" or "lower" setting or frequency, the energy consumption of an individual dwelling will rarely match the calculated result.

With the above in mind, comparison between predicted energy demand and measured energy consumption can only be made using average values. If the boundary conditions of the calculation are not a good approximation of the average values experienced in the field, then there will be a deviation between the measured average and the predicted value. However, if relevant boundary conditions are also monitored in the field, a comparison between the design intent assumed condition and the actually measured values in the field, can be made – this leads to so called normalized (post monitoring) energy balance calculations.

The prerequisite for the comparison of calculation and measurement was the exact analysis of heat consumption. For these buildings, monitoring including heat generation and heat transfer lossest. Measurements were based on total energy input (final energy) for the building. In this case, the energy consumption after the heat generator was also recorded (e.g. when natural gas is used) with heat meters. The proportion of heat losses associated with the heat distribution pipes outside the thermal envelope (e.g. in the basement), and the partially usable waste heat (inside the thermal envelope), was also measured or calculated.The following field monitoring studies compare the calculated design intent obtained from PHPP, calculated and published in the certificate before the buildings had been constructed, with the average space heating monitored in the development after occupation. After occupancy the standard deviation and the accuracy Δμ = σ/n0.5 associated with the mean value are documented in each of these field studies (Feist 2004) (Kah/Feist 2008). The measurement equipment and evaluation of each field study have been documented and are published in the individual monitoring reports, which have been cited for each of the developments.

Passive House settlement in Wiesbaden/Dotzheim

The PH settlement in Wiesbaden/Dotzheim (Figure 7) was the first large scale PH project in Germany. It was built in 1997 by Rasch & Partner and comprises 22 houses (Ebel et al.2003), (Feist et al. 2000). Figure 8 presents the results obtained from the heat meter readings for the 1998/99 winter. Heating is provided by a small district heating system in this development.

Figure 7: External views of the PH settlements in Wiesbaden/Dotzheim, Hanover/Kronsberg and Stuttgart/Feuerbach (left to right)

The average space heating consumption for the whole development, derived by fitting a Gaussian distribution function, was 13.4 kWh/(m²a) with a standard deviation of 5.3 kWh/(m²a), which equates to 40% of the mean space heating demand. The error associated with the mean value is therefore ±1.1 kWh/(m²a). The average consumption correlates well with the previously calculated design intent of 13 kWh/(m²a) obtained from the design-PHPP sheets published prior to construction. It is important to note that there are dwellings on the development with higher consumption as well as dwellings with lower consumption, as is to be expected from a random distribution of user behaviour.

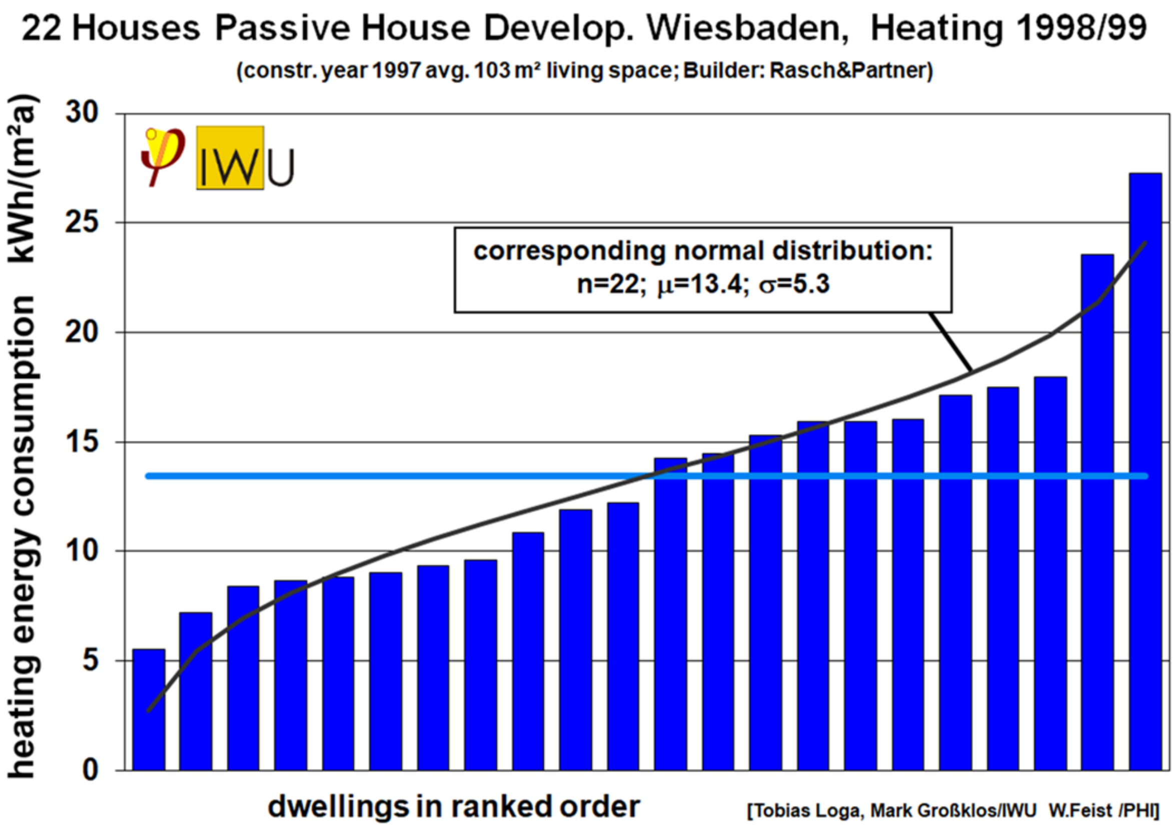

Figure 8: Consumption statistics for the PH settlement in Wiesbaden (Germany) and the corresponding Gaussian distribution, resulting in an average space heating energy consumption of 13.4 kWh/(m²a). (Ebel et al. 2003, Feist et al. 2000)

PH settlement in Hanover/Kronsberg

The PH settlement in Hannover/Kronsberg, which was built in 1998/99 as part of the Europe-wide CEPHEUS project (Schnieders 2003), (Schnieders 2006), (Feist et al. 2005), consists of 32 terraced houses built from mixed construction (concrete separation walls and floors, timber facades and roofs) (Peper/Feist/Kah 2001). The settlement was designed by architect Petra Grentz, and the development was built by Rasch & Partner. All of the buildings on the development are connected to a district heating system. Figure 9 documents the heat meter readings in the heating season of 2001/2002 (Peper 2002), (Feist et al. 2005). The average space heating consumption was 12.8 kWh/(m²a) **and** exhibits a standard deviation of 6.6 kWh/(m²a), resulting in a mean uncertainty of ±1.2 kWh/(m²a) (Peper 2002). The calculated space heating demand according to PHPP was 13.5 kWh/(m²a), which lies well within the measured value of 12.8 ±1.2 kWh/(m²a). These results compare favourably with average measured values of 14.9 kWh/(m²a) during 1999/2000 and 13.3 kWh/(m²a) in 2000/2001. Note the relatively small first year effect in this field monitoring. The investigation of thermal bridges and air leakages showed very good agreement with the expectations (Peper/Feist 2001). Another examination showed that the airtightness of the buildings (using a well thought-out airtightness concept) convinces by resulting in a high durability (Peper/Kah/Feist 2005).

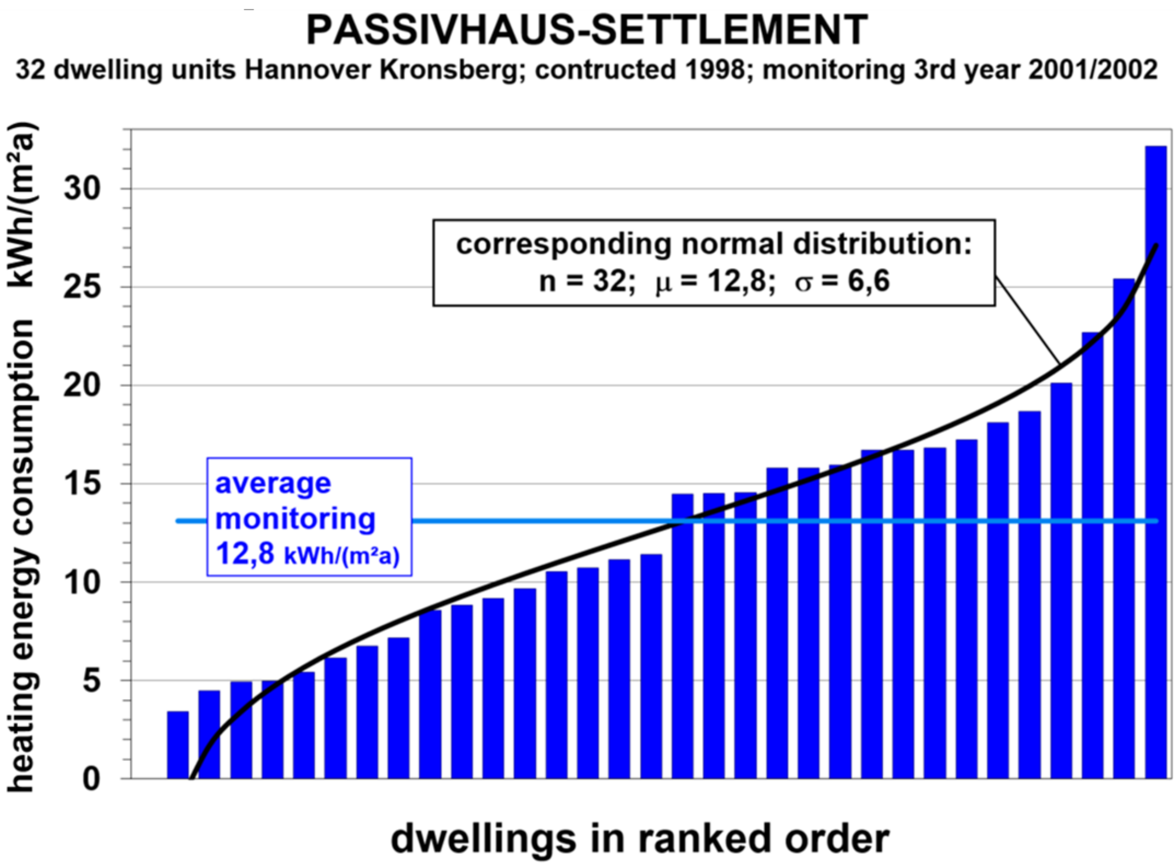

Figure 9: Space heating energy consumption statistics for the PH settlement in Hanover/Kronsberg (Germany). (Peper/Feist 2002)

PH settlement in Stuttgart/Feuerbach

The PH development in Stuttgart Feuerbach, which was completed in 2000, comprises 52 terraced and detached houses designed by architects Rudolf & Rudolf. Figure 10 documents the space heating demand for the 2001/2002 heating season. In this housing development, there were a few dwellings that were identified as being outliers (due to failure in the heat pump control systems), and as such, these were not included in the Gaussian fit. The resultant average space heating demand for the development was 14 kWh/(m²a), including the outliers. The μ-value of the corresponding Gaussian distribution is 12.8 kWh/(m²a), with a standard deviation of 5.5 kWh/(m²a) resulting in an uncertainty of ±0.8 kWh/(m²a) (Reiß/Erhorn 2003). The predicted design phase space heating demand according to PHPP, and published in the certificate, was 13.5 kWh/(m²a). This figure lies within the error range of the measured consumption, whether including or excluding the outliers.

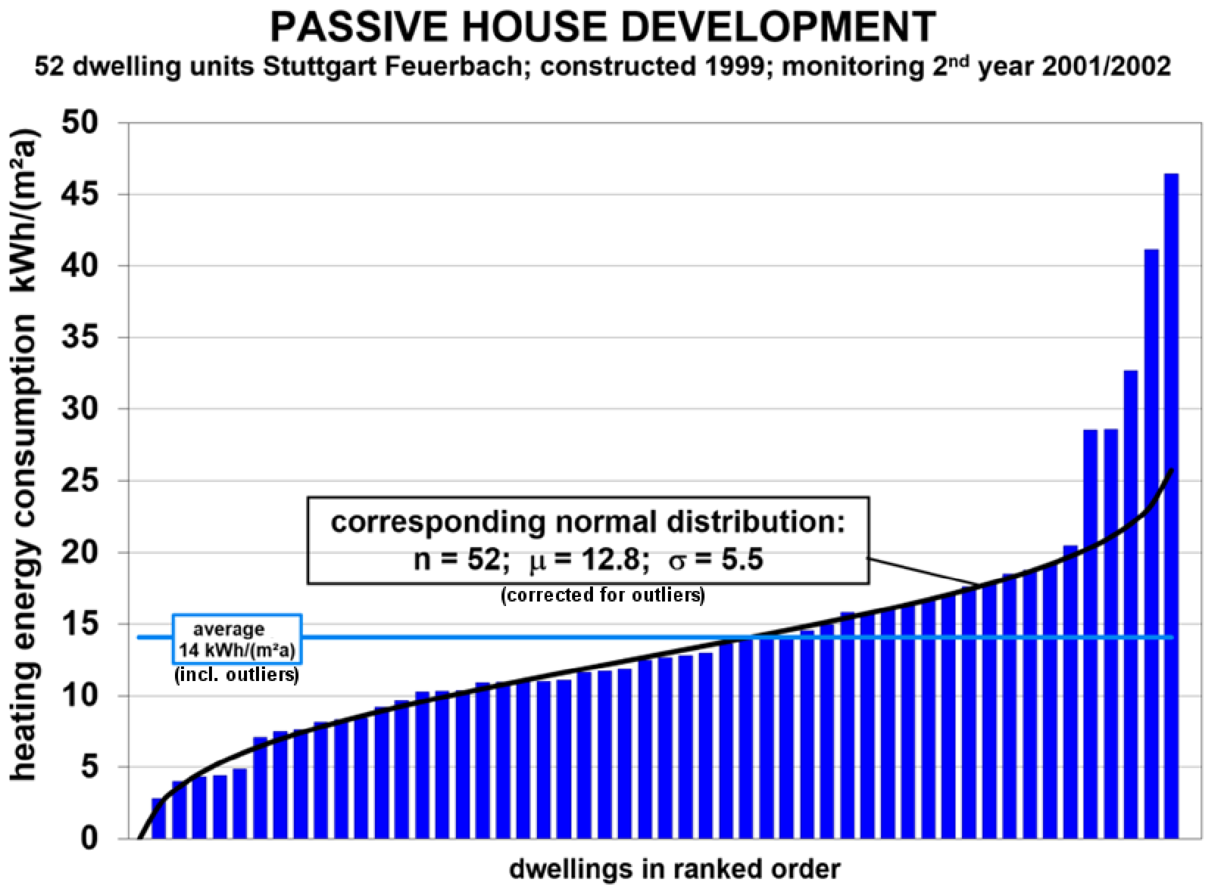

Figure 10: Consumption statistics for the PH development in Stuttgart/Feuerbach (Germany). (Data from (Reiß/Erhorn 2003), analysis and diagram by the authors; obvious outliers are easily identified – these are due to defect heat pump control systems: five bars on the right end)

For reference: Energy consumption of early low energy buildings, Niedernhausen

In order to demonstrate that occupied buildings with less challenging energy performance standards result in similar distribution patterns to PH dwellings, the results for a low-energy settlement in Niedernhausen, Germany (Loga, Müller, Menje 1997), are shown in Figure 11. As can be seen, the average annual space heating consumption in 1994, based upon heat meter readings measured for all homes, was 65 kWh/(m²a). The standard deviation here is 13.6 kWh/(m²a), much higher than in the PH samples. The mean value exhibits an uncertainty of ±2 kWh/(m²a). The standard deviation for this settlement is 21% of the average consumption value.

The national average space heating demand of the existing housing stock in Germany was 126 kWh/(m²a) (2014-2017) (Ziesing 2018), (BMWi 2018). It can be seen that the average annual space heating at Niedernhausen is considerably lower than the national average. In fact, compared to the national average stock, the *energy savings achieved* by the low energy standard buildings are 48±2 %, whilst the PH developments compared to the low energy ones are 79±3 % and 88±1 % compared to the national average.

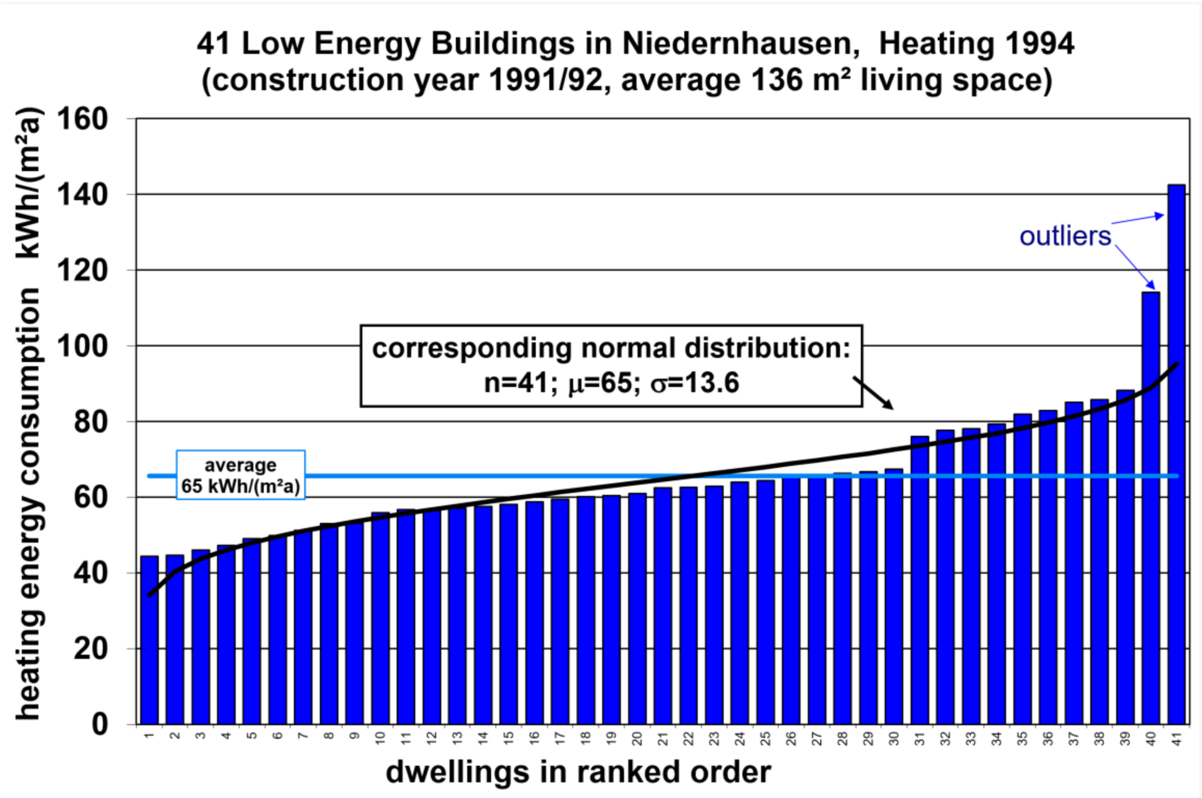

Figure 11: Annual space heating attributable to 41 low energy houses in Niedernhausen, Germany. The curve added in the diagram is the respective normal distribution. (Loga, Müller, Menje 1997).

Conclusion regarding statistical evaluation of housing developments

It is clear from Figure 8 to Figure 11 that the measured annual space heating energy consumption associated with all of the developments approximately follow a Gaussian distribution, enabling statistical error analysis to be undertaken. A comparison of the mean measured space heating consumption for the three PH developments (in total 106 dwellings), and the one low energy development (41 dwellings), clearly illustrates a significant difference between these values (see Figure 12. Although the highest measured space heating in one individual PH dwelling is comparable to the lowest consumption in one of the low-energy dwellings, a comparison of the mean values (horizontal blue lines) highlights a significant difference between the PH and the low-energy dwellings. The average measured space heating consumption of the three PH projects are very close to each other and satisfy the PH standards space heating demand criteria. When the performance of the PH developments is compared to the performance of the low-energy development, a saving of 79±3 % in space heating energy consumption has been achieved. In addition, the errors associated with the mean space heating values are very small (0.8 – 1.5 kWh/(m²a) for the PH developments and 2.1 kWh/(m²a) for the low-energy buildings in Niedernhausen) compared to the differences between the standards.

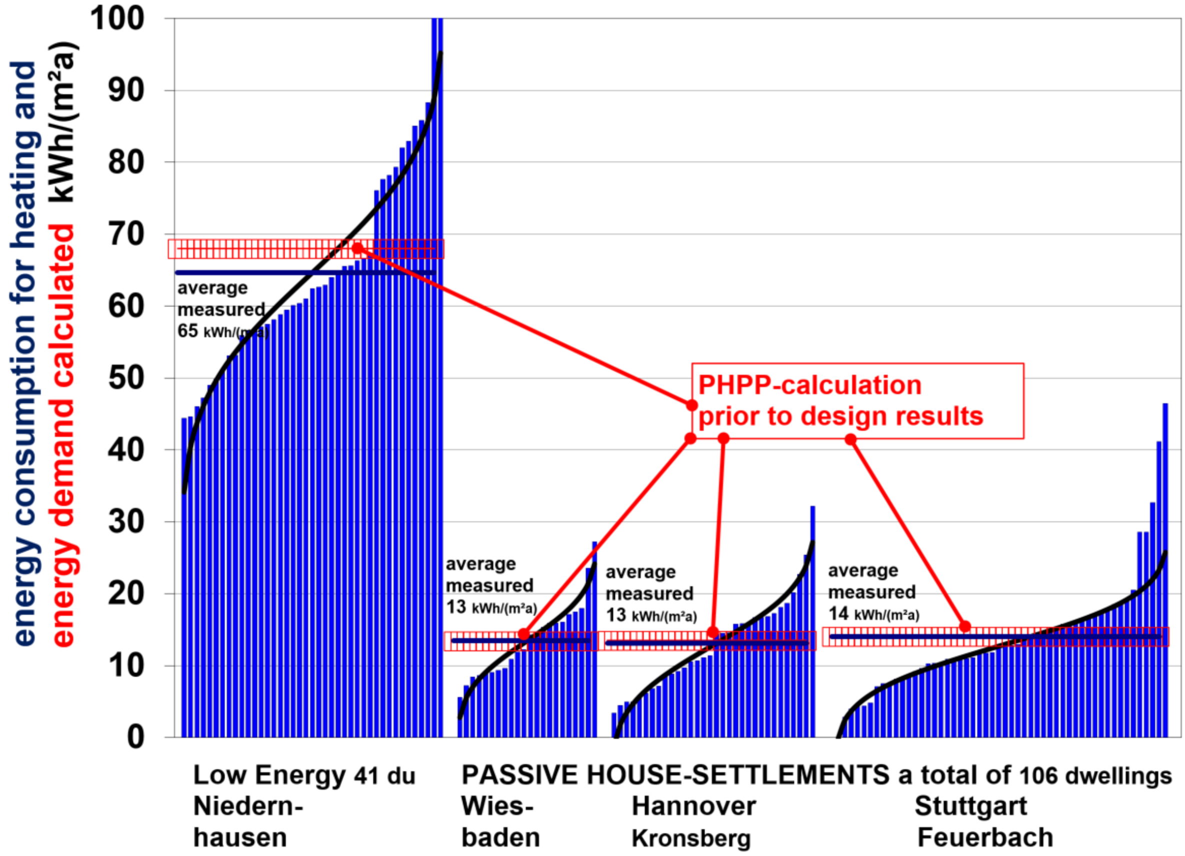

Figure 12: The measured space heat consumption of four different housing developments, a low-energy settlement (left) and three PH developments. PHPP heating energy demand values calculated during design (published prior to construction) also shown for comparison.

3.3 Performance evaluation of Passive Houses

The measured space heating energy consumption of more than 2000 newly built PH dwellings, and nearly 300 retrofitted dwellings that incorporate PH components, have been collated by Peper *et al.* (Peper/Feist 2015) and are illustrated in Figure 13. It includes: the aforementioned projects; the world's largest PH development in Heidelberg - "Bahnstadt", which was monitored at both block and building level; and over 600 dwellings from Vienna and Innsbruck (Austria). Figure 13 also incorporates the results obtained from a Passivhaus Trust study of 31 dwellings from the UK (PH Trust 2017 and Mitchel 2018), along with the results of an evaluation of a funding initiative undertaken in the state of Hesse, Germany of 166 EnerPHit projects (Kessler 2017). EnerPHit is the established Standard for refurbishment of existing buildings using Passive House components. Despite the slightly higher energy demand, it offers virtually all the advantages of the Passive House Standard. The EnerPHit Classes of Classic, Plus or Premium can be achieved depending on the use of renewable energy sources. However, it is important to note that there are differences in the level of disaggregation of the space heating data that has been measured and incorporated within this figure. For instance, in most of the larger projects, the space heating consumption was only available at an aggregated building level, rather than at the level of the individual dwellings. Despite this, the available data indicates that the mean space heating consumption for the approximately 2000 newly built PH dwellings is approximately 14.6±1.8 kWh/(m²a).

For comparison, the mean space heating energy consumption in Germany in 2014-17 was approximately 126 kWh/(m²a) (Ziesing 2018), (BMWi 2018) which is almost twice the mean value measured at the low-energy housing development at Niedernhausen (discussed earlier). The results also indicate that the PH Standard is capable of achieving extremely high space heating energy savings in a verifiable and reproducible manner. These savings equate to nearly 90 % compared to older existing buildings (Ziesing 2018), (BMWi 2018) and approximately 80 % on average when compared with the legally stipulated requirements for new buildings in Germany.

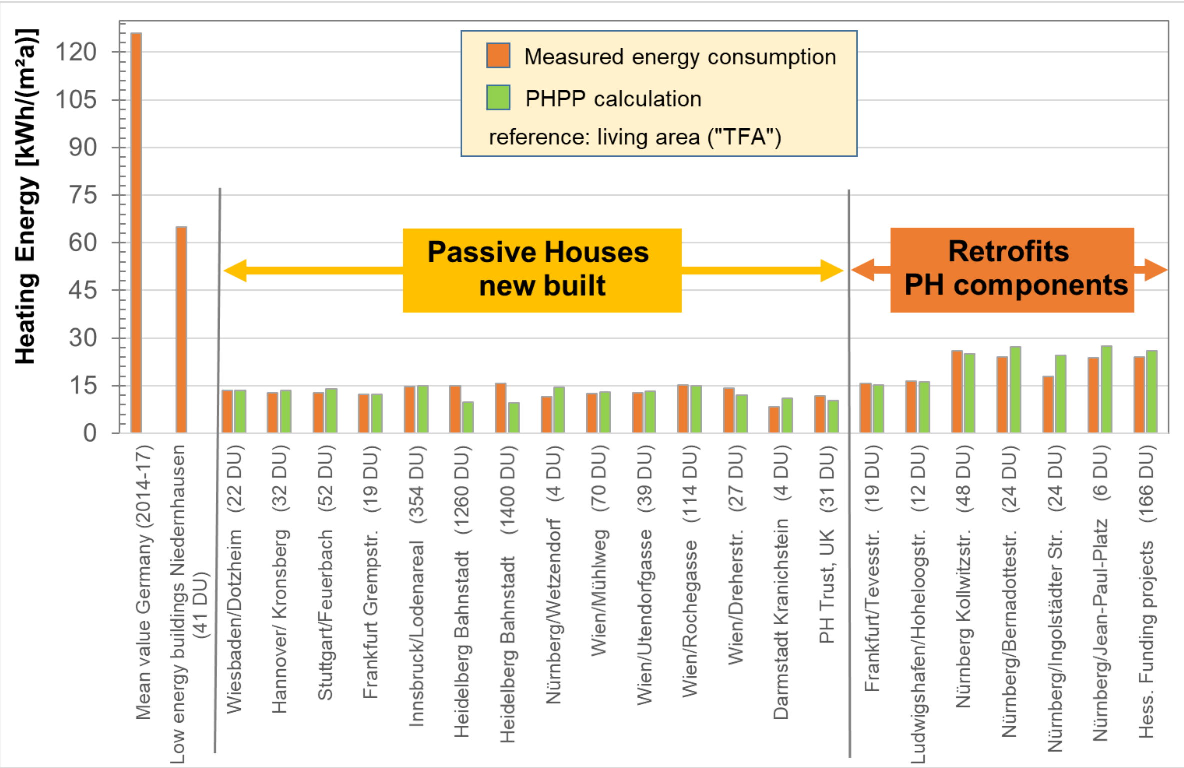

Figure 13: **Collection of measured specific annual space heating energy consumptions for several new built and retrofitted PH building projects, a low-energy project and the mean value for existing dwellings in multifamily buildings in Germany. For the PH and EnerPHiT projects, the PHPP demand calculations are shown as green columns.**

In Figure 14, the annual space heating energy consumption attributable to all of the PH dwellings incorporated within Figure 13 is plotted against the demand calculation produced by PHPP. The angle bisector (dashed line) is depicted for the case of a perfect match, and an error of ±2.0 kWh/(m²a) and uncertainty of ±3 kWh/(m²a) is assumed for the demand prediction, as discussed at the beginning of this paper. Limits for PH and the retrofit standard EnerPHit are depicted with dotted lines. It can be seen that all but four of the projects are within the expected error range, with two being above, and two being below. In comparison, it would be expected that in general, 1/3 of the results would statistically lie outside the standard deviation. This data, which has been obtained from more than 2000 dwellings, suggests that in terms of space heating energy demand, PH dwellings, in the main, perform as the design originally intended, i.e. there is no noteworthy ‘performance gap’ for this sample. It is important to note, that in all cases, *all* dwellings within a given development have been included in the statistics. Consequently, all samples are full evaluations of the given data, so bias was avoided as far as possible.

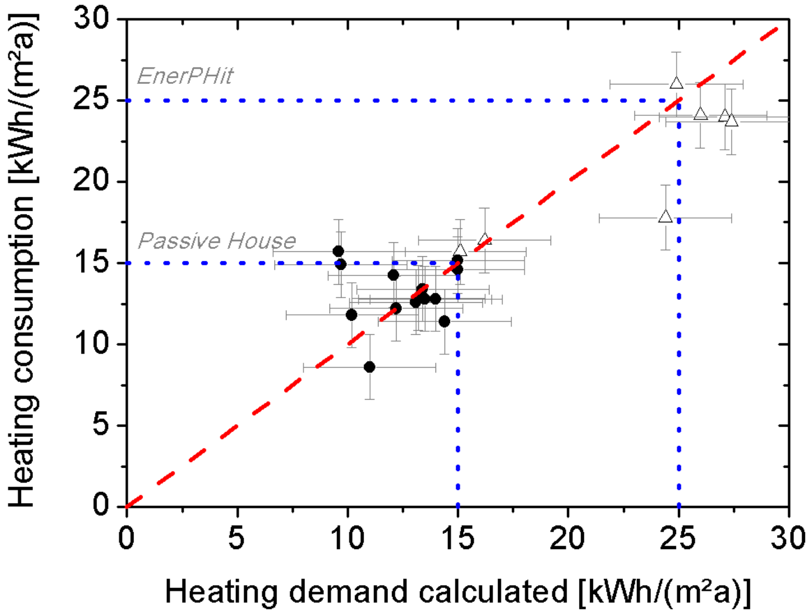

Figure 14:Calculated versus the measured specific annual space heating energy consumption of the newly built Passive Houses (circles) and retrofit projects (triangles) are depicted in Figure 13. For the demand an uncertainty of ±3 kWh/(m²a) and for the measurement an error of ±2 kWh/(m²a) is assumed and the ideal correlation between demand and consumption is depicted by a dashed line.

4 Conclusion

When adopting a quality standard that aims to reduce space heating demand, such as the PH Standard, policy makers, developers, designers and builders need to be confident their building/s will perform as predicted, i.e. they will be able to deliver the energy savings and carbon reductions they expect. The PH Standard does not require in-use measurements to be taken in order to verify the space heating demand has been met, nor does it require electric coheating tests or *in-situ* U-values to be measured. Nonetheless, this paper has presented the results obtained from undertaking *in situ* thermal performance measurements of the building fabric. Despite the small and non-random nature of the *in situ* fabric measurements showing some minor discrepancies between the measured *in situ* U-values and the design intent, the aggregate *in situ* thermal performance of the building fabric, for all of the PH dwellings studied, performed very close to the design predictions. The success of dwellings built to the Passivhaus Standard is particularly apparent when compared to the gross failings identified in non-PH dwellings i.e. those examples contained within the Leeds Beckett University Electric Coheating Test Database.

A comparison has also been made between the measured space heating energy consumption and the predicted space heating energy demand. Over 2000 newly built PH dwellings and 130 retrofitted dwellings were considered. The space heating energy consumption of the newly built PH dwellings averaged 14.6 kWh/(m²a), thus all the measurements fell within the expected 3 kWh/(m²a) range of uncertainty and below the performance threshold of the PH Standard. Consequently, the measurements illustrate as-built PH dwellings perform very close to the intent of the PH Standard.

The success of the PH Standard should not be considered commonplace. Measurements shown in this paper also demonstrate that non-PH dwellings, buildings that are not backed up with the same quality assurance methodology, suffer from larger heat losses and a significant *'performance gap'.* The *in situ* evidence from the UK suggests quality assurance of design and construction is the major cause of deviation. Whilst this performance gap could be exacerbated by imprecision in the calculation procedure used during the design process, this is not a subject area that has been explored in this paper.

These results suggest that by adhering to the physical characteristics associated a PH building and designing and constructing to a well-defined, evidence-based quality assurance standard using PHPP, performance gaps can be closed consistently. Furthermore, when the performance requirements of the PH standard are applied, energy demand for space heating can be reduced by approximately 90%, compared to the national average existing building stock.

By paying close attention to the building physics that has a direct influence upon building performance, the PH standard has demonstrated a proven track record lasting more than 25 years. In effect, it has stood the test of time and firmly established the benchmark for other energy performance standards to be judged against, not only in terms of establishing a yardstick for downsizing the energy demand and carbon emissions, but also in reducing gaps in performance.

On a global stage, and in recognition of the recent IPCC Special Report on 1.5 Degrees (IPCC 2018), these conclusions are significant. Avoiding undesirable performance gaps is important not only for the integrity of a building standard, but without an adequate and reliable evidence base, it becomes impossible to guarantee investment in energy efficiency is not being wasted and that energy demand and carbon emissions are being reduced in a meaningful fashion.

By reviewing research from a range of locations in different countries, with differing cultures, building techniques and construction technologies, this literature review demonstrates the quality assurance methods underpinning the PH Standard are transferable, reliable, repeatable and predictable. To this end, the authors conclude that the PH Standard reduces risk, facilitates design optimisation and cost effective value engineering based upon an understanding of the whole life cycle. Furthermore, it is reliable and has international application for addressing fuel poverty and climate breakdown.

5 References

AkkP - Arbeitskreis kostengünstige Passivhäuser, *Protokollband Nr. 25* (2004). Temperaturdifferenzierung in der Wohnung. Passivhaus Institut, Darmstadt, 2004 Research Group Cost-efficient Passive Houses, Volume 25: Temperature differentiation in an apartment. Passive House Institute.

Bagge, H. and Johansson, D. (2013). *Prediction and verification of energy performance in energy efficient multi-family dwellings*. 2013 ASHRAE Transactions. 2013, Vol. 119 Issue 2, pp. 1-8.

Bundesministerium für Wirtschaft (BMWi) (2018). *Energiedaten: Gesamtausgabe*. Stand 14.8.2018. https://www.bmwi.de/Redaktion/DE/Artikel/Energie/energiedaten-gesamtausgabe.html Accessed 6 January 2019).

Brooke-Peat, M. (2015). *Personal communication*, Leeds Beckett University, Leeds.

BSI (2014). BS EN ISO 9869-1:2014 *Thermal insulation –building elements – In-situ measurement of thermal resistance and thermal transmittance* Part 1: Heat flow meter method. London: British Standards Institution.

Butler, D., Dengle, A. (2013). *Review of co-heating test methodologies*. Report F54. NHBC Foundation.

Cambridge Architectural Research Ltd. (CAR 2011) (2011). 450023 Camden Passivhaus – Final Report, Domestic Buildings, Phase 1: Post construction and early occupation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: http://buildingdataexchange.org.uk/report/Camden+Passivhaus/811/ . Accessed 21 June 2018.

Cambridge Architectural Research Ltd. (CAR 2012) (2012). *450019 Future Works Passivhauses – Final Report, Domestic Buildings*, Phase 1: Post construction and early occupation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: http://buildingdataexchange.org.uk/report/Future+Works+Passivhaus/807/ .Accessed 21 June 2018.

Choice Housing (2014). *450080 Dungannon Passivhaus – Final Report, Domestic Buildings Phase 2*: In-use performance & post occupancy evaluation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: https://buildingdataexchange.org.uk/report/Dungannon+Passivhaus/848/ . Accessed: 21 June 2018.

Ebel, W., W. Feist (1997). *Ergebnisse zum Stromverbrauch im Passivhaus Darmstadt Kranichstein.* In: Protokollband Nr. 7 des Arbeitskreises kostengünstige Passivhäuser, pp. III/1 – III/18 Passivhaus Institut, Darmstadt.

Ebel W., Großklos M., Knissel J., Loga T., Müller K. (2003). *Wohnen in Passiv- und Niedrigenergiehäusern – Eine vergleichende Analyse der Nutzungsfaktoren am Beispiel der „Gartenhofsiedlung Lummerlund“ in Wiesbaden-Dotzheim*, Final Report; (German only) IWU, Darmstadt.

Energy Performance of Buildings Directive (EPBD) by European Comission, (2012). Accessed 18 January 2019 https://ec.europa.eu/energy/en/content/energy-performance-buildings-directive-epbd

Feist, W., J. Werner (1994). *Energiekennwert < 32 kWh/(m²a)*. In: *Bundesbaublatt*, Feb. 1994.

Feist, W.(1997a). Passive House Darmstadt Kranichstein: Planning, construction, results. Technical information PHI-1997/4EN, Passive House Institute, Darmstadt.

Feist, W. (1997b). Meßergebnisse zur Nutzerstreuung des Energieverbrauchs bei ausgewerteten Bauprojekten. In: Nutzerverhalten, *Protokollband Nr. 9 des Arbeitskreises kostengünstige Passivhäuser Phase II*; pp. III.1 – III.23, Passivhaus Institut; Darmstadt.

Feist, W (1997c). Meßergebnisse und ihre wissenschaftliche Auswertung im 1. Passivhaus Kranichstein. In: *Meßtechnik und Meßergebnisse, Protokollband des Arbeitskreises kostengünstige Passivhäuser Phase II Nr. 10*.pp.II/1 – II/19**,** Passivhaus Institut, Darmstadt.

Feist, W. (1997d).*Passive House Darmstadt Kranichstein: Planning, construction, Results. Technical information*.

Feist, W.(1998). Cost Efficient Passive Houses in Central European Climate. 1998 ACEEE Summer Study on Energy Efficiency in Buildings, proceedings. https://aceee.org/files/proceedings/1998/data/papers/0508.pdf.

Feist W., Loga T., Großklos M. (2000). *Durch Messungen bestätigt – Jahresheizenergieverbrauch bei 22 Passivhäusern in Wiesbaden unter 15 kWh/m² Wohnfläche* (German only; Annual energy consumption less than 15 kWh/m² in 22 Passive Houses in Wiesbaden - confirmed by measurements.

Feist, W.(2001). *Stellungnahme zur Vornorm DIN V 4108 Teil 6:2001 aus Sicht der Passivhausentwicklung*, CEPHEUS-Projektinformation Nr. 39, Fachinformation PHI-2001/10. Passivhaus Institut, Darmstadt.

Feist, W. (2004). Wärmeübergabeverluste im Lichte der Baupraxis. In: Wärmeübergabe- und Verteilverluste im Passivhaus; *Protokollband Nr. 28 des Arbeitskreises kostengünstige Passivhäuser Phase III*, pp. 123 - 156 Passivhaus Institut; Darmstadt.

Feist, W. Schnieders, J. Dorer, V. and Haas, A. (2005). Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings*, Volume 37, pp. 1186–1203.

Feist, W., Pfluger, R., Hasper, W. (2019). Durability of Building Fabric Components and Ventilation Systems in Passive Houses; In *Energy Efficiency Journal*, 2019.

Feist et al. 2005 Feist, W.; Peper, S.; Kah, O. and von Oesen, M (2005). Climate Neutral Passive House Estate in Hannover-Kronsberg: Construction and Measurement Results, *PEP-Projectinformation Nr. 1*; Pro Klima Hannover.

Feist et al. 2016 Feist, W.; Ebel, W.; Peper, S.; Hasper, W. (2016). Long-term experience and measurements from the first Passive House building in Darmstadt-Kranichstein. Proceedings of the

20th International Passive House Conference 2016 in Darmstadt, pp.273 - 281. Passive House Institute, Darmstadt.

Feist, W., Loga, T.(1997). Vergleich von Messung und Simulation. In: Energiebilanzen und Temperaturverhalten, *Protokollband Nr. 5 des Arbeitskreises kostengünstige Passivhäuser*, pp. 29 - 63. Passivhaus Institut, Darmstadt 1997.

Feist, W. und Werner, J. (1993). Erste Messergebnisse aus dem Passivhaus Darmstadt Kranichstein, gi, 114 Heft 5, Seiten 240-249.

Fox, M. (2012). *Passivhaus Development Inspection Report*. University of Plymouth, Plymouth.

Gaia Research (2015). *4 50072 Plummerswood - Final Report, Domestic Buildings Phase 2:* In-use performance & post occupancy evaluation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: https://buildingdataexchange.org.uk/wp-content/uploads/2015/11/450072-Plummerswood.pdf Accessed 10 July 2018.

Gale & Snowden Architects Limited (2014a) *450065 Knights Place Passivhaus Housing for Exeter City Council - Final Report, Domestic Buildings Phase 2*: In-use performance & post occupancy evaluation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: https://buildingdataexchange.org.uk/wp-content/uploads/2015/11/450065-Knights-Place-Passivhaus-Housing-for-Exeter-City-Council.pdf Accessed 10 July 2018.

Gale & Snowden Architects Limited (2014b). *450076 Rowan House Passivhaus Housing for Exeter City Council - Final Report, Domestic Buildings Phase 2*: In-use performance & post occupancy evaluation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: https://buildingdataexchange.org.uk/wp-content/uploads/2015/11/450076-Rowan-House-Passivhaus-Housing-for-Exeter-City-Council.pdf Accessed 10 July 2018.

Galvin, R. (2014). Making the ‘rebound effect’ more useful for performance evaluation of thermal retrofits of existing homes: Defining the ‘energy savings deficit’ and the ‘energy performance gap’. *Energy and Buildings*, Volume 69, February 2014, pp 515–524.

Galvin, R. (2014). Making the ‘rebound effect’ more useful for performance evaluation of thermal retrofits of existing homes: Defining the ‘energy savings deficit’ and the ‘energy performance gap’. Energy and Buildings, Volume 69, February 2014, pp 515–524.

Grove-Smith J., Krick B., Feist W. (2015). Balancing energy efficiency and renewables, 9th International Conference Improving Energy Efficiency in Commercial Buildings and Smart Communities, Conference Proceedings, pp 894-902.

Grove-Smith, J.; Aydin, V.; Feist, W.; Schnieders, J.; Thomas, S. (2018). Standards and policies for very high energy efficiency in the urban building sector towards reaching the 1.5 C target, Current Opinion in *Environmental Sustainability* 2018, 30: 103–114.

Glasgow School of Art (2015) *450097 Dormont Park Passivhaus Project - Final Report, Domestic Buildings Phase 2*: In-use performance & post occupancy evaluation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: https://buildingdataexchange.org.uk/wp-content/uploads/2015/11/450097-Dormont-Park-Passivhaus-Project.pdf. Accessed 10 July 2018.

Guerra-Santin, O. Tweed, C. Jenkins, H. and Jiang, S. (2013). Monitoring the performance of low energy dwellings: Two UK case studies. *Energy and Buildings*, 2013, Volume 64, pp. 32-40.

Gupta, R. and Kotopouleas, A. (2018). Magnitude and extent of building fabric thermal performance gap in UK low energy housing. *Applied Energy*, Volume 222, pp. 673-686.

Hens, H. Janssens, A. Depraetere, W. Carmeliet, J. and Lecompte, J. (2007). Brick cavity walls: A performance analysis based on measurements and simulations. *Journal of Building Physics*, Volume 31, No. 2, October 2007, pp 95-124.

Hens, H. Janssens, A. Depraetere, W. Carmeliet, J. and Lecompte, J. (2007) Brick cavity walls: A performance analysis based on measurements and simulations. Journal of Building Physics, Volume 31, No. 2, October 2007, pp 95-124.

IPCC (2018). Special Report on 1.5 Degrees Available online: http://www.ipcc.ch/report/sr15/index_background.shtml. Accessed 10 October 2018

Jack, R. Loveday, D. Allinson, D. and Lomas, K. (2017) First evidence for the reliability of co-housing tests. Building Research & Information, Volume 46, Number 4, pp. 383–401.

Johnston, D., Stevenson, F. (2013*). TSB BPE Project 450095 – Lancaster Co-housing Development: TSB BPE Phase 1 final report.* A report to the Technology Strategy Board as part of the Technology Strategy Board's Building Performance Evaluation Programme. March 2013, Centre for the Built Environment (CeBE), Leeds Metropolitan University, Leeds, UK.

Johnston, D., Fletcher, M. (2013). *TSB BPE Project 450014 – Gentoo Passivhaus Development: TSB BPE Phase 1 final report.* A report to the Technology Strategy Board as part of the Technology Strategy Board's Building Performance Evaluation Programme. July 2013, Centre for the Built Environment (CeBE), Leeds Metropolitan University, Leeds, UK.

D. Johnston, D. Farmer, M. Brooke-Peat & D. Miles-Shenton (2014). *Bridging the domestic building fabric performance gap*, Building Research & Information, link: http://dx.doi.org/10.1080/09613218.2014.979093.

Johnston D, Miles-Shenton D and Farmer D. (2015). *Quantifying the domestic building fabric 'performance gap'*. BSER&T 2015; 36: 614–627.

Johnston D, Miles-Shenton D, Farmer, D. and Wingfield, J. (2013). *Whole house heat loss test method (coheating)*. Leeds: Leeds Metropolitan University.

Johnston, D. and Siddall, M. (2016). The Building Fabric Thermal Performance of Passivhaus Dwellings - Does It Do What it Says on the Tin? *Sustainability*, 8(1), 97; DOI:10.3390/su8010097.

Kah, O., Feist, W.(2008). Bewertung energetischer Anforderungen im Lichte steigender Energiepreise für die EnEV und die KfW-Förderung. *Projekt-Nr. 10.8.17.7-06.13 Studie im Auftrag des Bundesministeriums für Verkehr, Bau und Stadtentwicklung sowie des Bundesamtes für Bauwesen und Raumordnung*, Februar 2008.

Kessler, A., (2017). Erfolgskontrolle – Passivhaus im Bestand – Tatsächlicher Heizwärmeverbrauch bei vom Land Hessen geförderten Gebäuden, *Protokollband Nr. 52 des Arbeitskreises kostengünstige Passivhäuser Phase V*; pp.133 -142. Passivhaus Institut; Darmstadt

Linktreat Ltd. (2014). *450038 Hastoe HA - 14 Passivhaus at Wimbish – Final Report, Domestic Buildings Phase* 2: In-use performance & post occupancy evaluation. A report to Innovate UK as part of the Building Performance Evaluation Programme. Internet Digital Catapult, London. Available online: https://buildingdataexchange.org.uk/report/Hastoe+HA+-+14+Passivhaus+at+Wimbish/932/ Accessed 21 June 2018.

Loga, Tobias; Müller, Kornelia; Menje, Horst (1997). *Die Niedrigenergiesiedlung Distelweg in Niedernhausen, Ergebnisse des Messprogramms* (German only; The low energy settlement Distelweg in Niedernhausen, Results of the monitoring programme), 1st edition, IWU.

Lundström E. (1986) *Occupant influence on energy consumption in single-family dwellings D5*: Swedish Council for Building Research, Stockholm.

Manioglu, G. Wouters, J. Meulenaer, V. De Hens, H. (2007). Thermal performance of a passive house: Measurements and simulation. Proceedings Performance of the Exterior Envelopes of Whole Buildings X. *ASHRAE*, Florida, pp. 1–8.

Meulenaer, V. De Veken, J. Van Der, Verbeek, G. and Hens, H. (2005) Comparison of measurements and simulations of a “passive house”. In *Building Simulation* 2005, 9th International IBPSA Conference. Montreal, Canada, August 15-18, 2005. pp. 769–776.

Mitchel, R.; Natarajan, S.: Providing Passivhaus: Post occupancy evaluation of certified Passivhaus homes in the UK, 2018, Passive House Conference 2018, pp. 531 – 536.

NBS (2006) *The Building Regulations* 2000 Approved Document Part L1A: Conservation of Fuel and Power in New Dwellings, 2006 Edition. NBS. London, UK.

Ottinger, O., Jürgen, S, Wolfgang, H., Wolfgang, F. (2016). Determination of the heat loss coefficient (HLC) of a Passive House. In: *Messtechnische Bestimmung der Wärmeverlustkoeffizienten von Passivhaus-Wohngebäuden*. Passivhaus Institut, Germany.

Pelsmakers, S. Fitton, R. Biddulph, P. Swan, W. Croxford, B. Stamp, S. Calboli, F,.C.F. Shipworth, D. Lowe, R. and Elwell, C.A. (2017) Heat-flow variability of suspended timber ground floors: Implications for in-situ heat-flux measuring. *Energy and Buildings*, Volume 138, pp. 396-405.

Peper, S.; Grove-Smith, J.; Feist, W. (2009). Sanierung mit Passivhauskomponenten Messtechnische Untersuchung und Auswertung Tevesstraße Frankfurt a.M. Passivhaus Institut, Darmstadt, 2009.

Peper 2014 EuroPHit; D2.6 Concept for a minimal monitoring of different buildings undergoing step-by-step energy-efficient refurbishment. Attachment from page 37. can be downloaded at: https://europhit.eu/sites/europhit.eu/files/EuroPHit_D2.6_ConceptForAMinimalMonitoring.pdf

Peper S.(2015): Building Monitoring Basics and Guidelines, Basis for monitoring in SINFONIA project, can be downloaded at: http://www.sinfonia-smartcities.eu.

Peper, S.; Feist, W.(2001). *Thermographische Untersuchung der Passivhaussiedlung in Hannover Kronsberg, Wissenschaftliche Auswertung*, Fachinformation PHI-2001/7, *CEPHEUS-Projektinformation Nr. 20.* Passivhaus Institut, Darmstadt, 2001.

Peper S., Feist W.(2002). *Klimaneutrale Passivhaussiedlung Hannover-Kronsberg*, Analyse im dritten Betriebsjahr, Endbericht, Hannover.

Peper S., Feist, W.(2015). Energy efficiency of the Passive House Standard: Expectations confirmed by measurements in practice, Passive House Institute, 2015, can be downloaded at http:/www.passiv.de

Peper, S.; Feist, W.; Kah, O.(2001). *Messtechnische Untersuchung und Auswertung* – Klimaneutrale Passivhaussiedlung Hannover-Kronsberg, PHI, Hannover 2001.

Peper, S.; Kah, O.; Feist, W.(2005). Zur Dauerhaftigkeit von Luftdichtheitskonzepten bei Passivhäusern – Feldmessungen, Endbericht. *IEA SHC TASK 28 / ECBCS ANNEX 38*. Passivhaus Institut, Darmstadt, 2005 .Durability of airtightness concepts for Passive Houses – field surveys, final report. IEA SHC TASK 28 / ECBCS ANNEX 38. Passive House Institute, Darmstadt, 2005. (German only).

Passivhaus Trust (2017). *The performance of Passivhaus in new construction: Post occupancy evaluation of certified Passivhaus dwellings in the UK*: Early Results Internet, Passivhaus Trust, London Available online: http://www.passivhaustrust.org.uk/UserFiles/File/Technical%20Papers/The%20performance%20of%20Passivhaus%20in%20new%20construction_July%202017%20V2.pdf. Accessed 10 October 18.

Passive House Institute (2016). Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, Passive House Institute, 2016. Accessed 18 January 2019 https://passiv.de/downloads/03_building_criteria_en.pdf.

Passive House Planning Tool (PHPP) W. Feist et al.(2015) PHPP Passivhaus Projektierungs Paket Version 9 (2015). Anforderungen an qualitätsgeprüfte Passivhäuser; Passivhaus Institut; Darmstadt.

Randall Simmonds (2012) Passivhaus at Ford Close, St Ive, Cornwall. (Internet) Randall Simmonds, Available online: http://www.randallsimmonds.co.uk/wp-content/uploads/2012/09/Passivhaus-Brochure.pdf. Accessed 21 June 2018.

Reiß J., Erhorn H.(2003). Messtechnische Validierung des Energiekonzeptes einer großtechnisch umgesetzten Passivhausentwicklung in Stuttgart-Feuerbach, *IBP report* WB 117/2003, Fraunhofer Institute for Building Physics, Stuttgart.

Schnieders, J. (2003). *CEPHEUS – measurement results from more than 100 dwelling units in passive houses. European Council for an Energy Efficient Economy (ECEEE) Summer Study*. Stockholm, Sweden.

Schnieders, J. and Andreas, H. (2006). CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. *Energy Policy*, Volume 34, Issue 2, pp 151-171.

Schnieders, J (2012). Messgenauigkeit und Fehlergrößen. In: Richtig messen in Energiesparhäusern, *Protokollband Nr. 45 des Arbeitskreises kostengünstige Passivhäuser Phase V*; pp.57 - 80. Passivhaus Institut; Darmstadt.

Schnieders, J et al.. (2019) Design and realization of the Passive House concept in different climate zones. *Energy Efficiency Journal*.

Schnieders, J.; Feist, W.;Pfluger, R. Kah, O. et al. (2001), CEPHEUS Wissenschaftliche Begleitung und Auswertung. Endbericht; *CEPHEUS-Projektinformation Nr. 22.* Passivhaus Institut. Darmstadt, Juli 2001.

Siddall, M. Trinick J. and Johnston D. (2013) Testing the real heat loss of a Passivhaus building: Can the UK's energy performance gap be bridged? Proceedings of the International Passivhaus Conference, Frankfurt.*pp 159 - 166.*

Stafford, A. Bell, M. and Gorse, C. (2012). Building confidence – a working paper. Centre for low carbon futures Report No. 008. York: The Centre for Low Carbon Futures, http:// www.lowcarbonfutures.org/reports/research-reports? page¼1 (March 2012). Accessed 24 March 2014.

Stamp, S. (2015). *Assessing uncertainty in co-heating test: Calibrating a whole building steady state heat loss measurement method*. PhD Thesis, University College London (UCL), London, UK.

Thomsen, K.E. Schultz, J. M. and Poel, B. (2005). Measured performance of 12 demonstration projects – IEA Task 13 ''advanced solar low energy buildings''. *Energy and Buildings*, Volume 37, Issue 2, pp 111–119.

The Technology Strategy Board (TSB) (2010). *Building performance evaluation, domestic buildings -* Guidance for project execution. The Technology Strategy Board, Swindon, UK.

Wingfield, J. Johnston, D. Miles-Shenton, D. and Bell, M. (2010) Whole house heat loss test method (Coheating). Internet, 2010, Leeds, Leeds Metropolitan University. Available online: http://www.leedsbeckett.ac.uk/as/cebe/projects/coheating_test_protocol.pdf. Accessed 21 June 2018.

Zero Carbon Hub (ZCH) (2010) Carbon compliance for tomorrow's new homes: a review of the modelling tool and assumptions. Topic 4: closing the gap between designed and built performance. Internet London, Zero Carbon Hub. Available from: http://www.zerocarbonhub.org/sites/default/files/resources/reports/Carbon_Compliance_Topic%204_Closing_the_Gap_Between_DvAB.pdf. Accessed 19 June 2018.

Zero Carbon Hub (ZCH) (2014) Closing the gap between design and as-built performance: end of term report. Internet, London: Zero Carbon Hub, Available from: http://www.zerocarbonhub.org/sites/default/files/resources/reports/Design_vs_As_Built_Performance_Gap_End_of_Term_Report_0.pdf. Accessed 19 June 2018.

Ziesing, H.J.(2018). Anwendungsbilanzen für die Endenergiesektoren in Deutschland in den Jahren 2013 bis 2017. Arbeitsgemeinschaft Energiebilanzen, Berlin.