Long Term Performance Of Passive House Buildings

Abstract

Long term experience with Passive House buildings is illustrated with two early large scale projects, a school and an office building located in Germany. Those were monitored in lump energy performance (school, commissioned 2004) and great detail (office, commissioned 2002) respectively. Moreover, they give an indication of the characteristics of such buildings subject to changes in usage intensity. Both buildings generally performed as expected with the school facing occasional overheating in the summer due to inflexible shading controls. Following an extension in schooling hours the addition of a canteen was required and the ventilation system was adapted to the changed usage. Nevertheless the building's user comfort and energy performance remain high,despite exceeding the Passive House primary energy target slightly due to increased electricity consumption.

The office likewise meets the calculated efficiency in operation. The ground coupled cooling worked well despite greatly increased internal heat gains due to unexpected usage. This extra heat input did not, however, exhaust the geothermal (passive) cooling capacity for the future. Thermal comfort proved near optimal at all times, despite a very simple control regime of the one-circuit concrete core activation system for heating and cooling.

In the last section air tightness design and measurement experience in the UK and particularly the question of long-term stability of the airtight building envelope is assessed. It was found that measurement results are not only repeatable in relatively short intervals such as a few months. The data available suggests stability of the airtight envelope over many years. Attention is required as regards the leakage of party walls of terraced buildings which need to be integrated in the overall airtightness concept. A high permeability of party walls in terraced buildings with a common airtight envelope presents a challenge for measuring air tightness. Long-term series of airtightness measurements exist for the Kranichstein House in Darmstadt/Germany and prove the stability of the chosen airtightness concept. Moreover, results for 17 early Passive House buildings in Germany in eight locations and various construction types revisited in 2001 (1.4 to 10 years after the initial airtightness test) suggest stability of air tightness values over time. Great advances have since been made in materials and methods available and the general understanding in the industry. This is supported by a large sample of 2934 Passive House projects of varied construction materials, locations, sizes and usages that yielded an average air tightness test result as low as $n_{50} = 0.41\ h^{-1}$.

Keywords

Passive House, Passivhaus, Non-residential building, long-term performance, thermal comfort, cost effectiveness, timber frame, airtightness, permeability

Introduction

This paper investigates the long-term experience with Passive House buildings in Germany and the United Kingdom pursuing two main aspects: Are the buildings durable and do they stand the test of time? Do large and complex non-residential buildings successfully cope with the challenges associated with the inevitably changing usage? Does the building fabric maintain its high quality standards, particularly of air tightness?

To this end one of the first Passive House school buildings and a very early, office building to the Passive House standard are documented. Both are large developments of a good 3000 m² and just short of 6000 m² respectively and as such a potential model for common building types. Both were developed in Germany at a time when Passive House buildings were still new, but considerable practical experience had been built already. In this regard they correspond well with most of the buildings in Germany that were revisited for airtightness testing a couple of years after completion.

The early examples from the United Kingdom in contrast do build on the experiences made earlier, particularly in Germany, but were developed in a building industry environment to which Passive House buildings were absolutely new.

1 12 years of operation in the first certified Passive House school in Aufkirchen, Germany

The Montessori School in Aufkirchen, Germany, has been in use since the summer of 2004 and was the first certified Passive House school worldwide (Figure 1.1). The school has received numerous awards (such as the 2007 Environmental Prize from the Bavarian State Foundation, finalist for the 2014 Passive House Award, and 2014 UNESCO Project School). A detailed description of the building can be found in [Vallentin 2005].

Over the years, it has attracted numerous visitors from Germany and abroad interested in its combination of technology and design. Its undulating shape (Figure 1.2) and roof that grows out of the landscape make it attractive in terms of both architecture and design. Shortly after completion, a master's thesis [Wrobel 2007] investigated all aspects of the investment costs in a comparison with several Passive House schools. It turns out that the Montessori School in Aufkirchen was able to comply with the Passive House Standard without additional costs.

Figure 1.1: Entrance to the Montessori School in Aufkirchen, Germany (photo: Kanzleiter)

Since commissioning the building has served several generations of pupils and the building has been the work environment to numerous teachers and staff members. Over the past 12 years, new requirements have come about, such as an increased number of pupils and extended school hours that required some changes also to the building.

Figure 1.2: Floor plan of the ground floor of the Montessori School in Aufkirchen (AW Vallentin)

Building concept and experience

The building was optimised for compactness and zones so that the Passive House Standard could be complied with as affordably as possible. The building has a basic north-south orientation so the main rooms benefit from solar gains; technical rooms and offices face to the north. An open circulation area and ancillary rooms are organised as a “supply zone” within the building, producing a great depth of about 20 to 28 metres. Large overhead glazing provides light to the open circulation area (Figure 1.3). The treated floor area (TFA) is 3275 m².

The façades only make up a small part of the envelope in this building geometry, which has a large share of glazing. Most of the building envelope consists of the roof and floor slab (shares: wall: 13 %, glazing 12 %, floor 35 %, roof 38 %).

The building is a hybrid structure that optimally utilises the benefits of solid construction (noise protection, fire protection and thermal mass) and timbered construction (insulation).

Figure 1.3: Interior “street” resulting from the building’s compactness, with interior façades (photo: Kanzleiter)

The design and concept of the design and structure have worked very well and continue to serve as the basis for concepts of many other large Passive House buildings. In the following projects particular emphasis was placed on summer heat protection. If we were to redesign the building, it would very likely employ a balcony in front to this end (see the Kinderhaus of the Erding Montessori Association). In the course of sustainability considerations, photovoltaics would be comprehensively used, and even more of the building would be timbered. Recent changes to fire safety regulations pertaining to building services mean that the fire prevention concept would also have to be changed.

Building services concept and experience

The efficient mechanical ventilation system with heat recovery considerably simplified the heating system. The additional costs for the improved building fabric to the Passive House Standard were thereby practically covered. The number of radiators could reduced from the original 130 to 25.

The central ventilation system with a rotary wheel heat exchanger has a volumetric flow of 5,800 m³/h in normal operation and a maximum flow of 8,200 m³/h. Air is distributed horizontally via the suspended ceiling in the ancillary room zone and passes into the tract of classrooms via “bridges”. The clear zoning of the plan is also reflected in the ventilation concept:

Classrooms/offices/meeting hall: supply air overflow
Hallway: overflow
Washrooms/ancillary rooms: extract air removal

Since additional window ventilation is always possible to cover infrequent peak demands, the controls for the central ventilation unit, the duct network and the ventilation zones could be implemented in a simple and cost-effective way.

Awnings with a central solar and wind monitoring and control system are used to provide removable shading for all of the glazed surfaces (including the skylights and on the north side). All of the skylights that open and all entry doors are driven with electric motors. The controls for ventilation and heating are independent and separate.

Changes in usage have required some adaptations; for instance, additional radiators were fitted to a single peripheral room that originally was not intended for classroom use but was later repurposed for teaching when school hours were extended beyond lunch time. Temperature preferences in the offices and classrooms turned out to be much higher (between 22 and 24 °C instead of 20 °C). The ventilation system and the heating system were successfully adjusted accordingly. Ventilation air has, however, sometimes been perceived as dry.

Indoor blinds were added as glare reduction in times when exterior shading is not desired to admit solar gains. In addition, a group of trees was planted on the south side in front of the classrooms, one in front of each section of glazing. In the summer, the trees have dense foliage; in the winter, the bare branches let through sunlight. Beyond the exterior shading and night ventilation that were implemented some active capacity to remove heat (such as using a hydronic underfloor floor tempering for heating in the winter and cooling in the summer and overnight ventilation with the MVHR) would be desirable in order to provide reserves for heat waves. At the Montessori School in Aufkirchen, the occasional cases of overheating were always the result of controls for shading not working properly. Unfortunately, the control settings are far too complicated, a situation we will not accept in future projects. Electrical planners are now to take into account controls that users and building managers can directly adjust.

Comparison of consumption values with demand figures calculated with PHPP

The consumption values available only provide general information from meter readings for gas and grid electricity. The gas-fired cogeneration system has an output of 12 kW of heat and 5 kW of electricity, so the shift in gas consumption needs to be taken into account. The system is operated year round (8760 hours) and is hence assumed to yield 43.8 MWh of electricity. In this simplified approach system losses are disregarded and all of the remaining balance is considered heat available within the building.

Usage of the school has changed and intensified quite a lot over the past 12 years. Originally built as a school for the morning, it has quickly established itself as an all-day school. As more hours were added on in the afternoon, the kitchen evolved from a teaching kitchen into a canteen kitchen. In the evening and during school holidays, clubs use rooms and the gymnasium for activities. Originally intended for occasional use by pupils, the showers are now used intensively from the early morning to late evening. Overall consumption, especially of domestic hot water (DHW) and electricity, has thus increased significantly. Higher room temperatures during the heating season have also increased consumption of space heating energy. These higher consumption levels are not taken into account in the following comparisons as detailed measurements would be needed for a revision of the original PHPP calculations. In hindsight some data logging of room temperatures and heat meters for DHW and space heating would have been valuable.

In order to allocate the total heat consumed (output of the cogeneration set) to DHW and space heating respectively it was assumed that the proportions of both quantities correspond to the PHPP calculations. The correlation between the PHPP results for final energy demand and the corresponding approximate consumption values derived from the gas and electricity meter readings (Table 1.1) is nevertheless good, taking account of the simplified approach taken.

	Consumption values					Passive House calculation					
Year	Metered electricity consumption [kWh/a]	Fuel for cogeneration Measurement values [kWh/a]	Estimated electrical yield from cogeneration [kWh/a]	Approx..heat output to DHW + space heating [kWh/a]	Approx. area specific Space heating consumption [kWh/(m²a)]	Final energy electricity [kWh/a]	Heat demand DHW + space heating according to PHPP [kWh/a]	Heat demand for DHW [kWh/a]	Heat demand for space heating [kWh/a]	Area specific demand space heating according to PHPP	**Notes on changes in usage.** The comparisons of PHPP and metered data only take account of the increase in hot water, not the increase in heat for higher indoor temperatures or the increase in internal gains resulting from greater usage duration and occupancy.
2006/ 2007	84,418	136,659	43,800	92,859	14.5	81,519	91,622	40,347	46,694	13.5	
2007/ 2008	88,821	169,965	43,800	126,165	15.7	81,519	114,747	62,364	46,694	13.5	Usage is expanded to the entire day / room temperature above 22 °C
2008/ 2009	90,000	118,319	43,800	74,519	9.3	81,519	114,747	62,364	46,694	13.5	40 pupils added to occupancy
2009/ 2010	79,370	178,026	43,800	134,226	15.1	81,519	126,385	73,372	46,694	13.5	The gymnasium is used every day from morning (pupils) to late evening (clubs) + during holidays
2010/ 2011	85,068	187,889	43,800	144,089	16.3	81,519	126,385	73,372	46,694	13.5	
2011/ 2012	87,994	177,122	43,800	133,322	15.0	81,519	126,385	73,372	46,694	13.5	
2012/ 2013	*93,559*	*213,921*	*43,800*	*170,121*	*19.2*	*81,519*	*126,385*	*73,372*	*46,694*	*13.5*	*Major construction works with higher electricity and heat-up demand)*
2013/ 2014	99,595	150,164	43,800	106,364	12.0	81,519	126,385	73,372	46,694	13.5	

Table 1.1: Comparison of estimates of final energy (heat) consumed and final energy (heat) demand as per PHPP, based on meter readings for electricity and gas to the cogeneration plant from 2006 to 2014 with PHPP

2 Monitoring results from a large Office building in Ulm, Germany

The ENERGON office building in Ulm was planned and certified in compliance with the Passive House Standard as an office complex, built by Software AG Stiftung (Darmstadt) and put into operation in 2002. The building is designed for 420 people and has a treated floor area of 5,962 m².

[STW 2006] describes the building in detail. Here, the focus is therefore on the primary construction principles:

- building envelope that complies with the Passive House Standard of a mixed type (reinforced concrete structural members with prefabricated timberframe envelope)
- ventilation system with heat recovery from a highly efficient combined circuit system

- concrete core temperature control for heating and cooling with controls based on reference indoor temperatures relative to the feed and return temperature (generally, no active individual room temperature controls)
- a field of 40 geothermal boreholes 100 m deep for passive cooling of the concrete ceilings and preheating of outdoor air in the winter
- residual heat and hot water supply from district heat and waste heat from server coolers within the building
- humidification of fresh air in the winter
- direct digital control (DDC) of all building services components, sun protection systems and vents during the heating season.

Thermal indoor air quality and user survey

Figure 2.1 shows the room temperatures measured in the 24 reference rooms relevant for controls in 2004 and 2005. For the entire year, they are within the desired comfort range. Although there are no individual room controls, a survey (unpublished) found that user satisfaction was high, especially with cooling in the summer. A few users complained about low temperatures in the winter, but most found the temperatures in the winter to be too high. Some users also felt the air was too dry in the winter. Fresh (supply) air humidity was therefore increased incrementally from 30 % to around 40 %.

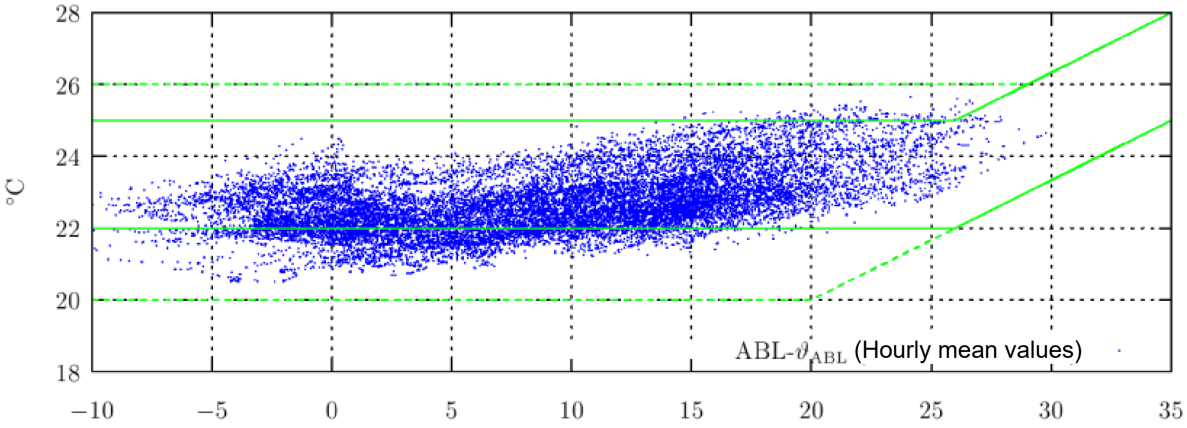

Figure 2.1: Room air temperatures measured in the 24 reference rooms over two years (source: [STW 2006])

Energy consumption

Figure 2.2 shows heat consumption from 2004 to 2014 based on the bills from the district heat provider. They are largely in line with the values from PHPP. The calculation for space heat demand was corrected to take account of measured outdoor temperatures and average room temperatures of 21.5 °C.

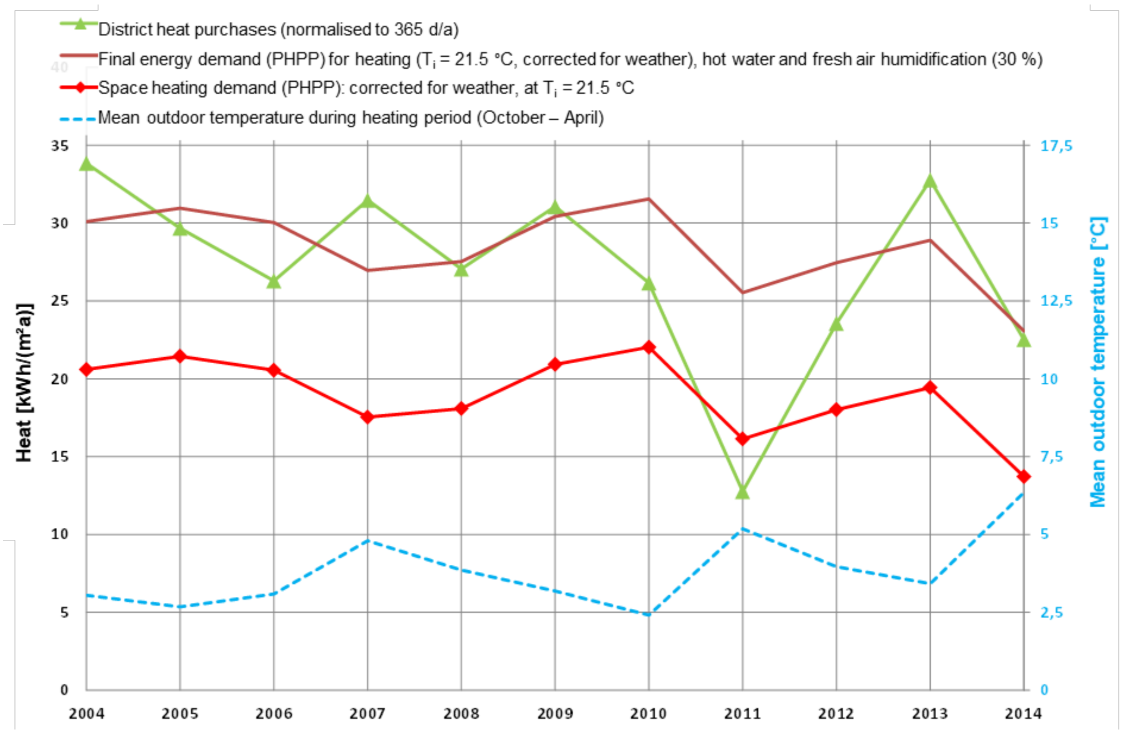

Figure 2.2: District heat purchases and PHPP calculations for space heating and final energy demand for heating (including hot water demand and heat for fresh air humidification)

The slight differences between district heat purchases and the calculated final energy demand are probably the result of the interior heat gains and waste heat feed, which were only rough estimates; they are assumed to be constant in PHPP. Furthermore, the humidity values for fresh air also increased from 30 % to 40 %, resulting in an additional heat demand of ca. 10 kWh/(m²a), depending on outdoor humidity.

Figure 2.3 shows the measurement results for electrical power consumption. For certification, only the auxiliary power demand for the planned building service components was checked and assessed. Power demand for lighting, the kitchen, office devices and other appliances was not taken into account. The measured auxiliary power correlates very well with the planned values. According to [STW 2006], the energy efficiency ratio for cooling from the geothermal boreholes ranges from 13 to 24 kWh_{therm}/kWh_{el}.

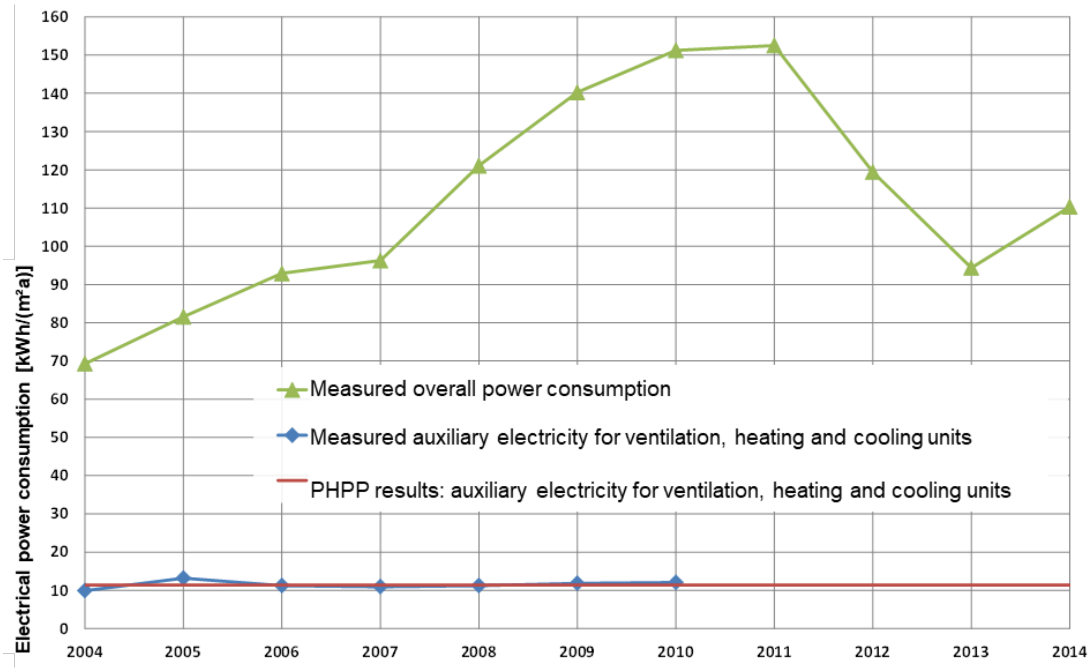

Figure 2.3: Measurements of power consumption and calculations of auxiliary power in PHPP

Over the years, the level of overall power consumption, including by devices, appliances, kitchen and lights, has skyrocketed. The main reason is the use of some of the rooms as development labs containing power-hungry measurement technology. Vapour-compression refrigerators were added to cover the resulting high cooling loads, thereby increasing power consumption even further. Only some of the waste heat from these additional cooling units is made available to the heating system (via extract air).

Power consumption measurements found average constant loads ranging from 13 W/m² to 28 W/m². According to PHPP (1999), the heating load is 13 W/m². Theoretically, the waste heat from power consumption alone would suffice to heat the building.

District heat generation: trend in PE factors

At the time of certification, the primary energy (PE) factor for district heat in this area was 1.06. Over the years, however, district heat has largely been switched over to biomass and cogeneration, so that the current PE factor has fallen to 0.20. As a result the carbon emissions related to operation of the building have dropped considerably, even though they were comparatively low from the outset due to high energy efficiency. The fundamental change in the non-renewable Primary Energy factor within a time span of less than two decades points to the inherent weaknesses of this rating method in times of fundamental changes of the energy supply system.

Trend in soil temperature around the geothermal boreholes

The temperature of the subsoil is measured with Pt1000 RTDs (ratiometric setup to cancel out errors in excitation current) at various depths ranging from 1 to 100 m in a non-activated borehole [Kahlert 2004]. This type of sensor offers stable characteristics over time in the environmental conditions prevailing in a borehole. Figure 2.4 shows the temperature development at a depth of 50 m over the past few years along with the (net) amount of heat fed into the geothermal field. In the first years of operation, heat input increased as building occupancy rose, thereby also increasing power consumption. As a result, the soil temperature simultaneously rose.

Plans for tempering the building for the summer via concrete core temperature control and the geothermal field were not designed for such high internal loads. Rather, cooling was designed for daily average loads from power consumption ranging from 10 to 17 W/m². The installation of new cooling units in several parts of the building with especially high power consumption is not surprising, nor is the increase in subsoil temperature. Figure 2.4 clearly shows a correlation between overall power consumption, reflecting the intensity of building usage, geothermal cooling and the subsoil temperature.

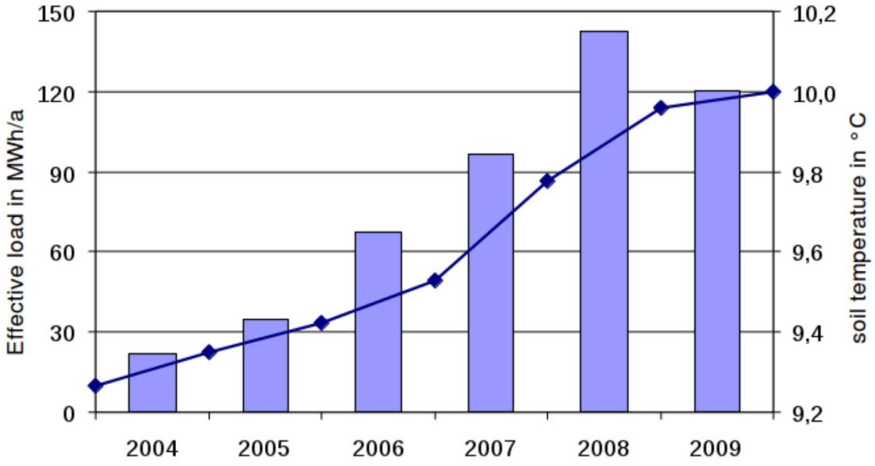

Figure 2.4: Geothermal cooling (heat input for cooling and cool input for air preheating) and measured subsoil temperatures (source: [STW 2014])

The ratio of the increase in the soil temperature and the (net) cooling work from Figure 2.4 is presented in Figure 2.5. The temperature increase underground became clearly “saturated” in 2009 and 2010 even though more heat continued to be added. The temperature around the geothermal boreholes can therefore be expected to plateau at a constant level. A reserve shaft could be used to connect an additional four geothermal boreholes in order to compensate for the slightly higher subsoil temperature when cooling the building.

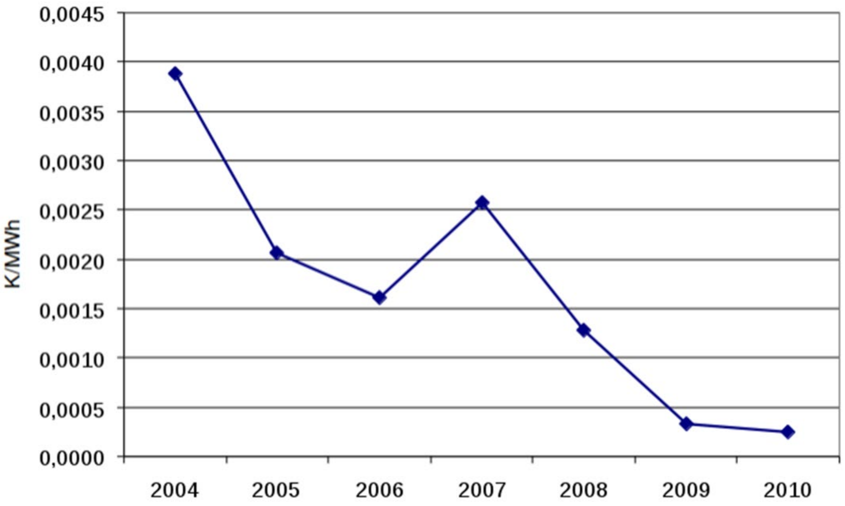

Figure 2.5: Ratio of temperature increase underground and (net) heat input (source: [STW 2014])

Affordability of the energy saving measures

The Passive House envelope cost an estimated 400,000 € extra, due on an evaluation by the author that is based on invoiced cost. In terms of cost groups 300 and 400 in the German building code (structure/fabric and building services), this amount is about 4 % of the total. The ventilation system is not included in this calculation. A ventilation system would have been required in any case of the interior offices and the atrium. The lower cost for the greatly simplified space heat distribution in the Passive House Standard was not taken into account, either.

At the time the building permit was applied for, the German Insulation Ordinance of 1995 still applied. Demand for space heat in PHPP was therefore calculated with those building envelope requirements (higher U-values and lower airtightness) and with available weather data. The additional heat costs in the old standard were based on an extrapolation of annual district heat bills; prices for district heat increased by an average of 7.6 % per year from 2004 to 2014. Higher auxiliary electricity demand due to longer pump usage and additional costs due to higher heat delivery rate were not taken into account to remain “on the safe side”. Table 2.1 shows the results of the economic feasibility assessment; they (retrospectively) clearly support the Passive House Standard.

Estimated additional costs for the Passive House envelope:			400,000 €
Saved energy costs 2004–2014:			624,000 €
Saved energy costs, monthly:			5,200 €
at an interest rate of	Total cost of additional investments including interest	Monthly instalment for 10 years (interest + repayment)	Profit after 10 years
5 %	509,114 €	4,243 €	114,886 €
9.5 %	621,108 €	5,176 €	2,892 €
1 %	420,500 €	3,504 €	203,500 €

Table 2.1: Affordability of the Passive House envelope at various interest rates

After ten years of use and an interest rate of 5 % (usual for buildings at the time), the profit is calculated at 114,886 €. Even at an interest rate of 9.5 %, the additional investments in the building envelope would have paid for themselves after ten years. At interest rates available today of around 1 % (KfW loans are currently even slightly lower), the profit would have exceeded 200,000 €, equivalent to an annual return of 4 %. If the building continues to be used this way over the next 30 years, the rate of return from the Passive House Standard will increase considerably even if energy prices drop.

Lessons learned

Once again, the PHPP has proven to be a very reliable planning tool for energy balances. The calculated amounts of energy correlate very well with measured data. By choosing to go far beyond the building code at the time and adopting the Passive House Standard, the building owner chose a financially very sensible type of architecture.

Waste heat from cooling units installed later in a few rented areas is only partly recovered. If these high levels of power consumption had been known during planning, this waste heat could have been planned as a part of the building's heat supply. A certain level of individual control in various rooms would probably also further increase user satisfaction (mainly for psychological reasons). The question is whether and how this option would be affordable. The shading element between the window panes in the atrium roof is partly defective and no longer available on the market. This system did not prove useful.

Monitoring

The comprehensive monitoring process conducted in the scope of the "Solarbaumonitor" programme is well documented in detail in the final report [STW 2006]. The building was found to serve its purpose very well, and the planned energy targets were met: "Control of concrete core temperature provides comfortable indoor climate conditions; circulation pumps run in cycles to minimise power consumption. The measurement results confirm that the goals of concrete core tempering were met and the planning requirements implemented […]. The tempering control performs all of the necessary tasks in a practically ideal manner day and night, in every season, and with very dynamically changing outdoor climates."

Individual design flaws were detected and remedied shortly after the building was put into operation. For instance, one valve in the geothermal system had an improper electrical connection, which (briefly) heated up the geothermal boreholes with district heat. If that flaw had not been quickly detected, the cooling output in the summer would have been considerably reduced.

3 Long Term Experience With Airtightness In Passive House Buildings

In new buildings it is not unusual for air infiltration to increase over time. Work undertaken by Elmroth and Logdeberg (1980) and Warren and Webb in the early 1980's suggests that the majority of this increase in air leakage occurs during the first year of occupation as the building fabric shrinks and settles. However, additional factors are also known to contribute to increased air leakage, such as wear-and-tear to window and door seals and changes to the building fabric made by the occupants. Set within this context, many construction industry professionals in the UK are sceptical about whether or not the Passive House Standard provides a robust long-term solution. A primary concern is that performance, notably airtightness, degrades over time in a similar manner to non-Passivhaus buildings.

Furthermore, to help prevent moisture damage in roof spaces, Protokolband 29 [Feist, 2005] recommends an air permeability of 2 m^3-h/m^2 @50pa where the fabric is diffusion open and an air permeability of 0.5 m^3-h/m^2 @50pa where it is diffusion closed.Therefore, in addition to considering the longevity of air barriers, this section of the paper also considers whether, after 5 years occupation, the dwellings in this study are protecting the building fabric from moisture damage.

In the North East of England the first homes achieving the Passive House Standard were completed in 2011 (25 houses at the Racecourse Estate) and a further house meeting the Passive House Standard was completed in 2013 (Steel Farm). To date, there are no other certified Passive House buildings in the North East of England. To understand and address the concerns that are being raised, the longevity of airtightness requires further examination.

Figure 3.0 Racecourse Estate (left), Steel Farm (right)

An Investigation into the Longevity of Airtightness

The Racecourse Passive House Estate is one of the largest projects of its kind in the UK. In 2016, it was five years since the dwellings became occupied. Building performance evaluation was undertaken during this period [see Fletcher & Johnston, 2014; Johnston & Fletcher, 2013]. There have been two significant findings.

Firstly, the measured *in-situ* heat losses from two of the dwellings were very similar to those predicted in PHPP [Johnston, 2014b]. In fact, it falls within the margin of error of the co-heating test of between ±8 to 10% (Jack, 2013 & Jack et al., 2018). This is significant because Leeds Beckett University have demonstrated that in the UK there is a significant building fabric thermal performance gap [Johnston 2014b] [Johnston 2015].

The work undertaken by Leeds Beckett University has proven that the measured *in-situ* heat loss tends to be far greater than that predicted, and in some extreme cases, has been over 100 % more than intended. The dwellings at Racecourse Estate are one of the first to demonstrate that the fabric thermal performance gap can be closed [Siddall 2013]. Secondly, following an occupant satisfaction survey using the building user satisfaction (BUS) methodology, the people living in these homes reported high levels of comfort and satisfaction [Siddall 2014].

Pressure Test Results (2011)

The dwellings at the Racecourse Estate are timber-frame and utilise diffusion-closed (i.e. highly moisture-resistant) construction. The air barrier was formed using a membrane with taped joints and an *in-situ* cast concrete floor. Services penetrations were sealed using proprietary EPDM grommets.

The original pressure tests were undertaken using the Passive House Standard, based upon BS EN 13829 [BS 2001] and ATTMA Technical Standard L1 [ATTMA 2010] [Outhwaite 2011]. As the dwellings are terraced, air leakage was determined using co-pressurisation, (also known as pressure equalisation) whereby the dwellings either side of the house being tested were also pressurised. This means air leakage from the test dwelling to neighbouring dwellings can be avoided during testing, and a more accurate understanding of the air leakage of the external envelope can be determined. This method is not normally used for ATTMA TS-L1-compliant Building Regulations assessments, which involves testing a single dwelling at a time without co-pressurisation.

Pressure Equalisation Tests

The two bungalows described here form part of a terrace of seven properties. The air barrier is continuous around the entire terrace of the seven properties rather than around each individual bungalow within the terrace. Whilst this results in a greater risk of air leakage between properties, at the design stage, the impact of this risk was considered to be lower than the risk of undetected thermal bypass occurring at the party wall.

Dwellings 1 and 2 were independently tested by Leeds Beckett University a few weeks after practical completion, but immediately prior to the commencement of an electric co-heating test. The total fabric heat loss area of the dwelling as used in the electric co-heating test was

245.6 m^2 for Dwelling 1 and 244.5 m^2 for Dwelling 2. Table 3.1 shows ATTMA-derived air leakage results, and Table 3.2 shows the results obtained from the pressure equalisation tests.

Dwelling	**Date**	**Depressurisation only**	**Pressurisation only**	**Mean air permeability**	**Pre / post co-heating test**
		m^3 h^{-1} m^{-2} at 50 Pa	m^3 h^{-1} m^{-2} at 50 Pa	m^3 h^{-1} m^{-2} at 50 Pa	
Dwelling 1	08 Nov 2011	0.83	0.94	0.89	Pre
	21 Dec 2011	0.86	0.91	0.89	Post
Dwelling 2	09 Nov 2011	1.30	1.33	1.31	Pre
	22 Dec 2011	1.30	1.33	1.31	Post

Table 3.1: Tested to ATTMA Technical Standard L1 [ATTMA 2010] [Johnston 2012]

Dwelling	**Date**	**Depressurisation only**	**Pressurisation only**	**Mean air permeability**	**Pre / post co-heating test**
		m^3 h^{-1} m^{-2} at 50 Pa	m^3 h^{-1} m^{-2} at 50 Pa	m^3 h^{-1} m^{-2} at 50 Pa	
Dwelling 1	08 Nov 2011	0.43	0.46	0.44	Pre
	21 Dec 2011	0.62	0.54	0.58	Post
Dwelling 2	09 Nov 2011	0.66	0.62	0.64	Pre
	22 Dec 2011	0.59	0.67	0.63	Post

Table 3.2: Pressure Equalisation Tests [Johnston 2012]

Dwelling 1 is an end-terrace plot, and Dwelling 2 is mid-terrace. This means that Dwelling 1 has one party wall, and Dwelling 2 has two party walls. It may be considered that the only difference in air leakage between the ATTMA tests and the pressure equalisation tests is through the party wall. Using the reference envelope areas to calculate the difference in flows between these two tests enables calculation of the assumed flow through the party wall area. Each party wall has an area of 29.3 m^2; it can be determined from these two test regimes that the air permeability of the party walls themselves ranges between 2.6 and 3.8 m^3 h^{-1} m^{-2} for these four tests. Thus, although the party wall is only a small proportion of the envelope area, its permeability is calculated to be far higher than that of the external envelope.

Whilst it was not possible to access Dwellings 1 and 2 for the latest series of pressure tests, it is anticipated that the nature of the air leakage and the variations between test conditions remained similar. However, the air leakage through the party wall is known to be significantly influenced by the conditions within the adjacent property. If any doors or windows are open, this will facilitate flow through the party wall, whereas if the adjacent dwelling is sealed, there will be less flow through the party wall. Therefore, the potential performance of a party wall cannot be properly considered without also controlling the conditions within the adjacent dwelling, which is not possible if the residents do not agree to cooperate with the tests.

Pressure Test Results Two and Three Years On (2013 / 2014)

Leeds Beckett University undertook extensive monitoring in one of the Racecourse Estate dwellings located at the end of a terrace as part of an in-use monitoring project funded by the Technology Strategy Board, now Innovate UK [Fletcher & Johnston 2014]. As part of this project, a series of pressure tests were taken in 2013 and 2014 which are detailed in Table 3.3.

Dwelling	**Date**	**Depressurisation only**	**Pressurisation only**	**Mean air permeability**	**Pre / during / post in-use monitoring**
		$m^3 h^{-1} m^{-2}$ at 50 Pa	$m^3 h^{-1} m^{-2}$ at 50 Pa	$m^3 h^{-1} m^{-2}$ at 50 Pa	
Dwelling 7	09 Apr 2013	0.99	1.02	1.01	Pre
Dwelling 7	10 Feb 2014	1.01	1.15	1.08	During
Dwelling 7	22 Jul 2014	1.45	1.28	1.36	Post

Table 3.3: Tested to ATTMA Technical Standard L1 [ATTMA 2010] [Johnston 2014a]

Due to concerns regarding access, they were not able to use the pressure equalisation method. Broadly speaking there is good correlation between the results contained within Table 3.1 and Table 3.3. The results in Table 3.3 could suggest that air leakage increased over time, however, it is possible that during the test on 22 July 2014, given that this was during the summer, windows are more likely to have been open in the adjacent property. This could have unduly affected the result.

Pressure Tests Five Years On (2016)

In 2016, it was possible to undertake a further set of pressurization tests on a number of the dwellings. However, as neighbouring residents did not wish to take part in the tests, the air leakage was determined solely by testing single dwellings to ATTMA Technical Standard L1. As a consequence, the air leakage through the party wall into the neighbouring property was included in the measurements. Fortunately, generalised comparative analysis was possible, as reference could be made to the earlier Leeds Beckett University tests.

Terraced Dwellings Air Leakage Detection Five Years On (2016)

Temporary air sealing was undertaken around door and window openings in order to determine the extent of the air leakage associated with these components. For Dwelling 7, thermographic imaging and a thermometer anemometer were used to assist with leakage detection. In practice, it proved difficult to identify specific leaks, due to the very low leakage. The results from the pressure tests without additional sealing are shown in Table 3.4.

Dwelling	**Date**	**Depressurisation**	**Pressurisation**	**Mean air permeability**
		$m^3 h^{-1} m^{-2}$ at 50 Pa	$m^3 h^{-1} m^{-2}$ at 50 Pa	$m^3 h^{-1} m^{-2}$ at 50 Pa

Dwelling 7 (terraced)	11 Dec 2015	0.79	0.91	0.85
Dwelling 7 (terraced)	05 Jan 2016	0.84	0.82	0.83
Dwelling 9 (terraced)	10 Dec 2015	1.13	1.23	1.18
Dwelling 3 (terraced)	06 Jan 2016	1.24	1.34	1.29

Table 3.4: Results of air leakage tests by Apex Acoustics

Using the data determined by calculating the effective party wall air leakage, as discussed earlier, the authors have developed corrected air leakage calculations in order to estimate a likely range of air leakage through the fabric of the external envelope excluding the party wall leakage. The range of potential permeabilities illustrated for the party wall area are between the extremes measured, i.e. between 2.6 and 3.8 $m^3 h^{-1} m^{-2}$. The results are shown in Table 3.5, noting that Dwelling 7 has one party wall, whereas Dwellings 3 and 9 each share two party walls.

Dwelling / mean result from positive and negative pressure tests	Date	Low party wall air leakage	High party wall air leakage	Co-pressurisation tests, 2011
		$m^3 h^{-1} m^{-2}$ at 50 Pa	$m^3 h^{-1} m^{-2}$ at 50 Pa	$m^3 h^{-1} m^{-2}$ at 50 Pa
Dwelling 7 (terraced)	11 Dec 2015	0.54	0.40	
Dwelling 7 (terraced)	05 Jan 2016	0.52	0.38	0.41
Dwelling 9 (terraced)	10 Dec 2015	0.56	0.28	0.51
Dwelling 3 (terraced)	06 Jan 2016	0.67	0.39	0.44

Table 3.5: Theoretical external envelope only air leakages compared with original co-pressurisation tests [Outhwaite 2011]

Detached Dwelling Air Leakage Detection Five Years On (2016)

There are three detached bungalows on the Racecourse Estate. The dwellings were the first constructed on the site. In essence, they provided the test ground for the terraces that were built later. Although these dwellings were constructed using the same fabric standards (including airtightness), construction technologies and building services, they do not suffer from the added complexity of a party wall. In terms of energy performance, the only major difference is that fact they have a worse surface area to floor area ratio. Consequently, they do not satisfy the Space Heating Demand requirements of the Passive House Standard.

It was only possible to gain access to one of these dwellings. The history of pressure test results are shown below in Figures 3.6 and 3.7. It should be noted that the 14/04/11 test was undertaken when the air barrier was accessible and before any building services were installed, hence prior to practical completion.

Dwelling	Date	Depressurisation only	Pressurisation only	Mean Air Permeability	Comments
		$m^3.h^{-1}.m^{-2}$ @ 50Pa	$m^3.h^{-1}.m^{-2}$ @ 50Pa	$m^3.h^{-1}.m^{-2}$ @ 50Pa	

Dwelling 19	10/02/16	0.48	0.46	0.47	Occupied
Dwelling 19	12/08/11	0.31	0.47	0.39	Completion
Dwelling 19	14/04/11	0.35	0.28	0.32	Pre-services

Table 3.6: Area-related results of air tightness tests by Apex Acoustics compared with original tests [Outhwaite, 2011]

Dwelling	Date	Depressurisation only	Pressurisation only	Mean Air Permeability	Comments
		h^{-1} @ 50Pa	h^{-1} @ 50Pa	h^{-1} @ 50Pa	
Dwelling 19	10/02/16	0.50	0.48	0.49	Occupied
Dwelling 19	12/08/11	0.27	0.41	0.34	Completion
Dwelling 19	14/04/11	0.35	0.27	0.31	Pre-services

Table 3.7: Volume-related results of air tightness tests by Apex Acoustics compared with original tests [Outhwaite, 2011]

During the period of occupation one pane of triple glazing was removed and replaced due to a manufacturing error. The pressure tests identified that the glazing beads were poorly installed resulting in avoidable air leakage. It is considered that the majority of the increase in air leakage is associated with this window as no other significant air leaks could be readily identified throughout the house. A number of minor leaks appeared to exist at the corner of other windows.

Observations in the Projects Covered and Comparison with International Findings

Terraced Dwellings

Due to the limitations of the test regime, reliable comparison cannot be made with the air leakage requirements of the Passive House Standard. However, accounting for the potential range of air leakage through the party wall shows that current performance may not have changed since the original tests were undertaken in 2011.

Estimation of party wall air leakage is only possible by utilizing the test results from both the Passive House and the normal ATTMA methods on the same dwellings; this type of information is not usually available. In this case, it illustrates that the party wall is far leakier on average than the external envelope.

Undertaking pressure tests years after project completion using co-pressurisation is always likely to be practically very difficult, as it requires a very high level of cooperation from the residents on either side of the party element. For this reason, it would be preferable to undertake this type of investigation on detached buildings.

Detached Dwelling

In the detached dwelling, air leakage has increased in real terms by 0.08 $m^3.h^{-1}.m^{-2}$ @ 50Pa (0.15 h^{-1} @ 50Pa). The fact that this level of air infiltration is not significantly worse is considered to demonstrate that air tight design and construction, when undertaken properly, can perform over time. In this case, it also means that the air infiltration remains below the threshold required by the Passivhaus Standard.

The tests undertaken in 2016 suggest the performance criterion of 0.5 $m^3 h^{-1} m^{-2}$ @50pa are likely to be achieved for the external envelope. According to Feist [2005] this means the risk of moisture damage in roof spaces has been reduced to an appropriate and practical level.

Other Long-term Analysis

A long-term series of airtightness measurements exist for the Kranichstein House (cf. dedicated article in this issue) and prove the stability of the chosen airtightness concept over a 25 year period. Furthermore, results from 17 early Passive House buildings in Germany, comprising detached dwellings, duplexes and terraced dwellings, suggest stable air tightness test results can be achieved across an extended period of time [Peper, 2005]. These houses are in eight locations and were built using various construction technologies. They were revisited during the course of research for IEA SHC TASK 28 / ECBCS ANNEX 38 in 2001/02, some 1.4 to 10 years after the initial airtightness test. For more information about the tests refer to Figure 3.1.

At the time of testing these structures, German experience of airtight construction was at a similar stage of development and maturity as the UK was for the projects covered above. Great advances have since been made in materials and methods available and the general understanding in the industry.

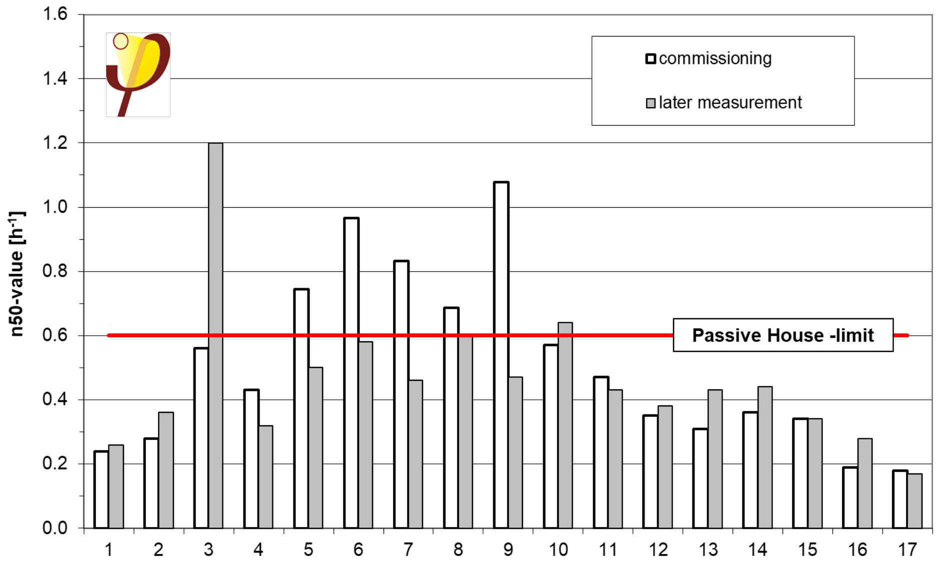

Figure 3.1 airtightness test results from 17 early Passive House projects in Germany at commissioning and some years later

This conclusion is empirically backed up with an analysis of airtightness test results for Passive Houses in the www.passivhausprojekte.de database, as of 2015. The sample comprised 3014 projects in total, including deep retrofits with Passive House technology (EnerPHit) [Peper 2015].

For Passive House buildings the requirement is $n_{50} \leq 0.6\ h^{-1}$ (for retrofits $n_{50} \leq 1.0\ h^{-1}$) Figure 3.2 gives an overview of the airtightness test results for 3014 projects of various construction types and usages and sizes and locations. A total of 2934 buildings meet the Passive House (new build) criterion for air tightness. The strict requirement is improved upon in the majority of cases.

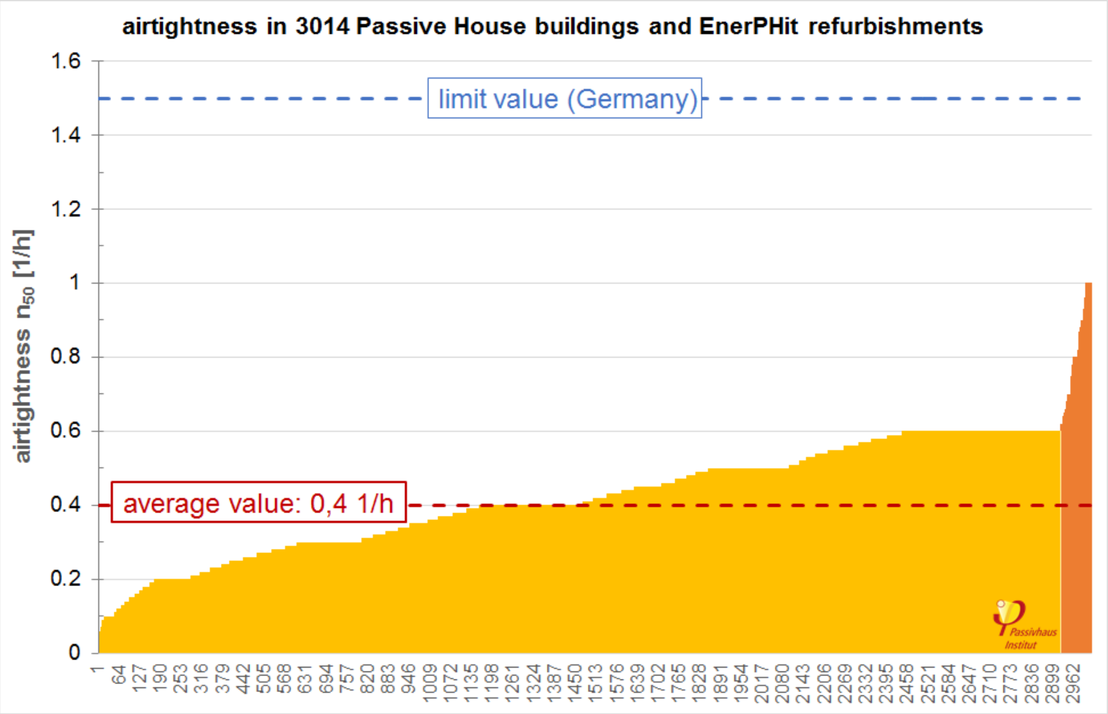

Figure 3.2 Evaluation of airtightness test results for 3014 projects of the www.passivhausprojekte.de database, including deep retrofits (dark hue)

The statistically relevant number of samples results in an arithmetic mean value of $n_{50} = 0.41\ h^{-1}$, Sd = 0.14. If the retrofit examples are included, now totaling 3014 samples, the mean value is slightly increased to $n_{50} = 0.43\ h^{-1}$, Sd = 0.16. If only the 80 retrofit cases with values $0.6\ h^{-1} < n_{50} \leq 1.0\ h^{-}$ are considered, the mean value calculates as $n_{50} = 0.85\ h^{-1}$, Sd = 0.11.

4 Summary and Conclusion

After many years and much more intensive usage than originally anticipated, the school building is still performing well as a Passive House. The changes in usage and occupancy were successfully managed in terms of both structure and building services. The measured energy consumption is in line with the expected values from the design calculations to the accuracy of the available data. The exterior movable shading was later supplemented with an interior glare protection device to allow solar gains in the winter without impairing the visual comfort. In hindsight some capacity for additional heat extraction from the building, such as a reversed underfloor heating system coupled to a heat sink (the ground or a heat pump) would be an asset to improve the robustness of the summer operation as higher occupancy and more frequent heat waves combine to reduce the headroom of the original approach. Some elementary monitoring of fundamental data such as interior air temperatures, heat for space heating and DHW and submetering of electricity for the MVHR and kitchen would be considered for similar new projects. No signs of degradation in performance over time could be observed. The designers, users and building management expect the concept to continue to be successful in the coming years.

In the case of the office building substantial challenges were met in terms of usage deviating from the original design and much higher internal heat loads needed to be dealt with. Thanks to a comprehensive monitoring programme detailed data on the building services reaction to the increased load is available. Initially the ground coupled concrete core activation was the only means of heat extraction from the office spaces. This proved insufficient in areas where a complete change in usage, from office use towards a highly loaded development lab, took place. Conventional cooling equipment was successfully added there to meet this challenge. Nevertheless also the ground probe system was loaded much higher than anticipated and the ground temperature rose, but stabilised at an un-critical level. In similar cases the heat supply from district heating system could be expediently replaced with a heat pump system coupled to the ground probes, thus unloading a considerable amount of heat from the ground in the winter. Otherwise the building services systems coped well and the energy consumption for space heating is in line with the values expected from the energy balance modelling with PHPP. No signs of deterioration in performance could be observed. At least two years of post-occupancy monitoring is recommended as a standard procedure for complex building services systems and facilitates to trace and amend the inevitable flaws in hardware and controls. Generally, it is sufficient to properly capture key parameters relevant for technical operation. This could be affordably integrated in the anyway existing control system. Alternatively, simple, inexpensive data loggers can be used.

The two large non-residential Passive House buildings do stand the test of time and adapt to changes in usage just as buildings to lower energy performance standards. They show no signs of deterioration in energy performance over time. Changes in usage did result mainly in higher occupancy/increased internal heat loads in the summer in both cases and heat extraction became an important issue. In future cases some moderate extra heat removal capacity should be considered in order to cater for changes unforeseen at the design stage.

The examples from the UK indicate that even in an environment where Passive House was a rather recent phenomenon at the time of construction high standards of air tightness could be achieved and maintained over time. Early German projects were also revisited some years after completion and no evidence of systematic time-related deterioration was found. This is particularly well documented in the case of the first Passive House in Darmstadt-Kranichstein. A large sample of 2934 Passive House projects yielded an average air tightness test result as low as $n_{50} = 0.41\ h^{-1}$. This supports the conclusion that very low infiltration rates can be ensured with reasonable effort in every day building practice if design and build are in the hands of qualified personnel and adequate techniques and products are used. The airtightness thus achieved can be considered persistent.

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