A longitudinal building fabric and energy performance analysis of two homes built to different energy principles

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Abstract

This paper reports on the building performance monitoring and annual energy demand of two homes built side-by-side over an occupancy period of three years. The study compares the results from on-site monitoring against the assumed parameters and calculations from compliance modelling at design stage. It focuses on the differences and impact of occupancy behaviour, weather conditions, quality of construction and operation which contribute to an increase in energy consumption creating a gap in performance between design and actual. The results from the study show disparities in the fabric performance reflecting on the overall consumption of energy. This longitudinal analysis highlights how building performance needs to be evaluated over longer periods in order to fully understand how homes and their occupants operate and consume energy. The impact of the real performance of homes in Scotland over longer periods needs to become standardised, and a mechanism for feedback into regulatory mechanisms and construction practices applied, if carbon emission targets are to be met.

Keywords: Post-occupancy; building performance; energy; social housing; longitudinal studies.

1. Introduction

The analysis of energy consumption and carbon emissions from buildings has been well documented, particularly domestic properties subject to reduced performance levels [1–6]. According to Itard & Meijer [7], in the EU 30% of energy use comes from the residential sector where 57% is consumed by space heating, 25% for water heating, 7% cooking and 11% electrical appliances. In Scotland, excluding the transport sector, 40% of total energy consumption (electricity and heat) is consumed domestically [8]. The above figures show that the energy performance of existing and new stock residential buildings is of concern and creating new policies and addressing the technical and social issues around them should be of importance.

To address these issues, the Energy Performance of Buildings Directive (EPBD) 2002/91/EC and its recast 2010/31/EC [9] requires each Member State to evaluate and certify their buildings. These guidelines introduced the use of Nearly Zero Energy Buildings (NZEB) in 2010, suggesting low energy demand linked with on-site renewable energy use [10]. The UK's approach introduced the Code for Sustainable Homes (CfSH) in England & Wales now enforced in Part L Building Regulations [11] [12] and in Scotland the Section 7 Sustainability [13] in the Scottish Building Standards (SBS) Technical Handbooks as recommended by Sullivan [14] and Zero Carbon Homes [15] [16]. For energy calculations the National Calculation Methodology (NCM) created the Standard Assessment Procedure (SAP) generating Energy Performance Certificates (EPC) [17] [18] [19]. EPC results have become the commercial and analytical method of understanding building performance as discussed by Sutherland et al. [20], SBS [21] and Castellano et al. [22].

There are other EU standards aligned to the NZEB criteria. An example is the *Passivhaus* standard, seen as being a rigorous method of minimising heat loss through a highly insulated envelope, its design and construction criteria is explained fully by Feist et al.[23] & Müller & Berker [24]. It relies on a hybrid heating system evaluated with its own calculation method called the *Passivhaus* Planning Package (PHPP) [25] [26].

The aim of this study is to assess the performance of two homes during three years of occupation and to learn if new and innovative building methods of construction are performing as expected. Results from monitoring are presented and analysed, later compared against regional benchmarks. This comprehensive measurement of building fabric and energy consumption provides an insight into the impact of identified issues in low energy homes, such as incompatibilities between the as-designed calculations and the as-built occupant behaviour.

This study is significant because it equally assesses two homes that have performed over a period of occupation. Most studies report on one property and its performance [26] or have uncommon elements to compare against and are apart from each other [27] [28]. Their proximity, placement, orientation, wind exposure and solar incidence, make these homes worthy of comparison. Occupation and dwelling demographic is also distinct throughout this study; resident numbers and hours of use have remained marginally unchanged, allowing for a straightforward comparison between years, unpresented in the social housing sector.

2. Literature review

Despite the rigorous calculation process adopted in the UK and by the *Passivhaus* standard, making sure homes have been built as-designed and calculated has not been a streamlined process. Many studies in the UK and other EU countries have noticed a gap in performance demonstrating discrepancies between the calculated energy use and the actual energy consumed [26], [29], [30].

Performance gap has been largely attributed to the design stage, particularly the proficiency and quality of the energy calculation [31] [32]. de Wilde [31] highlights faults that overestimate energy requirements such as accuracy and proficiency of the thermal compliance model. Other issues have been studied such as accuracy of the manufacturer's energy efficiency data for technology and materials [34] [35], complexity of original design [36,37], badly assembled and interpreted thermal details during the construction process [38], poor supervision and site communication between main contractors and sub-contractors [39] and also installed inefficiencies and complicated controls [40] [41].

Occupant behaviour also contributes to disguised energy use often unaccounted for. Recent studies identifying behaviour patterns have contributed to the performance of low carbon homes [42]. Thermal comfort and the energy rebound effect are also relevant [43], [44–46]. These occupant related issues are difficult to predict [31], [47] and Post Occupancy Evaluations (POE) help to measure the effect of occupant behaviour. Techniques for assessing buildings and occupants revealing avoidable waste, bad maintenance, wrong occupant training, and bad management have provided evidential data of buildings performance [47,48], [49–52].

Further tests at post-construction stage and after occupancy to assess the building fabric quality and services efficiency are required to realistically assess buildings against as-designed calculations, preferably after whole twelve month periods [29,53]. Building fabric performance and energy consumption while homes are occupied are effective evaluations [54]. Techniques such as; air leakage testing, in-situ U-value of selected components, infra-red thermography and internal/ external hygrothermal monitoring [1], [33], [47] can demonstrate performance. Other techniques such as co-heating and tracer gas decay used in other studies [26,29], deemed to be important but impractical in occupied dwellings.

Also essential to recognising building performance is analysing actual energy demand from regulated and un-regulated electricity use and space and water heating needs. Legislation on efficient building fabric and services has considerably decreased energy use for heating, however electricity demand has risen as a result of increased use of appliances in households [55] questioning the real operational performance of buildings once occupied. The current compliance model used in the UK (SAP) [18] calculates heating needs as well as regulated electrical demand, omitting un-regulated electrical demand from household appliances. This creates issues surrounding the direct comparison of delivered electrical energy against the assumed at design stage [18]. For comparison purposes benchmarks and similar archetype and household occupancy types are a useful method to account for total electricity use in households. Yohanis et al. [56] have developed a correlation between average annual electricity consumption and floor area of representative dwelling types. White et al., [57], White, [58] and Zimmermann et al. [59] obtained household energy consumption values based on survey-reported expenditure and owner-occupier domestic appliance use, useful as consumption benchmarks. Studies by DECC, [46] and The Scottish Government, [8] use benchmarks of sub-national household energy consumption statistics, including the National Energy Efficiency Data Framework (NEED) that considers lower domestic meter ranges and the removal of estimated meter readings [61]. A comparison of these benchmarks can be seen in appendix B in this paper.

3. Dwelling characteristics

The two homes analysed in this paper are part of the Housing Innovation Showcase (HIS), an award winning housing development by Kingdom Housing Association (KHA). It comprised of twenty seven homes in ten blocks using ten different methods of construction [62] [63]. A site plan and a description of the systems can be seen in Figure 1 and Table 1 where the case study dwellings are highlighted. A front elevation of both homes is shown in Figure 2.

Figure 1 (left): HIS site plan with boundary line around analysed block.

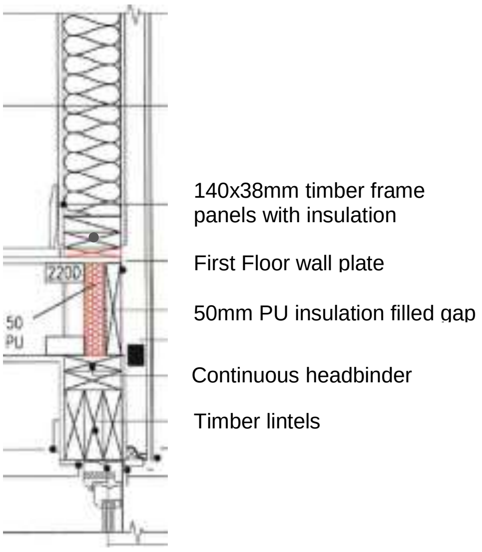
Figure 2 (right): Front elevation of the Passive House (left) and the Control House (right).

Table 1: Housing Innovation Showcase block types and construction systems

Block No.	Evaluation criteria	Building type	Construction system	Type
1	2010 SBS	4-in-a-block	Steel volumetric system	Off-site
2	2010 SBS	4-in-a-block	Timber closed panel	Off-site
3	2010 SBS	4-in-a-block	Timber closed panel	Off-site
4	2010 SBS	Semi-detached bungalow	Insulated clay block	On-site

5	2010 SBS	Semi-detached bungalow	SIP (timber)	Off-site
6	2010 SBS & *Passivhaus*	Semi-detached 2 storey house	Timber open/ closed panel	On & Off-site
7	2010 SBS	Semi-detached 2 storey house	Timber closed panel	Off-site
8	2010 SBS	Semi-detached 2 storey house	Timber closed panel – breathing wall	Off-site
9	2010 SBS	Semi-detached 2 storey house	Timber closed panel	Off-site
10	2010 SBS	Semi-detached 2 storey house	Concrete wall-form	On-site

One home, evaluated using SAP version 9.90 (SAP2009), is the control house (CH) that epitomised current KHA housing typology and specification designed to meet 2010 Scottish Building Standards [64]. Adjacent is the second property designed to the *Passivhaus* (PH) standard also evaluated using SAP2009 and PHPP energy tool. The two dwellings share the same orientation and configuration, also built by the same contractor. Differences include wall system and the energy efficiency methods implemented at design stage. The homes although similar in appearance have distinct differences as detailed in Figures 3 and 4 and Table 2.



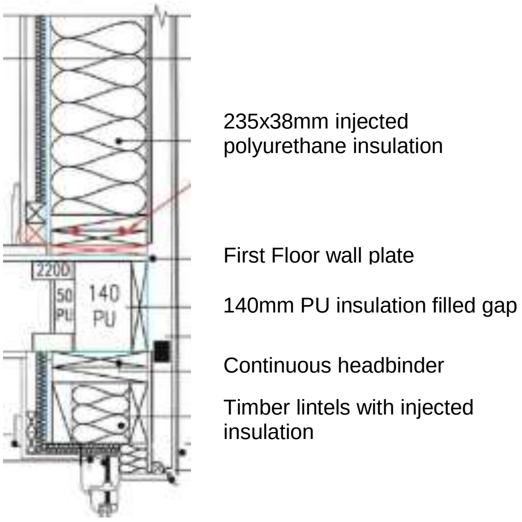


Figure 3 (left): Control House typical wall detail *Figure 4 (right): Passivhaus typical wall detail*

Table 2: Wall assembly description

Control house (CH)			*Passivhaus* (PH)		
Layer (in-out)	ʎ (W/mK)	Thickness (mm)	Layer (in-out)	ʎ (W/mK)	Thickness (mm)
Plasterboard	0.21	12.5	Plasterboard	0.21	12.5
vapour control layer	-	1	Partially filled service void with rigid board insulation	0.035	25+25
Mineral wool insulation	0.040	140	vapour control layer	-	1
OSB board	0.13	9	OSB board	0.13	9
Breather membrane	-	1	Injected polyurethane insulation	0.035	235
Cavity/ timber battens	-	50	OSB board	0.13	9
Proprietary render board	0.25	10	Breather membrane	-	1
			Cavity/ timber battens	-	50
			Proprietary render board	0.25	10
U-value (W/m^{2}K)	0.23	223.5	U-value (W/m^{2}K)	0.10	377.5

Table 3 shows the properties specifications and design parameters implemented in the SAP2009 and PHPP calculations.

Table 3: Comparison of design specification and targets, Control house and Passivhaus

	Control house (CH)	Passivhaus (PH)
Certification	2010 SBS	10W/m2 peak load, PHPP certified, 2010 SBS
Design Strategy	Baseline for HIS	Maximising the benefit of solar & internal gains

Typology	2 storey semi-detached		2 storey semi-detached	
Floor area	96 m^2		94 m^2	
Layout	3 bedrooms		3 bedrooms	
	Open kitchen/ dining room		Open kitchen/ dining room	
	Separate living room		Separate living room	
Fenestration	Triple Glazing, low-e, uPVC		Triple Glazing, low-e, uPVC	
Space & water heating	Gas system boiler (88% eff), radiators, 180lt cylinder		MVHR, gas system boiler (88% eff), radiators & 180lt cylinder	
Envelope U-value (W/m^{2}K)	Wall:	0.23	Wall:	0.1
	Floor:	0.15	Floor:	0.15
	Roof:	0.1	Roof:	0.1
	Windows:	0.8	Windows:	0.8
	Door:	1.4	Door:	1.0
Thermal bridging (W/mK)	0.05 (user defined)		0.08 (user defined)	
Design Ach@50Pa (n50)	4.8 (Depressurised)		0.6 (mean value)	
Ventilation	Natural – window trickle vents, extract fans.		Mechanical with heat recovery - MVHR	
Occupants	2012-2014: 1 working adult, 2 studying children 2014-2015: 2 adults; Working/ unemployed, 2 children studying		2012-2015: 1 retired adult, 3 working/ studying adults	
Renewables	None		None	

4. Methodology

This study includes fabric performance evaluation and energy demand monitoring since the dwellings completion in May 2012 to the last monitoring period in December 2015. Data has been retrieved by visiting the properties on a continual basis before occupation followed by an annual inspection and data retrieval period. Property evaluation started in May 2012 where air leakage testing was performed. Handover took place in the latter days of June. The research started by deploying testing equipment and conducting an early occupation study during winter 2012. The measurements included in-situ U-value testing of building components and internal/ external infra-red surveys of the properties. At handover, energy meter readings were taken combined with the commissioning and deployment of In-home Displays (IHD) for logging hourly energy consumption. Subsequently, energy retrieval took place on a yearly basis in July 2013, 2014 and 2015 together with occupant surveys and deployment of temperature and humidity loggers. A second phase of fabric performance monitoring took place in November and December 2014 repeating the wall in-situ U-value testing and air leakage tests. Appendix A shows the technical elements of the monitoring equipment.

4.1 Air leakage and smoke tests

The properties were assessed at key stages of the pre and post occupation period by using the standard Blower Door and fan test equipment, as seen in Figure 5. Accuracy of the tests results is based on the BS EN Standard 13829:2001 (BS EN, 2001) and dependent on test equipment as shown in Appendix A [66]. Smoke test were conducted in 2014 using a smoke-stick identifying air flows, drafts and the direction and main air leakage points [2]. Air tightness tests can identify air leakage pathways where uncontrolled flow of air passes through cracks, around openings, gaps in air-tight layers and service penetrations [67–70].

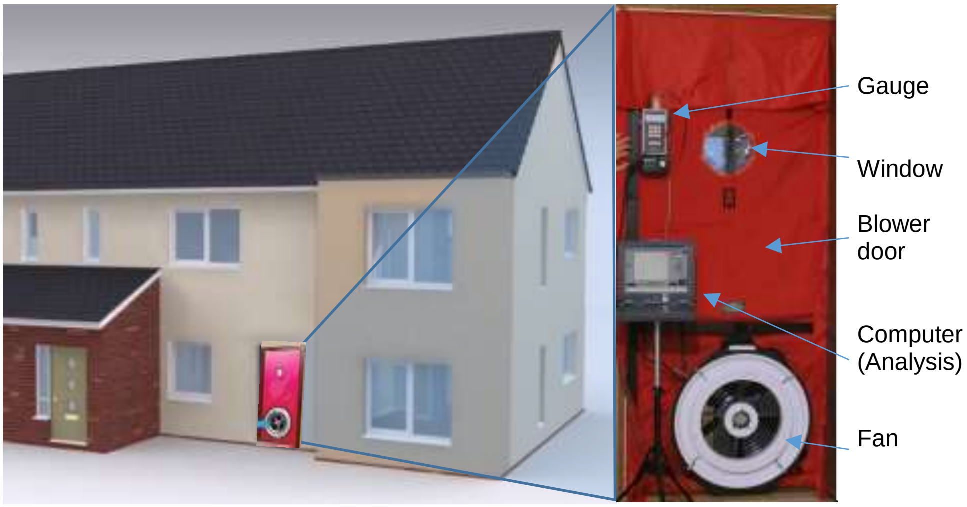


Figure 5: Air permeability blower door testing equipment (Source: Building animation LCBTG [71]*)*

4.2 In-situ U-value

In-situ U-value tests were conducted during winter 2012/13 and winter 2014/15 using Grant Squirrel data loggers with Hukseflux HFP01 thermopile-based heat flux transducers and four K-type thermocouples, deployed at five minute intervals for a period of between 14 and 21 days. Figure 6 shows where equipment was mounted.

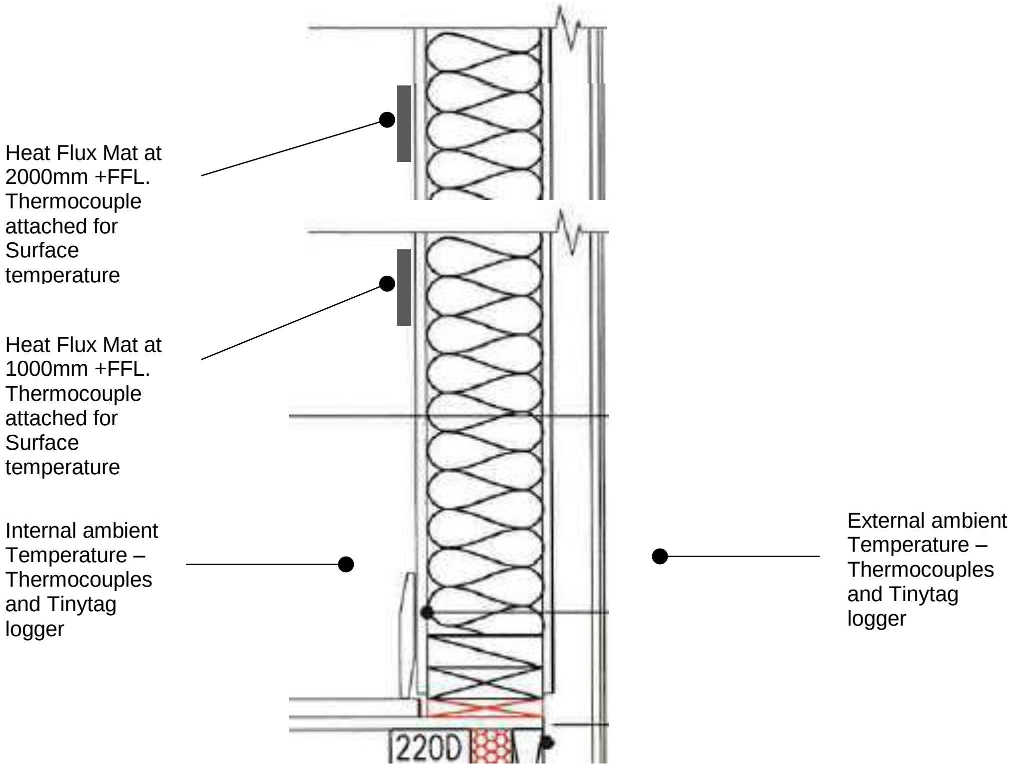
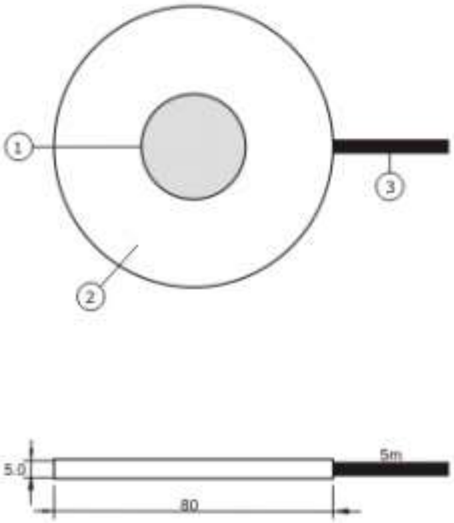


Figure 6: Typical positioning of HFM, thermocouples and temperature loggers – example in Control House

The testing complied with BS ISO 9869:2014 guidelines and calculations [72] [73] as seen in Figures 7, 8 & 9. Reliable results are obtained with a temperature differential (ΔT) of >10°C across the building element.



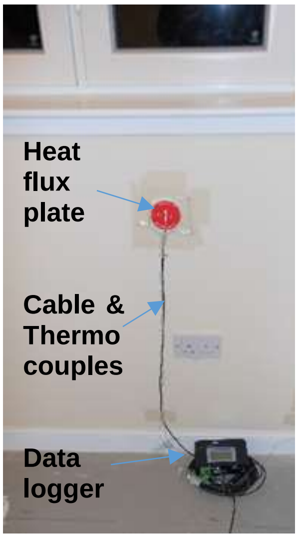


Figure 7 (left): Typical HFP sensor by Hukseflux.

Figure 8 (centre): Sensor diagram: (1) Sensor area; (2) guard of ceramics-plastic composite; (3) cable connected to data logger [74].

Figure 9 (right): Typical installation on external wall – affixed internally.

All measured values undergo an error analysis which suggest small errors may exist in such tests of between 5-8% within the uncertainty of the equipment's calibration. The calculation process and results analysis is dependent on the temperature data retrieved [73] [75].

4.3 Infra-red thermography

The survey was conducted on both properties during the first heating period. It included an internal and external survey concerning all elevations of the dwellings with close-up thermograms for specific analysis. Infra-red thermography is a non-destructive qualitative test carried out with a thermal imaging camera following the methodology in BS EN 13187: 1999 [76]. It is a tool that establishes surface temperature variations caused by building defects in insulation layers or thermal bridging [77] & [78]. Methodology of testing and the analysis of thermograms is discussed by Hart, [79], Lo & Choi, [80] & Guerra-Santin et al., [33].

4.4 Indoor and outdoor environmental conditions

Hourly temperature and relative humidity conditions were collected using Tinytag data loggers in living rooms in both dwellings from June 2012 to December 2015. External readings for the periods from June 2012 to September 2014 were collected by a nearby weather station located in Crossford, Dunfermline, Fife, approximately 4.5 miles from the properties. From the period of September 2014 to December 2015 a site located Logic Energy LeNET Mobile weather station was deployed 60 meters from the properties. It recorded; temperature, relative humidity, wind speed, wind direction, barometric pressure, and southern solar radiation.

4.5 Energy consumption

Delivered energy consumption data for each dwelling was obtained from In-home displays (IHD) supported by a reconciliation of metered energy use, to obtain total gas and electricity consumed over three years at twelve monthly intervals [81] [82]. A comparison was made between the design performance indices calculated by SAP2009 for space, water heating and electrical use against delivered energy for the three years of occupation. This assessment of normalised performance indices is explained in the BS EN15217:2007 [83] and discussed by Castellano et al., [22], Burman et al., [58] and O'Leary et al., [90]. The consumed yearly energy demand (kWh/m^2/yr), total yearly carbon emissions (kgCO$_2$/m^2/yr) and total yearly cost of energy use (€/yr) were compared against as-designed calculations and Great Britain and Scottish benchmarks shown in Appendix B.

5. Results

In this section the results of the three yearlong monitoring study are presented. To begin with, section 5.1 describes the as-designed results and the differences observed with the as-built conditions. It follows the fabric performance evaluation in section 5.2 presenting results from in-situ U-value measurements, air leakage and infra-red thermography. This section informs key variables that affect the properties energy demand over the period of monitoring. Section 5.3 compares delivered energy against the design calculations and other benchmarks in Appendix B. The final analysis comes in section 5.4 comparing cost and carbon performance.

5.1 Design stage results

During the design stage, SAP2009 compliance models and PHPP for certification calculated the total annual expected gas and electricity (regulated) consumption, as well as the total primary energy required and the carbon emission rate of the two dwellings. Table 4 below presents the results for the two analysed dwellings.

Table 4: SAP2009 & PHPP design results for SBS 2010 compliance

Evaluation	Control House	*Passivhaus*	
	SAP2009	SAP2009	PHPP
Annual Space Heating (kWh/m^2/yr)	33.7	19.45	16.0
Annual Water Heating (kWh/m^2/yr)	26.2	30.0	31.7
Annual Electricity (kWh/m^2/yr)	8.2	9.1	5.36
Annual Total (kWh/m^2/yr)	68.1	55.1	56.6
Primary energy (kWh/m^2/yr)	79.85	72.66	66.7
CO_2 emissions (kgCO_2/m^2/yr)	16.3	14.8	15.4
SAP rating	84	84	-
SAP EI rating	85	88	-

The results obtained in Table 4 are based on conventional values broadly dependant on buildings location, floor space and occupancy. During the analysis of the calculated results it was observed that these values were not representative of the as-built conditions. In SAP2009 the assumed number of occupants is based on the total floor area (TFA) of the living room, providing figures for internal gains, hot water demand and electrical regulated energy. Although assumed, in reality occupant behaviour can vary, both in quantity and hours of occupation. For this model, the calculation resulted in having 2.71 occupants for the CH and 2.68 for the PH. PHPP similarly calculates occupancy using the total floor area assuming a limit of 35m^2/person, thus 2.6 occupants is used. In reality the occupancy of the homes differ. The CH has two children and one regular adult with intermediate occupancy by another adult. The PH has four adults with an intermediate occupancy dependant on employment.

For the external weather applied to the calculation process, SAP2009 uses monthly values and PHPP uses a worst case scenario weather file [85,86]. Figure 10 shows external temperature during the three years of monitoring. The average figures show that temperatures during the three years of monitoring are similar to the values used in PHPP but lower than those used in SAP2009. Other determinants are wind speed and solar radiation where more variations were observed that impact the actual performance compared with the calculations.

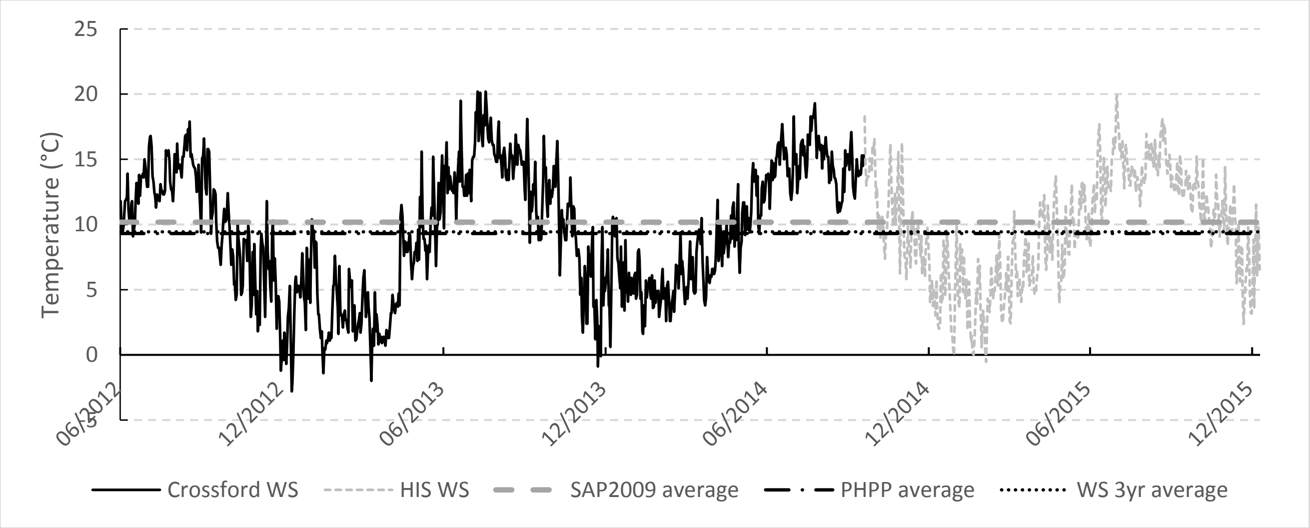


Figure 10: Average monthly dry bulb temperature (°C), Crossford, Fife & on-site HIS weather stations.

The internal design temperature used by SAP2009 of 21°C also differ from the actual experienced. PHPP calculations use two temperatures, 20°C during winter months for heating demand calculations and 25°C during summer months for cooling demand calculations. Temperatures above 21°C in both dwellings occur during nine months throughout the three years of study, particularly in July and August. Figure 11 shows the CH internal temperatures fall below the comfort range stated by CIBSE (2015) between 20 and 26°C, with low and high readings of 15°C and 27°C respectively. However the average throughout this period is in the lower range of the comfort level at 20.5°C. The readings show temperature is susceptible to fluctuations, particularly in the winter months.

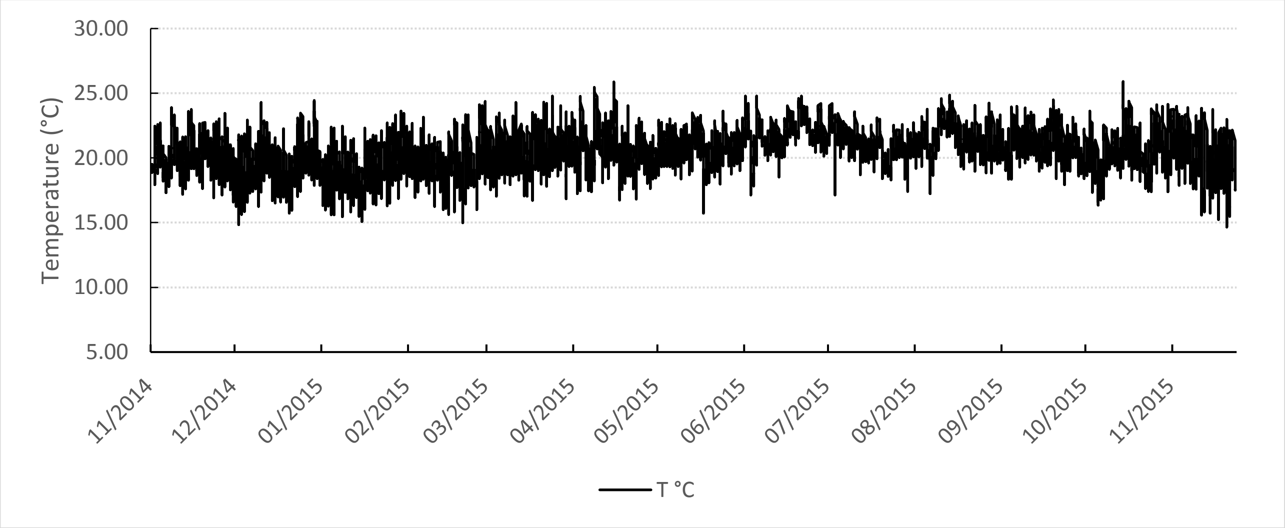


Figure 11: Control House internal environmental conditions between November 2014 & December 2015

The internal temperature for the PH in Figure 12 appears condensed and with a lower amplitude, meaning it hasn’t been influenced by external fluctuations. Temperatures seldom reach below 18°C however some higher temperatures are reached closer to 27°C but generally clustered to the mean of 22°C.

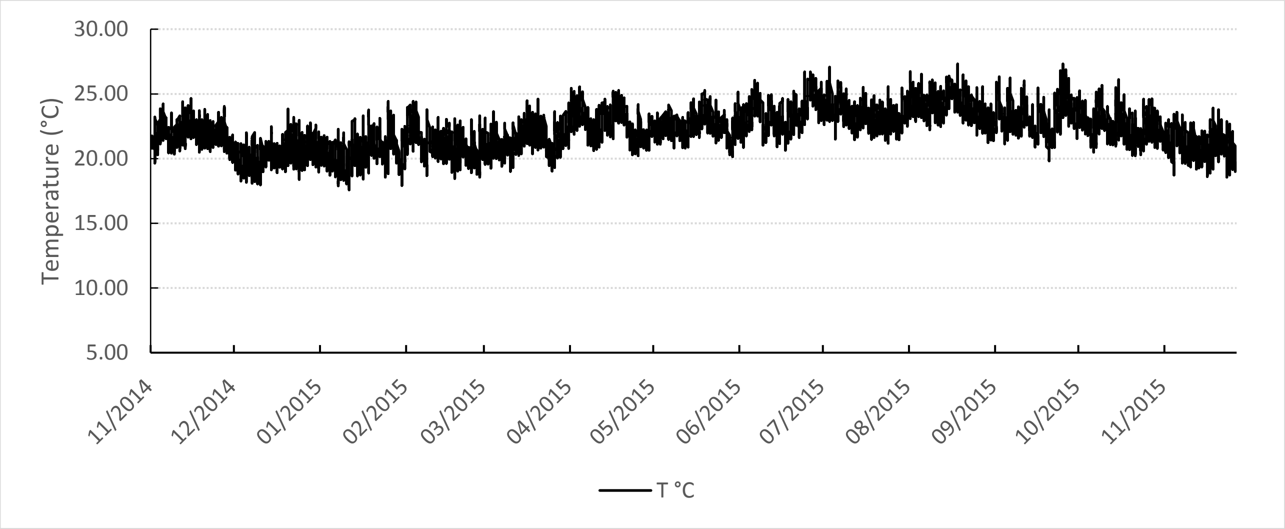


Figure 12: Passivhaus internal environmental conditions between November 2014 & December 2015

5.2 Fabric performance monitoring

5.2.1 Air Leakage and smoke tests

Table 5 shows the comparison between the two tests conducted to measure the air leakage rate of the dwellings. Three figures are shown worth comparing; the first is the assumed air leakage used for compliance calculations, followed by the two in-situ tests performed.

Table 5: Summary table of air leakage results at post construction stages

	Building characteristics					Post-construction - 2012			Post-construction - 2014		
	Floor area (m^2)	Volume (m^3)	Envelope area (m^2)	Ratio Vol/area	Design Air leakage rate (n50)	Flow @50Pa (m^3/h)	Air flow exponent (n)	Air leakage rate (n50)	Flow @50Pa (m^3/h)	Air flow exponent (n)	Air leakage rate (n50)
CH	96.92	247.15	238.00	0.96	4.8	871.98	0.650	3.5	958.5	0.656	3.88
PH	93.96	232.00	224.00	0.97	0.6	123.11	0.813	0.53	468	0.666	2.01

The results show significant changes between initial tests conducted prior occupation and the tests two years after occupation. It has also shown differences in the design expected figure compared with the post construction stages as observed in Figure 13. An interesting observation is the air flow exponent or the air flow regime through orifices in the dwelling in a scale of 0.5 to 1.0 (ATTMA, 2010). Larger apertures have a value closer to 0.5 whereas values closer to 1.0 demonstrates dispersed laminar air flow orifices. Tests conducted in 2012 and 2014 show small variations, however the PH has changed from having small orifices to larger ones, created by the occupants with uncontrolled penetrations (picture hanging, etc) or third party TV service penetrations.

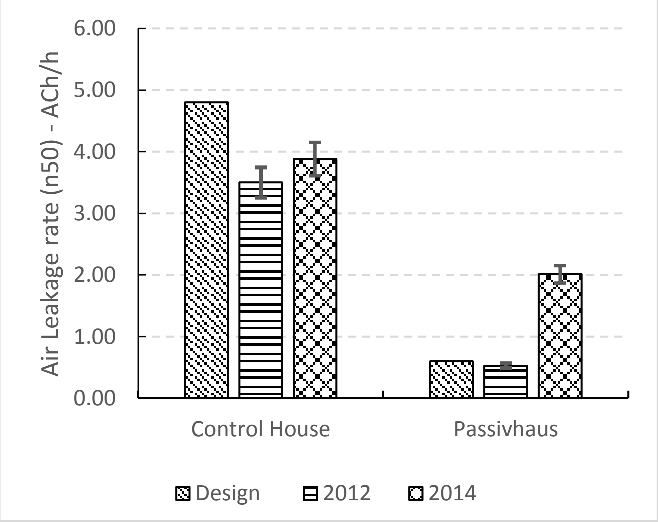


Figure 13: Graphical results between design and measurements air tightness

The smoke pencil test detected minor leakage areas, most were in the CH at junctions between floor and wall at first floor level, gaps around attic hatch, leakage through and around windows, doors and services penetrations as seen in Figures 14 & 15.

Figure 14 (left): leakage around WC discharge pipe. Figure 15 (right): cracks appearing around internal finishes

5.2.2 In-Situ U-value results

The In-situ U-value monitoring was undertaken during the first winter in 2012 and two years afterwards in the winter of 2014. Table 6 and Figure 16 show the results of the two tests against the design calculations and SBS 2010 maximum permitted values for walls.

Table 6: U-value results compared with Design calculations and maximum U-values SBS, 2010.

	U-value (W/m^2K)			
	SBS 2010	**Design SAP & PHPP**	**2012**	**2014**
CH	0.25	0.23	0.26	0.38
PH	0.25	0.10	0.12	0.11

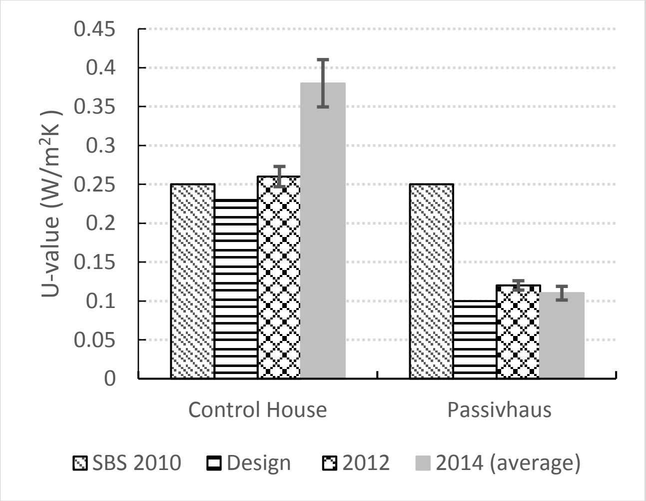
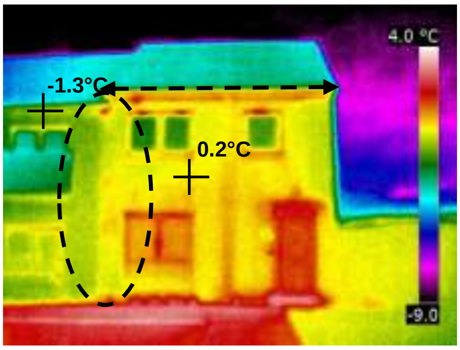


Figure 16: U-value results in comparison with design calculations and SBS 2010 maximum values

The CH has presented a 46% increase in thermal transmittance, however the PH has remained consistent in the two tests with a minor decrease in transmittance attributed to the accuracy of the tests.

5.2.3 Infra-red Thermography

An infra-red thermography survey were conducted prior to handover and occupation. External thermogram in Figure 17 easily distinguishes the two properties. On the left the PH property shows lower surface temperatures than the CH on the right. Higher uneven temperatures on the wall and around openings of the CH clearly indicate envelopes reduced capacity to limit heat loss. The analysis of Figure 18 shows heat loss at the ceiling level of the front elevation in the CH.



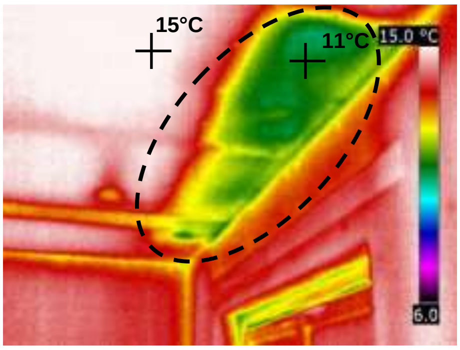
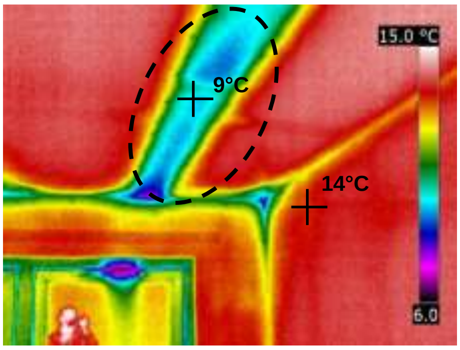


Figure 17 (left): External image of the PH and CH. *Figure 18 (right): Internal CH first floor ceiling in.*



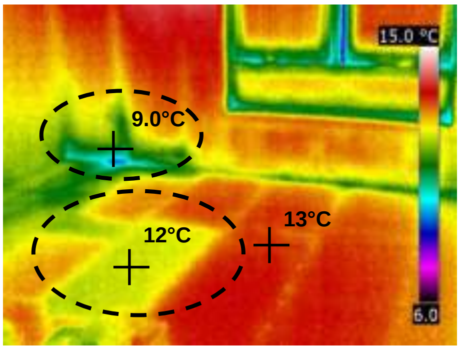


Figure 19 (left): Internal thermograms in the CH *Figure 20 (right): Ground floor heat loss in the CH*

Thermography is also good at evidencing thermal bridging, Figure 19 shows a thermogram taken of the CH first floor bedroom ceiling where timber joists are creating a linear thermal bridge. Thermogram in Figure 20 shows missing insulation between floor joists and also an air leakage pathway where missing insulation and an existing gap behind dry lining is causing heat loss. The PH has some deficiencies, despite being of low impact, Figure 21 shows missing insulation at the first floor ceiling and Figure 22 in the bathroom where a pipe or duct detail creates heat loss.

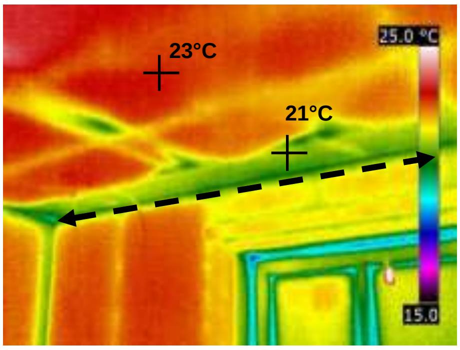


Figure 21 (left): PH: bedroom ceiling

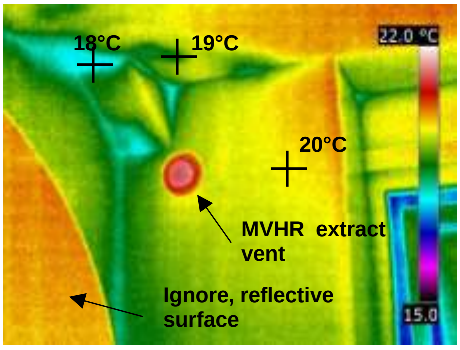


Figure 22 (right): PH: Bathroom junction

5.3 Delivered energy performance

The two analysed properties use natural gas as their main fuel for space and water heating. Electricity is used for appliances, pumps, fans and lighting. The mechanical ventilation with heat recovery (MVHR) unit in the *Passivhaus* provides recovered heat from the wet rooms and is powered by electricity. Both properties have an electric shower in the ground floor while other needs are provided by a system boiler and water cylinder. A back-up 3kW immersion heater is also installed in the cylinder but rarely used by the residents.

5.3.1 Electricity

The delivered electricity demand in each dwelling for each of the monitored years is shown in Table 7. The electricity consumption data shows both regulated and unregulated sources. Alongside the totals are benchmarks and calculations relative to the two dwellings. The PHPP calculation allows appliances and cooking loads to be included in the criteria for evaluation. It calculated that 1,755kWh/yr (18.7kWh/m^2/yr) is used, a figure that is 2.5 times lower than the total delivered for year one. The benchmark used from research by Yohanis et al., [62] of 40kWh/m^2/yr is 1,200kWh/yr more than the CH delivered for year one, showing that the occupants were frugal in their use of electricity. The estimation used by Yohanis (ibid) is lower by 600kWh/yr than the three year average consumption for the *PH* and 800kWh/yr lower than the CH*.*

Table 7: Total delivered electricity against benchmarks and calculations

	Total delivered electricity (kWh/yr)				Benchmarks & calculations (kWh/yr)				
	Year 1	Year 2	Year 3	3 year average	SAP2009 (regulated demand)	PHPP (Aux & appliances)	Yohanis et al. (2008)	GB average	Scottish average
	2013	2014	2015						
CH	2,650	3,268	3,111	3,010	620	-	3,840	4,100	3,915
PH	4,716	4,321	4,150	4,396	563	1,756	3,760		

Figure 23 compares the normalised electricity consumption during the three different years of monitoring. Year one is often used as an adjustment period reflecting high energy use. The PH has consumed more electricity than the CH because of the larger hours of occupation and number of adults living in the property together with the added appliances and technology used.

The PHPP uses regulated and unregulated energy assumptions in its calculation. The normalised figure used as a design comparison is 18.7kWh/m^2/yr, more than half of the benchmark used from Yohanis et al (ibid). Scottish and British averages are useful to place the dwellings within a regional grouping, both of which are above the delivered demand.

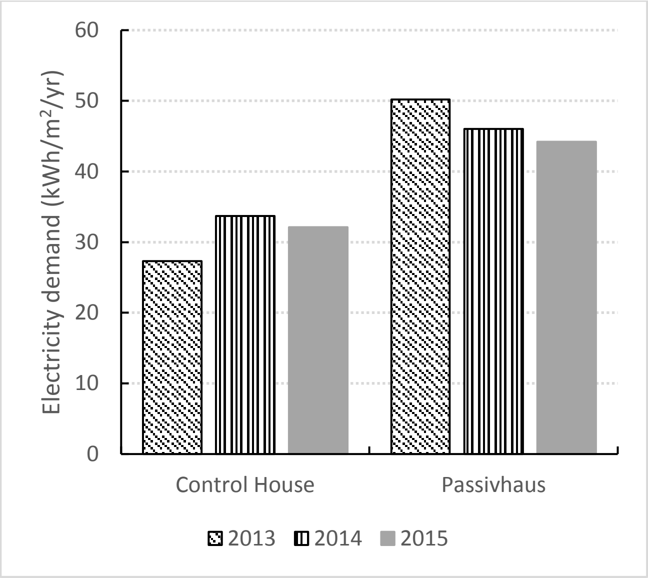


Figure 23: Distribution of delivered electrical energy during the time of study

5.3.2 Gas (Heat)

The amount of gas consumed for space and water heating in each dwelling over the three year period is shown in Table 8.

Table 8: Total delivered gas against benchmarks and calculations

	Total delivered gas (kWh/yr)			Benchmarks & calculations (kWh/yr)				
	Year 1	Year 2	Year 3	3 year average	SAP2009	PHPP	GB average	Scottish average
	2013	2014	2015					
CH	8,266	5,884	6,173	6,774	6,359	-	13,500	13,872
PH	5,875	6,739	6,226	6,280	4,821	1,480		

Gas consumption is variable across both dwellings, with the highest consumption found in the CH during year one reduced by 29% and 26% in years two and three respectively. The lowest consumption came from the PH during year one, it was 29% lower than the CH, however it increased in year two by 14% and by 5% in year three. SAP2009 calculations are 7% lower (-415kWh) and 30% lower (-1,459kWh) than the delivered three year average for the CH and PH respectively. There is no obvious explanation for this, except that the occupant behaviour in this dwelling has a significant impact on how energy is consumed. Figure 24 further explains the distribution of delivered gas for heating over the period of study. The CH has consumed more during its first year of occupation adjusting itself in subsequent years, to 60kWh/m^2/yr in years two and three. The PH started low and increased by 10kWh/m^2/yr between year one and two later falling closer to the year one consumption during the last year of monitoring.

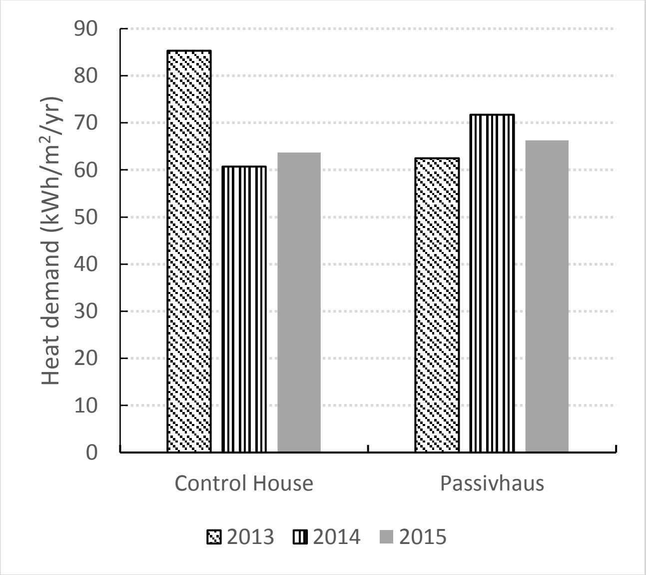


Figure 24: Distribution of delivered heat energy during the time of study

The results indicate that whilst there is variability in the consumption of gas across the three years of monitoring, there is a downward trend in consumption with both dwellings consuming a similar three year average. It is clear that the CH suffered the most during the colder winter of 2012/13 with increased gas consumption approximately 25kWh/m^2/yr higher than subsequent years. The PH has shown that despite being designed with an envelope of lower thermal transmission, the last year has consumed similarly than the less efficient CH.

5.4 Carbon emissions & cost

Relevant to the environmental impact of the homes are the carbon emissions attributed to the excess energy consumed against the design calculations. Taking the normalised performance indices averaged over the three years, a comparison can be made. The CH has a combined emission of 27 kgCO$_2$/m^2/yr against the design aspiration 34 kgCO$_2$/m^2/yr. The PH has a combined emission of 34 kgCO$_2$/m^2/yr compared with 32 kgCO$_2$/m^2/yr. The PH has a higher carbon impact largely attributed to the higher electricity consumption, increased occupant numbers and behaviour with greater non-regulated electricity use, shown in Figure 25.

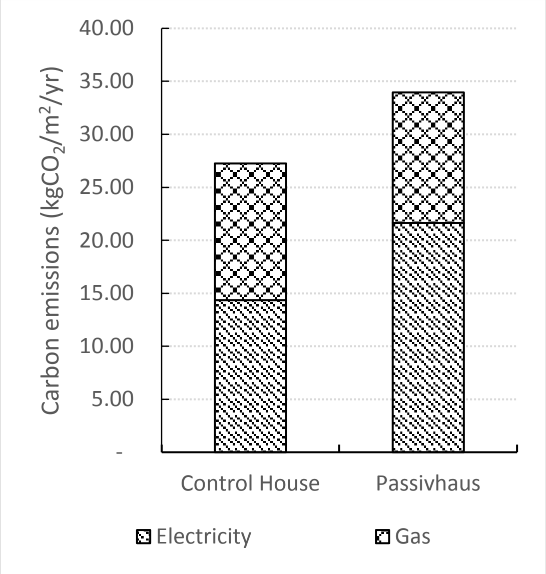


Figure 25: Duel fuel carbon impact of the properties over the analysed period of study

Higher energy demand impacts on occupant's fuel costs. Using the cost of fuel for heating a property, the CH average expenditure over the three years of occupation came to €360/yr while the PH was €333/yr. This represented a difference against the SAP2009 calculations of €51 in the CH and €106 in the PH. The average Scottish expenditure on heat is €790/yr which represents a saving of €430/yr in the CH and €450/yr for the PH.

6. Conclusions and discussion

This study set out to evaluate the actual performance of two homes designed to meet *Passivhaus* and SBS 2010 criteria. Comprehensive fabric performance and delivered energy was collected during a three year continuous cycle. The analysis of the collected data show a number of key findings which are summarised below.

Measured data of environmental conditions in both dwellings were found to reside within normal and predicted ranges and neither property created identifiable conditions that were likely to be unhealthy to the occupants. The measured parameter of internal temperature showed some variation across the homes indicating how occupancy influences the comfort conditions and subsequent use of energy. Given the small sample analysed, these variations need to be compared with larger data sets of similar properties in order to identify significant trends in the data. However, distinctions between the two properties led to a recognition that fabric efficiency plays an important role in minimising fluctuations of internal temperatures; contributing to a decline in thermal comfort.

The results from the fabric performance tests showed that the homes performed differently to expectations and calculations. However, evaluation of the homes after occupation has shown that the envelope was susceptible to poor maintenance and envelope deterioration was observed over time. This was particularly evident with the air leakage results for both homes; with increasing air permeability recorded each year from the initial tests conducted in 2014, particularly in the PH. Thermal transmission in the CH has also increased since the initial design. Possibly due to reduced performance of the insulation and open timber frame panel system. However the PH wall performed as originally designed; perhaps showing robustness and reliability of the system.

Moreover, the results generally support previous work in the field [3–5,87] [33] , though there are four key areas which stand out, as indicated below:

6.1 Impact of assumptions and actual data

Previous studies have shown that performance of low energy homes relies on the initial quality of the design. The impact of assumed data over actual figures represent differences in final as-built energy use. The properties present some differences between data used for calculations and actual monitored data which impact on final energy demand. This further demonstrates that compliance tools are limited in terms of the data used and are unable to accommodate realistic scenarios of occupation and weather patterns.

6.2 Specification, construction phase, commissioning

The performance of the homes is also influenced by the interpretation of specifications, build quality, and the correct installation of the building services; highlighting the importance between the interaction of technology and the end user. Usability of services technology requires clear guidance on their design and operation and recognising when maintenance is required. Although a handover procedure took place where explanations of technology were made [62], the user often felt detached from the controls, operation and maintenance of such technology, partly due to its complexity but also because liabilities between owner (social landlord) and occupant are misunderstood. This causes confusion, frustration and leads to greater energy use.

The role of the construction phase and the quality of its contractors and builders to construct the homes goes beyond the scope of this research, however poor interpretation of specifications and the skill level of trades and contractors can have a large impact on energy use once occupied. The only realistic way of quantifying this is by conducting construction performance checks and tests, such as those proposed by Guerra-Santin et al., [29] and Littlewood & Smallwood, [93] where poorly-performing fabric conditions can be corrected at set stages, further refining its performance to match intended specification. Improving the workforce skills can also help to reduce construction stage faults and defects causing the performance gap.

Adequately commissioning the services can also help to identify faults that impact on building energy use before handover to residents. Reporting back to the residents on the faults identified or malpractice can save energy in the future and further inform the residents on the correct operability of such technology. Performing a second commissioning stage after initial corrections have been made further provides confidence to the building owner and occupier that the technology will perform as first planned.

6.3 Occupant behaviour

Taking account the small sample of monitored dwellings in this study and the variations in occupant behaviour, the consumption of gas in the CH has been surprisingly close to that assumed in the compliance models, however for the PH it is over4 times higher than the PHPP calculations suggest and 25% higher than SAP2009; highlighting the importance of initial building design, construction quality, and occupant behaviour. Electrical demand over the three years has shown that occupancy influences its usage, with disparities shown in the assumed calculations, the CH is 55% lower than the benchmark obtained by Yohanis et al., [62] and the PH is very close but nearly 2.5 times higher than that calculated in PHPP.

6.4 Impact of carbon emissions

The normalised as-built total carbon emissions emitted by the two homes in comparison with other studies shows correlations and similarities. Comparisons with results by Ridley et al.,

[91] on two Passivhaus properties and Gill et al., [32] of four affordable low carbon homes are shown in Figure 26. Another study by Stinson et al., [82] shows similar results for semi-detached social rent homes built in 2010, using timber open panel wall systems and no renewable energy technology.

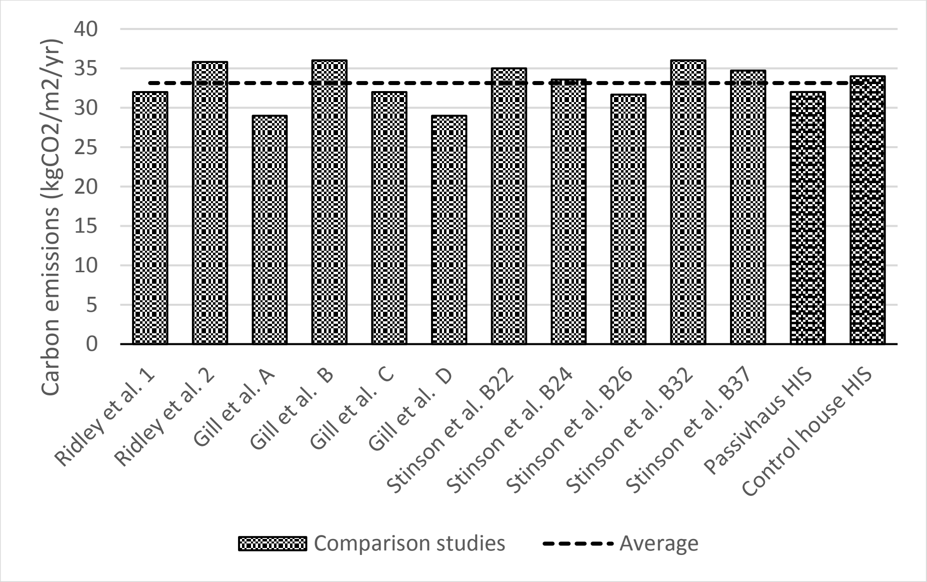


Figure 26: Carbon emissions against other similar homes

Out of the twenty seven homes in the KHA HIS development, this paper analyses a statistically small, yet directly comparable, sample of low energy homes. Despite this, the study contributes usefully to the comparison of the as-built performance against as-design calculations by identifying important differences. Over a longer occupied period these differences will not only exacerbate the dwellings environmental impact but also have a detrimental effect on occupant’s health, wellbeing and energy consumption.

Drawing conclusions from these results with respect to wider domestic housing stock or carbon policy measures in the UK is difficult, however the results do reveal that house building practices need to change in order to achieve stated carbon reduction targets.

Further building performance evaluation and post-occupancy evaluation work is being conducted in order to assess the occupant’s impact on the overall performance of these two homes as well as others in the HIS development. The larger sample size of this enhanced study into the different methods of construction in the development will give a greater appreciation of the performance of current housebuilding in the UK; determining the impact of the users and the role that dilapidation of the building fabric performance has on actual energy performance over time.

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9. Appendices

Appendix A: Test equipment and methodology specifications

Test equipment	Make	Model	Calibration type	Accuracy	Range	Logging interval	Guidance
Blower Door Fan	Energy Conservation	Minneapolis – Model 3	UKAS (Yearly)	± 7%	-	-	ATTMA, 2010 & BS EN 13829:2001
Micro-manometer	Energy Conservation	DG-700	UKAS (Yearly)	± 2 Pa	0 - 100 Pascals	-	ATTMA, 2010 & BS

							EN 13829:2001
Thermometer	Testo	110	UKAS (Yearly)	± 1°C	-20°C - +40°C	Spot measurements	ATTMA, 2010 & BS EN 13829:2001
Barometer	Druck	DPI 705	UKAS (Yearly)	± 5 mbar	950-1050 mbar	Spot measurements	ATTMA, 2010 & BS EN 13829:2001
Anemometer	Skywatch	Xplorer 2	-	<20m/s=3%	0.8 - 40 m/s	Spot measurements	-
Smoke test	Hayes UK	-	-	-	-	-	-
Data logger 24 bit	Grant Squirrel	SQ2020 & SQ2010	-	± 0.05% & 0.1%	-	5 min	-
Heat flow mats	Hukseflux	HFP01	ISO (bi-annual)	±3%	-0.075 to 0.075 V	5 min	ASTM C177 – ISO 8302
Thermo-couples	RS Components	K-type: Chromel – alumel - 41 µV/°C	In-house	± 1.5°C	200 to 1372°C	5 min	IEC 60584
Thermal camera	FLIR	B335 - 320 x 240 pixel resolution	ISO	-	70 mK to < 50 mK.	-	BS EN 13187:1999
Temperature & Humidity	Gemini	Tinytag Ultra TGU-4017	ISO	± 0.5 to 0.4°C	-40°C to +85°C	5 min	-

Appendix B: Household domestic energy consumption benchmarks – Semi-detached home.

Benchmark name	Date	Author	Origin	Household type or archetype	Benchmark			
					Heat		Electricity	
					kWh/yr	kWh/m^2	kWh/yr	kWh/m^2
Real-life energy use in the UK	2008	Yohanis et al.	Peer reviewed journal	Semi-detached house (97m^2)	-	-	4,656	40
DIMPSA	2014	White	DEFRA	Younger working families in medium-sized rented houses	13,595	-	3,491	-
DIMPSA	2014	White	DEFRA	“Average” mains gas-heated households	15,280	-	3,585	-
Intertek report R66141	2012	Zimmermann et al.	DECC, DEFRA & EST	Semi-detached house	-	-	4,009	76
Intertek report R66141	2012	Zimmermann et al.	DECC, DEFRA & EST	Household with children	-	-	3,672	68

Intertek report R66141	2012	Zimmermann et al.	DECC, DEFRA & EST	Multiple person household with no dependent children	-	-	4,232	77
Sub-national - GB	2014	DECC	DECC	GB mean, weather corrected	13,500	-	4,100	-
Sub-national - Scotland	2012	DECC	DECC	Scotland mean	14,826	-	4,577	-
Sub-national - Scotland	2014	DECC	DECC	Scotland mean	13,872	-	3,915	-
ECUK	2014	DECC	DECC	UK (unweather corrected)	14,100	-	4,150	-
ECUK	2014	DECC	DECC	UK (weather corrected)	12,300	-	4,000	-
NEED - UK	2013	DECC	DECC	Estimates removed	13,600	-	4,000	-

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