40th IAHS World Congress on Housing
Sustainable Housing Construction
December 16-19, 2014
Funchal - Portugal

ENERGY PERFORMANCE EVALUATION OF A PASSIVE HOUSE BUILT TO SCOTTISH BUILDING STANDARDS

***Julio Bros-Williamson[1], Jon Stinson[2], John Currie[3]**

1: Scottish Energy Centre, Institute for Sustainable Construction
School of Engineering and Built Environment
Edinburgh Napier University
42 Colinton Rd, Edinburgh, Scotland, UK, EH10 5BT
e-mail: j.broswilliamson@napier.ac.uk, web: http://www.napier.ac.uk/sec

2: Details same as above - e-mail: j.stinson@napier.ac.uk
3: Details same as above - e-mail: j.currie@napier.ac.uk

Keywords: Passivhaus, Social housing, Thermal performance, Performance gap, Energy efficiency

Abstract: *Ensuring that predicted (simulated) energy performance figures are realised once a building is in-use has been of growing concern since issues surrounding the 'performance gap' were realised in the mid 1990's* [1]. *Increasing energy demand and a decrease in thermal comfort with an added pressure on fuel poor occupants has questioned why some dwellings are not delivering their design expectations.*

In accordance with the Energy Performance of Buildings Directive (Directive 2010/31/EC,EPBD) [2], *each EU member state is required to evaluate at design stage the energy performance of buildings. Following these predictions, it is expected that the completed building is constructed to a performance level which ultimately reflects the design model. There is, however, significant evidence to show that buildings are not achieving these aspirational energy requirements which often translates into higher energy bills for the occupant(s).*

This paper has evaluated the difference in energy demand at the design stage and early-occupation stage of two similar dwellings constructed in Scotland for a large social landlord. The dwellings were constructed side-by-side, built using a similar timber frame system fabricated by the same manufacturing firm. One dwelling was constructed to Passive House (Passivhaus) standards, the other in accordance to conventional 2010 Scottish Building Regulations. Furthermore, this paper presents in-situ thermal envelope evaluation results that were measured at post-construction and early occupation stage.

The early findings from this research have shown that energy figures obtained through real-time hourly data of space and water heating for the Passive House and the more conventionally designed house during the first year of occupation were 37% and 35% higher in energy consumption, respectively, than the predicted figures. Field test results have provided evidence to suggest that this increased demand is, in-part, due to some deficiencies of the thermal envelope. Other factors that influence the operation of the dwelling, for example building services efficiency, control systems and occupant behaviour have also contributed to widening the performance gap.

1. INTRODUCTION

An agreement in 2007 by the European Council to set precise, legally binding targets on climate and energy policy marked a turning point in tackling climate change. The focus was for each member states to provide secure, sustainable and competitive energy and to make the European economy a model for sustainable development in the 21st century [3]. The objective was to achieve a 20% reduction of the EU's energy consumption by 2020, set targets for the EU-wide development of renewable energy and the reduction of greenhouse gas (GHG) emissions [2]. Achieving such targets on energy consumption requires the improvement of the EU member state housing stock; accounting for 39% (direct and indirect) of the total in-use emissions reaching 1,000Tg of CO_2 equivalent in 2010 [4]. With the introduction of the Energy Performance of Buildings Directive (Directive 2010/31/EC,EPBD) [1] each member state will require guidelines to evaluate and certify the energy efficiency of buildings and introduce energy saving methods in buildings, hence the proposal of the EU's Nearly Zero Energy Buildings (NZEB) suggesting low energy demand linked with on-site renewable energy use [5]. In the UK, the National Calculation Methodology (NCM) was created which required dwellings to be evaluated using the Standard Assessment Procedure (SAP) to assess the energy efficiency of new buildings and by generating an Energy Performance Certificate (EPC). The NZEB requirements (see Figure 1) will be met by complying with the Zero Carbon standard created in 2007 which requires fabric energy efficiency, on-site low/zero carbon heat and power and a final stage called "Allowable Solutions" used as a trade-off for carbon not able to be mitigated by the dwelling [6] (see Figure 2).

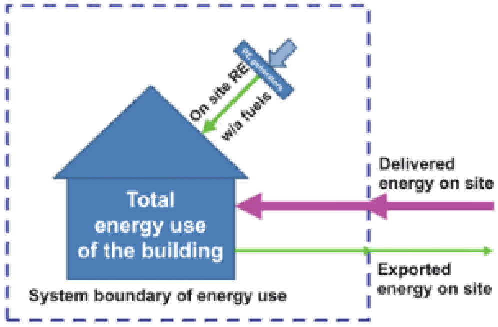


Figure 1. NZEB Boundaries of energy on site

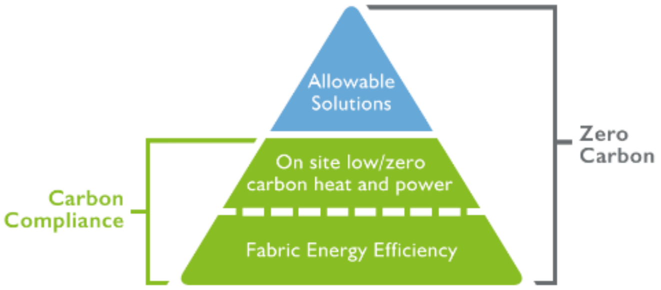


Figure 2. UK's Zero Carbon core requirements

Significant methods to reduce energy demand by requiring the use of low energy building technology have been conceived differently by each member state. One method developed since 1991 is the Passive House (PH) standard which seeks to improve energy efficiency through improving the building envelope and allowing substantial simplifications of the heating system. It achieves this by utilising passive and active solar use and loss reduction; for example introducing air-tight envelopes with a whole-house ventilation system with heat recovery. According to Schnieders & Hermelink [7], PH offers between 15-20% space heating demand while the extra costs of implementing the standard are in the region of 10% above the total building costs for conventional dwellings.

An award winning housing development by Kingdom Housing Association in Dunfermline, Scotland, labelled the Housing Innovation Showcase (HIS) involved the construction of 27 new homes using 10 different Modern Methods of Construction (MMC). The homes were designed and fabricated using different architects, contractors and system providers proposing a variety of solutions, from timber and steel-framed "off-site" construction to clay block and concrete formed systems built "on-site". The showcase also attempted to build in accordance with a number of differing sustainability standards, for example, Scottish Building Standards (SBS) Section 7 Sustainability labelling system, and the above mentioned German and Austrian "Passive House" (PH) standard. Within the development a home which epitomised current Kingdom HA housing procurement standards, denominated as a "control house" (CH) was built to comply with the minimum requirements set by SBS at the time of construction. Both the PH and CH were built side-by-side; sharing one common wall and were built using the same timber frame building system (see Figure 9).

1.1. Objectives

In order to measure the energy efficiency of all the housing systems built in the HIS development, the Housing Association requested a detailed Building Performance Evaluation (BPE) of each building system (13 homes) and a Post Occupancy Evaluation (POE) of all 27 homes in the development. The BPE consisted of an as-built fabric and services evaluation, while the POE conducted an early occupation social study and energy consumption evaluation. This paper presents the comparative results of the two study dwellings by identifying fabric and energy demand variances. Building user surveys and non-destructive building monitoring equipment were utilised to assess the impact of MMC and Low Carbon Technology in meeting perceived energy efficiency and occupant thermal comfort needs.

2. AS-DESIGNED SPECIFICATIONS

This comparison between the dwellings arose because of their relative proximity, orientation, comparable wall system, contractor used, and dwelling type. The homes are orientated south (front) north (back) with each having an exposed gable end wall and back garden. The results presented include the BPE and the energy consumption values captured during the first year of occupation.

2.1. Building characteristics – Control House (CH) plot 17

This dwelling is a two storey, 97m^2, three bedroom town house built to meet the SBS technical handbooks 1 to 5 with an emphasis on part 6 Energy [8]. The dwelling was built with a 140mm closed panel timber frame wall system, sheathed both sides with Oriented Strand Board (OSB) and injected with a high performance polyurethane foam insulation filling. A reflective outer breather membrane was installed on the outer of this with a 50mm air gap and a 5mm external render system applied to a 10mm proprietary render board. Internally, a vapour control layer was fitted inside a single layer of plasterboard. The party wall was different in that it has an additional 19mm plank plasterboard installed for acoustic isolation purposes. Intermediate floors are timber framed with chipboard floor and plasterboard ceiling finishing's. The ground floor and foundations consisted of a concrete slab with 100 and 50mm EPS rigid insulation below and above respectively. The roof was of a similar timber frame system as the wall. Fenestration in the dwelling uses triple glazed u-PCV windows with solid timber doors. The dwellings water and space heating were powered by a gas combi-boiler to a manufacturer's quoted 89% seasonal efficiency, and linked to a pre-insulated 180lt water storage cylinder. Trickle-vent passive ventilation was used in conjunction with fan extract ventilation in kitchen and bathrooms. No low carbon heat or power generation technology was installed in this property.

2.1.1. As-designed specifications

The property was used as a baseline to benchmark other dwellings constructed in the HIS development. It was specified and evaluated by the architects using the SAP tool for energy and carbon compliance. The following specification and results were obtained:

Thermal efficiency - U-value (W/m^2K)		SAP calculations–annual energy requirements	
Walls	0.23	Total space heating	33.7 $kWh/m^2/yr$
Ground Floor	0.15	Total water heating	26.2 $kWh/m^2/yr$
Roof	0.1	Total electricity use	8.2 $kWh/m^2/yr$
Windows	0.8	Total energy use	68.1 $kWh/m^2/yr$
Doors	1.4	CO_2 emissions	15.2 $Kg/m^2/yr$
Thermal bridges (ψ)	0.05 W/mK	SAP & EI rating	83.7 / 86
Air tightness q50	$5m^3/m^2.h$@50 Pa	Primary energy	79.85 $kWh/m^2/yr$

Table 1. Building fabric design specifications & SAP results – Control House

2.2. Building characteristics – Passive House (PH) plot 18

The dwelling is a $93m^2$, two storey town house built to achieve the Passive House standard. There are distinct differences between the PH and the CH, and although they share the same dwelling design, they are expected to perform differently. The wall consist of a similar wall system to the CH except that the insulated frame increases to 235mm with an additional internal 25mm polyurethane insulation board followed by a service void and a12.5mm plasterboard finish; thus reducing the internal volume. The property has a similar concrete slab ground floor to the CH; with two layers of rigid polyurethane insulation above it; one 45mm and another of 150mm, and a chipboard flooring. The roof is fully insulated with the same build-up as the walls and intermediate floors are similar to the CH. Specified fenestration has used a u-PVC triple glazed window system, including two highly insulated and sealed doors certified by the *Passivhaus* Institute. Expected high airtightness levels offer the opportunity to install a Mechanical Ventilation with Heat Recovery (MVHR) system used to extract hot air from wet rooms and supply heated air to bedrooms and living room. The space/water heating is provided by a gas combi-boiler connected to a 180lt water cylinder.

2.2.1. As-designed specifications

A PH dwelling seeks to *"improve the thermal performance of the envelope to a level that the heating system can be kept very simple"*[9]. This dwelling was initially evaluated using the Passive House Planning Package (PHPP) to comply with the PH criteria, see Table 2. For the purposes of building control, the dwelling was also evaluated using the SAP calculation, see Table 3. From the predicted design figures it is clear that there are elements which don't meet the PH criteria, for instance thermal bridges and space heating demand. The total 12 month occupation energy demand should give an insight on the impact on its as-built performance.

Space heating demand	15kWh/m2/yr	U-values of opaque elements	0.15W/m2K
Maximum heating load	10W/m2	U-values of windows	0.8W/m2K
Primary energy use	120kWh/m2/yr	Thermal bridging	<0.01W/mK
As-built air tightness	1.5 m^3/m^2.h@50 Pa	MVHR efficiency	>75%

Table 2. Building design & construction criteria to meet the Passive House standard

The architects who designed the property achieved the design criteria as best as possible with the following as-designed results:

Thermal efficiency - U-value (W/m^2K)		SAP calculations –annual energy requirements	
Walls	0.1	Total space heating	16 $kWh/m^2/yr$
Ground Floor	0.15	Total water heating	30 $kWh/m^2/yr$
Roof	0.1	Total electricity use	9.1 $kWh/m^2/yr$
Windows	0.8	Total energy use	55.1 $kWh/m^2/yr$
Doors	1.0	CO_2 emissions	13.66 $Kg/m^2/yr$
Thermal bridges (ψ)	0.08 W/mK	SAP / EI rating	84.2 / 88
Air tightness q50	0.6m^3/m^2.h@50 Pa	SAP primary energy demand	72.7 $kWh/m^2/yr$
PHPP Space heating	16 $kWh/m^2/yr$	PHPP primary energy demand	111 $kWh/m^2/yr$

Table 3. Building fabric design specifications & SAP results – Passive House

3. TESTING METHODOLOGY

The buildings were evaluated using the same methodology and monitoring techniques over similar periods and climatic conditions. The applied monitoring techniques were adopted from relevant post-construction testing guidelines published by the UK's Energy Saving Trust [10]. Guidelines of specific testing followed British Standards and ISO standards relevant to the evaluation methods. In order to evaluate the fabric efficiency, infra-red thermography, air tightness testing and in-situ U-value testing were used with the following considerations:

- **Infra-red thermography:** Internal and external thermograms were taken under controlled conditions. Properties were heated to achieve a temperature gradient of >10°C between the interior and the exterior ambient temperatures. Conditions were chosen such that external building components were dry and the wind speed was <2m/s. Surveys were conducted at least 4 hours after sunset to avoid the influences of solar radiation on the building mass [11].
- **Air Tightness:** The test involves taking readings over a range of pressure differences between 10 to 60 Pascals and recording the volume flow rate of air into the building. The results are referred to as 'air permeability' and calculated by dividing the air leakage flow rate at a reference pressure by the surface area of the building envelope tested [12].
- **In-situ U-value monitoring:** Involves continuous monitoring of heat flux sensors and ambient/ surface temperature sensors affixed to the building envelope for a minimum period of two weeks. The measured values are used to calculate the thermal

transmission values averaged over the period of testing. A northerly orientation is preferred during the winter months in order to reduce insolation effects and provide a good temperature gradient between interior and exterior ambient conditions[13].

Energy consumption data for each dwelling was obtained from In-home Displays (IHD) and supported by regular meter readings, to obtain total gas and electricity consumed over a twelve month period. A comparison between the initial design SAP calculations for space and water heating against actual consumption data was then made. This was more difficult in respect of electrical consumption, as SAP omits un-controlled energy use, however benchmarked normalised household energy use (kWh/m^2/yr) was used as a means of making some comparative evaluation.

4. MONITORING RESULTS

4.1. Fabric Performance

- **Air tightness testing:**

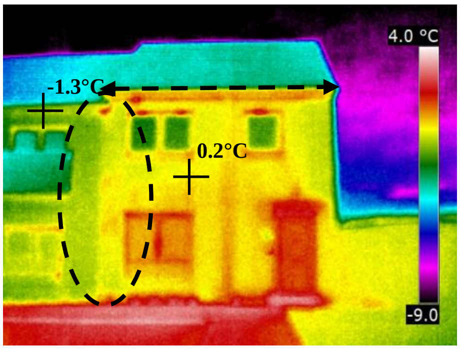
The properties were tested for air tightness under the method prescribed in BS EN13829 [12]. The CH obtained a depressurisation air permeability score of 3.7m^3/hr.m^2@50Pa compared with the figure used in the SAP model of 5m^3/hr.m^2@50Pa. The air flow exponent (n) of this test reached 0.65, n values closer to 0.5 represent turbulent flow through the dwelling elements with air flow through rather large apertures, when n values reach closer to 1.0 a more laminar like flow is experienced representing higher air tight structures, or those with numerous very tiny holes [14]. The PH was tested under both depressurisation and pressurisation with an average taken from these scores. The PH scored 0.55 m^3/hr.m^2@50Pa with an n value of 0.813 signifying a highly air tight envelope.

- **In-situ U-values:**

In-situ U-value testing of the dwellings walls were conducted over a period of 15 days between the 11th and 25th of January 2013. The average internal ambient temperature during this period was 20°C whilst the average external temperature was 6°C. Several walls were tested during this period, all northerly orientated in order to reduce influences from solar radiation. Under the BS EN ISO 9869 calculation, the CH obtained a U-value of 0.27 ±0.1 W/m^{2}K compared with the calculated value used for compliance purposes of 0.23W/m^{2}K. The PH obtained a U-value of 0.12 ±0.1 W/m^{2}K very close to the calculated of 0.1W/m^{2}K.

- **Infra-red Thermography:**

The thermography survey was completed between 01:30 and 02:30 on the 14th of June 2012 (sunset occurred at 22:00). Climatic conditions during the test showed that external ambient temperatures were 5.0°C with overcast sky conditions, dry building surfaces and atmospheric pressure of 1000.2mbar. Internally the ambient temperature was 19.4°C providing a Δt of 14.4°C, in accordance with BS13187 [11] guidelines.



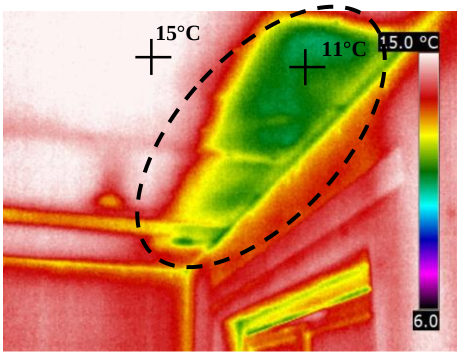


Figure 3. (left): External image of the Passive House and Control House. Figure 4. (right): Internal CH ceiling.

It is evident from Figure 3 that there are differences in wall surface temperatures between the PH (left) and the CH (right). The PH shows generally lower surface temperatures (-1.3°C) compared with the CH (0.2°C). Additionally, the roof eaves of the CH show distinct heat loss with temperatures ranging from 2.5 to 0.6°C.

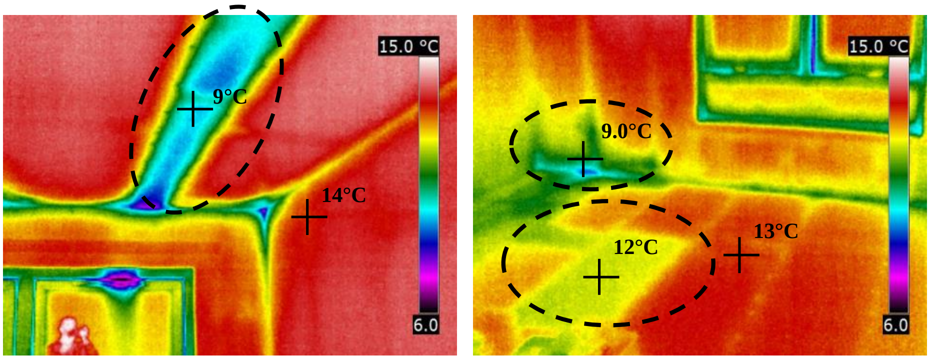


Figure 5. (left), & 6. (right). Control House: Internal thermograms

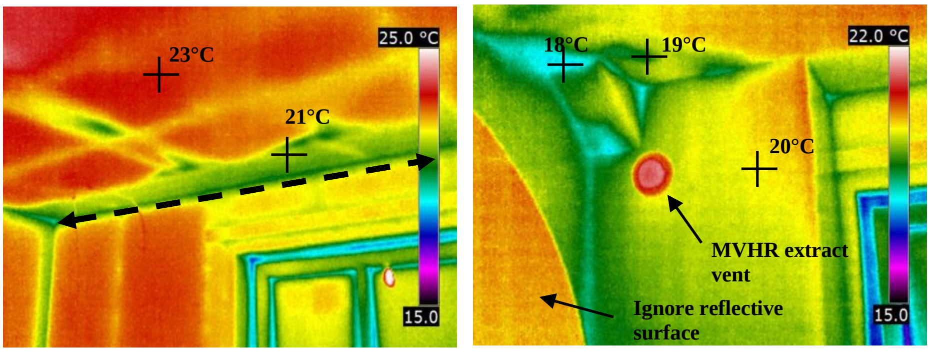


Figure 7. (left) & 8. (right). Passive House: Internal thermograms of first floor ceilings showing heat loss.

Figure 4 shows a thermogram of a first floor ceiling where ventilation at the roof eaves enters the roof void and either an absence of insulation or poor construction detailing has resulted in higher rates of heat loss. Figure 5 shows a thermogram of heat loss appearing at the ceiling level where insulation has been mis-installed or is absent below a structural roof element or a service duct. Figure 6 shows a ground floor thermogram with insulation missing or mis-installed in sections between the floor joists and at skirting level; where increased air leakage is evident. The PH shows lower rates of heat loss since thermal bridging and air leakage is kept to a minimum at the design outset. Figure 7 shows a thermogram of heat loss around the ceiling where apparent ventilation into the roof void creates cold spots. Figure 8 shows some detailing problems at a wall and ceiling junction where surface temperatures drop from 18 to 20°C.

4.2. Energy demand

The occupied properties had energy consumption logged at one hour intervals for both gas and electricity. For data checking and comparison purposes, meter readings were also taken during this period of monitoring in order to correlate the data. Finally, the data was compared with the predicted compliance results generated by the SAP software.

Figure 9. (left) Front elevation of the Passive House (left) and the Control House (right).

Figure 10. (right) In-House Display (IHD) installed in each property.

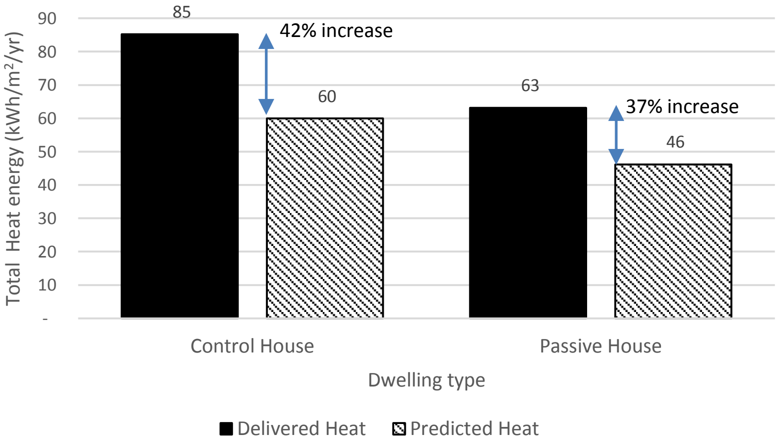


Figure 11. Total Heat Energy Delivered & Predicted (DHW & Space heating)

As seen in Figure 11 for total heat consumption, the CH consumed 85kWh/m^2/yr (8,260kWh/yr) compared with the expected design value of 60kWh/m^2/yr (5,800kWh/yr); which is 42% more energy than predicted. The PH, with its highly efficient envelope consumed 63kWh/m^2/yr (5,900kWh/yr) compared with the design value of 46kWh/m^2/yr

(4,300kWh/yr); a 37% increase in energy for space and water heating. These delivered figures were obtained from total gas consumption and aren't distinguished by space and water heating. In terms of the electricity consumption, the CH consumed 27.3 kWh/m^2/yr (2,650 kWh/yr) of controlled (lighting, fans and pumps) and uncontrolled (appliances) energy. On the other hand, the PH consumed 51kWh/m^2/yr (4,715kWh/yr). A typical UK benchmark for electrical consumption in semi-detached dwellings of 48kWh/m^2/yr [15] demonstrates that the CH is 43% below this reference whereas the PH is 6% above it. The lower consumption in the CH might be explained by a reduced number of adult occupants and domestic appliances in the property whilst the PH has more adults, a mechanical ventilation system and a higher appliance load.

5. CONCLUSIONS

The two case studies demonstrate the performance of two similar properties designed to comply with different building methods. The process and strategic approach delivered by such housing will assist in meting low carbon targets in the affordable housing sector. They are also evidence of how MMC have the potential to drive higher performing homes to meet low carbon targets set by UK and EU legislation. Most housing developers often chose to comply with minimum thermal requirements, but Kingdom Housing Association have moved in the opposite direction by testing a variety of methods and standards in order to prepare for future requirements. The PH dwelling provides vital lessons on how this standard can be applied to social housing. The results show how well its fabric performed as initially designed with both airtightness and wall in-situ U-value results close to the predicted. The CH obtained an improved airtightness score which, in-turn, reduces ventilation heat loss. The in-situ wall results showed a marginal difference of 0.04W/m^{2}K between as-designed and as-built which is within error margins for this type of testing. Heating energy requirements of 42% and 37% above the predicted demonstrates that a significant gap in performance exists due to differences in occupant numbers (design and actual), complexities with controls and as-built variances in services and fabric efficiency. Electrical energy differences are directly related to occupant behaviour, services controls and amount of appliances in the household. Fabric efficiency can be increased if focused supervision at the design and construction stage ensure that work is delivered as specified. If the EU is to achieve carbon reduction targets with the reduction in the gap between the as-designed and the as-built energy demand, a focus on improving design, construction, supervision and maintenance led practices is required.

6. ACKNOWLEDGEMENTS

Kingdom Housing Association, Campion Homes Ltd, Stuart King Architecture & Design, Oliver & Robb Architects, and Scotframe Timber Engineering.

7. REFERENCES

[1] Bordass B, Cohen R, Standeven M, Leaman A. Assessing building performance in use 2: technical performance of the Probe buildings. Build Res Inf 2001;29:103–13. doi:10.1080/09613210010008027.

[2] EU Parliament. Directive 2010/30 & 31/EU of the European Parliament and of the Council of 19 May 2010. Off J Eur Union - L153 2010;53:40.

[3] CEC. 20 20 by 2020 Europe’s climate change opportunity. Brussels: 2008.

[4] Fernandez R, Watterson J. End-user GHG emissions from energy - Reallocation of emissions from energy industries to end users 2005–2010. Brussels: 2012.

[5] Kurnitski J. Technical definition for nearly zero energy buildings - Active House Alliance. J Fed Eur Heating, Vent Air Cond Assoc 2013;50:22–8.

[6] Zero Carbon Hub. Zero Carbon Homes and Nearly Zero Energy Buildings UK Building Regulations and EU Directives. London: 2014.

[7] Schnieders J, Hermelink A. CEPHEUS results: measurements and occupants’ satisfaction provide evidence for Passive Houses being an option for sustainable building. Energy Policy 2006;34:151–71. doi:10.1016/j.enpol.2004.08.049.

[8] SBS. Scottish Building Standards - Technical Handbook - Domestic Section 6 Energy. Edinburgh: 2013.

[9] Feist W, Schnieders J, Dorer V, Haas A. Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. Energy Build 2005;37:1186–203. doi:10.1016/j.enbuild.2005.06.020.

[10] EST. Post-construction testing – a professional ’ s guide to testing housing for energy efficiency Introduction. London: 2006.

[11] BS EN. British Standard 13187 - Thermal performance of buildings - Qualitative detection of thermal irregularities in building envelopes. Brussels: 1999.

[12] BS EN. British Standard 13829 - Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method. Brussels: 2001. doi:ISBN 0 580 36935 8.

[13] BS EN ISO. ISO9869-Thermal insulation - Building elements - In-situ measurement of thermal resistance and thermal transmittance. Geneve: 1994.

[14] ATTMA. Measuring Air Permeability of Dwellings. vol. 44. Nothhampton: 2010.

[15] Yohanis YG, Mondol JD, Wright A, Norton B. Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use. Energy Build 2008;40:1053–9. doi:10.1016/j.enbuild.2007.09.001.