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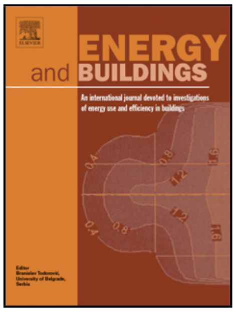

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The monitored performance of four social houses certified to the Code for Sustainable Homes Level 5

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Key words: Low energy homes; Monitoring performance; Energy use; Water use; Carbon emissions; Code for Sustainable Homes; Post occupancy evaluation

Abstract

This paper presents the energy and water use of 4 social houses certified to the Code for Sustainable Homes Level 5 in Gainsborough, UK. The houses were monitored over 2 years, from July 2012 to September 2014. As the houses have the same construction and energy efficiency characteristics, the study offered a unique opportunity to investigate the effects of occupant behaviour on the dwellings performance. Electricity, gas and water consumptions were measured through data logging and meter readings. Surveys and interviews were conducted throughout to gain insights into tenants understanding and interactions with low energy features in their homes. Significant differences were observed in the amount of energy and water used. The annual space heating consumptions differentiated by a factor of 2.2 per square metre of floor area. Hot water heating demands varied by a factor of 3.5 per square metre of floor area or by 2.5 per person per year. Mains water consumptions varied by a factor of 2.2 litres per person per day in 2013.

Introduction

There is a growing concern about the contribution of the building industry to environmental impacts and climate warming. In Europe and the USA, energy consumption of buildings accounts for 20–40% of total energy use [1]. Buildings are a significant contributor to greenhouse gas emissions, with space heating alone responsible for over half of all UK dwellings end use emissions [2]. In 2007, the UK government put in place a National Energy Efficiency Action Plan (NEEAP) to reduce emissions from the UK housing stock by 31% based on 1990 levels by 2020. More recently, the government’s Climate Change Act [3]. sets a legally binding target to reduce greenhouse gas emissions from buildings by at least 80% on 1990 levels by 2050. In 2008, the residential sector accounted for 27% of the total CO2 emissions in the UK [4].

The potential of the residential sector to reduce CO_2 emissions has been identified in numerous studies and sources [5-10]. Buildings are currently rated for energy performance potential of the fabric and services at design and on completion. Thereafter they can be rated by comparison of actual annual fuel consumption [11]. There are standards that address environmental performance of the design and build; for example Passivhaus, Code for Sustainable Homes, BREEAM, amongst others. The codes and standards have created lively debates on their practicality which has resulted in a raised awareness within the building industry about the actions required to tackle climate change [12].

In order to reduce the whole life impact of buildings, Life Cycle Assessments (LCA) should be carried out to identify collective distribution of different impacts. As shown in, Figure 1, adopted and modified from [12]. Performance Assessment Methods (PAM) should be used at the design stage (PMc) to predict and reduce energy demands of buildings, to minimize operational impacts (Rc). Post Occupancy Evaluations (POE) should also be carried out when the building is completed to measure its actual performance.

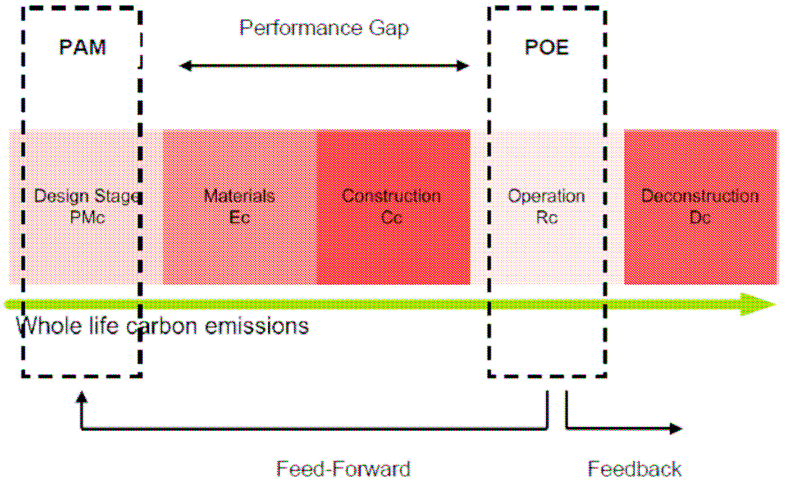


Figure 1: Whole Life Carbon Emissions of Buildings showing the roles of PAM and POE

There is extensive evidence [13-17] to suggest that buildings do not usually meet the energy efficiency targets set at the design stage. In other words, there is a Performance Gap between POE results and PAM as depicted in Figure 1.

Performance Assessment Methods (PAM) utilizing prediction modeling tools may be used to predict the future performance of buildings when built. Currently numerous assessment tools exist ranging from advanced dynamic computer simulation programs, capable of representing complex interactions in buildings, to more simplified and stationary calculation methods and tools. While dynamic programs require extensive and detailed value input data, simplified tools may be used with less data and hence with limited scopes and capabilities. J. Hensen and R. Lamberts [18] provide a general view of the background and current state of building performance simulation programs.

Williamson [17] suggests that more stringent building regulations and higher energy efficiency standards, to make buildings more energy efficient, might result in over-optimistic predictions, creating a wider gap between the expected designed targets and the actual constructed and occupied building. Others [19,20] argue that there are also performance gaps between other performance indicators, such as comfort and indoor air quality, between design predictions and what is actually achieved in buildings when occupied.

In the UK, the Standard Assessment Procedure (SAP) [21] was first published by DOE (now the Department of Energy and Climate Change, DECC) and BRE in 1993. Currently SAP is used as proof of compliance with Part L1A of the Building Regulations [22] in the UK, to evaluate the consumption of fuel and power to determine the performance of dwellings. It is also used in a range of UK governmental measures and policies requiring the calculation of the energy performance of dwellings such as the Code for Sustainable Homes (CSH), Warm Front, the Carbon Calculator, Stamp Duty Exemption for Zero Carbon Homes, Green Deal, Renewable Heat Incentive (RHI), and Energy Performance Certificates (EPC).

SAP is a simplified version of BREDEM, Building Research Establishment Domestic Energy Mode [23] and is based on energy balance, taking into account a range of factors that affect the energy performance of dwellings. These include: building materials used, thermal insulation, air leakage characteristics, heating system efficiency, solar gains through openings, type of fuel used, energy consumption by lighting, pumps and fans, as well as energy produced by microgeneration technologies. SAP does not however include a range of other factors such as electricity demands of electric appliances which contribute to the so called unregulated energy consumptions of homes. These omissions are in line with the Part L Building Regulations, requiring an estimation of the energy that will be consumed in the building for space heating, cooling, water heating, and lighting, as well as energy required to power their controls. Inherent in simplified methods, SAP also uses standard patterns as parts of its inputs. For example it assumes standard occupancy and space heating patterns representative of national norms. The main purpose of SAP may therefore be viewed as a national rating system to give a standardised measure from which the energy performance of dwellings can be compared against each other in a meaningful and systematic way. Such an approach may however lead to rather imprecise approximations of real consumptions for individual homes [24].

In light of wide spread gaps between predicted and actual performances, the construction industry and research community are increasingly realising the benefits of Post Occupancy Evaluation (POE) in narrowing the gap between design intents and actual performance of build. POE can be effectively used to improve the whole life performance of buildings and reduce their carbon emissions. As schematically depicted in Figure 1, POE can be used to feed-forward information to the Design Stage (PMc), to improve the design as well as the prediction of its performance through the enhancement of Performance Assessment Methods (PAM). It can also be used to feedback information and data to users and facility managers, to better understand and work with the building and its component, which in turn should reduce operational impact (Rc) and enhance user comfort and satisfaction.

Aims and objectives

The aim and scope of this paper is to investigate the actual performance of 4 recently built dwellings designed to Code for Sustainable Home (CSH) Level 5, through environmental monitoring with a view to identifying influencing factors which might affect the performance of houses. Although comparisons have been made between actual and predicted performance, the intension is not to solely demonstrate the accuracy of SAP, which has been used for the purposes of Building Regulation compliance and design stage CSH assessments to predict energy consumption, but how energy demands in 4 houses built to the same specifications may be varied due to occupancy behaviour.

Research Methodology

The research uses a mixed approach using both quantitative and qualitative analyses and investigations. The former required quantitative measurements and forensic investigation using environmental monitoring and diagnostics testing, while the latter employed a range of socio-technical methods using structured interviews, surveys, walk through and questionnaires. Performance evaluation approaches, combining quantitative and qualitative techniques in POE have received considerable attention in recent years [25-27].

Longitudinal approaches covering various seasons have been recommended for POE in order to achieve meaningful and detailed analysis [28]. The results reported in this paper span over two years, started in July 2012 and completed in September 2014, analysing the performance of the houses through different seasons.

Quantitative Measurements: Environmental Monitoring

The monitoring systems were installed in June 2012. The monitoring systems use a Wi5 data hub GPRS wireless data logging installed in House 3 to process data collected from all four houses. All data was collected at 5 minutes intervals. All the instrumentation provided and installed for monitoring purposes complied with the requirements contained in CE298 'Monitoring energy and carbon performance in new homes' [29]. An on-site weather station measured external air temperature and relative humidity. The data collected in each house includes;

Room air temperature and relative humidity in the main bedroom and living room.

Concentrations of CO_2 in the living room

Air temperature and relative humidity at supply and extract positions of MVHR

Electricity generated by PV

Utilities metering for electricity (kWh), gas (m^3), and mains water (m^3)

Building performance tests, including air permeability, infra-red thermography, and in-situ U-value measurements were conducted to analyse the performance of the building fabric. Continuous review of the monitoring equipment and systems were conducted to ensure their performance through commissioning checks.

Qualitative Measurement: Occupant Surveys, Engagement and Feedback

Occupant surveys were carried out throughout the POE period to establish those aspects of tenants' lifestyle and profile affecting environmental performance of their homes, and to gain insights into the ways they interact with their homes including the energy efficiency measures and renewable technologies installed.

Among the techniques employed were; 1) Longhurt Group Scheme Review process using their New Resident Questionnaire and associated interviews to establish tenants' satisfaction with the energy efficiency aspects of their homes and 2) Building Use Studies (BUS) evaluations measuring users' satisfaction and comfort. BUS was developed as part of the Probe Process [30,31].

Pilot Study

This pilot study, focuses on the performance of four social housing designed to Code 5 of Sustainable Homes [32] built in the town of Gainsborough, UK. Gainsborough (latitude: 53.4 N, Longitude: 0.77 W) is a small town with a population of about 20, 000 located in the Lincolnshire County, in the East Midlands Region of the UK. It is situated 135 miles north of London and 55 miles west of the North Sea. As a generalisation, Lincolnshire's eastern location provides for a relatively drier, warmer and sunnier climate with a mean annual temperature of about 10 °C.

Code Level 5 requires a 100% reduction in emissions from regulated energy under the Standard Assessment Procedure (SAP) of the Building Regulations including heating, domestic hot water, lighting, and electrical used for pumps and mechanical ventilation. Emissions resulted from unregulated energy consumptions, i.e. appliances, are not included in the procedure for compliance.

Monitoring of the dwellings that took place over two years, was funded through two grants received from Innovate UK, formerly known as Technology Strategy Board, under the Building Performance Evaluation Programme. The first monitoring project was for a 6 month duration, started in July 2012 and completed in November 2012, focusing on construction and initial energy performance of the dwellings. The second monitoring project was for a 2 year duration, started in October 2012 and completed in September 2014. The second project continued with detailed monitoring of energy performance, together with analysing users' interactions and satisfaction with their new homes. Although data has been collected since July 2012, the paper concentrates on the results obtained from October 2012 to August 2014. This is to eliminate initial problems with the installation and monitoring equipment setup which affected the accuracy and consistency of the data collected. There have been two changes of tenancy in two housing units during the monitoring period.

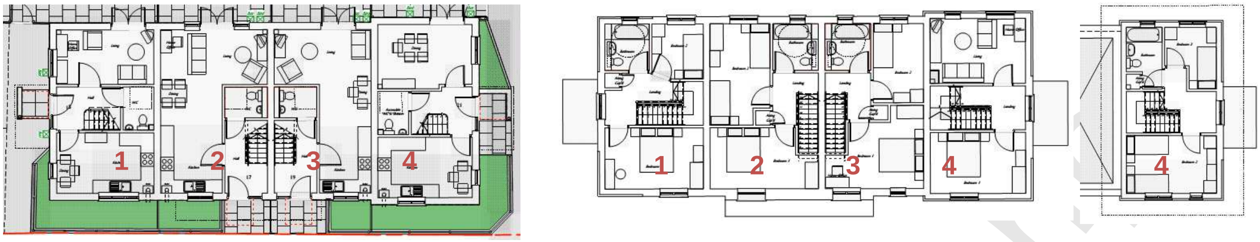
Construction work started in August 2011 and completed in July 2012. L&H Homes, part of Longhurst Group, are the Registered Social Landlord. The monitoring of these houses has been jointly conducted by University of Lincoln and Longhurst Group.

The mix of the 4 new dwellings, hereby referred to as houses 1, 2, 3 and 4, includes 2 and 3 bedroom houses generally 2 storeys in height and rising to 3 at the northern end providing a mix of type and sizes suitable for small to larger families. In line with Government guidance and the Code for Sustainable Homes a home office space is provided to all four new properties.

The houses use pre-fabricated Structural Insulated Panels (SIP). The SIP superstructure took 3 weeks to complete as the panels were manufactured off site to reduce waste, noise and dust pollution to nearby residents. During the construction phase there was a clear focus on sourcing environmentally friendly products and minimising carbon footprint. Nearly 90% of plant, subcontractors and materials were sourced within 30 miles of the site reducing transport miles and carbon emissions while stimulating the local economy. In line with the Code for Sustainable

Homes guidelines, all timber has been sourced under the FSC/PEFC sustainability of timber scheme and a high percentage of none timber materials have been sourced from companies who hold ISO 14001 certification [33].

Figure 2 shows floor plans for the four new houses. Total internal gross floor areas are; 67.24m^2, 72.54m^2, 65.72m^2 and 101.5m^2 for houses 1, 2, 3 and 4 respectively. Figure 3 and Figure 4 show images of the completed project.



Ground Floor First Floor Second Floor

Figure 2: Floor plans for the four new houses

Figure 3: South Elevation Figure 4: East Elevation

Monitoring Results

The environmental and energy strategy for the four new houses is based on creating a highly insulated building fabric with close attention paid to reducing the air permeability. The following sections discuss the results of the research carried out.

In-situ U-Value measurements

The U-values of external walls to determine their insulation performance were measured by placing HFP01 sensors [34] on the north facing wall of House 4 using the “Average method” detailed in ISO 9869:1994, Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance [35]. For calculation purposes, internal air temperatures were recorded within the dwelling adjacent to the sensors and outside air temperature adjacent to the corresponding wall space. Measurements were recorded over a two week period in February 2013 whilst the property was occupied and heated. The data taken as the U-Value is the average of values taken during the last seven days of measurement, with the first seven days data excluded to allow for stabilisation of the instrumentation. The value measured is a U-Value of 0.12 W/m^{2}K. The in-situ U-Value is an improvement on the target U-Value for the external wall as reported in Table 1.

Table 1 shows the design U-values for different building elements as predicted by SAP calculations based on construction specifications.

Table 1: Specification of the main construction elements

Elements	**Summary Specific characteristics**	**Target U-Value (W/m^{2}K)**
Ground Floor	Proprietary suspended concrete beam and block with 20mm of insulation	0.12
External walls	142mm Structural Insulated Panels (SIPs) finished in Brick or render clad.	0.14
Party walls	Open panel timber frame	
Roof	Single ply roofing membrane fixed to 142mm Structural Insulated Panels (SIPs) and 50mm rigid insulation.	0.12
Door	Munster EcoClad timber board effect with triple glazed side screen	1.20*
Windows	Munster EcoClad triple glazed windows.	1.15*

* U-Values suggested by the manufacturer

Air Tests

The dwellings have a design air permeability of $3.00\mathrm{m^3/hr.m^2}$. Pre-handover air test was carried out by Lincolnshire Air Testing in May 2012 according to the procedures laid down by "The British Institute of Non-Destructive Testing" (BINDT) using an air depressurisation technique (ATTMA TS1) [36] incorporating the whole building envelope at an imposed pressure of 50Pa. Two further air leakage tests were carried out after the handover of the dwellings. These were carried out by BSRIA Ltd [37] in July 2012 and August 2014 using an air depressurisation and pressurisation technique (ATTMA TS1). Air was supplied to the dwellings at a variety of flow rates to create a pressure differential between the internal and external envelope. Figure 5 shows the equipment used during the air tests. Table 2 shows the results of air leakage tests at pre-handover stage, post-handover and post-occupancy.

Table 2: Air Tests results from May 2012, July 2012 and August 2014

House	**Pre-handover Test - 08.05.2012**				**Post-handover Test - 20.07.2012**				**Post-occupancy Test - 14.08.2014**			
H1	DP	2.97	Average ($\mathrm{m^3/hr.m^2}$)	**2.97**	DP	2.34	Average ($\mathrm{m^3/hr.m^2}$)	**2.12**	DP	3.63	Average ($\mathrm{m^3/hr.m^2}$)	**3.65**
	P	-			P	1.9			P	3.67		
H2	DP	2.99	Average ($\mathrm{m^3/hr.m^2}$)	**2.99**	DP	3.43	Average ($\mathrm{m^3/hr.m^2}$)	**3.51**	DP	4.8	Average ($\mathrm{m^3/hr.m^2}$)	**5.09**
	P	-			P	3.59			P	5.38		
H3	DP	2.96	Average ($\mathrm{m^3/hr.m^2}$)	**2.96**	DP	3.31	Average ($\mathrm{m^3/hr.m^2}$)	**3.46**	DP	4.51	Average ($\mathrm{m^3/hr.m^2}$)	**4.72**
	P	-			P	3.61			P	4.92		
H4	DP	2.92	Average ($\mathrm{m^3/hr.m^2}$)	**2.92**	DP	2.37	Average ($\mathrm{m^3/hr.m^2}$)	**2.45**	DP	3.3	Average ($\mathrm{m^3/hr.m^2}$)	**3.38**
	P	-			P	2.53			P	3.46		

DP = Depressurisation, P = Pressurisation

The results of the pre-handover test carried out in May 2012 are better than the target design limit of $3\mathrm{m^3/hr.m^2}$ and well below the maximum allowable level of $10.00\ \mathrm{m^3/hr.m^2}$ at 50 Pa. as required under the Building Regulations Approved Document L1A 2010.

Comparing the results of the pre-handover and the first post-handover tests, i.e. the tests carried out in May and July 2012, one can see that Houses 1 and 4 have a reduced air leakage rates in the second test while the trends for Houses 2 and 3 are the other way round. The variations in results might also be partly due to the fact that the pre-handover test was carried out by a different organisation.

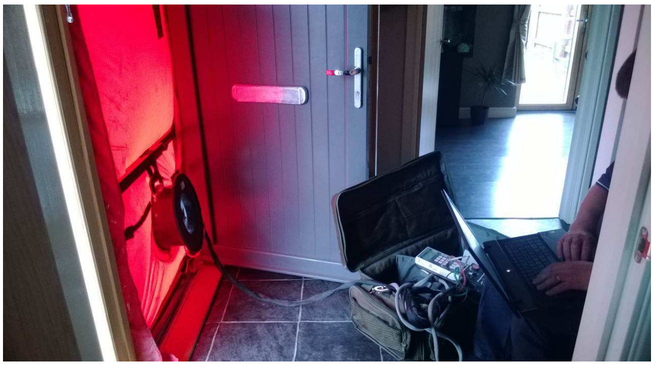


Figure 5: Equipment used during the Air tests

In the first post-handover test, the average air leakage rates for Houses 1 and 4 are below the design value of $3m^3/hr.m^2$, while the rates for Houses 2 and 3 exceed the design value. Comparing the results in Table 2, one can see that all 4 houses have poorer air leakage rates after 2 years. The main reasons for the increases might be due to a range of influencing factors such as occupants' effects on the building fabric, possible building movements, inaccuracy in the tests carried out and/or a combination of all the factors. There is an expected general trend in results that dwellings show higher air leakage rates under pressurisation conditions. The only exception here is House 1, which has a lower rate under pressurisation in the first post-handover test carried out in July 2012.

Thermographic Survey

The thermographic survey was conducted in accordance with the simplified testing requirements of BS EN 13187:1998 Thermal performance of buildings – Qualitative detection of thermal irregularities in building envelopes – Infrared method (ISO 6781:1983 modified) [38].

A selection of thermograms is shown in Figure 6 and Figure 7. The thermographic survey was undertaken during early morning in February 2013. The weather on that day could be described as a still cold overcast winter day with no sunshine, rain or falling snow. The external air temperature during the thermographic survey was recorded as $0.3^{o}C$. Internal air temperatures recorded as $8.9^{o}C$ in House 1 (not occupied in February) , $19.2^{o}C$ in House 2, $20.5^{o}C$ in House 3 and $21.9^{o}C$ in House 4.

The results of the thermographic survey indicate that the buildings are adequately insulated, with good level of air tightness. However, a number of the images show some possible effects due to thermal bridging. This is most noticeable on the rendered sections of walling between SIPs at floor junction. There is also a consistent increase in surface temperature at the ground floor and external wall junction. In addition some weaknesses were identified at the openings.

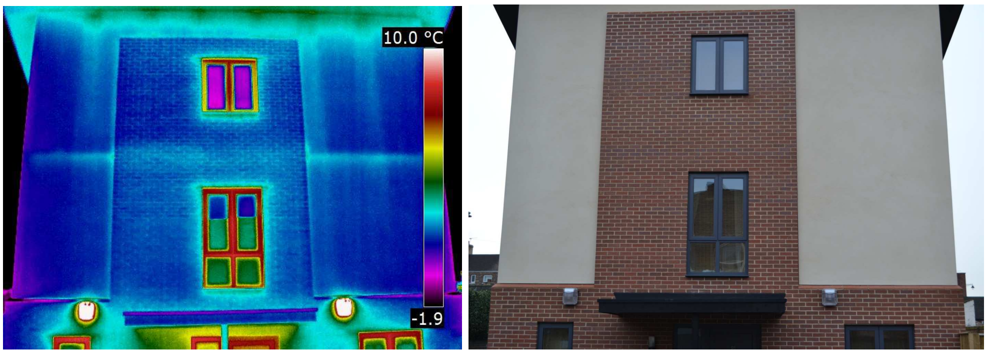


Figure 6: Thermal image of House 4 (courtesy of BSRIA)

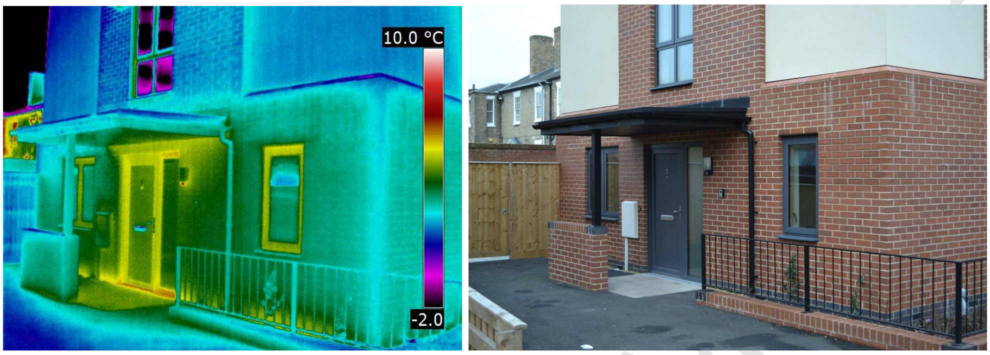


Figure 7: Thermal image of House 1 (courtesy of BSRIA)

Internal and external environmental conditions

Figure 8 shows the monthly average external temperatures and the Mean Internal Temperatures (MIT) in the living rooms of different houses predicted by SAP together with corresponding values measured during the monitoring programme. There were changes of tenancy in House 1 during January and February 2013 and in House 3 during December 2013, January and February 2014 during which the houses were partially empty and not heated as a result, hence drops in measured internal air temperatures.

Standard Assessment Procedure (SAP) utilises standardised regional climatic data adopted by the UK government as part of the national methodology for demonstrating compliance with building regulations and for providing energy ratings for dwellings. As seen in Figure 8, internal air temperatures predicted by SAP are close to each other in different houses without sharps peaks and lows. This is due to the fact that the calculation method uses more normalised patterns, such as occupancy patterns. The external air temperature used in SAP is also smoother compared with measured temperatures. The measured external air measures are in line with the British Met office records suggesting the winter of 2012/1013 was the coldest in 40 years due to a very cold February to April while winter 2013/14 was milder than the previous year [39].

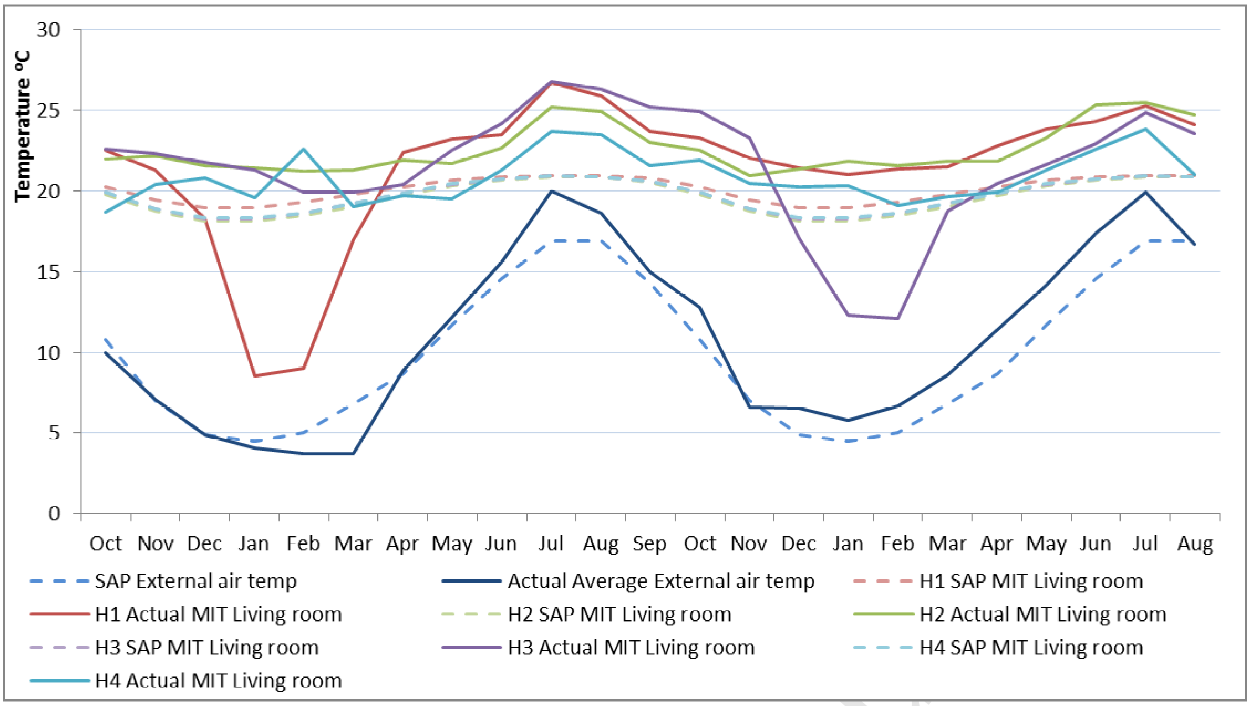


Figure 8: Predicted and measured internal and external temperatures for Oct 2012 to Aug 2014

Gas Consumption

Each house was fitted with a gas meter measuring the fuel used in cubic metre. Gas consumptions measured in m^3 have been converted to kWh using an average Calorific value of $40MJ/m^3$, a Correction factor of 1.02264 and a kWh conversion factor of 3.6 (kWh = $m^3 \times 40 \times 1.02264/3.6$) [40].

Space heating and hot water heating is provided by a Potterton Promax combination boiler, with a manufacturer's quoted efficiency of 91%. Sub meters have not been used to differentiate between the energy used for space heating and hot water heating separately. The actual total gas consumptions reported in Table 3 are therefore the combined space heating and hot water heating consumptions. The space heating is controlled by two Honeywell room thermostats, in the hall and master bedroom.

To overcome issues associated with tenancy changes resulting for Houses 1 and 3 being vacant for some time, the following extrapolations have been made in order to arrive at annual consumptions in order to compare the performance of the houses against each other, as well as with data reported in the literature.

For House 1, gas consumption in January and February of 2014 have been used instead,

For House 3, gas consumptions of December 2012 has been used instead, Gas consumptions of the three replacement months (January and February 2014, and December 2012) have been adjusted using the ratio of external air temperature from the replacement months against the original month temperatures.

Table 3: Predicted and Measured Annual Gas Consumption in 2013 (kWh)

House	SAP						Actual		Increase Actual/ SAP %
	Space Heating	Space Heating per m^2	Hot Water	Hot Water per m^2	Total	Total per m^2	Total	Total per m^2	
H1	**1863.4**	**27.7**	**2243.6**	**33.4**	**4107.0**	**61.1**	**5306.4**	**78.9**	**29%**
H2	**2377.8**	**32.8**	**2312.5**	**31.9**	**4690.3**	**64.7**	**9044.9**	**124.7**	**93%**
H3	**1997.0**	**30.4**	**2214.1**	**33.7**	**4211.1**	**64.1**	**4894.0**	**74.5**	**16%**
H4	**2931.1**	**28.8**	**2562.0**	**25.2**	**5493.1**	**54.1**	**6707.9**	**66.1**	**22%**

Annual predicted and measured gas consumptions for space and hot water heating for the year 2013 are shown in Table 3. For the SAP calculations, the standardised climatic data for the region as part of the national methodology for demonstrating compliance with building regulations has been used. The actual measured climatic data on the site however may be different with the corresponding data in SAP climate file as shown for example in Figure 8 for external air temperatures over the monitoring period. This together with inherent limitations and the use of standard occupancy patterns in SAP which might not closely represent the real conditions in the 4 houses monitored may results in imprecise approximations of actual consumptions and hence contributing to the differences between predicted and actual consumptions as seen in Table 3.

The annual gas consumption per square metre of floor area predicted by SAP does not vary significantly between houses due to similar assumptions used in the prediction model for occupant influences in the calculation programme. The actual operational energy of buildings may however vary considerably by influencing factors such as building use patterns and occupants behaviour. Similar cases have been reported in the literature indicating that actual consumptions of similar buildings could be varied due to different occupancy patterns and family typologies [41-47].

Hot water and space heating consumption were not metered separately in the four houses monitored. An attempt has therefore been made to distinguish between the two sources of consumptions. Actual hot water heating for 2013 has been estimated based on the following assumptions;

Gas consumption from June to September (4 months) during which SAP calculations indicate no space heating is required has been used as gas used for hot water heating during this period.

For the remaining eight months of the year, actual monthly hot water heating demands have been estimated using the average daily gas consumption over the summer, i.e. June to September multiplied by the number of days in each month. The figures were then adjusted by the ratio of SAP average daily hot water heating of the month over the average SAP daily gas consumption over the summer to take into account the effect of weather.

For House 1, as the gas consumption in June and July were excessively high with no apparent reason, the consumptions in June and July 2014 have been used.

Actual hot water heating for Houses 1,2,3 and 4 using the above procedure is estimated to be of the orders of 1952kWh, 7317kWh, 3393kWh and 3086kWh respectively. These represent 37%, 81%, 69% and 46% of the total gas used in the houses respectively. Annual SAP predicted hot water demands for different households range from 2214.1kWh to 2562.0kWh for 2013, differentiating by a factor of 1.2. The differentiating factor for the actual annual (2013) hot water heating using the above procedure is of the order of 3.7. The actual estimated hot water heating demands range from 29.03kWh/m^2 to 100.87kWh/m^2 differentiating by a factor of 3.5. The numbers of occupants living in the houses are two in House 1 and three in the other three houses each. Hot water heating usage per person in 2013 is therefore of the order of 2.7kWh, 6.7kWh, 3.1kWh and 2.8kWh in Houses 1, 2, 3 and 4 respectively differentiating by a factor of 2.5.

Gill et al. [44] report that domestic hot water could vary by a factor of 7.1 between similar households. Ridley et al. [39] have shown that domestic hot water demand could be responsible for a considerable portion of the total gas consumption. They have reported that, in the two Welsh Social Houses monitored with actual performances meeting Code for Sustainable Homes Level 5 and Level 4 where hot water and space heating consumptions were metered separately, the hot water demand in the Code 5 house constituted for 37% of the total gas consumption, while in house meeting Code Level 4 the respective percentage was 23% [39].

Figure 9 shows a reasonably good correlation between actual estimated hot water heating and the amount of water used from the mains in different houses in Gainsborough. As water needed for outdoor watering and flushing toilets is mostly provided by harvested rain water, one therefore may assume that fresh water is mainly used for hot water consumption.

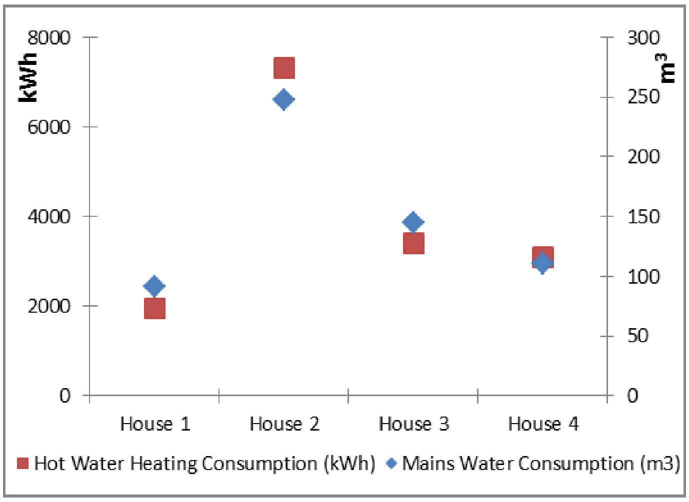


Figure 9: Correlation between total hot water heating and mains water consumption in 2013

Actual space heating demands of the four dwellings have been estimated by deducting the hot water demands arrived at from the total measured gas consumptions as reported in Table 3. Annual space heating requirements of Houses 1, 2,3 and 4 are estimated to be of the orders of 3354.4kWh, 1727.9kWh, 1501kWh and 3621.9kWh for the year of 2013. Space heating requirements per square metre of floor area are 49.98kWh/m^2, 23.88kWh/m^2, 22.88kWh/m^2 and 35.78kWh/m^2 for houses 1, 2, 3 and 4 respectively. While space heating demands of Houses 1 and 4 exceed the SAP predictions, the actual estimated space heating demands of Houses 2 and 3 are smaller than those predicted by SAP.

In order to reduce space heating to a level for which low to zero carbon technologies can efficiently be used to achieve zero carbon operation, Zero Carbon Hub (ZCH) suggests that the maximum space heating energy demand should be 39kWh/m^2/year for apartments and mid terrace houses, and 46kWh/m^2/year for end of terrace, semi-detached and detached houses [48]. House 1, an end of terrace house, exceeds the ZCH target of the 46kWh/m^2/year while House 4, the other end of terrace house satisfies the ZCH target. Houses 2 and 3, both mid terrace houses satisfy ZCH target of 39kWh/m^2/year.

Figure 10 depicts the total monthly predicted and measured gas consumptions. Discrepancies in gas consumptions observed among the four dwellings are; the actual gas consumption in House 2 is consistently high throughout the course of the year, the actual gas consumption in House 1 over the summer, is exceptionally high and actual consumption in House 4 is high at the beginning of the year but starts following the trends in other houses from May onwards.

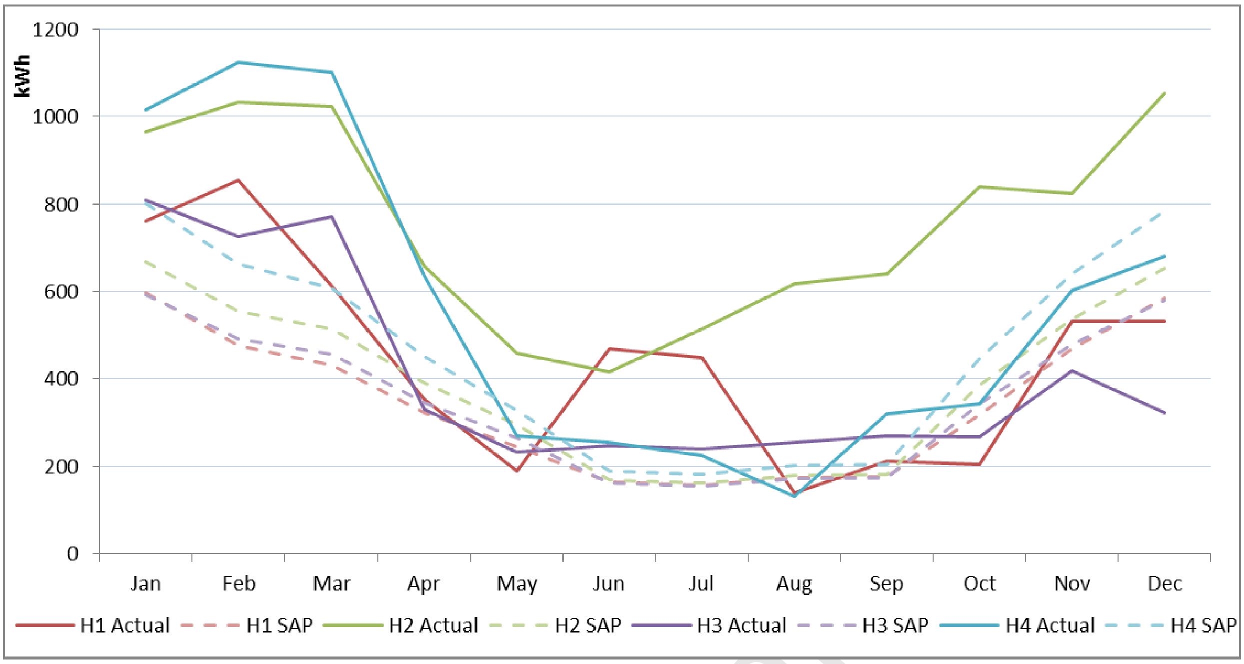


Figure 10: SAP predicted and Measured Annual Gas Consumption for 2013

The differences between total actual and SAP predicted gas consumptions are therefore deemed to be due to three main influencing factors; firstly, the hot water demand is higher than the assumptions made in SAP and varies considerably in different houses. Secondly, the actual external air temperatures in February and March in 2013 are noticeably lower than those used in SAP weather file as shown in Figure 8 contributing to higher space heating demands. Thirdly, the differences between the assumptions made in SAP regarding occupancy patterns and the actual patterns which are more varied among the families occupying the dwellings. Similar results are reported in the literature. For example; in a study by Guerra-Santin et al. [49] the results confirm that occupant characteristics and behaviour significantly affect energy use. Similarly, Emery and Kippenhan [50] in a monitoring project of four houses in Seattle Washington, USA over a period of 15 years found that the occupants displayed significant differences in operating the houses and thus the total energy consumption, but generally simulations ignore the behaviour of the occupants in estimating the energy demands. Among the main findings of the study that differentiated the different tenants was their hot water usage. Guerra-Santin and Tweed [51] through their literature review also conclude that standard occupancy patterns used in predicting energy demands of buildings can be very different to actual occupancy patterns resulting in differences between actual and predicted energy performance. In the monitoring project carried out by Gill et al. [52] on the low energy housing estate in the UK the actual maximum and minimum annual heating demand for the 4 houses they monitored (space heating and hot water) ranged from 46.0kWh/m^2 to 144.9kWh/m^2.

Electricity Generation and Consumptions

Each house was fitted with a metre measuring the amount of electrical energy drawn from the national grid and the amount of PV generated on site in kilowatt hours. Electricity generated on site is supplied by a site total of 80m^2 of Hengji PV-Tech Mono-crystalline Photovoltaic Panels (PV) with a Fronius IG300 inverter and mains electricity. A 3kW Peek PV system has been installed at Houses 1-3 and a 3.5kW peek PV system at House 4. During the monitoring period, it was found that the mains electricity metres in Houses 1 and 4 were incorrectly recording the amount of electricity exported to the grid from the PV and not consumed within the property. The connections were swapped and the meters began to increment correctly in April 2013.

Figure 11 shows the monthly electricity generated by the PV panels and amount imported from the national grid. Sub meters were not installed to distinguish between the portion of electricity generated by the PV panels used directly on site and the amount exported to the national grid. Due to the issues with the mains metres, there is missing data in Figure 11 for Houses 1 and 4 as the electricity exported to the grid was recorded and not imported from the grid.

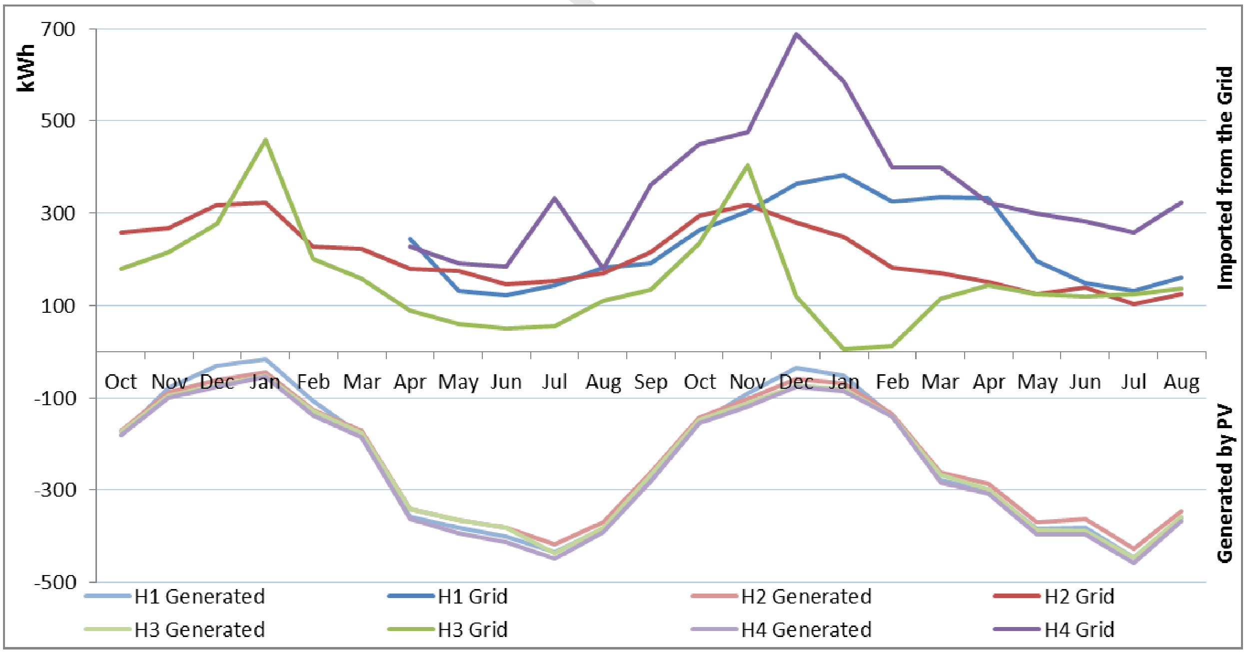


Figure 11: Actual Electricity generated and imported from the grid from Oct 2012 to Aug 2014

Annual predicted and actual electricity generation and consumptions for 2013 are shown in Table 4. To overcome issues associated with main electricity meters in Houses 1, 3 and 4, the following extrapolations have been made in calculating annual total energy taken from the grid;

For Houses 1 and 4, electricity consumption in January, February and March of 2014 have been used instead,

For House 3, electricity consumptions of December 2012 have been used instead.

SAP predicts regulated demands such as electricity used for mechanical ventilation, central heating pump, boiler flue fan and electricity used for lighting as shown in Table 4. It does not however include unregulated consumptions used by devises and equipment such as fridges, freezers, Televisions, computers, kettles, etc. Electricity consumption from household electrical appliances whose number has increased in recent years is responsible for a considerable portion of the total electricity consumption. A report by Internal Energy Agency (IEA) [53] suggests residential appliances make a major contribution to the recent growth in total residential electricity use accounting for 30% of electricity generated in OECD countries and predicted further growth in appliance energy use in years to come. The report also suggests that appliances left in standby mode constituted for 10.1% of residential electricity consumption in 25 OECD countries in 2005.

In energy efficient houses regulated electricity consumption is minimized through energy efficiency measures such as low energy lighting. In a survey carried out by Gago et al. [54], they found that lighting made up just 3.8% of the total electrical demand. In the two Welsh Social Houses, the total lighting demand was 5.5% and 3.4% in House 1 and 2 respectively [39]. Therefore it can be assumed that unregulated demands will constitute a larger percentage of the total electricity consumption.

Ridley et al. [39] report that unregulated electricity in the two Welsh Social Houses they monitored accounts for 67% and 60% of the total loads. Sharp and Morgan [55] have concluded that unregulated demand in the 4 Passivhaus dwellings they monitored over a 2-year monitoring programme in Scotland is responsible for 46.87% to 82.11% of the total electricity used in different houses.

Table 4: Predicted and Measured Annual Electricity Generation and Consumption in 2013 (kWh)

House	SAP						Actual		
	MVHR	Central heating Pump	Boiler flue fan	Lighting	Total from grid	Total PV generated	MVHR	Total from grid	Total PV generated
H1	**214.5**	**130**	**45**	**300**	**689.5**	**-2575.2**	**92.1**	**2995.9**	**-2819.9**
H2	**231.36**	**130**	**45**	**335.95**	**742.31**	**-2575.2**	**143.1**	**2708.5**	**-2782.5**
H3	**209.61**	**130**	**45**	**307.67**	**692.28**	**-2575.2**	**733.1**	**2234.8**	**-2860.6**
H4	**315.09**	**130**	**45**	**416.79**	**906.88**	**-3004.40**	**50.4**	**4478**	**-3012**

Apart from MVHR units whose electricity consumptions have been measured separately, no other sub meters were installed in the houses in Gainsborough to distinguish between different demands. The measured data in Table 4 is therefore the sum of regulated and unregulated consumptions. Unlike SAP predictions from which the total electricity demands may be obtained by adding the absolute values used from the grid and PV generation, it is not possible to determine the actual electricity consumptions of the houses as only parts of the electricity generated has been used directly on site.

As seen in Table 4, there are large differences in the measured electricity consumptions of MVHR units in different houses and that the recorded consumptions differ considerably from predicted consumptions. The next section explains possible parameters affecting the results.

MVHR Performance

Ventilation in all four houses is provided by Vent-Axia whole-house Mechanical Ventilation and Heat Recovery (MVHR) unit ‘Lo-Carbon ASTRA’. Each house was fitted with a metre measuring the MVHR consumption in kilowatt hours. As seen in Figure 12 there are wide variations in the monthly recorded electricity consumed by MVHR units in different houses. In Houses 1 and 4, the units were found operating at different positions for all or for part of the time. Through discussions with tenants, it was understood that tenants were controlling the operation of MVHR units manually.

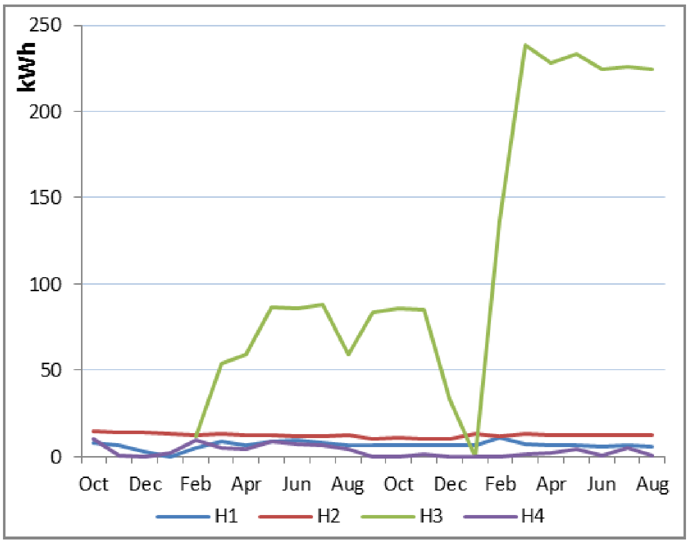


Figure 12: Actual MVHR Electricity Consumption (kWh) from October 2012 - August 2014

The operational status of the unit at House 3 during the monitoring period is not fully understood and early data collected indicated that the unit was not operating at all. However, when the unit was inspected in February 2013 it was found that the unit was operating but it was not logged via the monitoring system due to an unknown fault. To overcome the problem, the sensor in House 3 was replaced. In addition, the system appeared to be turned off during the night by the tenant; the tenant claimed this was down to noise. In February 2014, before the new tenants moved in, the MVHR unit in House 3 was set to the medium position and the cupboard locked by the Housing Association. This intervention resulted in an increase in the monthly electrical consumption of the unit. Although the increase could partly be due to the fact that the MVHR was running continuously compared to operation only during the day, as influenced by the previous tenant, the reason for large monthly consumptions as compared with other houses has not been established. It is important to note that tenants in House 3 may not have noticed the rise in energy consumption from the MVHR units due to energy supplied by the PV panels towards the MVHR demand. Similar occupant behaviour, in relation to operating MVHR units is reported in the literature. Park and Kim [47] in a field study using a large sample of occupants in apartments with mechanical ventilation found that households use mechanical ventilation in different ways due to different perceptions and beliefs.

Although in principle, MVHR could be considered as an energy efficient solution [56], the monitoring results from the Cross Street properties in Gainsborough highlight concerns about the MVHR systems, that occupant misunderstandings of how to operate the controls can wholly undermine the energy performance of MVHR unit [57]. Similar conclusions have been made by Guerra-Santin and Tweed [51] who suggest that with the incorporation of new technologies, occupants are faced with complex systems that are difficult to operate, which can lead to an increase on energy use and reduction in overall satisfaction. Stevenson and Rijal [58] have also expressed that resident perception, understanding and interaction with features in low energy homes has a significant effect on energy use. This has also been recognised in the 2007 Report by the World Business Council for Sustainable Development that stated the behaviour of occupants can have as much impact on energy consumption as the efficiency of equipment [10].

Differences in MVHR units' performances have also been observed in their supply and extract temperatures and relative humidity within the systems installed at the four properties in Gainsborough during the whole monitoring period. The difference between the average external and supply temperatures, i.e. before and after the heat exchanger, shows approximately a 7.6°C to 12.4°C gain. An average difference of 10°C has been recorded at House 2, the only property where the MVHR system operated as intended and is an indication of good performance. Data for the other three properties is less reliable due to the occupancy behaviours and technical difficulties experienced during the monitoring period. A minimum of 2.9°C was recorded during the summer and a maximum of 19.2°C recorded in winter.

Operational carbon dioxide emission

Table 5 shows breakdown of CO_2 emissions associated with energy generations and consumptions reported in Table 4. The same conversion factors have been used to convert SAP perditions and actual consumption. The factors are; 0.2 for gas, 0.52 for electricity supplied by the grid and 0.53 for electricity generated by PV panels to convert kWh into CO_2.

The differences between predictions and measured values are mainly due to the following reasons. 1) SAP only includes regulated electricity consumption while actual electricity consumptions are due to both regulated and unregulated demands. 2) In SAP, electricity generated by PVs is taken to be directly used on site. In the measured data, this is not the case as parts of the electricity generated by PVs are exported to the grid. This does not however affect the carbon accounting as the savings are calculated based on the amount of energy produced regardless of how it is used.

Table 5: Breakdown of annual in use energy and associated CO_2 emissions

	SAP	Actual

House	**Gas**	**Electricity**	**PV generation**	**CO_2 Total**	**CO_2/m^2**	**Gas**	**Electricity**	**PV generation**	**CO_2 Total**	**CO_2/m^2**
H1	**821.4**	**358.5**	**-1364.9**	**-185**	**-2.75**	**1061.3**	**1557.9**	**-1494.6**	**1124.6**	**16.7**
H2	**938.1**	**386**	**-1364.9**	**-40.8**	**-0.56**	**1809**	**1408.4**	**-1474.7**	**1742.7**	**24**
H3	**842.2**	**360**	**-1364.9**	**-162.7**	**-2.5**	**978.8**	**1162.1**	**-1516.1**	**624.8**	**9.5**
H4	**1098.6**	**471.6**	**-1592.3**	**-22.1**	**-0.2**	**1341.6**	**2328.6**	**-1596.4**	**2073.8**	**20.4**

The actual annual emissions including all regulated and unregulated loads per square metre of floor area range from 9.5 to 20.4$kgCO_2/m^2$ per annum for the four houses in Gainsborough. The Sigma House, a pair of semi-detached prototype house designed to Code for Sustainable Homes Level 5 [59] has a predicted annual CO_2 emissions of 14$kgCO_2/m^2$/year calculated by SAP. The House has a reported measured carbon emission rate of 36$kgCO_2/m^2$/year [60]. The actual monitored results in the Sigma House should however be treated with caution due to the monitoring issues observed during the monitoring period [58].

A review of cases reported in the literature revealed that for example; the actual annual CO_2 emissions for the two Welsh Houses are reported to be 9.4$kgCO_2/m^2$ for House 1 meeting Code Level 5 and 24$kgCO_2/m^2$ for House 2 meeting Code Level 4 [39] The predicted annual CO_2 emissions for the Camden House in London certified to the Passive House standard is 11.3$kgCO_2/m^2$ excluding appliances and 23.6$kgCO_2/m^2$ overall [61]. The total measured emissions in the Camden house were 20.5kg/CO_2m^2 per annum. Removing appliance socket loads, the Camden house emitted 14.5$kgCO_2/m^2$ per annum [61]. In a monitoring project carried out by Gill et al. on the low energy housing state in the UK [44], the total measured maximum and minimum carbon emission rates for the four houses they measured ranged from 15.3$kgCO_2/m^2$/year to 38.4$kgCO_2/m^2$/year.

Water consumption

All four new houses in Gainsborough have each been designed with a large capacity rainwater harvesting tank that collects water to be re-used by the household to utilise rainwater for outdoor watering and flushing toilets. Sub meters have not been used to measure the utilisation of harvested rain water in individual houses. Each house has a small garden only with no outdoor tap, therefore there is no evidence to suggest that water has been used to wash cars or water the garden.

In 2013 an estimated 64m^3 of rainwater was harvested taken from the Met Office data for annual rainfall in 2013 for Waddington, 20miles from Gainsborough [62]. The effective total roof rain-water collection area is 124 m^2 using a roof collection efficiency of 75% for the pitched roof over House 4 [52]. Assuming 100% utilisation of harvested rainwater and a filter efficiency of 90% [63], the harvested rainwater is offsetting approximately 14litre/person/day for the tenants living on the site (11 occupants).

Water saving measures have been installed that include flow restrictors in pipes and low flow rate outlets. Table 6 shows the annual mains water consumption in 2013. To overcome issues with change of tenancy, tenancy voids and water leaks, the following extrapolations have been made;

For House 1, water consumption in January and February of 2014 have been used instead,

For House 3, water consumptions of November and December 2012 has been used instead,

Table 6: Measured Mains Water Consumption and average use per person per day in 2013

House	Total use (m^3)	Total per m^2 (m^3)	Total per person (m^3)	Person per day (litres)
H1	**91.0**	**1.4**	**45.5**	**124.7**
H2	**247.2**	**3.4**	**82.4**	**225.8**
H3	**144.6**	**2.2**	**48.2**	**132.1**
H4	**110.5**	**1.1**	**36.8**	**100.8**

Main water consumptions in different houses are shown in Table 6. The water consumption in House 2 is the highest in 2013 totalling an annual use of 247.2m^3 representing an annual consumption of 3.4m^3 per square metre of floor area or 82.8m^3 per person per year or 225.8 litres/person/day. House 4, the largest house, has the least consumption in terms of total per square meter of floor area and total annual consumption per person. The largest variation between House 2 and House 4 having maximum and minimum total water consumption per square meter of floor area per year is of a factor of 3.1. Larger variations have been reported in other studies. For example in a study of 25 low energy houses on a site in the UK, it was found that the water consumption had the largest versions by a factor of 7.1 [52].

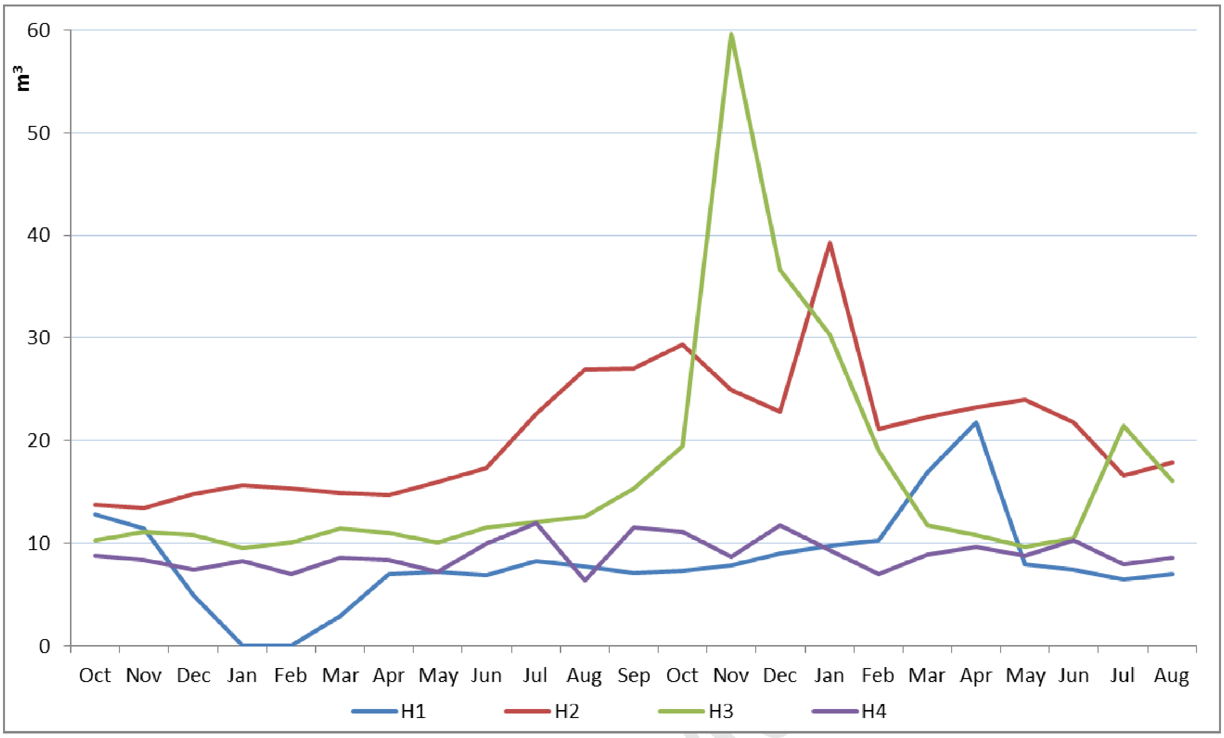


Figure 13: Actual Water Consumption (m^3) during October 2012 – August 2014

Average monthly mains water consumptions per person from October 2012 to August 2014 are shown in Figure 13. Only House 1 in March and House 4 in May and August have consumptions below 80litres/person/day, a mandatory water consumption limit to satisfy Code for Sustainable Homes Level 5. Total average consumption per person per day as shown in Table 6 exceeds the maximum limit of 80 litres in all houses even without considering the contribution made by rainwater harvesting. The excessive water use in House 3 in November (Figure 13) was due to a faulty valve in the downstairs toilet allowing the water to overflow continuously. Compared with national trends, only House 2 uses more water than the UK average consumption of 148litres/person/day [52]. The other three houses use less than the average national consumption. During interviews with the residents, it was found that the high water consumption in House 2 was due to residents' lifestyle.

Discussion and conclusions

The main aim of research carried out was to investigate the performance of energy efficient new homes through a pilot study consisting of 4 recently built dwellings designed to Code 5 of Sustainable Homes built in the City of Gainsborough in the UK in 2012. Quantitative measurements using a mixed method approach involving data logging, surveys and interviews was carried out over 24 months.

The longitudinal approach adopted spanning from July 2012 to September 2014 made it possible to investigate the performance of the dwellings through different seasons. It also made it possible to selectively extrapolate some data to arrive at annual consumptions where there were missing and/or inaccurate monitoring data due to issues such as voids in tenancy, issues with monitoring equipment and controls.

As the houses have the same construction and energy efficiency characteristics, the study made it possible to investigate the effects of occupant behaviour and lifestyle on the performance of the dwellings. The families displayed significant differences in operating their homes affecting the energy and water consumptions. The annual space heating requirements in 2013 ranged from 22.88kWh/m^2 to 49.98kWh/m^2, differentiating by a factor of 2.2. The trends in hot water heating demands showed more variations ranging from 29.03kWh/m^2 to 100.87kWh/m^2 differentiating by a factor of 3.5. Hot water heating demand varied by a factor of 2.5 based on consumptions per person per year in 2013. Variations in hot water heating demands amongst houses correlated with the trends in main cold water consumptions.

The total actual gas consumptions (space heating plus hot water heating) per square metre of floor area in 2013 are higher than those predicted by SAP by 29%, 93%, 16% and 22% for houses 1 to 4 respectively. Although the higher gas consumptions as compared with predictions may be partly due to the colder winter in 2013 as compared with the SAP weather file, the fact which is of more interest is the variations between the actual total gas consumptions among houses varying by a factor of 1.9. Taking into account that all houses have the same construction and energy efficiency measures the results confirm how much users can influence the energy consumption of their homes.

Findings of the research may be classified into two categories relating to the LCA model depicted in Figure 1. These are;

Energy predictions using Performance Assessment Methods, and SAP within the context of this research

Post Occupancy Evaluation

Energy predictions using Performance Assessment Methods - SAP

In order to reduce carbon emissions of homes and meet national targets, it is crucial to identify the best possible design solutions and techniques at early stage of design to achieve low to zero carbon homes. In the UK, Standard Assessment Procedure (SAP) is used as parts of Building Regulations as the national method for compliance and the assessment of a building’s energy use and carbon emissions. SAP is not mainly considered as a modelling tool to accurately predict the performance of dwellings due to its inherent limitations and its use of standard occupancy patterns and weather data. It is mainly used as a rating method to compare the performance of dwellings with a view to ensure them meeting the minimum accepted performance set by Building Regulations. To this end, it can be argued that it is a useful national method for reducing the environmental impact of the housing sector as a whole in the UK.

This paper demonstrated the effect of parameters affecting the actual energy performance of 4 houses as apposed to their performance predictions at the design stage. The research findings highlighted the influence of life style and occupants' behaviors on total energy and water consumptions in homes. Using standard patterns representing the national norms might lead to considerable differences and gaps between assumed and actual consumptions especially if a small sample of dwellings are considered.

Like any performance assessment method and tool, SAP should be continuously reviewed in order to improve its capabilities and accuracy. The feed-forward link suggested between POE and PAM as shown in Figure 1, will be a useful approach to feed the findings of POE results into PAM including SAP to narrow the performance gap.

Post Occupancy Evaluation -POE

Post Occupancy Evaluation (POE) of buildings provides invaluable insights into the environmental performance and user's behaviour which can be used for two main purposes. Firstly, the information obtained can be used for fine tuning the building's operation resulting in energy savings and enhanced user comfort and wellbeing. Secondly, it can be used as a learning loop to feed-forward lessons learnt to better inform the design making process at the design stage.

Post Occupancy Evaluation of buildings does not however take place widely in the UK. If the UK is going to meet its carbon reduction targets, it is crucial for POE to take place in the mass market in order to realistically reduce the performance gap which is widely experienced between design and build. To achieve this, the building industry should foster a transparent and open culture for the actual performance of buildings to be shared across the industry. There is also a need for investment in R&D to create more robust, innovative and cost effective strategies and techniques for POE.

Among the main lessons learnt from the POE of the 4 dwellings in Gainsborough was that users' interactions with their homes and their life styles were among the determining factors influencing the energy and water consumptions of their homes. This suggests that focus should be shifted towards adopting a socio-technical approach to the procurement of sustainable low energy buildings as compared with too much reliance on technology alone.

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Figures

Tables

Highlights

The energy and water use of four social houses certified to the Code for Sustainable Homes Level 5 were monitored over two years.

As the houses have the same construction and energy efficiency characteristics, the study made it possible to investigate the effects of occupants behaviour and lifestyle on the performance of the dwellings.

Occupants behaviour significantly affected energy and water consumptions in different homes.

Post Occupancy Evaluation (POE) of the dwellings provided invaluable insights into the actual environmental performance of the dwellings and the way energy and water consumptions are influenced by the users.