The Monitored Performance of the first new London dwelling certified to the Passive House standard

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Abstract

The monitored performance of the first new London dwelling certified to the Passive House standard is presented. The first detailed analysis of the energy consumption of the heating, ventilation and domestic hot water systems are given. The annual space heating demand of the 2 bedroom, 101m^2 dwelling was 12.1 kWh/m^2, achieving the 15kWh/m^2 Passive House target. The annual primary energy demand was 125kWh/m^2, marginally above the 120 kWh/m^2 target. The measured internal heat gains of 3.65 W/m^2 are much greater than the 2.1 W/m^2 suggested as standard for dwellings. The Passive House Planning Package, PHPP, is found to be a good predictor of space heating demand and the risk of summer time over heating. Winter space heating demand is sensitive to occupant blind use. With a total metered energy consumption of 65kWh/m^2, the Camden Passive house is one of the lowest energy, small family dwellings, monitored in the UK.

Keywords: Dwellings, Low Energy, Building performance, Passive House, Space Heating, Ventilation

Introduction and Background

This paper reports on the thermal and energy performance of the Camden Passive House, built in London in 2010. Designed by Bere Architects, the house is being monitored under the Technology Strategy Board, Building Performance Evaluation Programme. The project received support for post construction evaluation and ongoing monitoring of performance for 2 years, which is supervised by academics at University College London and RMIT University, Melbourne.

The Passive House standard is a rigorous, voluntary building standard conceived in Germany in 1988 as a result of collaboration between Professors Bo Adamson of Lund University, Sweden, and Wolfgang Feist, founder of the Passivhaus Institute (Feist 2007). It is based on the principle of primarily minimizing the heat loss through highly insulated, airtight and thermal bridging free construction. Heating demand is further minimized by means of passive solar heating and reduction of ventilation heat losses through use of mechanical ventilation with heat recovery (MVHR). As a result, heating demand is so low that the conventional heating system can be omitted, with heat provided by pre-heating the air supplied by the ventilation system. In order to achieve Passive House certification, a building needs to meet three basic criteria (Feist, 2007):

- Specific Space Heat Demand max 15 kWh/m^2
- Entire Specific Primary Energy Demand max 120 kWh/m^2
- Pressurization Test Result max 0.6 h^{-1}@50Pa

The building performance is assessed using Passivhaus Planning Package (PHPP). It has been estimated that in 2012 there are approximately 64,000 Passive House standard dwellings in Europe (PASS-NET 2010). The monitored performance of over 100 dwellings from 11 EU CEPHEUS (Cost Efficient Passive Houses as European Standards) projects found that Passive Houses achieved a space heating demand of 15 to 20% of conventional new buildings, (Schnieders 2006). In the UK a small number of passive houses both new builds and retrofits have been built, and are currently being evaluated and monitored. The Princedale Road Passive House retrofit project, which is being monitored under the Retrofit for the future programme, has reported an annual energy (electricity) consumption of 5436 kWh in an 87 m^2 dwelling, hence a primary energy demand of 169 kWh/m^2, between March 2011 and April 2012, thus exceeding the Passive House primary energy demand target by 41%. (Passivhaus Trust 2012). The Lime and Larch Passive houses, (Mcleod et al 2010), designed by the same team behind the Camden Passive

House are also being monitored under the Technology Strategy Board, Building Performance Evaluation scheme, results of the first year of monitored occupation will be available in May 2013. The construction of the first Passive Houses in the UK can be put in the context of current UK Building Regulations (HM Government 2010), The Code for Sustainable Home, (Department for Communities and Local Government, 2006) and strategies to achieve “Zero Carbon” housing from 2016 (Department for Communities and Local Government, 2007). Current UK good practice is defined within the Fabric Energy Efficiency Standard (FEES) which aims to limit heating and cooling demand to reasonable levels so that LZC technologies can be used in an efficient way and thus guarantee achievement of carbon compliance and consequently “Zero Carbon” operation. According to FEES (ZCH, 2009), maximum space heating and cooling energy demand should be:

- 39 $kWh/m^2/yr$ for apartments and mid terrace houses
- 46 $kWh/m^2/yr$ for end of terrace, semi detached and detached houses

Building performance evaluation has shown that the gap between predicted or “designed” and actual performance of low energy dwellings can be significant and that it partially originates from failures in detailing, construction of the building fabric and installation and commissioning of services (Wingfield, et al., 2009; Branco, et al., 2004; Clevenger, et al., 2007). Similarly it has been shown that occupant behaviour is also an important factor in the performance of low energy dwellings (Vringer, 2005; Gram-Hanssen, et al., 2010). In a group of recently monitored low energy UK dwellings, (Gill 2011), it was found that space heating and domestic hot water varied by a factor of 3 between similar households, and water use by a factor 7. Great care must be taken not to over sate the results from single case study houses, only when the monitored performances of several UK Passive House dwellings become available, will an assessment of their overall performance be possible.

Aims and Objectives

The Camden Passive House is an interesting case study in that it provides hard evidence of the performance of a Passive House standard dwelling built in the UK, allowing comparison with design targets and predictions of design tools. As the number of Passive House dwellings in the UK is very limited, there is little or no data on the performance of these types of houses, not only in terms of space heating and domestic hot water demand but in terms of the temperature, internal gains, moisture and ventilation performance. The aims of this paper are therefore two fold, firstly to present evidence on the performance of this case study dwelling and secondly to provide metrics and insight on the performance of low energy dwellings in the UK in a more generic form suitable for those interested in assessing and understanding the impacts of low energy design and refurbishment on energy, temperature and occupant health. Simulation studies, (Shrubsole et al, 2012, Wilkinson et al, 2009), have identified the potential health benefits of MVHR systems, by reducing the risk of mould, concentrations of indoor generated pollutants such as PM2.5 from cooking, the build up of radon, and the reduction in ingress of externally generated PM2.5. The findings of these studies however have to be placed in the context that there is little monitored data, with the exception of the Derwentside study, (Lowe et al 1997) on the as built performance, quality of commissioning, reliability, fan power and efficiency of MVHR systems in the UK. This paper presents the results of the first year of monitoring; the primary aims of the paper are to analyse:

1. Winter space heating consumption
2. Comparison of PHPP predictions with measured data
3. Summer time over heating risk
4. Commissioning, specific fan power and efficiency of MVHR system

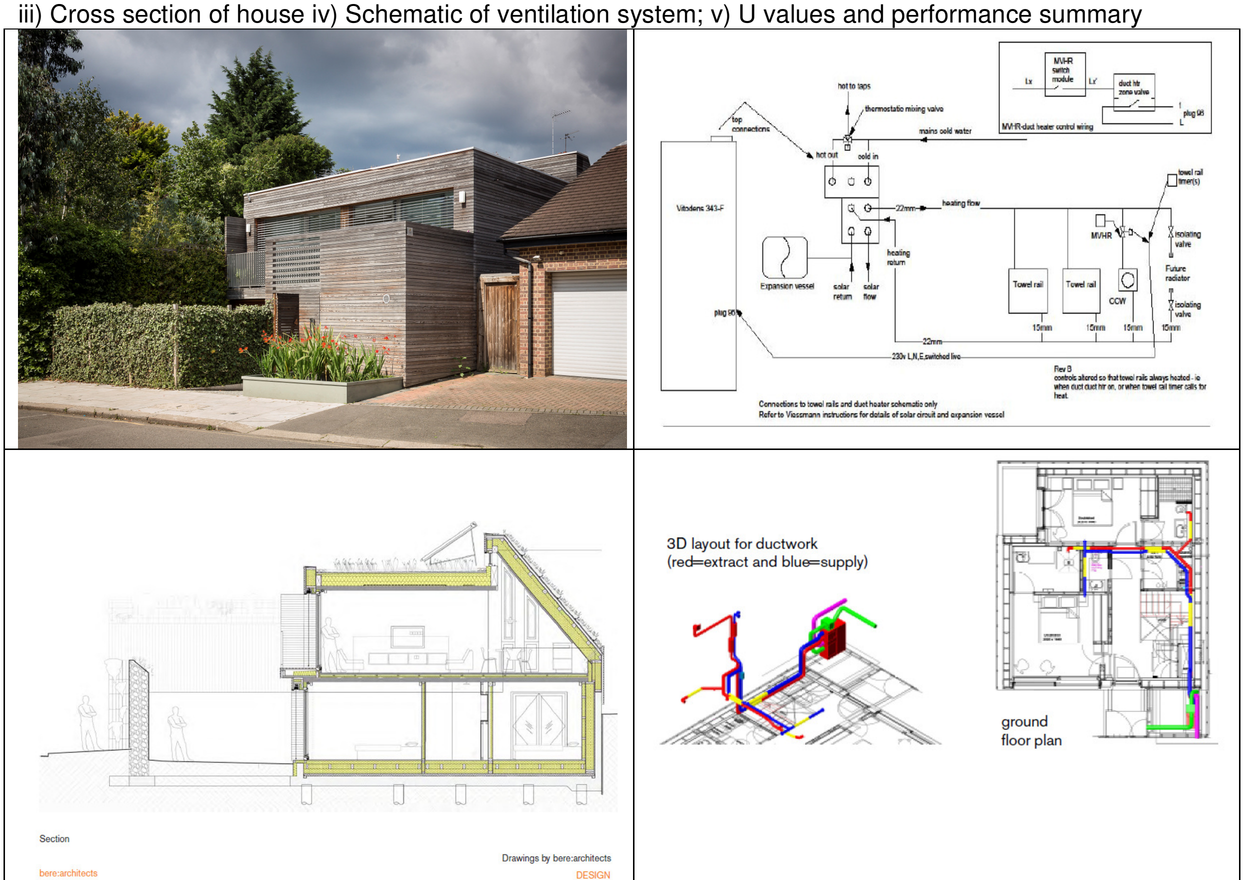
The PHPP tool played an integral role in designing the house (Lewis 2011); this paper compares the real and predicted performance. The house successfully achieved passive house certification and post completion pressure testing determined that the target level of air tightness had been achieved.

The Camden Passive House

This timber framed $101m^2$, two bedroom house is the first certified new build Passive House in London. The primary objective of the project was to achieve a comfortable home for the client’s young family, while minimizing energy consumption. The $101m^2$, two bedroom, family house is constructed with a heavily insulated prefabricated timber frame set inside 3m retaining walls and clad in European larch. The site is located in London which means that the over-shadowing of adjacent buildings had a major impact on the energy balance and design decisions. The Passivhaus Planning Package (PHPP) was used from the very start of the project to determine the optimum position for the house on the site and the optimum percentage and orientation of the glazing. The final design of the house provides bright and airy rooms with large, tilt and slide, draught-free triple-glazed windows to the south and west. Summer shading is provided by means of retractable external venetian blinds with automatic solar control, whilst inward-tilting windows provide secure summer night-time purge ventilation. Carefully detailing and use of air tight vapour control layers resulted in a very air tight construction, with post completion pressurisation testing measuring an air infiltration rate of 0.44 ach^{-1} at 50Pa, below the PHPP target of 0.6 ach^{-1} at 50Pa. The house is ventilated by a Paul Thermos 200 MVHR unit located in an insulated enclosure in the bike shed attached to the building, with a quoted heat recovery efficiency of 92%. The system is designed to provide a constant background ventilation rate of 130m^3/hr (36l/s), 0.48 ach^{-1}. Space heating is provided by a 1kW heater battery in the supply air duct of the ventilation system, supplying warm air at 55 ^oC, complemented by heated towel rails on demand in the bathrooms. A Viessman Vitodens 343F compact energy tower system, comprising of a condensing gas boiler, integrated 200 litre hot water cylinder with direct solar thermal connection supplies heat to the heating system and for domestic hot water. A south facing 3m^2 Vitosol 200, evacuated tube solar collector is installed on the flat roof.

Figure 1

i) Photograph of south façade of completed house; ii) Schematic of heating and domestic hot water system; iii) Cross section of house iv) Schematic of ventilation system; v) U values and performance summary



U-value lower external walls:	0.122 W/(m^2K)	**PHPP Space Heat Demand:**	**13kWh/(m^2a)**
U-value upper external walls:	0.110 W/(m^2K)	PHPP Primary Energy Demand:	97kWh/(m^2a)
U-value ground floor slab:	0.103 W/(m^2K)	Air test:	0.44h^{-1}
U-value flat roof:	0.067 W/(m^2K)	Heat Recovery Unit Efficiency:	92%
U-value sloping roof:	0.110W/(m^2K)		
U-value terrace:	0.140W/(m^2K)		

A water filtration system ensures clean water for both drinking and bathing. Mains water use is reduced by an underground rainwater-harvesting tank, which provides water for the garden. PHPP predicted annual CO_2 emissions are 11.3kg excluding appliances and 23.6kg overall. Biodiversity was very important for this project which incorporates two, wild flower meadow green roofs, a south facing garden and, an ivy covered gabion stone wall. The occupants, two adults, moved into the house over the Christmas of 2010, and completed A BUS questionnaire and semi structured interview in the summer of 2011, to measure their satisfaction with the house and to understand how they interact with the dwelling.

Monitoring System

An Eltek wireless data logging and monitoring system, compliant with the specification of the BPE programme and the UK Energy Saving Trust CE 298 (EST 2008) protocol, was installed in July 2011. All data is recorded at 5 minute intervals. The details of the system are as follows.

- An on site Weather Station measures Dry Bulb Temperature, Relative Humidity, Wind Speed and Direction, Global Solar Radiation, Atmospheric Pressure, Precipitation.
- Room Temperature and Relative Humidity are measured in the Living Room, Kitchen, Master Bedroom, En-suite Bathroom, and Guest Bedroom. Concentrations of CO_2 are monitored in the Living Room and Master Bedroom.
- Utilities metering consists of Total Electricity, Total Gas, Total Water Consumption, with further detailed electricity sub metering on the following circuits: Kitchen Sockets, Down Sockets, Up Lights, Up Sockets, Down Lights, Blinds, Hob, Utility Room Sockets, Oven, Auxiliary Loads, Mechanical Ventilation and Heat Recovery (MVHR).
- Duct Temperatures are measured at the following positions in the MVHR system: Air Off heater, Duct Heater Flow, Duct Heater Return, MVHR Supply, MVHR Extract, MVHR Intake, Master bedroom Supply, Living Room Supply, and Kitchen Extract.
- Heat Meters were installed on the hydronic systems to measure the space heating supplied by the Heater Battery in the MVHR supply, the space heat supplied by the towel rails in the bathrooms, the solar input to the hot water cylinder, Domestic Hot Water Consumption.

The monitoring system was designed to measure the space heat output from both towel rails using one heat meter, however during installation access could only be gained to insert the heat meter at a location after the two circuits had split from the joint feed. Hence it was only possible to measure the heat input from the towel rail in the master bedroom, not on the second en suite in the guest bedroom. However the heating system is configured in such a way that if the heater battery in the MVHR duct switches on, the towel rails both switch on at the same time. Therefore it is known that the output from the guest en suite towel rail will be equal to measured output of the en suite towel rail, if the MVHR heater is on. The Master en suite towel rail was monitored to switch on at times the MVHR heater battery was not on, contributing an extra 150 kWh in winter. A site visit in autumn 2011 found that the second towel rail was not working correctly and not providing heat. The results presented assume that the second towel rail was not used to provide supplemental heat, when the MVHR heater battery was off. During the first year of monitoring approximately 3 weeks of data was lost, due to equipment failure or unplanned events at the dwelling. It was assumed that consumption during these missing days was equal to the daily average of the month during which the loss occurred.

Results

The monitoring system was installed in July 2011, in this paper we present the data from the first full year of monitoring, from August 2011 to July 2012 inclusive. We will concentrate on the heating season performance between October 2011 and Mar 2012 inclusive. A summary of the month by month performance of the house, in terms of energy consumption, internal and external temperature is given in Tables 1 to 6, and Figures 2 and 3. The average electricity power consumption during the first year was 3.87 W/m^2. With occupancy of 2 people, the per capita electricity consumption was 1680 kWh/person. The Electricity consumption can be compared to the UK average and that of the recent EST household electricity use study (EST 2012). The typical average annual domestic electricity consumption currently used in the UK is 3,300 kWh (OFGEM

2012). The EST study households were using on average 3,638 kWh which is ten per cent higher than the official average consumption figures. Average per capita consumption for the EST study was 2,012, kWh/person compared with1,375 kWh/person nationally.

Table 1
Electricity Consumption (kWh)

	Lights	Sockets	Cooking	Blinds	Boiler and Pumps	MVHR	Total Electricity
Aug 11	90	121	2	2	125	21	380
Sep 11	59	117	2	0	141	23	365
Oct 11	57	109	0	0	127	21	333
Nov 11	53	111	1	0	97	22	303
Dec 12	66	126	3	0	124	28	369
Jan 12	81	137	4	0	92	26	360
Feb 12	38	117	1	0	50	23	227
Mar 12	38	94	0	0	32	21	184
Apr 12	47	128	3	0	37	23	234
May 12	38	107	2	0	35	28	201
Jun 12	23	97	1	1	37	27	178
Jul 12	34	130	3	6	35	24	225
Total	**623**	**1393**	**23**	**9**	**933**	**289**	**3359**
%	**19**	**41**	**1**	**0**	**28**	**9**	

During the first six months of monitoring a number of faults were identified and subsequent adjustments were made to the boiler and solar thermal system (see forensic investigation, troubleshooting and interventions). At the end of the year the parasitic loads had been reduced to 16% of the electricity consumption. The total auxiliary or parasitic energy consumption of the boiler, pumps and MVHR system was measured to be 1222 kWh. After adjustments and trouble shooting, results from the final 5 months of monitoring suggest that this value had been reduced to 708 kWh. The PHPP predicted auxiliary electricity demand was 645 kWh.

Figure 2
Breakdown of Electricity consumption by end use

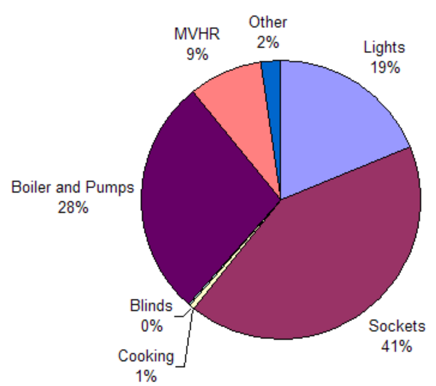
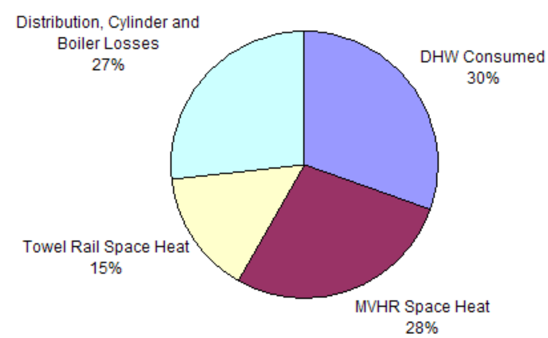


Figure 3
Breakdown of Gas consumption by end use



Total Space heating consumption Winter 2011/12 between October and March inclusive is 1220 kWh, 12.1kWh/m^2. The total annual gas consumption of the house was 3217 kWh. This can be compared to the average gas consumption of a dwelling in greater London, between 2005-2010, of 16,500kWh (DECC 2010). It can be seen that distribution, storage and boiler losses account for 27% of the gas consumption. Assuming an annual average boiler efficiency of 90% (Sedbuk 2009) the distribution and storage losses (DSL) of the heating and DHW system can be estimated:

DSL (kWh) = (0.9* Gas Consumption) + Solar Input – Space Heat Consumption – DHW Consumption   Eqtn 1.

Table 2
Gas consumption, Space Heating and Domestic Hot Water consumption (kWh)

	DHW Consumed	Solar Produced	MVHR Space Heat	Towel Rail Space Heat	Total Space Heat	Distribution and Storage Losses	Total Gas
Aug 11	78	167	0	0	0	110	23
Sep 11	73	149	0	0	0	134	64
Oct 11	50	86	1	0	1	104	77
Nov 11	42	17	34	23	57	111	214
Dec 12	87	14	153	218	371	97	601
Jan 12	103	18	217	146	363	87	594
Feb 12	104	17	318	80	398	68	614
Mar 12	63	67	16	6	22	73	101
Apr 12	114	45	76	24	100	79	275
May 12	84	0	6	3	9	72	183
Jun 12	82	4	36	11	47	78	226
Jul 12	100	5	35	17	52	74	246
Winter	449	219	739	473	1212	539	2201
Total	981	589	892	525	1420	1085	3217

The annual space heating and DHW distribution and storage losses for the house were 1085 kWh, or 10.7kWh/m^2. This figure is in line with the 10 kWh/m^2 figure of DHW heat losses recorded in other UK low energy dwellings (Clarke and Grant 2010). From August to February it is known that there was a problem with the solar hot water controller. The solar pump was on 24 hours a day; hence at night the cylinder was effectively losing heat to the solar panel. After February, when this issue was resolved the losses are reduced by 28% and the average rate of loss was 74 kWh per month, or a heat loss rate 1.0 W/m^2. It should be noted that prior to the middle of January, the heat from the MVHR heater battery was not being efficiently transferred to the supply air due to a partially closed valve, the heat consumption of the MVHR heater battery during this time was 290 kWh.

The total gas and electricity consumption of the house in the first year of monitoring was 6576 kWh, or 65.1 kWh/m^2 per annum. The Camden Passive House is therefore one of the lowest energy dwellings ever monitored in the UK. The BedZed development consumed approximately 90 kWh/m^2, The Long House 80 kWh/m^2 (Gill 2011), The Bioregional One Brighton apartments have a median energy consumption of 72 kWh/m^2 (Bainbridge 2011). Only the Princedale Road retrofit dwelling with a total energy consumption of 62.5 kWh/m^2 is less than the Camden passive House.

Assuming the PHPP primary energy factors of 1.1 for gas and 2.7 for electricity; the primary energy demand of the dwelling was 12600 kWh or 125 kWh/m^2; 4% greater than 120 kWh/m^2 target. Assuming a UK carbon intensity of 0.19 kg CO_2 per kWh from gas and 0.422 kg CO_2 from delivered electricity, the house emitted 2030 kg CO_2, or 20.5 kg/m^2 per annum. Removing appliance socket loads, the house emitted 1440 kg $C0_2$ for lighting, space heating, domestic hot water and auxiliary loads, 14.5kg CO_2/m^2 per annum.

Average winter living room temperatures, 22.4 ^{o}C are slightly higher than expected; some summer time over heating in the living room, 22.5% of hours above 25 ^{o}C, is observed. Substituting measured external temperature, global horizontal solar radiation and internal heat gains into PHPP, the number of hours of overheating above 25 ^{o}C is predicted to be 22.3%, agreeing well with the measured values. PHPP predicts the number of hours above 28 ^{o}C in the living room to be 7.3%, compared to the 2.8% measured. Figure 4 gives a frequency distribution of the number of hours the heating system operated as a function of living room temperature. The heating system is observed to be sometimes on even during periods of high indoor temperature. The thermostat would appear to be set at a high value. The heating operates for 200 hours when the living room temperature is already above 24 ^{o}C.

Table 3
Average Room Temperatures °C and Relative Humidity % and Weather Conditions

	Living Room T	Master Bedroom T	Living Room RH	Master Bedroom Bed RH	External T	Average Global Solar Horizontal W/m^2	Degree Days (base18)	Kew TRY Degree days (base 18)
Aug 11	24.5	23.4	49.4	55.2	16.3	164	64	29
Sep 11	24.5	24.0	50.6	58.1	15.9	157	82	91
Oct 11	25.3	22.8	43.9	52.1	13.6	111	126	191
Nov 11	20.9	19.2	50.7	57.9	9.7	43	231	280
Dec 12	21.2	19.8	43.4	47.9	6.4	31	358	366
Jan 12	21.7	20.3	41.7	47.5	6.3	38	362	365
Feb 12	22.1	19.9	34.8	41.9	4.5	68	393	328
Mar 12	23.2	19.4	37.2	47.2	9.8	183	174	337
Apr 12	21.7	18.9	39.7	49.2	8.1	152	299	251
May 12	22.4	19.7	46.9	58.2	13.1	194	168	145
Jun 12	23.6	21.0	48.3	59.5	14.5	180	116	77
Jul 12	24.8	22.5	60.1	51.1	16.4	186	73	16
Total						**1508**	**2446**	**2476**
Winter Average	**22.4**	**20.2**	**41.9**	**49.1**	8.4			
Summer Average	**23.6**	**21.6**	**49.2**	**55.2**	14.1			

Table 4
Summer time Over-heating, % of Hours over 25 °C and 28 °C

	Living room		Master Bedroom		Kitchen		Guest Bedroom	
	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C
Aug 11	38	4	11	0	57	5	0	0
Sep 11	25	5	1	0	44	7	0	0
Apr 12	0	0	0	0	1	0	0	0
May 12	23	1	0	0	25	3	0	0
Jun 12	14	1	1	0	23	2	2	0
Jul 12	35	6	8	0	51	8	7	0
Average	22.5	**2.8**	3.5	**0.0**	33.5	**4.2**	1.4	**0.0**

Dwelling Heat Loss

The daily rate of heat input to the dwelling was regressed against the daily internal – external temperature difference. The total heat input consisted of all gains from electricity consumption, (except the MVHR unit which is situated outside the heated envelope), occupancy gains, solar gains and space heating, gains from distribution and storage losses of the domestic hot water system, but allowing for cold water feed and evaporation losses.

Solar gains are calculated using the following formula

$$G_{solar} = 0.9 \times A_w \times S \times f \times FF \times Z \qquad \text{Eqtn. 2}$$

Where
0.9 is a factor representing the ratio of typical average transmittance to that at normal incidence
A_w is the area of an opening (a window or a glazed door), m²
S is the solar flux on a surface, W/m²
g is the total solar energy transmittance factor of the glazing at normal incidence
FF is the frame factor for windows and doors (fraction of opening that is glazed)
Z is the solar access factor

The values of g, FF, Z are set equal to those used in PHPP, S the solar flux on each façade is calculated from the horizontal global solar irradiance measured on site. Bedroom blinds are closed during the day, (as reported in occupant interviews and observed on site), external blinds are assumed to be open during winter. Gains from occupancy are assumed to be 0.88 W/m^2.

Figure 4
Distribution of hours the heating system operated as a function of living room temperature.

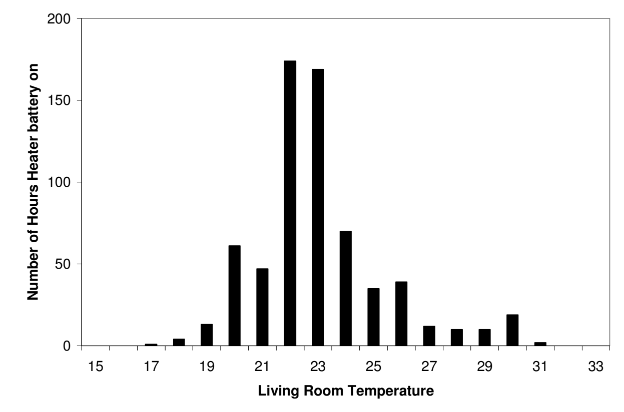
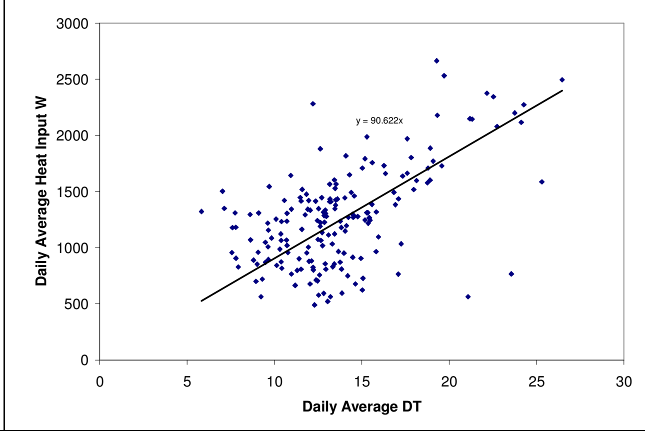


Figure 5
Measured Daily Heat input and internal external temperature difference



The measured average total heat loss of the building based on 182 winter days is 90.6 W/K +- 2.2 W/K (standard error in mean of Daily Input/Daily DT). With a heated floor area of 101m^2, the heat loss co efficient of the dwelling is measured at 0.90W/K/m^2.

<u>Re commissioning and testing of the MVHR system</u>
The MVHR system was recommissioned and tested in June 2011, prior to the commencement of the monitoring period. The originally specified G4 filters were replaced with F8 filters.

Table 5
MVHR System; Design and measured air flow.

Air distribution balance by rooms m^3/hr					Actual measured figures m^3/hr					
	Before correction		Balanced		Fan speed 1		Fan speed 2		Fan speed 3	
Room	Supply	Extract	Supply	Extract	Supply	Extract	Supply	Extract	Supply	Extract
Level: Ground										
Bedroom1	40		40		27		33		40	
Bedroom2	40		40		23		28		33.5	
Bathroom1		28		24		12		16.5		21.5
Bathroom2		28		24		13		47		21
Toilet		21		18		11		14		17
Utility		28		17		9		1.25		15
Level: First floor										
Kitchen		47		47		35		42		55
Living room	32		50		37		45		56	
Totals	112	152	130	130	87	80	106	102	129.5	129.5
Balance deviation from supply/extract mean %					8.38		3.85		0.00	
Total in m2/hr					82.81		104.08		129.5	

	External and fan settings					
	Intake	Exhaust	Intake	Exhaust	Intake	Exhaust
	Fan speed 1		Fan speed 2		Fan speed 3	
External Air flow measurements m^3/hr	87	89	110	113	135	138
Fan speed setting	68%	55%	79%	64%	93%	76%

Table 6
MVHR Electrical power as a function of fan speed

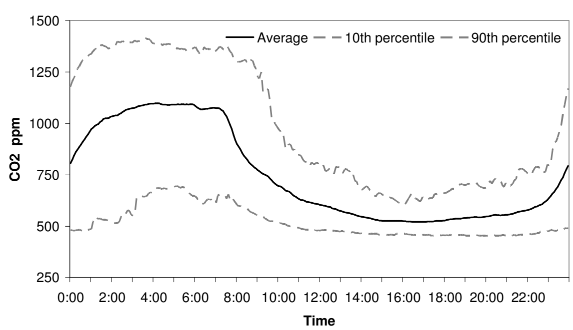
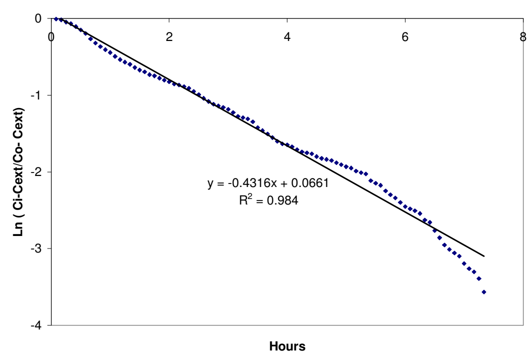
Electrical consumption measurements with clean filters and F8 intake.			
Fans off	Fan Speed 1	Fan Speed 2	Fan Speed 3
10.5 W	23 W	30 W	42
0 m^3/hr	72 m^3/hr	99 m^3/hr	128 m^3/hr

Tables 5 and 6 show the design extract and supply rate for each room, and the actual rates measured for the 3 MVHR fan settings. The system was found to meet the Passive House standard of less than 10% balance deviation. The fans speed percentages are the settings from the PAUL Thermos 200 air handler control system. These show that more effort is required from the intake/supply fan than from the extract/ exhaust fan for a given volume of air. The electrical power consumption of the MVHR at 4 fan speed settings was measured, with clean F8 filters in place

<u>In use Monitored Performance of the MVHR System</u>

The average monthly energy consumption of the MVHR system is 23kWh, corresponding to an average power consumption of 36 W. Comparison with the measured flow rates as a function of fan speed and electricity consumption would imply an average fan speed between 2 and 3 with a volume flow of approximately 114m3/hr. The MVHR was set up to deliver 130m^3/hr, or 36 l/s, which is an air change rate of 0.48ach^{-1}.

Average CO_2 concentrations, (Figure 6) in the living room are 700ppm, with an average evening peak of 815ppm. Average Master bedroom concentrations peak during the night 1085ppm. The average decay in CO_2 in the mornings when the bedroom is unoccupied, (Figure 7) allows a simple air change rate to be calculated. As internal doors are generally open and the MVHR is always on, inter room air flow is high and the bedroom decay may be used as an indicator of whole house air change rate. The average air change rate from 7 am to 2pm is 0.43 ach^{-1}, or 116 m^3/hr, 32.2 l/s.

Figure 6 Average hourly profile of Master Bedroom Room CO_2 concentration	**Figure 7** Estimation of average ventilation rate from decay or Master Bedroom average CO2 concentration
	

The ventilation rate measured by the CO_2 decay and the flow rates measured at the MVHR unit are in close agreement. The measured average ventilation rate of 32 l/s and the measured average power consumption of 36 W, results in a measured specific fan power of 1.1W/l/s or electric power consumption, P_{el} of 0.31 Wh/m^3 for the MVHR system.

The Passive House certification for the Paul Thermos MVHR quotes a P_{el} of 0.31 Wh/m^3. The thermal efficiency of the MVHR system, $\eta_{HR\ eff,}$ was calculated by measuring the air temperature in the extract, intake and exhaust ducts, the electrical power consumption and the air flow rate.

Thermal efficiency was calculated using the following formula:

$$\eta_{HR\ eff} = ((T_{EXT} - T_{EXH}) + P_{el}/m.c_p)/(T_{EXT} - T_{INT}) \qquad \text{Eqtn. 3}$$

where;
T_{EXT} = Extract Temperature K
T_{EXH} = Exhaust Temperature K
T_{INT} = Intake Temperature K
P_{el} = Electric power consumption of Fan Wh/m^3
m = Air flow kg/hr

C_p = Specific heat capacity of air 1005 J/kgK

The average measured thermal efficiency, $\eta_{HR,\,eff}$, of the MVHR during the winter heating season, based on an average air supply of 32 l/s, was 82%, compared to the designed and certified value of 92%. For Passive House certification P_{el} should be less than 0.45 Wh/m^3 and $\eta_{HR,\,eff}$ should be greater than 75%, hence although the measured heat recovery efficiency performance is slightly worse than expected it still meets Passive House standards.

Comparison with PHPP design targets

The Passive House Planning Package (PHPP) was used as the certification tool for the house; the estimated annual heating demand was 13.2 kWh/m^2. This was calculated using a standard PHPP GB London weather file and standard design assumptions about internal heat gains and internal temperature. For comparison with the measured data the PHPP assessment was recalculated using monitored heat gains, onsite weather conditions, and monitored internal temperature and measured MVHR efficiency.

Internal heat gains are calculated as per PHPP methodology, dwelling electricity consumption, excluding MVHR consumption is 3.5W/m2, occupancy gain (2 adults) is 0.87 W/m^2. The cold water feed and household evaporation reduce gains by 0.69W/m^2, an estimated 0.15 W/m^2 from the faulty solar pump is lost to the solar panel, resulting in an estimated internal heat gain of 3.65 W/m^2.

The space heat demand predicted by PHPP for 2011/12 conditions for the as designed house with MVHR efficiency of 93% is 545kWh (5.4 kWh/m^2) The space heat demand predicted by PHPP for 2011/12 conditions for the as built house with MVHR efficiency of 82% is 941kWh (9.3 kWh/m^2) compared to the measured space heat input of 1220 kWh, (12.1 kWh/m^2). The monitored space heat consumption is 23% higher than predicted.

Table 7

Original PHPP Design Calculation; Space Heating Demand and As Measured PHPP Design Calculation

ORIGINAL PHPP CERTIFICATION CALCULATION T INT 20 °C, IHG 2.1 W/m2, MVHR 92%				AS MEASURED PHPP CERTIFICATION CALCULATION T INT 22.4 °C, IHG 3.65 W/m2, MVHR 82%			
Month	Ext T	Global Horizontal Solar kWh.m2	Space Heat Demand	Month	Ext T	Global Horizontal Solar kWh.m2	Space Heat Demand
Oct	10.7	52	15	Oct	10.7	52	0
Nov	7.1	26	187	Nov	7.1	26	108
Dec	5.3	15	355	Dec	5.3	15	266
Jan	4.3	20	377	Jan	4.3	20	245
Feb	4.4	33	272	Feb	4.4	33	287
Mar	6.8	68	84	Mar	6.8	68	1
Space Heating Demand 1307 kWh,13.2 kWh/m^2				Space Heating Demand 941 kWh, 9.3 kWh/m^2			

It should be noted that the internal gains of 3.65 W/m^2 used in this PHPP calculation do not include the 1.0 W/m^2 of potential gains from the distribution and storage losses of the heating and DHW system. If these gains were included the space heating demand would drop to approx 650 kWh.

One of the main uncertainties in predicting the space heating of the dwelling is the effect of blind and shade use by the occupants. Interviews with the occupants and site visits show that the occupants often close internal blinds during winter. The blinds in the bedroom are continuously closed to provide privacy. The living room blinds, which are closed at night, are also sometimes left closed during daytime. If additional winter time shading is applied to the bedrooms in PHPP (additional shading input set to 10%), the predicted as built space heating consumption, increases to 1185 kWh, 11.7kWh/m^2, if shading is also applied to the living windows the space heating demand increase to 2300 kWh.

The predicted space heating performance is clearly very sensitive to shading and hence occupant blind use. If the observed additional occupant blind use in winter in the bedrooms is included in the as built PHPP modelling there is a very good agreement between predicted and measured space heating demand.

Normalised Predicted Space Heating Consumption under standard climate and occupancy conditions and observed use of shading

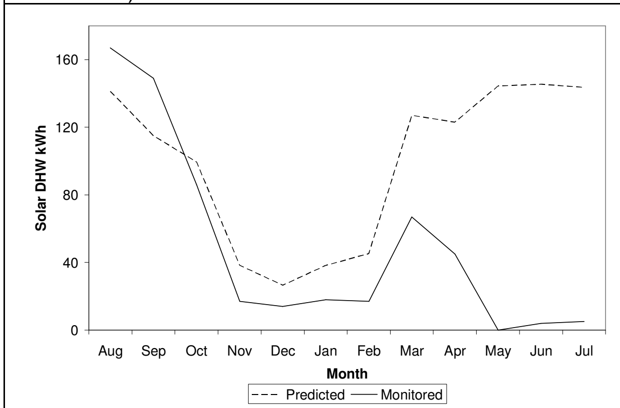
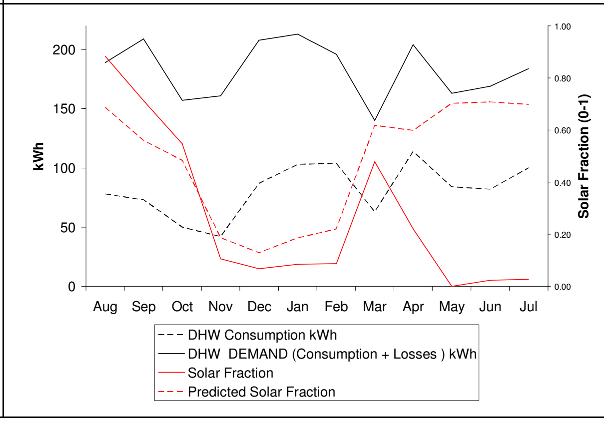
The predicted space heating requirement under standard conditions, adjusted for as built performance and occupant use of bedroom blinds has been calculated as follows.

- Internal temperature to 20 ^{o}C in winter
- Standard London PHPP TRY weather file
- Internal heat gains 3.65 W/m2, (consistent with and occupancy of 2.4 people)
- 82% MVHR efficiency
- Bedroom blind use in winter

PHPP predicted space heating = 1150 kWh, 11.4 kWh/m^2

Performance of the Solar Hot water system

Using measured solar radiation data in the PHPP the predicted solar hot water production, during the monitoring period is 1190 kWh. The monitored solar hot water production was 600 kWh. The solar system produced very little heat after March 2012 due to a faulty fuse. It is known that maintenance work took place in February 2012 to adjust the solar system to prevent the solar pump running continuously. The average solar fraction, of the domestic hot water demand (DHW consumption plus storage losses), was 0.27, due to the above fault, compared to the PHPP predicted value of 0.51.

Figure 8 Solar Hot Water Production; PHPP Predicted (Real solar data) and Measured	**Figure 9** Solar Fraction; PHPP Predicted (Real solar data) and Measured
	

Standardised Temperature, Relative Humidity and Vapour Pressure Excess

In order to normalise for the weather conditions during the monitoring period and to facilitate comparison with data from other studies and datasets, the standardised temperature and relative humidity in the test house were calculated according to the Warmfront methodology (Oreszczyn et al, 2006). The indoor temperature is regressed against the outdoor temperature, including quadratic terms of outdoor temperature to allow for non-linearity of the relationship. From the resulting dwelling-specific regression equation, we derived the predicted indoor temperature and its standard error at 5 ^{o}C outdoor temperature. Data was excluded from any day when the maximum temperature was above 15 ^{o}C and from any period of monitoring, if the coldest day during that period had a maximum temperature above 7 ^{o}C. For the living room data for the daytime hours of 8 a.m. to 8 p.m. is used and for bedroom the night time hours of 8 pm to 8 am.

The standardised temperature in the living room and bedroom were 21.5 ^{o}C, 19.5 ^{o}C respectively. The empirical relationship between standardised temperature and building energy efficiency, (defined as dwelling heat loss divided by efficiency of primary heating system), derived from the Warmfront database of over 1500 UK dwellings, predicts that the Camden Passive House would be expected to have a standardised living room and bedroom temperature of 19.1 °C, and 17.3 °C respectively. It can be seen that the dwelling is substantially warmer. Only 3 dwellings in the Warmfront database had an energy efficiency of less than 100 W/K. The data suggests that the relationship from the Warmfront database may underestimate the standardised temperatures of very low heat loss and passive houses. This is an important finding as the Warmfront relationship has been used extensively to estimate the temperature gains and subsequent health impact of refurbishing dwellings to higher levels of insulation. Similarly the standardised relative humidity in the living room and bedroom were calculated using the Warmfront methodology of (Wilkinson et al 2007), was found to be 39% and 46% respectively. These low values of standardised RH would suggest a low risk of mould growth and indicate that the MVHR system was providing an adequate ventilation rate.

Time profiles of energy Consumption and activities

The data from the winter heating season was binned into 5 minute time slots over the 24 hour daily cycle and analysed to obtain the average profile of energy use, temperatures and activities within the home. Such data is useful as it allows the interaction and synchronisation of systems and end uses such as gas use, domestic hot water and space heating to be examined forensically. The profiles are also a valuable research resource for those wishing to simulate the performance of UK low energy dwellings; such simulation requires reliable and realistic profile schedules. There is a clear peak in DHW consumption between 6 am and 8am associated with morning showering. Space heating is controlled by a timed programmer and takes place between 6am and 9pm in the evening. The peak in gas consumption at 5 am in the morning is associated with heating the hot water cylinder ready for morning demand. Water consumption in the first year was 71,200 litres, corresponding to an average daily water consumption of 195 litres or 98 litres per person per day. This can be compared to average metered UK water use of 150 litres per person per day (Defra 2008). In terms of when the water is consumed 40%, is used between 6am to 9am; there is a smaller peak from 9pm to 1 am, accounting for 25% of daily consumption, presumably associated with bathing and dish washer use.

The profile of electricity consumption is as expected with the minimum occurring at 5 am in the morning, and then increasing throughout the day peaking at 9pm. Kitchen socket use peaks at breakfast and evening meal times. Upstairs living room lights and sockets peak in the evening. It is notable that the minimum average consumption at 5 am is still 200 W. The profile of the MVHR consumption is very flat with no evidence of regular switching to boost mode synchronised with morning hot water use or evening cooking. The Electricity consumption can be compared to that of the recent EST, UK electricity use study (EST 2012).

The temperature profile in the living room is very stable, with 80% of the readings between 19 °C and 24 °C, the average daily temperature range is between 21 °C and 22 °C. The master bedroom is slightly colder with 80% of the readings between 17.7 °C and 22 °C; the average daily temperature range is between 19.6 °C and 20.4 °C.

Figure 10
Average hourly profile of Gas, Domestic hot water and Space Heating Consumption

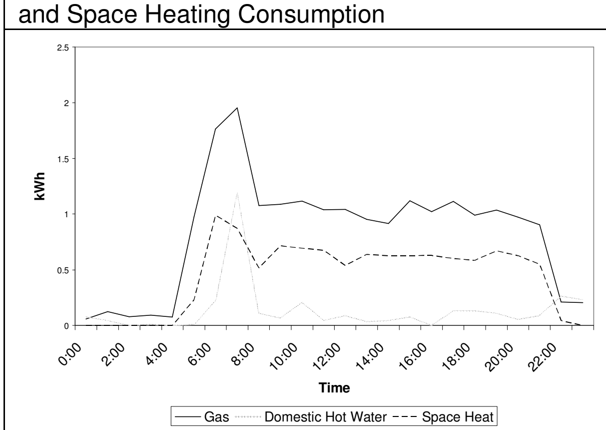


Figure 11
Average hourly profile of Water Consumption

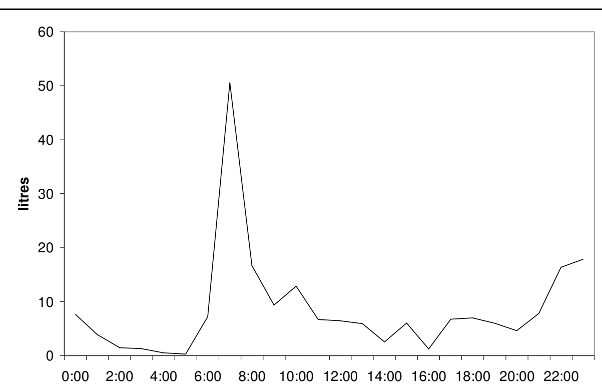


Figure 12
Average hourly profile of Electricity Consumption with average UK (EST study) profile

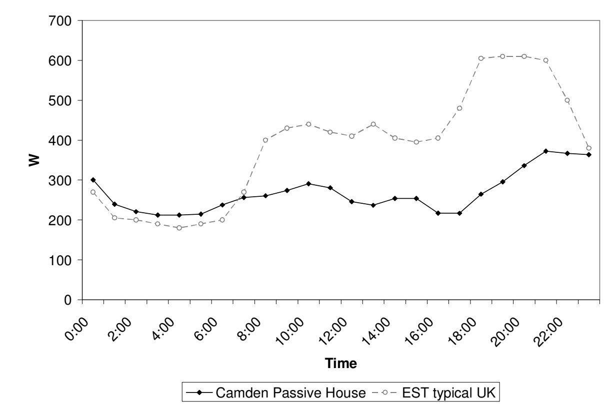
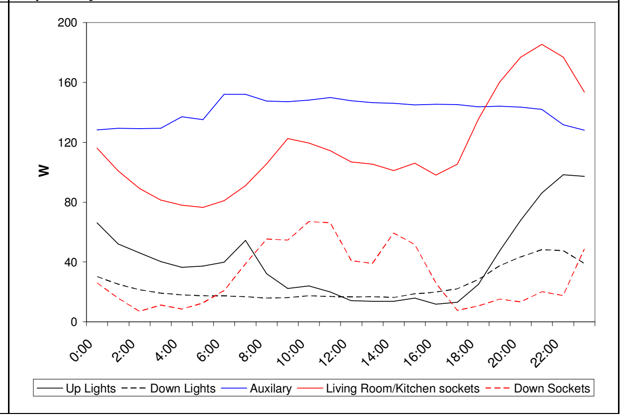


Figure 13
Average hourly profile of Electricity Consumption split by use



Relative humidity in the habitable rooms is very stable with 80% of readings in the living room lying between 32 and 48%. Only the bathroom experiences high peaks of RH, attributable to morning and evening bathing, however the 90th percentile peak of RH in the bathroom is still below 70%. Daily, weekly and monthly average RH in all rooms, suggest the risk of mould growth is very low. Average vapour pressure excess in the living room, master bedroom and kitchen are 292Pa, 328 Pa and 283 Pa respectively. Vapour pressure excess peaks at 500Pa in the living room and kitchen but these evening peaks are in the 90th percentile of occurrence. The relative humidity and CO_2 concentrations in the living room and bedroom indicate good IAQ and appropriate ventilation rates.

The average summer (May to September) temperature profile in the living room is very stable, fluctuating between 23.5 and 24.5 ^{o}C. The 95th percentile of summer living room temperatures is above 28 ^{o}C and occurs between 3 and 7 pm, with the maximum at 5pm. The 90th percentile of summer living room temperatures is above 26 ^{o}C and occurs between Midday and Midnight, with the maximum at 5pm. Hence the living room temperature in 1 in 10 summer afternoons and evenings is over 26 ^{o}C. The master bedroom temperature profile in summer is very stable, with average temperature between 21 and 22 ^{o}C, rarely breaking through 24 ^{o}C.

Forensic investigation and troubleshooting

During the monitored period a number of faults and sub optimal performance issues were spotted, these were then investigated on site by the architects, M&E consultants and service engineers provided by the product manufactures. A site visit in June 2011 noted that the solar thermal panels had been installed with an incorrect orientation, this was corrected. Analysis of the daily profiles of domestic hot water consumption, solar hot water production and gas consumption, suggested that the DHW system had not been optimised to make use of solar input. Gas consumption was high even though the solar input to the cylinder was greater than the hot water consumption. No space heating was being used. In August and September total solar production was 316 kWh, while DHW consumption was only 135 kWh; however 84kWh of gas was still consumed.

The daily gas peak, Figure 20, due to the hot water charging being enabled at midday irrespective of solar input was in part due to a diverter valve (DHW charging circuit) having been set to reheat the whole 250 litres DHW cylinder rather than top 80 litres, as is recommended for solar connected units. This setup was rectified on the 14th of Nov 2011. In autumn and early winter the electrical consumption of the boiler and associated pumps was very high, accounting for approximately 50% of the total dwelling electricity consumption. The high electrical consumption of the boiler was found to be due to 2 pumps running continuously, the solar pump and the heating pump. The solar pump was running even though not called for by the solar controls. The heating pump ran continuously even when the boiler was switched to hot water only. The solar pump had been incorrectly wired to the solar control system; the solar pump cable was not in the correct solar pump socket, but in an identical adjacent “permanent live” socket. The heating pump fault was attributed to the installation of a non standard boiler controller board, fitted in order to allow the heating to be controlled by the MVHR system. This controller had been incorrectly programmed to work with the boiler. These problems were resolved on site and the effect is seen in the reduction of boiler and pumper electricity consumption in February.

Figure 14
Average hourly profile of Living Room winter temperature

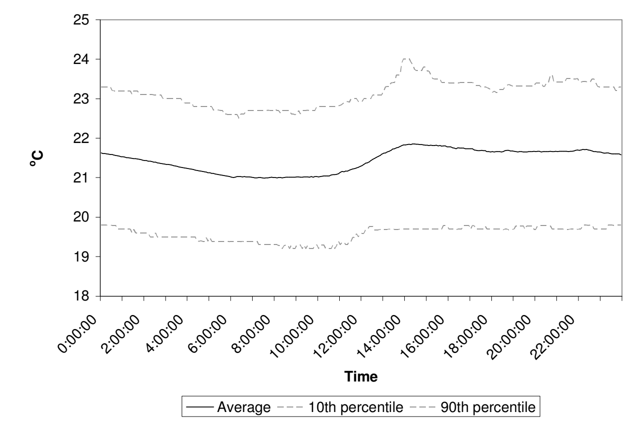


Figure 15
Average hourly profile of Master Bedroom winter temperature

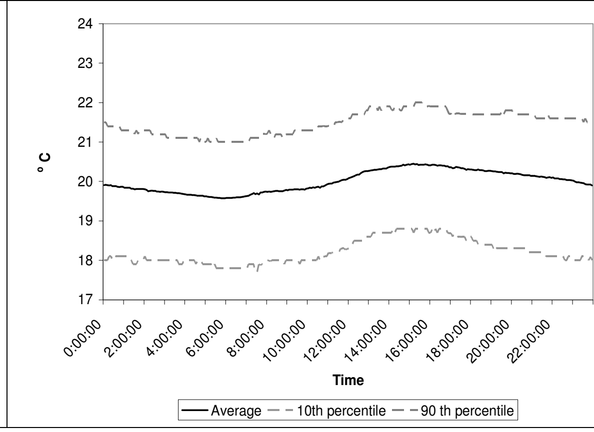


Figure 16
Average hourly profile of Living Room winter relative humidity

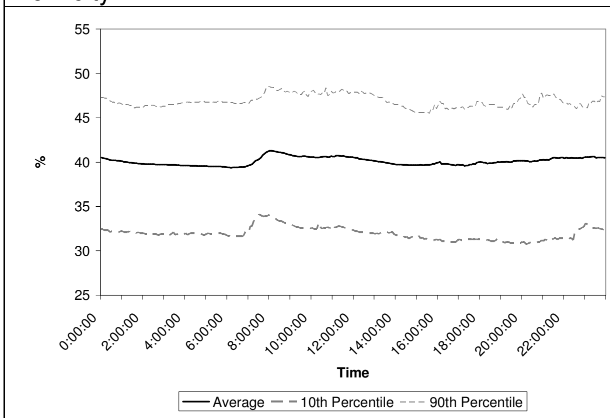


Figure 17
Average hourly profile of Bath Room winter relative humidity

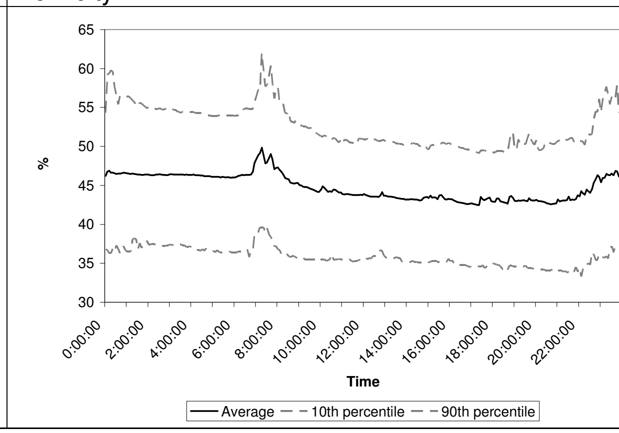


Figure 18
Average hourly profile of Living Room summer temperature

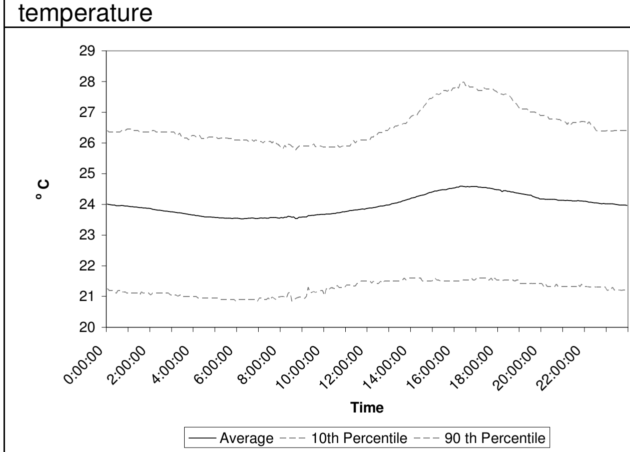


Figure 19
Average hourly profile of Master Bedroom Room summer temperature

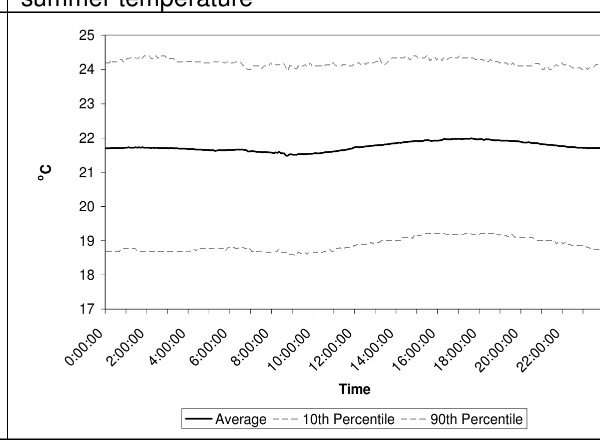


Figure 20
Synchronisation of Gas and hot water consumption with solar production

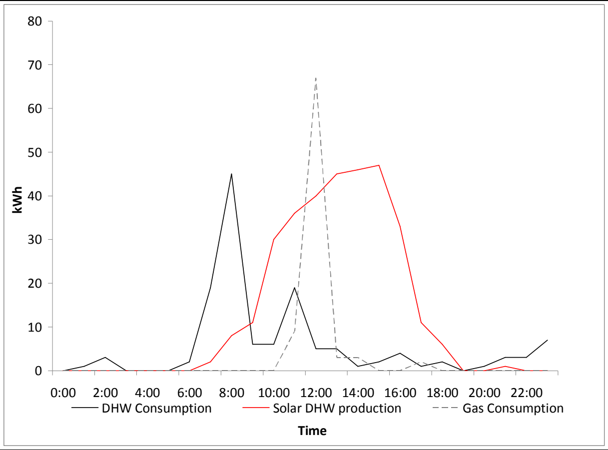
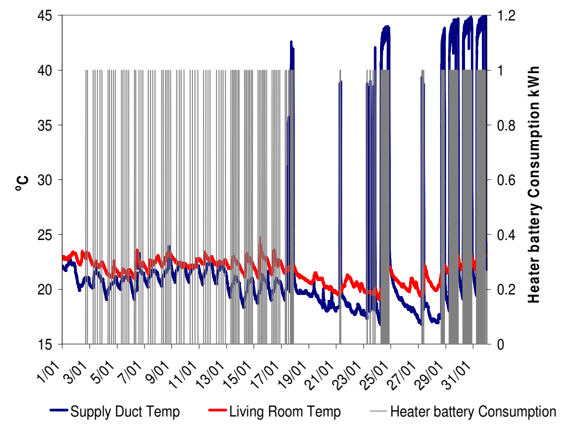


Figure 21
Supply Air Duct temperature and Heater battery energy consumption, Diagnosis of fault 17 January 2012



In December and January, when there was a space heating requirement in the dwelling, the monitoring system identified that the heater battery in the MVHR supply duct was not heating the supply air, Figure 21. The heat meter on the heater battery circuit was detecting small heat consumption possibly from heat leaking through a closed or “stuck” valve, but there was no impact on the air temperature. A site visit on the 17th of January found that a valve on the heater battery had been closed, once opened the duct temperatures rose as expected. Prior to the 17th on January the MVHR heater battery had not been working correctly, with the heat output not being delivered to the supply air. Site visits in the autumn of 2011had previously identified that the towel rail in the second bedroom was not working correctly.

Discussion

Data from the first monitored heating season of the Camden Passive House provides a valuable insight into the performance of a low energy dwelling in the UK. Problems with the installation and control of the DHW and heating system were identified and rectified. These teething problems must be seen in the context of the Camden House being a very carefully designed, constructed and commissioned dwelling, which has received the enthusiastic and knowledgeable attention of specialist contractors and consultants, which had already undergone a more rigorous and “softer landing” and hand over than a standard volume house builder could deliver. The need for thorough testing and commissioning of heating and DHW systems is evident. The danger of modifying or adapting systems, for example changing the boiler controller to interface with the MVHR system can be difficult. The first monitored heating season can be viewed in part as a period during which problems were identified and resolved. However this was the second heating season the house had been occupied, without detailed monitoring and investigation, some of theses installation issues would not have been found, resulting in sub optimal performance.

<u>Summary of House performance</u>

- The dwelling is meeting the Passive House design target of space heating demand < 15kWh/m^2. (12.1 kWh/m^2)
- The dwelling just failed to meet the total primary energy target < 120kWh/m^2. (124 kWh/m^2).
- Savings of 500kWh were identified by rectifying problems with solar thermal heating and domestic hot water system. Allowing for these modifications the primary energy demand of the dwelling would have been reduced to 113 kWh/m^2.
- The level of internal gains is 3.65 W/m^2, 43% more than the standard value of 2.1 W/m^2 assumed for a Passive house.
- The measured space heating consumption of the dwelling is in good agreement with the as built performance predicted by PHPP. For privacy reasons the occupants reported and were observed to use blinds in the bedrooms winter. This extra shading increases space heating consumption.

- Distribution and storage losses from the heating and DHW are or the order of 10.7kWh/m^2.
- Analysis of the heat input into the dwelling and the resultant internal to external temperature difference estimate that the heat loss of the building is approx 90 W/K.
- The heating system appears to be used in an ON or OFF mode rather than under thermostatic control
- The house is very comfortable, with the occupants choosing an average winter living room temperature of 22.5 ^{o}C.
- Indoor air quality, in terms of relative humidity and CO_2 is very good, with a very low risk of mould growth predicted even in bathrooms and kitchen.

The performance of the Camden dwelling is compared to other recently monitored low energy dwelling in the UK in Table 8.

Table 8: Comparison with recently monitored UK dwellings

	Area m^2	Primary Energy kWh/m²	Space Heat kWh/m²	Electricity kWh	Natural Gas kWh	Wood kWh	LPG kWh	Total kWh	Total kWh/m2
Hay Tor	79	147		1995	5684			7679	97
Withy Cottage	58	111		1528		8000	600	10128	176
Dartmouth Avenue	90	185		3684	6162			9846	109
Grove Cottage	138	120	35	3312	6937			10249	74
East Cambusmoon	234	98	32	7976		3180	697	11853	51
Longwall house	270	97		9705				9705	36
LEH Ross on Wye	250	96		3732	12690			16422	66
Manor Farm Close	78	209		3418	6353			9771	126
The Oxlet	309	99		11123	492			11615	38
“Tony's house”	258	113	7.4	10800				10800	42
Birmingham ZCH	171	38	7.3	2280		1775		4055	24
Princedale	89	165		5436				5436	61
Camden	101	127	12	3359	3217			6576	66

Source Retrofit for the Future http://www.retrofitforthefuture.org/. Note this data is NOT normalised for internal temperatures or external climate

The monitoring system is performing well, the dataset allows the performance of the house to be understood and examined in detail. The main factors that still need to be estimated are the actual solar gain, with the gain through windows being determined using tabulated solar heat gain coefficients and assumptions on shading and occupant blind use rather than direct measurement. There is also uncertainty in the heat output of the towel rail in the guest en suite. One oversight is that the monitoring system measures the DHW consumption and the heat input to the cylinder from the solar thermal system, but the heat input to the cylinder from the boiler and the cylinder temperature are not directly measured. Similarly it would have been preferable to directly measure the total heat output of the boiler, to allow boiler efficiency to be calculated. However the installation of such a monitoring system to the Viessmann system post installation would be very difficult and impractical because this would compromise the warranty.

Conclusions

The Camden Passive House is one of the lowest energy dwellings ever monitored in the UK with a total meteredgas and electricity consumption of 65 kWh/m^2 per annum. For comparison comparable UK exemplars are BedZed 90 kWh/m^2, The Long House 80 kWh/m^2, One Brighton 72 kWh/m^2, Princedale Road 63 kWh/m^2. Monitoring is ongoing and with the rectification of faults identified in the first year, future energy consumption could reasonably be expected to be reduced further.

In terms of the wider lessons that can be learned from this case study that can inform low energy dwelling design and delivery in the UK, it is clear that the Passive house air tightness standard was successfully met. The measured specific fan power and efficiency of the MVHR also met Passive House standards.

The commissioning of the MVHR system was found to very good, ventilation rates measured both by testing with a flow hood and long term in use CO_2 decay, were close to design targets. The indoor air quality in the dwelling is very good, the vapour pressure excess is low, resulting in low RH. When the dirty G4 filters were changed after 6 months use, no measurable change in flow rate was observed between clean and dirty filters, suggesting no degradation in performance if filters are replaced in the prescribed time scale. However when high performance F8 filters were installed a reduction in supply rates was observed, requiring the system to be re commissioned.

The MVHR system and high level of air tightness were delivering both kWh and CO_2 savings at the same time as delivering a well ventilated indoor environment.

In terms of user interaction and satisfaction, the dwelling was very well received by the occupants. The house is built in a high density, urban area, on a heavily over looked site. For reasons of privacy the occupants showed higher than expected use of window blinds in winter, which reduced useful solar gain and increased space heating demand. In summer however the occupants wished to use the terrace and balcony area, connected to the living room, and wished to enjoy the summer view out, leading to less than expected summer shading in the living room. There is some evidence that the occupants interacted poorly with the heating thermostat, leading to some winter over heating.

If the hours the dwelling was above 28 ^{o}C are considered, (UK adaptive thermal comfort upper limit) summer time over heating was not excessive. However the considerable numbers of hours above 25 ^{o}C are a concern. The use of blinds by the occupants in summer could have been improved.

The case study suggests that with carefully design using PHPP and robust testing and commissioning of heating and hot water services UK dwellings with total energy consumption of 60kWh/m^2 should be possible to deliver. A co-heating test is planned to accurately measure the fabric heat loss of the dwelling.

The most problematic feature of the dwellings performance was the solar thermal system which suffered from installation and reliability issues. The high electricity consumption and heat losses due to the constantly running solar pump, and the malfunctioning of the system post March 2012 mean that the system was not effective in delivering either kWh or CO_2 savings.

The internal gains of 3.65 W/m^2 should also be noted, designers using PHPP in the UK may wish to use a higher figure than the standard 2.1 W/m^2. To further improve the performance of low energy dwellings in the UK attention must be paid to the storage and distributions losses of the hot water system.

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