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EVALUATION OF ENERGY AND INDOOR ENVIRONMENTAL PERFORMANCE OF A UK PASSIVE HOUSE DWELLING

Xinxin Liang*, Mohammad Royapoor, Yaodong Wang, Tony Roskilly
Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle upon Tyne, United Kingdom, NE1 7RU

* Corresponding author. Tel.: +44-191-208-4934; fax: +44-191-208-6920.
E-mail address: x.liang8@newcastle.ac.uk.

ABSTRACT

The preliminary findings of the energy and indoor environmental performance of a Passive House dwelling in North East of England is presented in this paper. This dwelling is designed to comply with the Passive House Standard (certified by the International Passive House Association) which aims to reduce energy consumption and carbon emissions. The property benefits from advanced building fabric design and materials, PV array, mechanical ventilation with heat recovery system (MVHR) and high efficiency domestic hot water storage vessel to minimise operational carbon emissions. Power generated by the PV panel, imported grid electricity and mains gas consumption of this house are monitored by a proprietary monitoring package; and data of indoor temperature, relative humidity and resident occupancy at several different locations in the dwelling are also recorded. A computational model of this property was developed using DesignBuilder software. The model was validated using the data monitored on site; and is used to predict and evaluate the performance of the house. The initial findings of this study shows the advantages of Passive House in achieving high thermal comfort and good indoor air quality with much lower energy consumption compares to the national average.

Key words: Passive House; DesignBuilder; energy consumption; house performance; data monitoring

INTRODUCTION

In the United Kingdom, the energy consumed within the domestic sector accounts for approximately one third of the energy use and subsequent carbon dioxide emissions, which is higher than the energy used in industry (17%) or road, transport (27%) (Palmer et al. 2013). Thus, the residential property energy demands present a huge opportunity to reduce the energy consumption and restrict the carbon dioxide emissions. The Passive House standard is one of the most outstanding standard for energy efficient construction. Wolfgang Feist, the founder of the Passivhaus Institute, conceived the standard in Germany in 1988, which promotes a fabric-first design concept which seeks high indoor air quality, thermal comfort and energy efficiency (International Passive House Association). Passive House required very low energy to achieve a comfortable indoor environment all the year round. Compared to a conventional house, an equivalent Passive House design could save up to 90 percent energy (International Passive House Association). Hence, the Passive House is an affordable, sustainable and comfortable alternative to conventional and current regulatory house designs and it would be the future direction of energy saving housing development (Ridley et al. 2013).

The aim of this study is benchmarking the performance of a passivhaus design in the North east of England using fine-grained environmental and energy data to evaluate a passive house energy consumption and indoor comfort conditions alongside simulation-based analysis of this case-study building (undetaken in DesignBuilder). To do so, a proprietary monitoring package was installed to record the energy and indoor environmental performance of the Passive House in order to qunatify its energy consumed and also to examine the thermal comfort of the dwelling. Air temperature and humidity levels are measured at 4 different spaces as indeces of indoor air quality. The building's total gas and mains electricity as well as PV production are also measured to map the energy flow into the building.

METHOD

Building description

The selected building for this case study is a two-storey detached family house located in Durham, North East England (*Figure 1*).

Figure 1 North façade of the Passive House

(Source: Mr Roger Lindley)

This is a new build timber construction that meets Passivhaus standards and is included in the Passive House database (ID: 4186) of International Passive House Association (International Passive House Association). This contemporary dwelling took three years to get planning approval and the construction finished in 2014. The property benefits from advanced building fabric design and materials (including triple glazing and high performance insulations), PV array, mechanical ventilation with heat recovery system (MVHR) and high efficiency domestic hot water storage vessel.

A field study of the passive house was conducted on in November 2015. The detailed dwelling information (including the accurate dimensions of each floor, size of each window and door, construction materials of walls and roof) and some energy consumption simulation results from Passive House Planning Package (PHPP) were collected from the property owner during the field study in order to undertake the preliminary virtual model developmenad and also to specify the proprietary monitoring package that was to be deployed for recording the energy and indoor environmental performance of the Passive House.

The treated floor area of the property is 219 m^2 based on the simulation of PHPP. This dwelling could be divided into three parts from west to east. Storey heights of ground floor for all three parts are 2.7 m. And the storey heights of first floor for each part are 2.65 m, 2.10 m and 2.65 m, respectively. The first floor (upper level) of this Passive House comprises entrance hall, office room, en-suite, living room, dining room and kitchen. The ground floor (lower level) consists of family room, utility room, cloakroom, bathroom, two bedrooms and a master bedroom with an en-suite.

Due to the preferences of the Passive House owner who does not want the outdoor views to be restricted by the walls of the dwelling, there are 4 external doors and 43 windows installed in this dwelling. However, this is a big challenge for keeping the house airtight and it is necessary to reduce the windows installation thermal bridges as close to zero as possible. Therefore, high quality thermal envelope was used for this dwelling. The U-values for different construction envelope components are shown in the Table 1 below.

Table 1

U-values of the construction envelope

COMPONENTS	U-value (W/m^2K)
External wall	0.123
Floor slab	0.09
Roof	0.064
Glazing	0.6

The Passive House also benefits from a 6kW PV array, a mechanical ventilation with heat recovery system (MVHR) with 92% heat recovery efficiency and an advanced high efficiency domestic hot water storage vessel. The water tank is heated by the power generated from the PV array. If no power available from the PV array, a regular gas boiler would heat the tank directly.

Software description

DesignBuilder simulation is used in the study to analyse the house energy consumption and indoor environmental performance. The software is the first comprehensive user interface to the Energy Plus dynamic thermal simulation engine (Fumo et al. 2010, Boyano et al. 2013), which has been widely audited by the research community and been demonstrated to have high prediction accuracies (Royapoor et al. 2015). Accurate energy consumption and environmental performance data could be generated at any stage for both new and existing buildings.

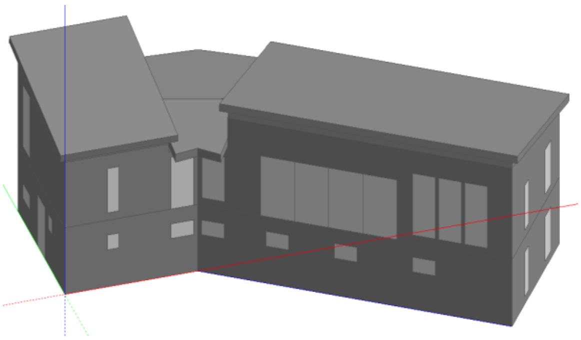

Figure 2 South façade of the Passive House simulated by DesignBuilder

In this work, a Design Builder model for the Passive House was set up to help decide the accurate energy demand trend and discover the indoor thermal comfort for this selected house. The Figure 2 above shows the external facade of the detached house modelled by DesignBuilder.

Actual vs. simulated results

As per the recommendation of (Christie et al. 2005), simulation error is defined in this work as reference value (observed) subtracted from the model forecast (simulated). In order words:

$$\varepsilon_i = M_i - S_i \quad [1]$$

Where *Mi* and *Si* are respective measured and simulated data at time instance *i;* and εi is the error at instance *i* (note that it would have the same measurement units as the original variables). Following the convention of using the measured values as the reference point, percentage error results are generated for energy and indoor climate predictions of the model by using expression 2:

$$\varepsilon_i(\%) = \frac{M_i - S_i}{M_i} \quad [2]$$

RESULTS AND DISCUSSION

The ongoing monitoring of the Passive House's performance began in early November 2015. Main electricity, solar PV electricity and gas consumption are recorded by the proprietary monitoring package. The monitoring intervals of all the energy meters are 1 minute. Figure 3 below shows the monitored energy consumption in a typical winter day. The electricity consumed in the evening is relatively higher than the morning period. In addition, the electricity peak demand appeared at around 9:30pm. The solar PV began to generate power at approximately 9am until 3pm in the afternoon. The peak generation value appeared at noon then it started to reduce from that time. It can be seen from the figure that when the solar PV generates power, the solar PV electricity would have priority to be used to supply the Passive House directly. Thus, when the PV power is enough to supply the house electricity demand, the main grid would stop providing electricity.

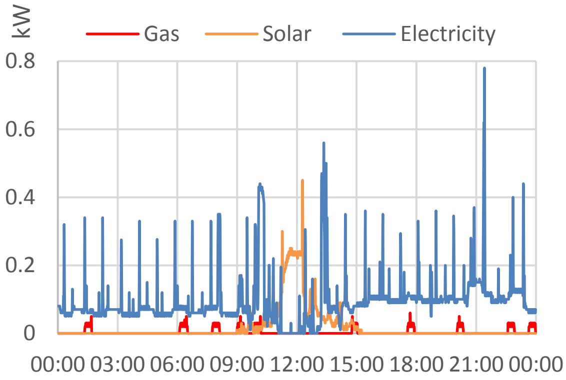

Figure 3 Monitored energy consumption in a winter day

The winter average daily energy consumption for each month from November 2015 to January 2016 are listed in Table 2 below. Thus, the winter total daily average energy consumption of the Passive House could be summarised as 72.37 kWh and the annual energy consumption is supposed to be 16000 kWh.

Table 2

The winter average daily energy consumption

MONTH	GAS (kWh)	PV (kWh)	ELECTRICITY (kWh)
Nov	29.99	0.36	17.26
Dec	84.56	0.19	17.72
Jan	50.34	0.16	16.52
Average	54.96	0.24	17.17

The winter hourly average monitored indoor temperature and relative humidity of four different zones (double height family room, office, master bedroom and living room) in this house are presented in Figure 4 and Figure 5, respectively.

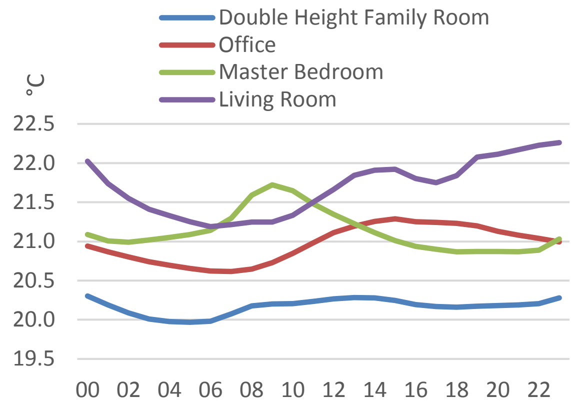

Figure 4 Winter hourly average monitored indoor temperature of the Passive House

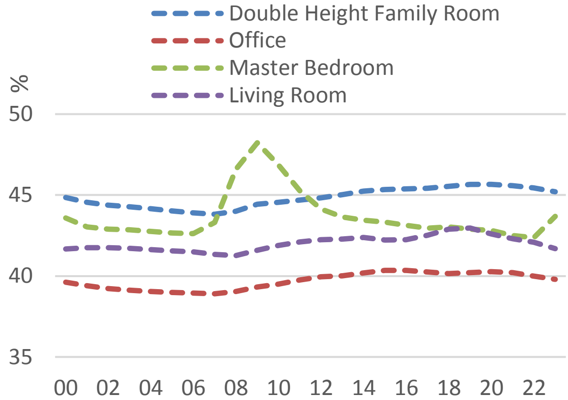

Figure 5 Winter hourly average monitored relative humidity of the Passive House

Figure 4 above shows the indoor temperature trends in the house during wintertime. It is clear that the temperature of living room is the highest (21.7°C) and the double height family room's temperature is the lowest (20.2°C) among the four monitored zones. All the temperature trends decrease from midnight and begin to rise again in the morning except the master bedroom. Not only the temperature but also the relative humidity of the master bedroom increase obviously in the morning because the residents having shower in the ensuite. Although the residents' behaviours occur some impacts on the house performance, the advanced design of the house ventilation could still control the indoor environment in a great level. The daily average temperature of master bedroom is 21.1°C, which is only 0.1°C above the office temperature.

The daily relative humidity of the Passive House stays stable although the shower produce some short-term effects on the master bedroom. Most of the time, all the relative humidity maintain in the range between 40%-45%, which is a very good living environment condition. Thus, the average indoor temperature of the Passive House is 21.0°C and the average relative humidity is about 42.6%.

The energy consumption and indoor environment simulation results of a calendar year for the Passive House generated by DesignBuilder are as follows. The total annual energy consumption is 14003.84 kWh. The monthly energy consumption is shown in Figure 6 below. The average energy consumed for each month during a year is 1166.99 kWh and the daily average energy consumption is about 38.37 kWh.

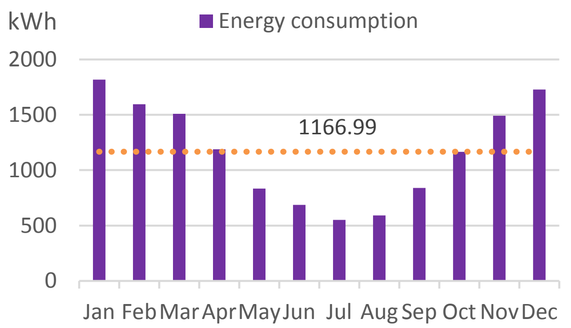

Figure 6 Monthly energy consumption simulation

The indoor temperature of the DesignBuilder model was set to 20°C. The simulated indoor environment conditions are presented in the Figure 7 below. From the figure, it can be seen clearly that during wintertime, the house temperature is stable and stays at around 19°C. The relative humidity of the Passive House keeps at around 37%, which is very good indoor environment quality.

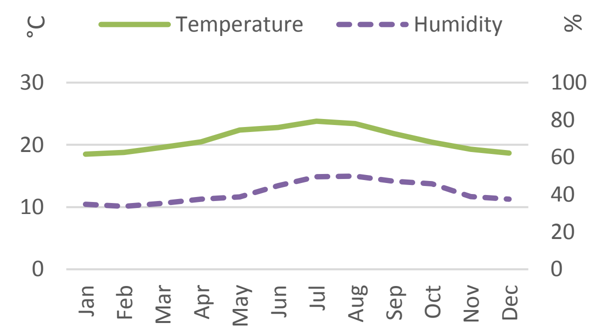

Figure 7 Monthly indoor environment simulation

This results could also be used to compare this nominal PassivHaus in the North East of England with the performance of traditional house in a calendar year in the same region (Liang et al. 2015). Then the methodology would be deployed for further application about the energy consumption analysis. This objective will be pursued in a following paper.

Using formula 2, the average hourly errors of the energy consumption, indoor temperature and relative humidity between simulation results and monitoring data (averaged over an observational period of 3 months) are 4%, 10% and 13%. This means that the DesignBuilder model is under-predicting the energy and environmental attributes of the monitored property. One reason for this is the use of a wood-burner in the property which is operated in the ad-hoc manner and quite understandably contributes to heating of the space. Similarly the occupancy schedule that was imposed on the model is a static and deterministic schedule which is not able to capture the large frequencies of the visits paid to the building owners by their extended family on a completely random bases. An extension of this work will be to use ASHRAE Guide 14 building model calibration method to more closely account for model prediction accuracy. The deviation of the energy consumption is acceptable and the reasons for indoor temperature and relative humidity errors are stated below. The temperature error occurs because the house owner has moved the position of the living area thermostat. This effects of raising the overall house temperature by between one and two degrees without actually increasing the thermostat temperature which is still set to 20°C. It is because this property is larger than normal residential buildings (approximately double size) and the position of thermostat was placed in a relatively lower temperature area in the house. Thus, the average indoor temperature of the whole house would be higher than 20°C, which is the thermostat setting temperature. The relative humidity error may occur by the residents' behaviours and this is hard to be predicted by the software. Having shower in the master bedroom leads to the short time increasing of relative humidity. Therefore, the long term monitoring (at least one year) of the house is necessary to evaluate the performance of the Passive House.

CONCLUSION

During the winter period, the monitored daily average energy consumption of the Passive House is about 72.13 kWh. In addition, the three-month monitoring data shows the winter average indoor temperature is 21°C and the relative humidity is 42.6%.

The simulation results generated by DesignBuilder demonstrated the indoor environment and the total annual energy consumption of this Passive House, which are matching with the actual data very well. DesignBuilder simulation shows the winter indoor temperature is about 19°C and the relative humidity is around 37%. The energy saving of this Passive House is about 88% compared to the national average level (Nigel Henretty 2013). Moreover, the annual carbon dioxide emissions therefore is nearly 12% lower than that of the national average.

Overall, the DesignBuilder model has been validated by the monitored data. Thus, this study shows the advantages of Passive House in achieving high thermal comfort, low energy consumed and low carbon emissions. It provides an extremely great quality environment for living. Passive House is a good example for sustainable housing and it points out a clear direction for the future household development.

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