In Proceedings of the 1st International Conference on Zero Carbon Buildings Today and in the Future, Birmingham City University, 11-12 September 2014.

BIRMINGHAM ZERO CARBON HOUSE - MAKING IT STAY ZERO CARBON THROUGH CLIMATE CHANGE

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ABSTRACT

The Birmingham Zero Carbon House is a retrofitted Victorian house that has achieved carbon negative performance. The house has been extensively simulated in parallel with detailed instrumental monitoring, collecting data of energy production and consumption as well as indoor thermal conditions, proving its zero carbon status in the current climate and in different locations.

Model calibration was carried out using two methods: 1) tracking the total annual energy consumption and renewable energy production using a bracketing approach that narrows down the error range until the relative error between the total simulated annual energy and total measured annual energy falls below 1%; 2) tracking the dynamic temperature behaviour and adjustment of model parameters so as to achieve less than 1 ^{o}C root mean squared error between simulated and measured temperatures. The calibrated model was used to study the building performance in different future climates, using probabilistic future weather data in a medium carbon emissions scenario.

The analysis indicates that the climate change will require a robust approach to the design of new and retrofit applications that not only deals with higher summer temperatures but also with lower winter temperatures.

INTRODUCTION

Context and aims

The Birmingham Zero Carbon House was originally built 170 years ago, and it achieved zero carbon status recently, through retrofit (Figure 1). The house is in fact carbon-negative, as it emits less carbon dioxide into atmosphere than it effectively absorbs. The house is occupied by its architect and owner, John Christophers and his family, and it is a living example that is ideal for analysis of zero carbon retrofit.

The house was a 2 bedroom dwelling, and was extended outward and upward, into a 4 bedroom dwelling over three levels. The house was highly insulated, with internal insulation on the front elevation and external insulation on the back elevation, achieving a U-value of 0.14 W/(m2k), the roof has a U-value of 0.08 W/(m2k), and the ground U-value is 0.14 W/(m2k).

Figure 1 Zero Carbon House: top – street view (top) and garden view (bottom)

The design of the house was inherited from the architect, and has been extensively simulated in parallel with detailed instrumental monitoring. The main features of the Zero Carbon House are:

- Solar gains from south west reduce space heating demand
- High air tightness and heat recovery ventilation
- Natural daylight
- Solar photovoltaic system generates electricity
- Solar thermal system heats domestic hot water
- Additional heating: Wood burning stove used only in very cold weather
- Energy efficient lighting

- Rainwater harvesting
- Use of locally sourced recycled materials
- High level of thermal insulation reduces heat transfer between inside and outside
- High amount of thermal mass smoothes out temperature fluctuations

Our aims are: 1) To study the current performance of the house through the monitoring, 2) To calibrate the dynamic simulation model using measured performance data, 3) To investigate the robustness of the building behaviour to climate change using dynamic simulation, and 4) To devise a set of design guidelines for robustness and adaptation to climate change.

UK climate projections

The UK Climate Projections 2009 (UKCP09) provide climate information for the UK up to the end of the century. Although weather projections are uncertain, they are crucial to develop future adaptation strategies. The UKCP09 weather projections are based on advanced climate modelling, past observations, the Intergovernmental Panel on Climate Change (IPCC) emissions scenarios and expert judgement. It has three carbon emissions scenarios; high, medium and low to represent the possible future states (UKCIP, 2010).

To quantify the uncertainties in the projections caused by: natural climate variability; modelling uncertainty; and uncertainty in future emissions; probabilistic projections are provided, based on 5 Cumulative Distribution Function (CDF) probability levels (of 10%, 33%, 50%, 66% and 90%) (UKCP09, 2010).

Simulations performed using future weather data allow risk-based analysis and adaptation strategies to be implemented in early design stages.

METHODOLOGY

In this section we describe the research method and how different components of the method are combined together to provide a holistic approach to the analysis of the Zero Carbon House. The underlying method for zero carbon design and retrofit is based on the work by (Jankovic, 2012), in which building performance must satisfy energy, comfort and economic criteria in order to comprise a successful zero carbon performance.

Instrumental monitoring

The Zero Carbon House is instrumented with a system of wireless sensors, sending information to the wireless data logger.

The monitored parameters include: internal air temperatures; internal relative humidity; carbon dioxide concentration; energy obtained from the solar hot water system; energy from the photovoltaic system, including generated, consumed and exported; energy imported from the electrical grid; energy obtained from the wood burning stove; energy used by the immersion water heater; solar energy falling on the roof surface; and external air temperature.

A total of 20 parameters are measured every minute and sent to the data logger. The data logger is then accessed remotely over the Internet, for the purpose of visualisation of the monitored parameters and for data download.

Thermal imaging

Methods such as monitoring and dynamic simulation rely heavily on numerical procedures. The thermal imaging described in this section is more of a qualitative method. When used externally, dark colours represent lower heat loss, and bright colours represent higher heat loss (Figure 4). The reverse is the case in internal thermal imaging, where dark colours represent higher heat loss, and bright colours represent lower heat loss (Figure 5). The thermal images from Figure 4 and 5 will be discussed in more detail in the results section.

Occupant survey

Occupant thermal comfort is one of the key ingredients of zero carbon design (Jankovic, 2012). The thermal comfort of occupants in the Zero Carbon House was established through a questionnaire and interviews. The main tool for establishing thermal comfort in this work was the seven point scale from Fanger (Fanger, 1970). Based on a number of responses from numerous volunteers, a relationship between the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) people is established (Figure 3).The meaning of zero vote is a thermal neutrality – a ‘Goldilocks’ zone in which a person feels neither warm nor cold, but just right. Thermal neutrality is therefore the best performance that the designer can achieve for the building occupants, even though the PPD for thermal neutrality is 5%, meaning that there will always be at least 5% of people who are dissatisfied with thermal comfort conditions in a building (Figure 3). The analysis of the occupant survey from this figure will be carried out in the ‘Main results’ section.

Dynamic Simulation

Dynamic simulation was carried out using IES Virtual Environment. The geometry of the model was built using architectural drawings and detailed measurements. The heat transfer parameters are based on detailed specifications obtained from the architect, and the occupancy patterns were obtained through occupant questionnaire and interviews. The Birmingham weather data file is obtained from a built-in library of the IES simulation software.

When it is first built, every simulation model contains a degree of inaccuracy, referred to as a ‘performance gap’. This is a discrepancy between the performance of the simulation model and the actual building (Monfet et al., 2009). In the case of non-existing buildings that are being designed, the performance gap can represent a real problem and can lead to over or under specification of the mechanical systems in the building.

This problem is however eliminated in existing buildings, which are being monitored as well as simulated. One of the purposes of the monitoring system described in the previous section is to provide information for calibration of the simulation model.

Calibration is a process of minimising the error between the simulated and actual building performance, by means of recursive adjustments of the simulation model until the error has reached the required level (Reddy et al., 2007). Two types of calibrations were carried out with the simulation model of the Zero Carbon House: 1) annual energy calibration; 2) temperature fluctuation calibration.

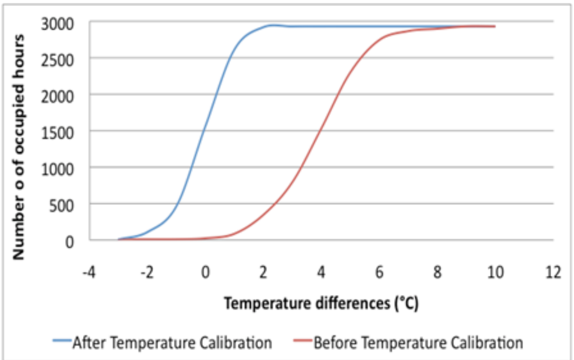

Figure 2 Cumulative frequency of occurrence of errors before and after temperature calibration

The annual energy calibration was carried out so as to achieve the error of less than 1% between the simulated and monitored energy consumption. The temperature fluctuation calibration was subsequently carried out so as to minimise the discrepancies between annual hourly temperatures between the simulation model and the actual building. The result of the temperature calibration is shown in Figure 2, where the cumulative number of occupied hours is shown as a function of temperature discrepancies between the simulation model and the actual house. The red curve in this figure shows that temperature discrepancies before the calibration were up to 8 ^{o}C in up to 3000 occupied hours. This compares with the discrepancies of less than 1 ^{o}C after the calibration, giving a much more accurate and responsive model that closely corresponds to the actual building. After the calibration, the simulation model can be used with confidence to investigate what-if scenarios of the building performance under different conditions.

EXPERIMENTS AND RESULTS

Energy and carbon emissions performance

The results of energy and carbon emissions performance of the calibrated simulation model are shown in Table 1. Thermal energy consumption is reduced considerably by the solar hot water system, so that the total annual thermal energy consumption is 5.56 MWh. The total electrical energy is negative (-1.33 MWh), as surplus, which is generated by the photovoltaic system, is exported into the grid. Therefore the grand total of the energy consumption is 4.23 MWh. As the house floor area is 206.8 m^2, the annual energy consumption per floor area is 20.45 kWh/m^2 (Table 1).

Carbon dioxide emissions are calculated using the energy consumption figures and applying the corresponding emission factors (Table 1) (DEFRA, 2014, IES, 2011). As the emission factor for grid displaced electricity is negative, the overall total of the carbon emissions is also negative, as shown in Table 1. The figure of -662 kgCO2/annum confirms the zero carbon, or indeed carbon negative, status of the house.

Thermal comfort performance

In summer, the predicted mean vote (PMV) is 0.09, corresponding to the predicted percentage of dissatisfied (PPD) of 5.17%. In winter, the PMV is -0.3 and the corresponding PPD is 6.87%. Taking into account that PPD for thermal neutrality is 5%, the PPD discrepancy from thermal neutrality in summer is 0.17% and in winter 1.87%.

It is important to emphasize here the meaning of thermal neutrality. This corresponds to a perception of an individual that he/she feels neither too warm nor too cold in a building, but just right. Designers should therefore aim to create buildings that provide thermally neutral environment for their occupants. As the diagram in Figure 3 shows, even in a thermally neutral environment there will be 5% of dissatisfied people, and this number will rise exponentially as PMV gets further from neutrality. In the Zero Carbon House, the departure from thermal neutrality is minimal, thus confirming high level of thermal comfort.

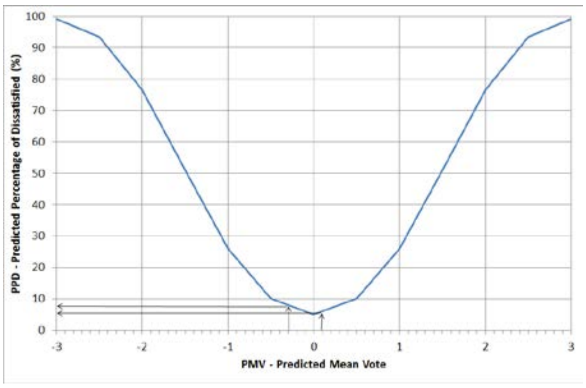

Figure 3 Occupant survey using predicted mean vote and predicted percentage of dissatisfied

Economic performance

Economic performance calculations are explained in detail by Jankovic (Jankovic, 2012). The initial investment into retrofit of the original house was

Table 1 Energy consumption and carbon emissions

	Energy (MWh/annum)	Carbon emissions factor ($kgCO_2/kWh$)	CO_2 emissions ($kgCO_2$/annum)
Space heating energy	1.78	0.013	23
DHW heating energy	7.86	0.013	102
Solar thermal energy	-4.08	0.013	-53
Sub-total thermal energy	5.56		72
Electrical energy used	2.73	0.517	1411
Total electricity generated	-4.06	0.529	-2145
Sub-total electricity energy	-1.33		-734
Grand total thermal and electrical	4.23		-662

£47,345, and the annual return £5,752, resulting from energy savings and income from the feed in tariff. When these savings are amended in order to take into account the future value of money normalised for the current time, assuming the inflation rate of 3% and actual investment interest rate of 3.05%, the financial returns vary from £5,581 in the first year to £5,517 in the 25th year.

As shown by Jankovic (Jankovic, 2012), not all zero carbon buildings are financially viable, and thus the process for zero carbon design must achieve financial viability as well as technical criteria for carbon-neutral or carbon-negative emissions and thermal comfort criteria for a minimum departure from thermal neutrality. Overall, the payback period is between 8 and 9 years, and the net benefit in 25 years time is £91,380. Taking into account the initial investment of £47,345, the return on investment, after all costs have been paid, is ROI = 193%. This is a significant figure. Although it will vary with inflation and the investment interest rate, it demonstrates high financial viability of the Zero Carbon House.

Results of thermal imaging

Thermal imaging was used as a qualitative analysis tool that complements other methods, such as instrumental monitoring and dynamic simulation.

Examples of the results of external thermal imaging are shown in Figure 4 and Figure 5. Dark colours in external images and light colours in internal images indicate low heat losses.

The external thermal images show clearly which part of the image is the Zero Carbon House and which part is not. The left side of the street image is much darker than the right side, showing a clear difference between the Zero Carbon House and the next door house. A tunnel between the two houses glows red, indicating high heat losses, and a closer inspection revealed that these heat losses were coming from the conventional house next door. The high level of insulation in the Zero Carbon House is evident from darker parts of both street and garden side images. The garden side image also shows that the heat loss from the window of the zero carbon house is comparable to that from the external wall in the conventional house next door. These external thermal images provided an independent confirmation of the low energy performance of the house obtained through instrumental monitoring and dynamic simulation.

Whereas external thermal images were used only as a confirmation the low energy performance, the internal images were used to detect any problems and to rectify them. These images revealed a crack between the wall and the ventilation duct (Figure 5-top) and a missing insulation on the door hinge (Figure 5-bottom), and this information was passed onto the developer for rectification.

Overheating analysis

Using the results of the calibrated simulation model, overheating analysis was first carried out for the current climate conditions. The overheating was considered to be occurring when the internal air temperature exceeded 28^{o}C in living spaces according to the CIBSE guide A (CIBSE, 2006). The results of this initial overheating analysis for the Typical Reference Year (TRY) and Design Summer Year (DSY) has shown no overheating in the current climate. Overheating occurs when applying future weather files, increasing steadily under TRY future climate predictions of 50th percentile, thus reaching almost 102% of the initial value in 2080 under the medium emissions scenario, 228% of the initial value under the high emissions scenario in the same year. The overheating appears to be worse under the DSY 50th percentile predictions, reaching 184% of the initial overheating hours under the medium emissions scenario in 2080, and almost 232% of the initial value under the high emissions scenario in the same year.

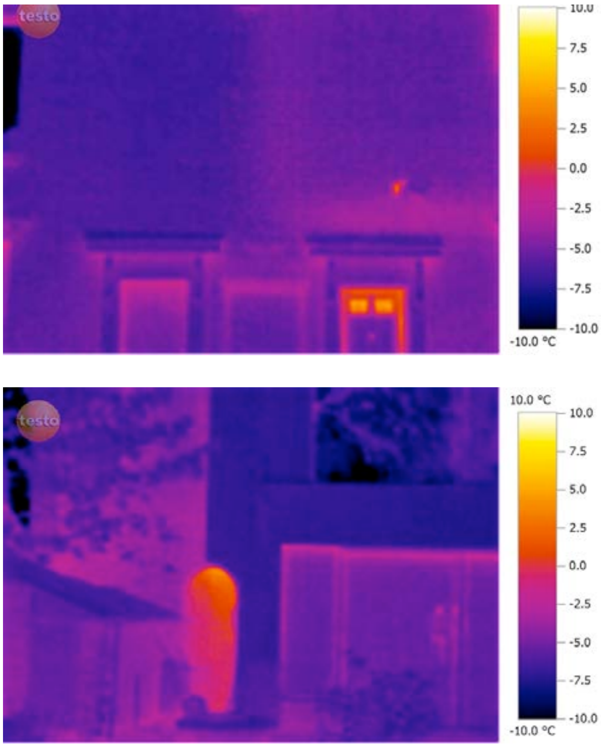

Figure 4 External thermal images from the street side (top) and garden side (bottom)

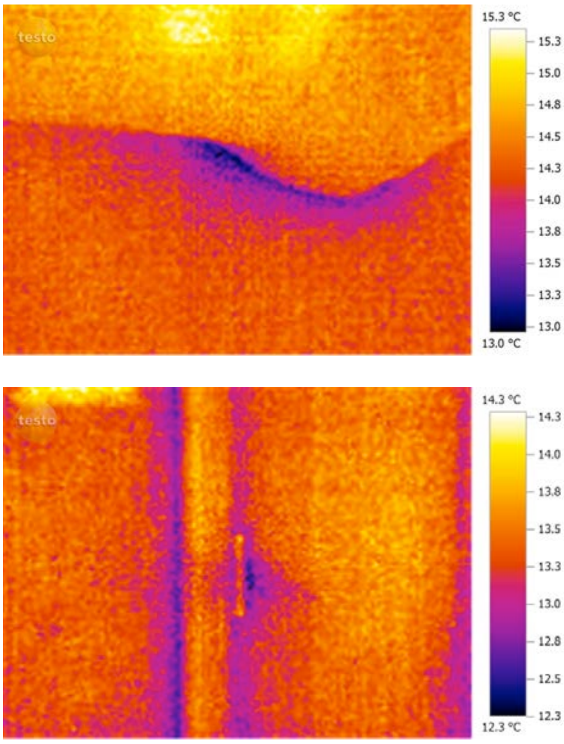

Figure 5 Internal thermal images: a crack around a ventilation duct (top) and missing insulation on the door hinge (bottom)

Mitigating overheating

As overheating predicted in this way appears to be significant, the question is whether it could be mitigated with relatively simple measures such as shading and/or free cooling. The analysis of mitigation of overheating was carried out for DSY climate files under the high emissions, being the worst case scenario.

Two types of shading devices were introduced into the simulation model, applied to the south-west facade. Brise-soleil shading of 120 cm, and external louvers for the summer months. The most significant reduction is in the year 2030, between 10% (120 cm brise-soleil) and 35% (louvers). The effect of shading is diminishing through the future climate years, so that the reduction of overheating is between 1% (120 cm brise-soleil) and 24% (louvers).

As the results of mitigation of overheating with shading devices was not entirely satisfactory, still leaving significant overheating in the building, the effect of free cooling was subsequently investigated.

Free cooling is a term that refers to cooling with external air, at the time when its temperature is lower than the inside temperature, whilst the inside temperature is approaching the overheating temperature. This is typically achieved using mechanical ventilation heat recovery (MVHR) systems in a bypass mode so that colder incoming air does not exchange heat with warmer exhaust air. As the simulated building already has the MVHR system, this type of cooling was considered to be realistic.

Firstly, a free cooling profile was created in the simulation model, so as to operate the mechanical ventilation under the following conditions:

1) external air temperature is lower than internal air temperature, and
2) internal air temperature is greater than 26 ^{o}C.

The somewhat lower temperature trigger for starting the free cooling of 26 ^{o}C was chosen in an attempt to prevent the overheating in advance, rather than to deal with overheating when it has already started to occur.

Secondly, three air change rates for free cooling were set in the internal conditions template: 1, 3 and 5 air changes per hour (ACH).

Similarly as in the case with shading, the most significant reduction of overheating through free cooling was achieved in the year 2030, with 56% decrease from the initial overheating hours under 1 ACH, and 60% decrease under 5 ACH. Unlike solar shading, free cooling provided significant reduction of overheating through the future climate years, achieving 19% reduction of the total overheating hours at 1 ACH in 2080, and 50% reduction at 5 ACH in the same year.

However, even with this significant reduction, the overheating was still occurring in the building. A question was then raised whether the combined effect of shading and free cooling could lead to more significant reduction of overheating. The results of the combined analysis are shown in Table 6. The combined effect of these two measures reduces the number of overheating hours to 20 in the year 2030 representing the reduction of almost 74.3%.

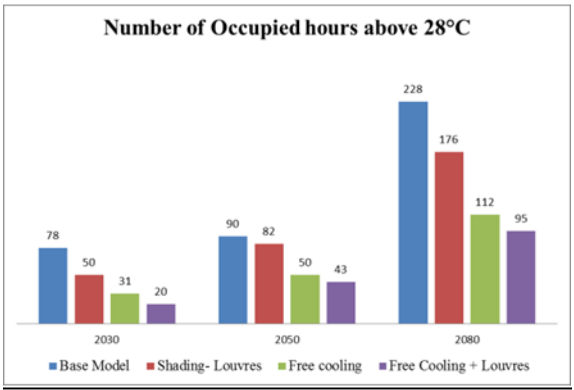

Figure 6 Reduction of overheating through mitigation

In 2080, the reduction is just over 59%, making the total number of overheating hours of 95. The effects of the mitigation measures are summarised in Figure 6.

DISCUSSION

The payback period, the net benefit at the end of the 25 year period, and the return on investment were calculated using the feed-in tariff and energy prices at the time of the original analysis. Although it is guaranteed for this house for 25 years, the feed-in tariff in the UK has changed since this analysis was carried out, so that newly retrofit houses would get much lower financial incentives, resulting in longer payback periods. Any future change of the carbon emission factors will result in changes to the actual carbon emissions from the house, although these are expected to be negative regardless of future changes.

The analysis of the Birmingham Zero Carbon House was carried out from the point of view of operational carbon dioxide emissions, without taking into account embodied carbon. However, most of the original structure of the house has been recycled, including bricks, timber in the roof and floor. Thermal insulation is partially made of recycled newspaper and internal rendering is made of lime with crushed recycled glass. All of this contributes to a considerably lower carbon footprint in comparison with newly built zero carbon houses.

The calibrated model was tested using medium and high emissions scenarios of 50th percentile. Both TRY & DSY weather files showed a great increase of overheating, which was related to the number of occupied hours over the CIBSE comfort threshold temperatures of 28^{o}C in living spaces.

The overheating increase of up to 228% indicated the need of future proofing buildings in the context of climate change, in order to maintain thermal comfort as well as a carbon negative performance. Several methods were used in order to mitigate overheating: external shading; free cooling; and a combination of shading and free cooling.

Mitigation methods need to be part of the retrofit decision-making process, in order to eliminate further costs in the future and also to help maintain a low energy performance. With the current focus on heating demands, we need to be aware of the highly possible cooling demands as shown in the dynamic simulation results

CONCLUSIONS

The paper investigated the performance of the Birmingham Zero Carbon House, a Victorian residence built 170 years ago that has achieved zero carbon status through retrofit. The combination of instrumental monitoring, dynamic simulation, thermal imaging, thermal comfort analysis, and economic performance analysis confirmed that Birmingham Zero Carbon House is carbon negative, that it provides good thermal comfort for the occupants and that it is financially viable with high level of return on investment.

The results of this paper show that overheating arising from climate change can be effectively but not fully mitigated using relatively simple measures, such as shading and free cooling. The combination of these two measures achieves the best results.

These results should not be generalised, as they correspond to a specific case of the Birmingham Zero Carbon House, which has high level of thermal insulation and thermal mass. The future climate data used for this analysis are probabilistic, which further restricts a generalisation. However, the results show a clear pattern of reduction of overheating hours, demonstrating that our homes would be able to provide comfortable shelters under increasingly difficult conditions resulting from the climate change. Therefore, it is advisable to prepare homes gradually for adaptation to climate change.

Considering that a large number of houses in the UK will survive till 2050 or beyond, zero carbon retrofit is increasingly being viewed as a necessary measure for reducing carbon dioxide emissions. Although this measure requires investment, the high economic viability of this particular design is very encouraging and it can be used as an example for the way forward.

ACKNOWLEDGEMENTS

The funding of instrumental monitoring by the Higher Education Innovation Fund and Birmingham City University, and the collaboration with Mr John Christophers of the Zero Carbon House are gratefully acknowledged.

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