Household Energy Demand Management using Retrofitting and Passive Energy Saving Methods

Thesis by

Xinxin Liang

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Sir Joseph Swan Centre for Energy Research
Newcastle University
Newcastle upon Tyne, United Kingdom

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Abstract

Currently, building energy conservation has turned into one of the most attractive topic worldwide as buildings contribute the most energy consumption than any other consumers and they also produce a large amount of greenhouse gas emissions. In the United Kingdom, the residential building becomes the biggest energy consumer, with nearly 30% of the total energy consumption. Among them, existing traditional old style households consume much more energy compared to those new build domestic properties that adopted various energy saving methods. Therefore, it indicates a great opportunity to cut down the energy usage and reduce carbon dioxide emissions from buildings by retrofitting conventional houses. A detailed background study and literature review were reported involving current building energy challenges, domestic energy demand features, conventional and low energy domestic properties and the retrofitting of buildings.

Two case studies were conducted to investigate the performance of a Conventional House and a Passive House, respectively. A set of data sensoring and recording instrument was installed in each house to record the properties' electricity and gas consumption, indoor temperature, relative humidity and CO_2 concerntration for more than one year. Compuational models for both dwellings to simulate their energy consumption and indoor environmental condition were developed by DesignBuilder software. A simulation study by applying Passive House standard to retrofit the Conventional House was conducted after the model validation, which included adding insulation, utilising triple glazing and improving gas boiler's efficiency. An investigation to minimise the risk of summer overheating in the Passive House was carried out to further enhance its performance.

The main findings of this research are: for the Passive House, the building performance was remarkable; for the Conventional House, retrofitting by using passive energy saving methods is essential to improve its building performance for reducing the energy demand and increasing the indoor temperature. Through the building fabrics improvement in the model simulation, the primary energy demand of the Conventional House was reduced significantly by 78% compared to its original status, and the indoor temperature was increased to comfortable level to satisfy the residents' requirement. Overall, the results from this research indicates the advantage of house retrofitting by using passive energy saving methods in achieving lower energy consumption and good thermal comfort. The fingdings of this study can be used as a reference for the future UK conventional household retrofitting.

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BEAM	Building Environmental Assessment Method
BREEAM	Building Research Establishment Environmental Assessment Method
CH	Conventional House
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CV(RMSE)	Cumulative Variation of Root Mean Squared Error
DHW	Domestic Hot Water
DPH	Demoted Passive House
ECUK	Energy Consumption in the UK
EPC	Energy Performance Certificate
EU	European Union
GBI	Green Building Index
GM	Green Mark
GS	Green Star
HQM	Home Quality Mark
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IEA	International Energy Agency
ktoe	Kilo tonne energy
kWh	Kilowatt hour
LEED	Leadership in Energy and Environmental Design
LED	Light emitting diode
MBE	Mean bias error
MVHR	Mechanical Ventilation with Heat Recovery
NZEB	Net Zero Energy Buildings

PH	Passive House
PHPP	Passive House Planning Package
PIR	Passive Infra-Red
ppm	Parts per million
PV	Photovoltaics
RCH	Retrofitted Conventional House
RH	Relative Humidity
RMSE	Root Mean Square Error
SAP	Standard Assessment Procedure
T	Temperature
TWh	Terawatt hour
UK	United Kingdom
US DOE	US Department of Energy
USA	Unite State of America
W	Watt

Chapter 1. Introduction

1.1 Research background

As the result of rising fossil fuels consumption and carbon dioxide emissions, climate change has become one of the most urgent environmental problems for all human being worldwide since the beginning of 21st century. A report published by the Intergovernmental Panel on Climate Change indicated the global surface temperature would increase a further 0.3°C to 1.7°C in the lowest scenario and 2.6°C to 4.8°C in the highest scenario in prediction [1]. This issue also causes great impacts on buildings. The global warming will increase the building internal temperature and this leads to increasing building energy demand particularly in the summer for internal heat release by air conditioning or ventilation system. On the other hand, the building heating demand during winter may decrease due to the climate change. No matter for the future design of new build buildings, or the improvement for the performance of existing building to adapt to the climate change, the development for energy management and retrofitting in building sector are very essential.

In order to solve the problem of global warming, the Climate Change Act aims to reduce 34% of UK carbon dioxide emissions by 2020 and cut down 80% CO_2 by 2050, against with the benchmark in 1990 [2]. Of the carbon dioxide emissions in the UK, 45% were from building sector, with 27% contributed by residential buildings and the rest (18%) was from non-domestic buildings [3]. Thus, to cut down the energy consumption in building sector is the key to reduce carbon dioxide emissions and mitigate the impact of climate change.

Buildings contribute the most energy consumption than any other consumers all over the world, and buildings produce a large amount of greenhouse gas emission as well. The exhaust gas emission of cars is more complicated than the greenhouse gas emissions from buildings and there are many standards and policies to restrict the emission of cars. However, as the biggest energy consumers around the world, the energy efficiency and the impact on energy, environment and economic of buildings have not been paid enough attention by specialists or public. The energy consumption in building sector accounts for approximately 40% of the total end use energy consumption in developed countries including the USA, the European countries [4] and the International Energy Agency (IEA) countries [5, 6]. For the global average level, the buildings consume about a quarter of the total final energy [7]. A report published in 2009 by the World Business Council for Sustainable Development presented that approximately 60% reduction of building energy consumption is achievable by 2050 [8].

Energy has become an important part of our life and plays an essential role in human advancement. It is not only for cutting down greenhouse gas emissions to solve environmental problems, i.e. global warming and climate change, but also satisfying energy demands by constructing sustainable buildings with much less energy consumptions. Improvement of energy efficiency does not just mean turn off the lights or air conditioners. It is about how to utilise energy in a more effective way with less investment using novel energy systems and energy saving methods. And the improvements of energy utilisation efficiency could make a large majority of people live in a more comfortable environment. So sustainable buildings mean that the energy be used in the most effective ways to reduce energy consumption and greenhouse gas emission.

Energy consumed in domestic sector is defined as the energy uses in household for supplying lighting, appliances, space heating, domestic hot water and all other household demands [9]. In the United Kingdom, the energy consumed within the domestic sector accounts for 29% of the energy use and subsequent carbon dioxide emissions, which is higher than the energy used in industry (17%) or road transport (27%) in 2015 [10]. Compare to the energy consumption in other sectors, more energy is consumed in the domestic sector and it indicates a considerable opportunity to cut down the energy usage and restrict the carbon dioxide emissions. A study published by the World Business Council for Sustainable Development predicted that about 60% reduction of energy consumption in buildings is possible by 2050. The UK Government has also set a number of ambitious targets and taken some steps to achieve 80% reduction of energy consumption and carbon dioxide emissions by 2050 compare to the 1990 levels [11, 12]. This is not only to reduce the domestic energy demand, but also to eliminate those adverse impacts to our environment.

Low energy domestic properties are the dwellings that consume less energy than conventional households. Not only because of the energy crisis and increasing environmental problems, the legislation and enforcement of energy efficiency building transformation leading by the government contribute significant development in building sector [13, 14]. The movement towards energy efficiency buildings from traditional properties since the 1970s [15]. A number of terms or concepts have been defined by different organisations worldwide for sustainable buildings, with low energy consumption, comfortable indoor conditions and friendly impacts to the environment. A low-energy building is any type of dwelling that from design, technologies and building products uses less energy, from any source, than a traditional property. In some countries the term relates to a specific building standard [16]. These high-performance buildings include Green Building (also known as Green Construction or Sustainable Building), Zero Energy Building (also known as Zero Net Energy Building, Net Zero Energy Building or Net Zero Building), nearly Zero Energy Building, Zero Carbon Homes, PlusEnergy House and Passive House.

The Passive House standard is one of the most outstanding standards for energy efficient construction. The concept for "Passive House" was launched by Dr. Wolfgang Feist in Germany and Professor Bo Adamson in Sweden in May 1988. The concept was developed through eight research projects and the explanation was given by the two originators: *"Passive Houses" were defined as buildings which have an extremely small heating energy demand even in the Central European climate and therefore need no active heating. Such houses can be kept warm "passively", solely by using the existing internal heat sources and the solar energy entering through the windows as well as by the minimal heating of incoming fresh air* [17].

The first Passive House dwelling was built in Darmstadt-Kranichstein, Germany, in 1990. The house has extremely good performance and was occupied by residents since 1991. Focus on the dwelling itself, mechanical ventilation heat recovery, thermal insulation, prevention of thermal bridges, airtightness and high quality glazing were the keys to minimise the Passive House's total energy demand [18]. In general, the building consumed less than 10% of the energy for heating compared to the German new-built building code at that time [19]. The Darmstadt Passive House still functions well as designed after more than twenty years since built: the annual energy consumption of space heating demand was under 15 kWh/m^2 yearly. Passive House required very low energy to achieve a comfortable indoor environment all the year round. Compared to a conventional household, an equivalent Passive House design could save up to 90% energy. 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.

Passive House is a well-recognized method to achieve low energy building with great indoor air quality, and it was first developed and spread in Europe through a number of project as it adapts the European climate very well. Passive House reduces building energy consumption significantly by its superb building fabrics and HVAC optimization. The cores of Passive House design include the four aspects as follows:

- Fabulous insulation with rarely thermal bridges;
- Outstanding airtightness level;
- Passive solar gains and internal heat gains;
- Excellent indoor environmental condition.

Passive House (or Passivhaus) buildings provide a high level of occupant comfort while using very little energy for heating or cooling. They are built with meticulous attention to detailed and rigorous design and construction according to principles. Passive House buildings achieve 75% reduction in space heating requirements, compared to standard practice for UK new build buildings. The Passive House standard therefore gives a robust method to help the industry achieve the 80% carbon reductions that are set as a legislative target for the UK Government. Passive House also applies to retrofit projects, achieving similar savings in space heating requirements. Evidence and feedback to date show that Passive House is performing to standard, which is crucial, given that the discrepancy between design aspiration and as-built performance for many new buildings in the UK can be as much as 50-100%.

The demand of building refurbishment and retrofitting is increasing because of the large number of existing unsuitable buildings on the market. Active methods, passive methods and integrated methods are the three main ways to enhance building performance according to previous research and studies. Active methods mean the implementation of approaches to reduce energy consumption by improving the energy efficiency of mechanical ventilation system, gas boiler, lighting system, onsite renewable energy system and other relative equipment within the building. Passive methods, in the opposite direction, are defined as the methods to minimise energy consumption using state-of -art building design and advanced construction materials including high standard triple glazing, fabrics and insulation, orientation selection, passive heating, passive lighting and passive cooling. Lastly, the integrated methods combine both active methods and passive methods to cut down energy consumption. Implement of both methods provides the possibility to save more energy as the building performance is doubling enhanced.

1.2 Outline of this thesis

Chapter 1 contains a brief background of this study, and its contributions to existing research. In Chapter 2, a literature review on relative research fields is presented, including domestic energy demand, conventional domestic properties, low energy domestic properties and improvement of building performance. Chapter 3 explains the methodologies used in the work in order to achieve the aim of this research. These involve building audits, actual data monitoring and collection, computational modelling and simulation, model validation and further application of the validated model. In Chapter 4, a Conventional House was selected as a case study dwelling. The target Conventional House was introduced, and the audit results are demonstrated in Section 4.1. Based on the actual monitored data presented in Section 4.2, the house performance was analysed in Section 4.3. A DesignBuilder model was set up and validated in Section 4.4 and relative retrofitting measures aim to improve house performance were predicted by the software, shown in Section 4.5. In Chapter 5, a Passive House was chosen as the target of second case study. The general information of the dwelling, actual energy and indoor environmental condition data monitoring procedure, house performance analysis and house model simulation and validation were presented in the first four section in this chapter. In Section 5.4 and 5.5, summer overheating problem of this Passive House was discovered and possible solution was recommended through the optimisation of the Passive House DesignBuilder model. Building performance between the Conventional House and Passive House was compared in Chapter 6. Both comparison of energy and indoor environmental condition show how excellent the Passive House is. The most important finding in this section is: the building performance of the Conventional House can be improved significantly to achieve better indoor environmental condition with relative low energy consumption using passive energy retrofitting methods. Chapter 7 draws conclusions of this research and makes recommendations for future work.

1.3 Contributions of this research

The regulations and policies for the building energy consumption and indoor environmental condition have become more and more comprehensive and rigorous. In the past years, a large number of studies and research were carried out to focus on energy conservation in building sector and adjusting to the revisions of building regulations. The majority concentrations on previous research are energy performance for commercial buildings and new build residential buildings. These studies mainly focus on the enhancement of one single area, for instance, building design, construction materials, building fabrics, insulation, lighting system, energy efficiency of mechanical ventilation or heating system, renewable energy application, thermal comfort and resource management.

The aim of this research is to investigate the energy demand and indoor environmental condition of different types of UK residential buildings and find out the optimised solutions for Conventional House retrofitting, overcome the summer overheating problem for Passive House, and then improve the building performance through case studies.

This study not only focus on new build high performance residential building, but also existing old household, and it intends to fill the gap of the shortage of current building standards for existing building retrofitting. According to the Government's statistic data from Housing Stock Report 2008, 95% of English housing stock was 'traditionally built' using masonry or timber as the main structural component. Nearly 65% of all the dwellings were traditional masonry cavity construction where all of the external walls are load bearing. The next most common type was solid masonry (27%) where the external loadbearing walls are made of brick, block, stone or flint with no cavity. However, these are a group of 'problem' dwellings with respect to energy efficiency and offer very poor thermal performance unless additional insulation is added. Thus, the retrofitting of traditional Conventional House is necessary to meet the energy saving and reduction of carbon dioxide set by the Government.

A third of dwellings in England are acknowledged to be 'non-decent' – unhealthy, in disrepair, in need of modernisation or providing insufficient thermal comfort, with 80% of these failing the comfort criterion. Current policy on decent homes sets a basic standard and a timetable for implementation. Homes should be free from serious disrepair, structurally stable, free from damp, have adequate light, heat and ventilation. Around 88% of energy consumption was consumed by traditional Conventional House in the UK Housing and this represents a huge opportunity to reduce the energy consumption in the domestic sector.

In addition, another purpose of this study is to fill the gap of the shortage of feasible solutions for current summer overheating problem happens in these super-insulated dwellings. The contributions of this research are summarised as follows:

- A detailed investigation of the energy consumption and indoor environmental condition of a Conventional House and a Passive House in a heating dominated country was conducted;
- Actual data of energy consumption and indoor environmental condition of the two target houses over 12-month period were monitored and collected, and these became the benchmarks of the computational models validation;
- A finding of the importance of advance building fabrics and insulation, and high energy efficiency heating system in energy conservation of Conventional House during traditional winter heating season;
- An optimisation on solutions of the summer overheating problem for the Passive House was conducted and two main methods were recommended to reduce both heating energy consumption and summer discomfort hours based on the simulation results;
- The impact of utilisation of solar PV technology in reducing net primary energy demand of the Passive House has been discussed;
- A novel methodology for building retrofitting based on two-way computational model validation has been developed. The prediction of future building performance after retrofitting such as energy consumption, indoor environmental condition, overheating risks and carbon emissions can be achieved.

Chapter 2. Literature review

2.1 Introduction

As the recent domestic energy demand and related environmental issues are rising, the advantages of sustainable buildings for energy efficiency, human and environment have been widely recognised. This chapter presents the domestic energy demand features, different types of residential properties and their corresponding performance and building retrofitting strategies. Electricity and heat demand in the UK are reviewed and characteristics of conventional domestic properties and low energy domestic properties, e.g. Passive House are reported. Also, the retrofitting strategies and methodologies for energy efficiency residential buildings are presented.

2.2 Domestic energy demand features

The global final energy consumption in 1973 was approximately 54335 TWh. As of 2014, the world consumption of energy was approaching 110000 TWh [5]. This twofold increase of the total energy demand in three decades is the results of the increase of world population and economy. Although the annual growth rate of the total energy demand worldwide dropped down from 2.8% to 1.3% in recent 5 years, it is still predicted to rise in the next coming decades [20]. The energy consumption for building sector represents those energy consumed in places where people spend most of time for live and work and buildings affect our life style and quality deeply. In 2009, buildings account for an unexpected high 40% of total energy consumption and the resulting carbon dioxide emissions in the world, significantly higher than those energy consumed for industry, transportation and other public services [8]. Energy consumed in buildings is a major component of global energy consumption and it plays an important role in achieving sustainability because the application of renewable energy to buildings contributes to the replacement of fossil fuels and reduction of pollutions [21].

Compare to transport, industry and service sector, the domestic sector is the most sensitive to the variation of weather and temperature among the four sectors in the UK. Moreover, the energy consumed in space heating and hot water in domestic sector are mainly provided by gas and it constitutes 80% of the total final energy consumption [22]. Besides temperature factors, the energy consumption of domestic sector is also affected by many other factors as follows: number of residents, expectation of energy bills, building fabrics and insulation condition, boiler efficiency and the usage of electrical appliances. The domestic energy consumption is very complicated as it is decided by a number of unpredictable factors. Understanding the characteristics of domestic energy demand is the key to reduce the consumption and corresponding carbon emissions.

Figure 2.1 represents the final domestic energy consumption trend by fuel type compared to mean air temperature since 1970 to 2016. In general, the total energy consumption fluctuated year after year since 1970. Compared to 1970, the data collection starting year, the overall energy consumption of 2016 increased approximately 12%. The energy consumption during a short period was affected by mean air temperature obviously. For instance, the peak values of energy consumption appeared in 1979, 1986, 1996 and 2010 and their corresponding annual mean air temperatures were all lower than adjacent years. On the contrary, the final energy consumption decreased along with the growth of mean air temperature, e.g. 1976, 1984, 1995 and 2011. This figure also shows the change of fuel type utilisation during the 36 years. In 1970, about half of final energy consumption was provided by solid fuels. But as of 2016, the solid fuels only accounted for 1% of the final energy consumption as the results of continuous falling coal production and the large scale extraction of North Sea natural gas since 1980s. During these decades, the proportion of electricity consumption remained relative stable at around 20% of the total domestic energy consumption, but it still increased from 18% to 22%. However, the gas consumption rose from 24% to 66%, and it becomes the biggest energy supplier particularly from 1980 onwards.

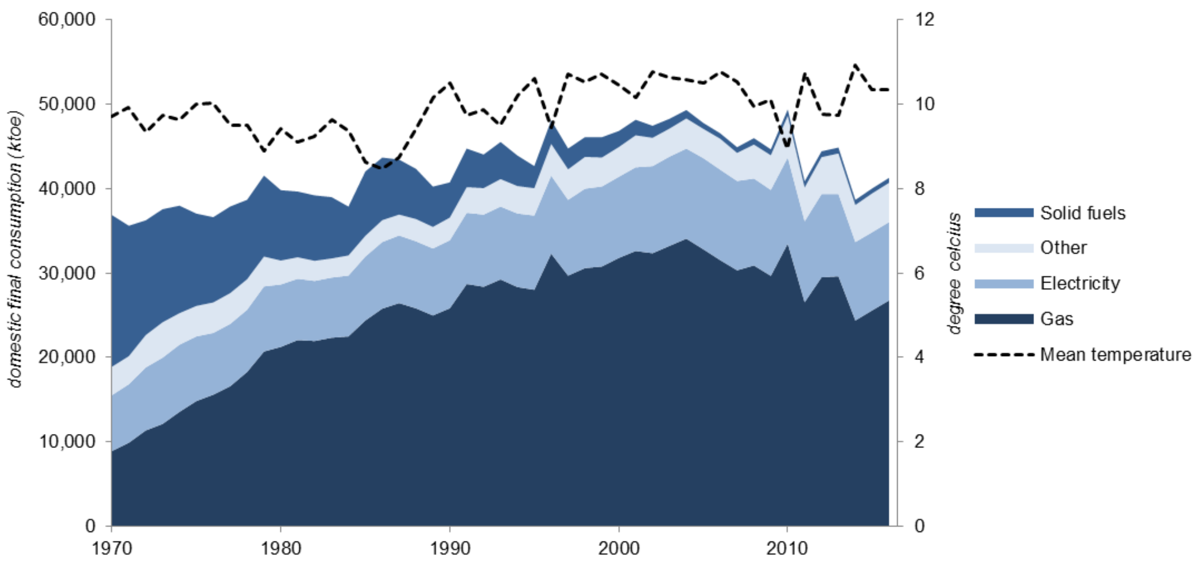


Figure 2.1 Final domestic energy consumption by fuel compared to mean air temperature (Source: Energy Consumption in the UK (ECUK) 2017, Table 3.01).

Energy consumed in domestic sector is defined as the energy uses in household for supplying lighting, appliances, space heating, domestic hot water and all other household demands [9]. In the United Kingdom, the energy consumed within the domestic sector accounts for 29% of the energy use and subsequent carbon dioxide emissions, which is higher than the energy used in industry (17%) or road transport (27%) in 2015 [10]. Compare to the energy consumption in other sectors, more energy is consumed in the domestic sector and it indicates a considerable opportunity to cut down the energy usage and restrict the carbon dioxide emissions. A study published by the World Business Council for Sustainable Development predicted that about 60% reduction of energy consumption in buildings is possible by 2050. The UK Government has also set a number of ambitious targets and taken some steps to achieve 80% reduction of energy consumption and carbon dioxide emissions by 2050 compare to the 1990 levels [11, 12]. This is not only to reduce the domestic energy demand, but also to eliminate those adverse impacts to our environment.

2.2.1 *Electricity demand*

Domestic electricity consumption is mainly decided by two factors: the number and type of electrical appliances per household; and the use of electrical appliances by the residents within a property [23]. Even in the houses with similar structure, different number and type of electrical appliances in use leads to different electricity consumption in each household. In addition, the impacts of residents cannot be omitted because the electrical appliances they prefer and the way they use results in a wide range of different electricity consumption. Although the electricity consumption in domestic sector is not easy to predict due to the factors listed above, a fully understanding of domestic electricity demand is very essential for the improvement of house energy efficiency measures and the utilisation of onsite electricity generation system [24].

The key electrical appliances are classified to six categories according to their purposes in [22]: lighting appliances; cold appliances; wet appliances; cooking appliances; home computing and consumer electronics. Lighting appliances, including standard, halogen and energy saving light bulbs, fluorescent strip lighting and light emitting diodes (LEDs). Cold appliances, such as refrigerators, fridge-freezers, chest freezers and upright freezers, are very popular and essential for domestic food storage. Wet appliances, involving dishwashers, washer-dryers, washing machines and tumble dryers. Cooking appliances, such as microwaves, electric hobs, electric ovens and kettles, are necessary for household cooking.

Home computing, including laptops, monitors desktop computers, printers, copiers and multifunction devices. Consumer electronics, such as televisions, DVDs, set-top boxes, games consoles and power supply units, are still consuming electricity even they are not in use but in standby mode [25]. Look back to 2005, the annual domestic electricity consumption rose to a peak of 10809 ktoe and began to decrease afterwards, even though the average number of electrical appliances per household keeps increasing since 1970. The average number of electrical appliances per household is shown in Table 2.1.

	Lighting appliances	Cold appliances	Wet appliances	Cooking appliances	Home computing	Consumer electronics
1970	16	1	1	1	0	2
1980	20	1	1	2	0	2
1990	22	1	1	2	1	4
2000	24	1	2	3	1	8
2010	26	2	2	3	3	13
2015	27	2	2	3	3	13
2016	27	2	2	3	3	13

Table 2.1 Average number of electrical appliances per household in the UK (Source: Energy Consumption in the UK 2017, Table 3.12).

Similarly, Firth et al. defined all the electrical appliances into four categories according to their pattern of use: continuous appliances; cold appliances; standby appliances and active appliances [23]. Continuous appliances, for instance, broadband modems, clocks and alarms, are continuously switched on and with constant power consumption. Cold appliances, are also continuously switched on but their power consumption are not constant and between zero and a set power level under the thermostatic control. Standby appliances have three fundamental modes of operation: switched on; on standby and switched off. When they are not in use, the electricity consumption may be non-zero if on standby mode. Home computing and consumer electronics mentioned in [22] are belong to standby appliances. Active appliances can be only switched on or off as they have no standby mode. When they are not in use, their electricity consumption must be zero. Lighting appliances, wet appliances and cooking appliances can be classified to this type of electrical appliances. The typical four appliance categories and their corresponding appliance power consumption are summarised in Table 2.2.

Appliance category defined in [23]	Appliance category defined in [22]	Example appliance	Typical in use power (W)	Typical standby power (W)
Continuous appliances	-	Broadband modems	4	-
		Clocks	2.5	-
		Alarms	5	-
Cold appliances	Cold appliances	Fridges/freezers/fridge freezers	80-250	8.8
Standby appliances	Home computing	Desktop computer	100	7.1
	Consumer electronics	Televisions-CRT	84	3.5
		Televisions-LCD	130	2.0
		Televisions-plasma	253	2.7
		Set top boxes	17	8.0
		Audio HiFi	14	8.2
		Mobile phone chargers	4	2.8
Active appliances	Lighting appliances	Lighting-CFL	9-13	-
		Lighting-incandescent	60-100	-
	Wet appliances	Washing machine	2000	-
	Cooking appliances	Kettles	2000-3000	-
		Electric hobs	2500	-
	-	Electric showers	4000-9000	-

Table 2.2 Typical electric appliances in use in UK domestic buildings [26-30].

It can be seen from the table above those continuous appliances and cold appliances are non-occupancy related appliances. They are always switched on and consume power no matter how the residents occupy the property. In addition, standby appliances and active appliances are occupancy related appliances as their working status is controlled by the residents in the properties. The occupancy related appliances can be switched on even if there is only one occupant in the household.

The use of electrical appliances in a dwelling is definitely related to the number of residents who actively occupies the property. It represents the status and behaviour of residents' daily lives when they are at home and awake [31]. Detailed electric appliances in use information within households help us understand the characteristics of domestic electricity demand better and deeply. Moreover, this is the basis to set up electricity consumption models that reflect actual domestic electricity demand and make accurate prediction for the future. In a study conducted by Richardson et al. previously, a developed method was used to generate active occupancy data for numerous residential properties. The one-day occupancy activities in thousands of households were recorded at 10-min interval and the detailed data was presented in the United Kingdom 2000 Time Use Survey (TUS) [32]. The report describes the detailed information for each participate household including location of dwelling, number of residents and typical activities in weekday and weekend. The active occupancy represented in the electricity consumption model supplies a proper electricity demand profile for domestic dwelling, for instance, low consumption during night time and growing demand since early morning. The conspectus of UK domestic electricity consumption can be drawn by the TUS data. However, this method is not able to predict the particular utilisation trend of all electric appliances as the data set does not reach the standard of high-resolution.

The importance of utilising high-resolution data in investigating the patterns of domestic electricity demand was discovered in [33]. The most common monitoring time resolution to measure energy consumption within a building for electricity, heating and even cooling demand is one-hour interval. The advantage is the data recorded by one-hour interval is easy to gather. It is feasible to present the general view of building energy consumption without the needs of high standard monitoring instruments. In large scale commercial buildings, including offices, hotels, shopping centres and museums [34], heating, ventilation and air conditioning (HVAC) system becomes the biggest energy consumer [35-37]. Moreover, in both Southern Mediterranean and North Coastal Europe countries, the energy consumption of HVAC system in office buildings accounts for more than 90% of total building end-use energy consumption, and the rest are mainly lighting energy consumption [38]. The energy use for non-residential buildings is relative regular compared to domestic buildings that with at least four different types of electric appliances. The hourly resolution for electricity consumption is acceptable for commercial buildings. But for domestic dwellings, the electricity load and fluctuation cannot be captured precisely by low-resolution measured data of one hour, 30-minute and even 10-minute as some appliances are only used for a few minutes or seconds.

To receive high-resolution electricity consumption data, sensors, data loggers and even smart meters are installed in domestic properties and this has become a trend to understand the features of electricity demand worldwide [39, 33, 23, 40-43]. All the sensors measurement intervals in these investigations are not under 1-minute because the researchers believe most electricity loads and performance can be covered within the high-resolution monitoring work. In addition, higher resolution sensors also require more cost investment to purchase the measurement instrument. The advantage of sensors utilisation to measure energy consumption within the domestic dwellings is to make the complicated household electricity flow clearer and present more detailed using pattern of appliances. However, the sensor installations are determined by the residents as they may feel uncomfortable as their daily life would be recorded by others. In the future, application of smart meters is the trend to record domestic household energy consumption because they are not only to work as traditional energy meters to display realistic energy consumption but also measure very detailed energy usage and store the data in their own systems. This is very meaningful to understand current energy usage and predict future energy demand in worldwide.

Figure 2.2 to Figure 2.5 show the actual domestic electricity consumption monitoring studies conducted previously. The data were measured by hourly, half-hourly, 5-minute and 1-minute time resolutions, respectively. From these figures, it is clearly that with high-resolution data measurement, the detailed appliances working time can be distinguished in the electricity file. The impacts of each electric appliance to the total electricity consumption didn't reflect from the low-resolution monitoring data.

Household electricity consumption recorded by different time-resolution in a typical day was compared in Figure 2.6 and Figure 2.7. The measured time-resolution in Figure 2.6 was 1-hour, 10-minute and 1-minute while those time-resolutions in Figure 2.7 were 1-minute, 30-second and 5-second, respectively. From these two figures, we know that a large number of electricity peak loads were missing if the data was measured by relative lower time resolution. This is very obvious for the data comparison which was presented by 1-hour, 10-minute and 1-minute resolution in Figure 2.6. The hourly electricity data only represented the average electricity consumption during a comparatively longer specific period (e.g. within a day, a week or even a month). The exact behaviour and performance of the electric appliances, especially those short working time cooking appliances such as kettle, microwave, electric hob and coffee machine can be shown via the 1-minute high-resolution data.

1-minute resolution data is good enough to present detailed electricity consumption data. However, if exact electricity loads during a several hours period is required, the recorded time resolution can be improved to 30-second or 10-second. To use such high time resolution for measurement is equivalent to conduct a very detailed investigation to understand the exact performance of each electric appliance.

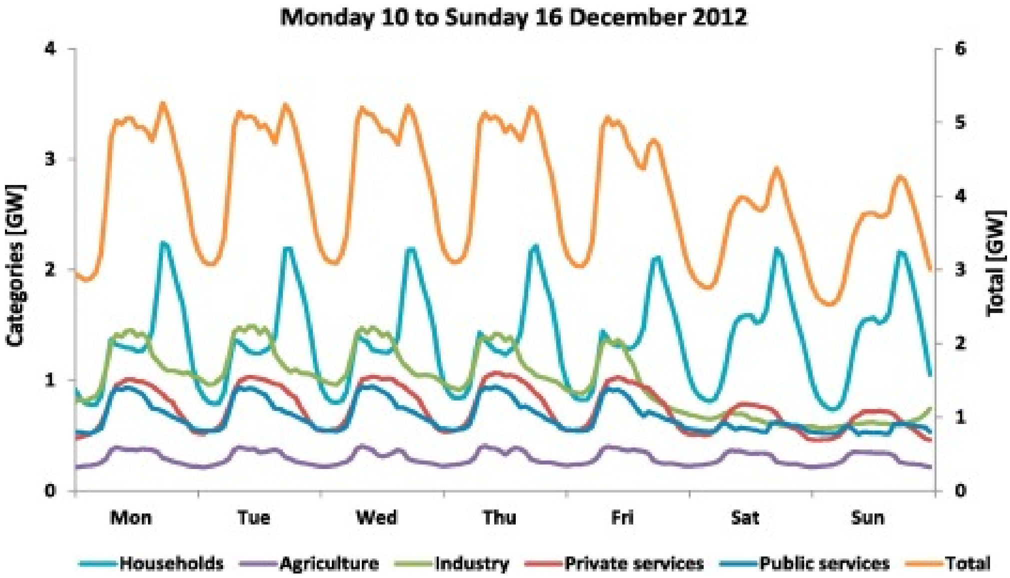


Figure 2.2 Hourly electricity consumption by customer category for a week in 2012 [44].

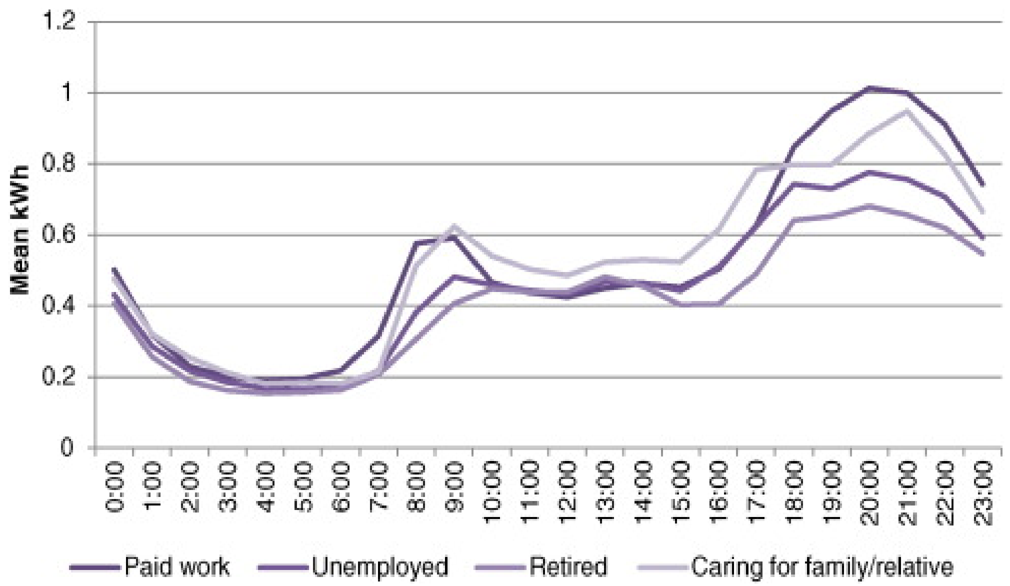


Figure 2.3 Mean half-hourly electricity consumption by different employment status residents in the households [45].

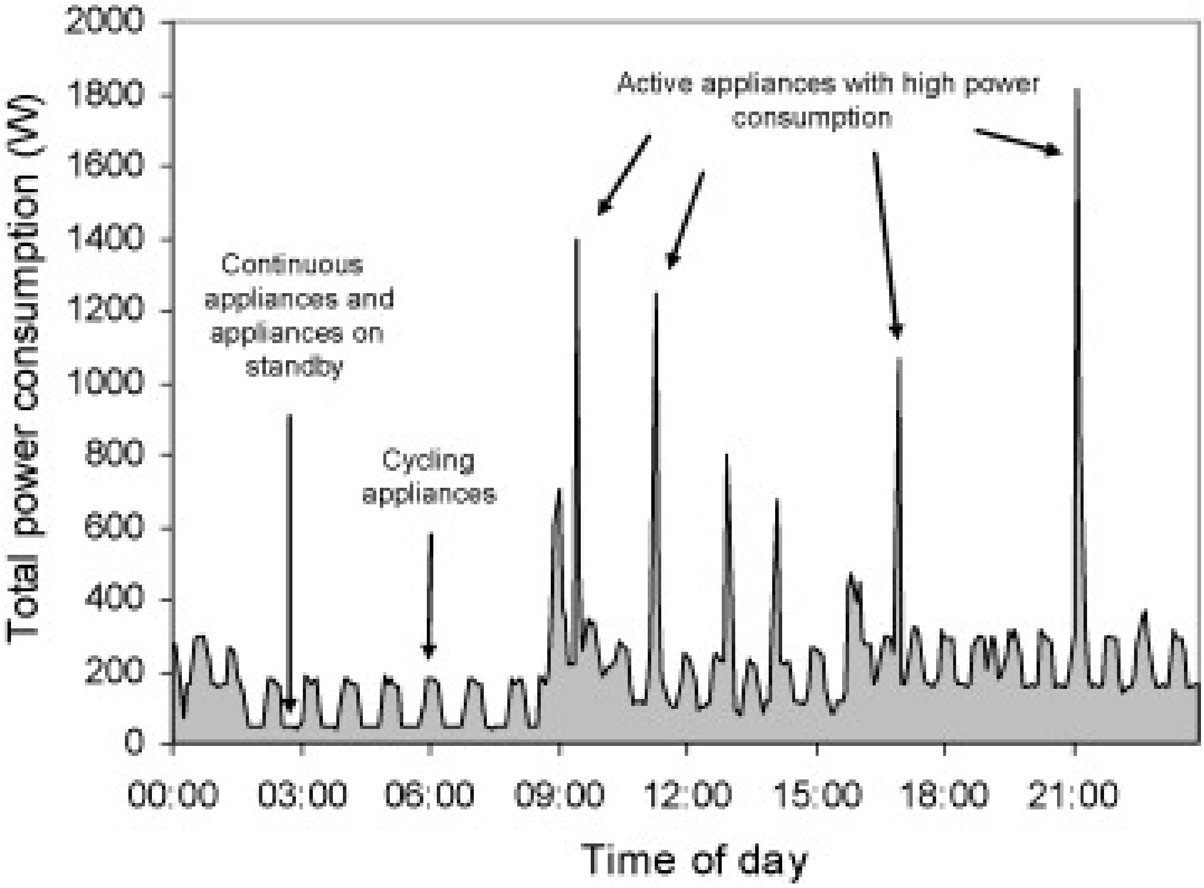


Figure 2.4 5-minute electricity consumption of a household recorded in a typical day [23].

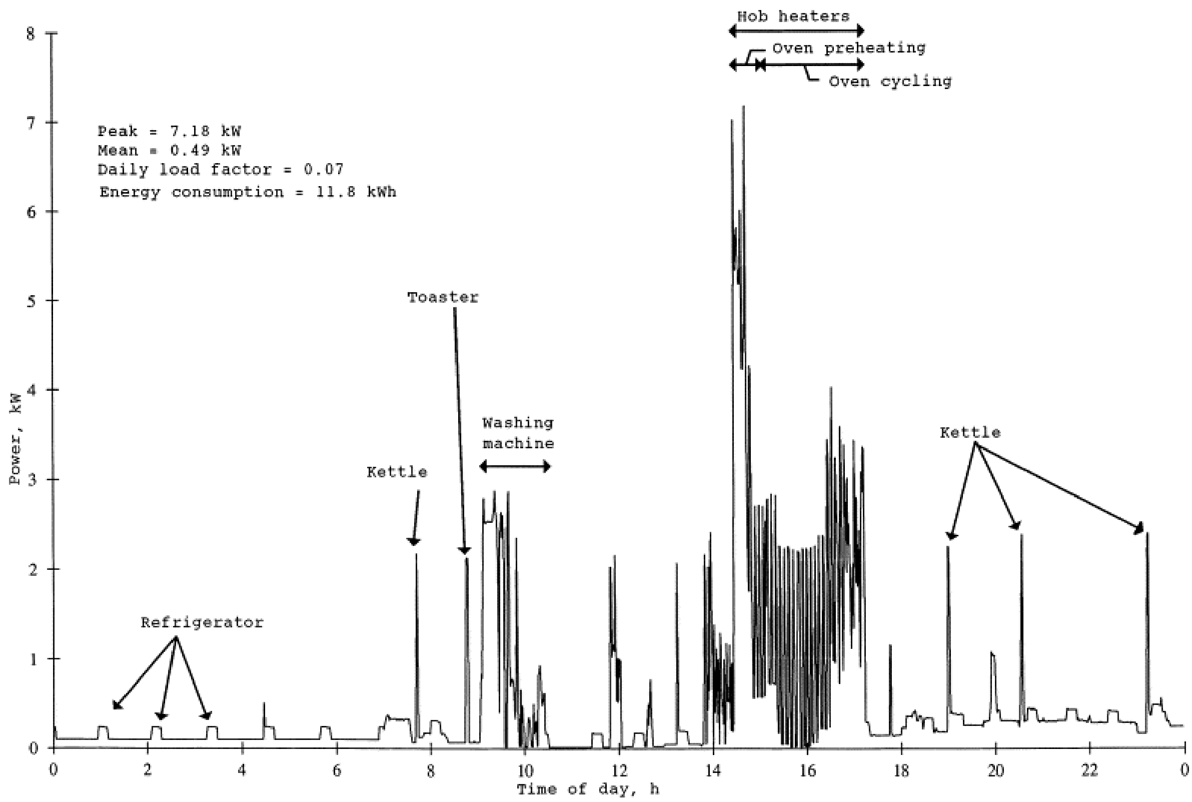


Figure 2.5 1-minute electricity consumption of a household recorded in a typical day [39].

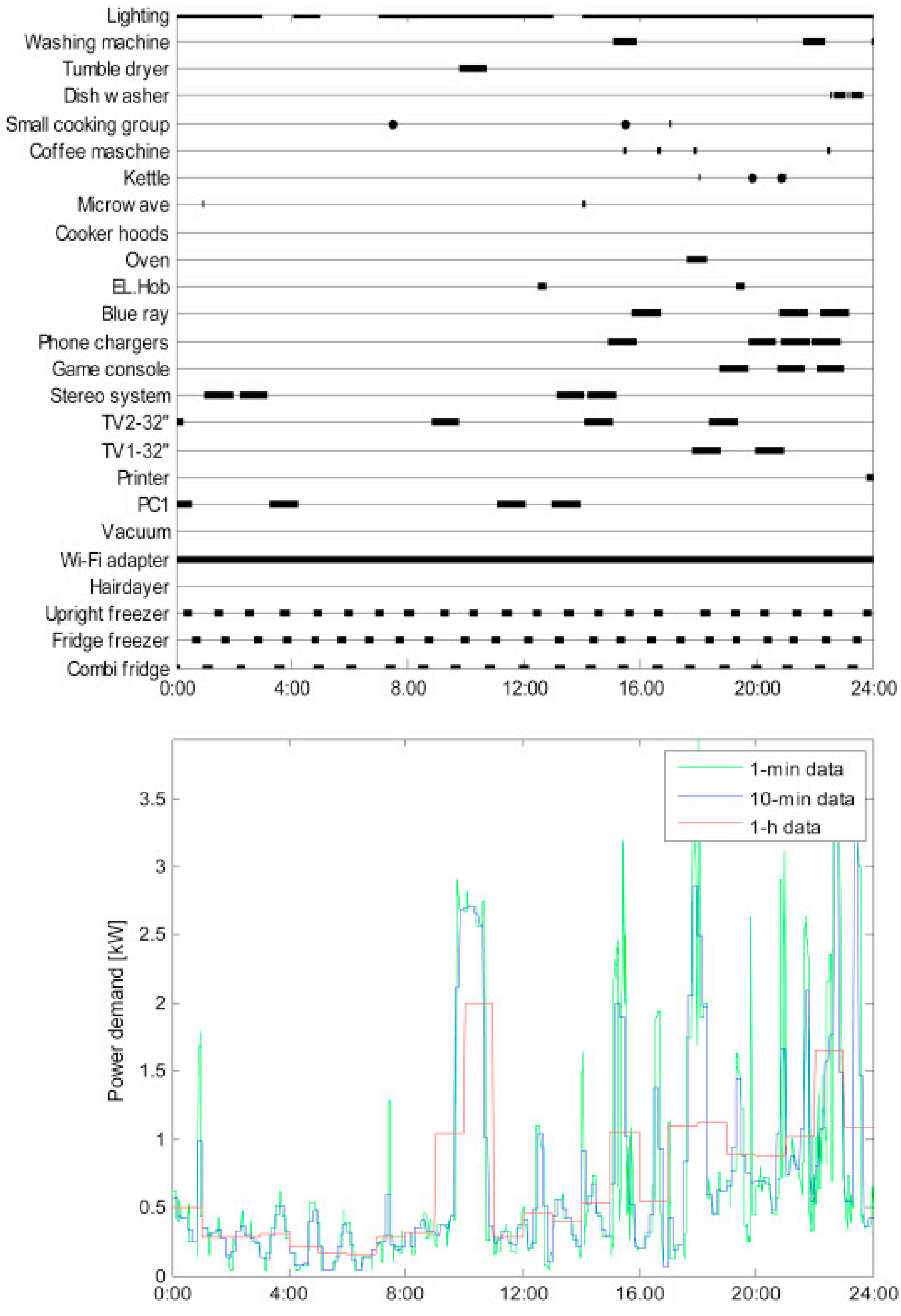


Figure 2.6 Household electricity consumption recorded by different time-resolution in a typical day [46].

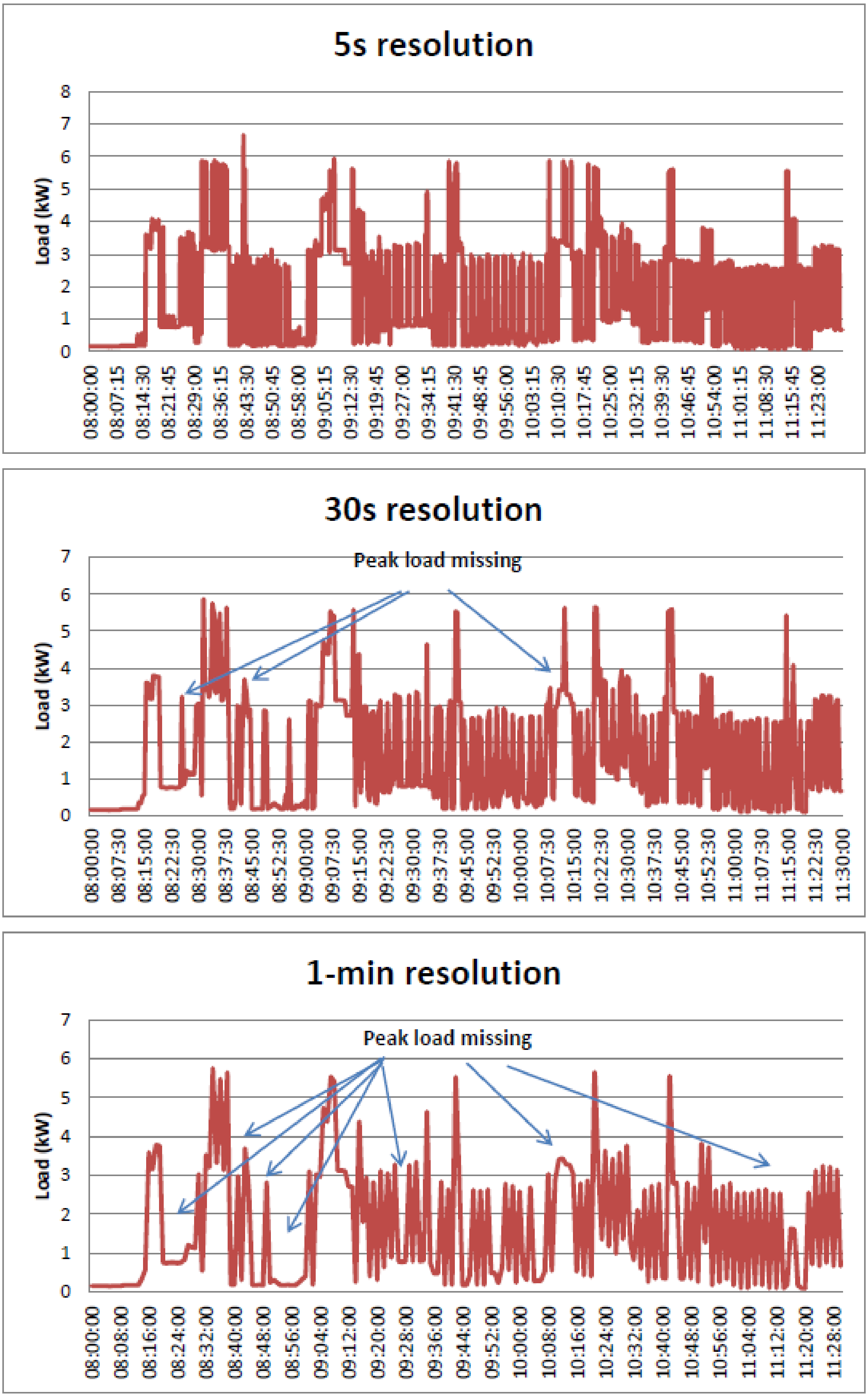


Figure 2.7 Domestic electricity consumption recorded by different time-resolution [47].

2.2.2 *Heating demand*

Heating energy is the biggest portion of the household energy consumption in the UK so far. Over the past 40 year, energy consumption for space heating in the UK has increased by about 33% [48]. Based on the data summarised from the Office for National Statistics in 2011, for England and Wales, about 75% of total household energy consumption were consumed as gas and the majority gas consumption was used to supply space heating [49]. Reducing household heating demand is the key and one of the most significant solutions to cut down both total energy consumption and carbon dioxide emissions in order to achieve the goals set by the UK government and related organisations.

The UK household space heating demand from 1970 to 2010 is shown in Figure 2.8. It can be seen from the figure that the space heating demand keeps increasing during this forty-year period. Approximately 65% household energy demand was used as space heating energy. In the past 15 years, heating energy increased slowly just over 10% and it was much lower than the 44% increase speed of number of UK households. Particularly, the household heating demand dropped down rapidly since 2009 and this indicates the advantages of implementation of house insulation and improvement of heating system's energy efficiency. These measures offset the effect of growing number of household and satisfy the requirement of achieving warmer homes.

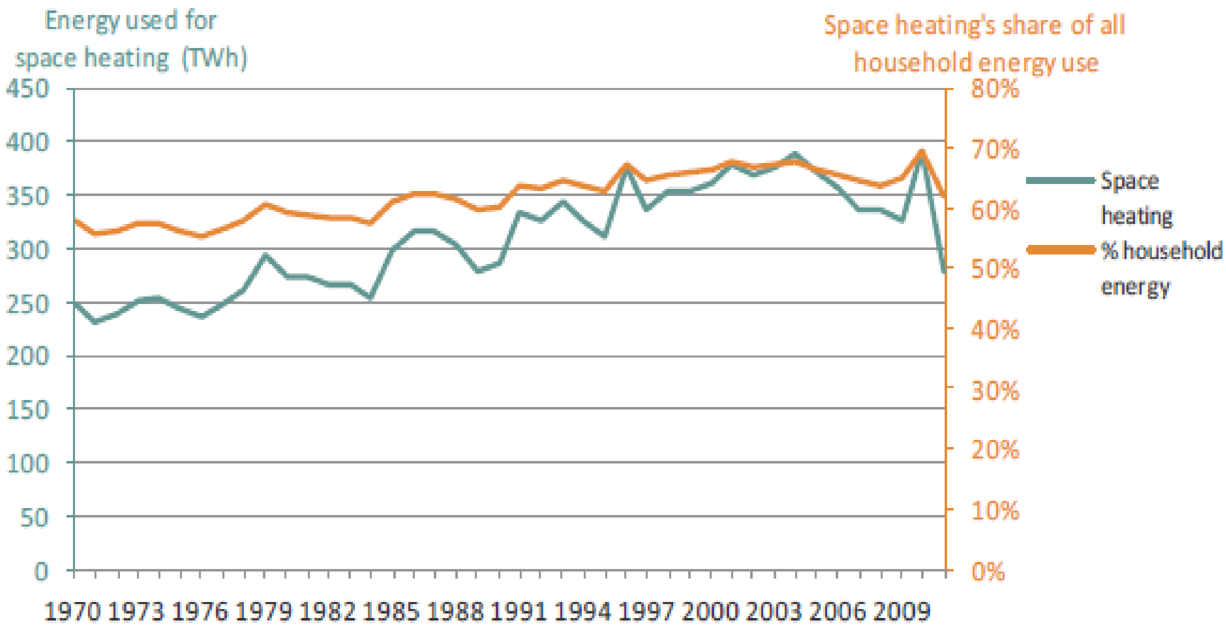


Figure 2.8 Household energy use for space heating [48].

Domestic heating demand is mainly decided by the house location, building fabrics, property size and energy efficiency of its heating system, e.g. boiler [50]. Differ from the electricity demand, daily occupancy of residents does not affect the domestic heating demand at all because the factors listed above are fixed for each dwelling. The Standard Assessment Procedure (SAP) is a method to calculate the household energy performance which was launched by UK Government. This rating system has been used for more than 20 years since 1993.

The SAP methodology used for the calculation is based on the BRE Domestic Energy Model (BREDEM) [51-55], which provides a framework for the calculating the energy consumption in dwellings. It is a government- controlled procedure to support related energy efficiency policies and initiatives. In 1994, SAP was cited in Part L of the Building Regulations for the 'Conservation of Fuel and Power' within new-built and existing residential buildings. The assessment is based on a number of following factors that contribute towards energy efficiency [56]:

- Materials used for construction of property
- Thermal insulation of the building fabric
- Air leakage ventilation characteristics of the property, and ventilation equipment
- Efficiency and control of the heating system
- Solar gains through openings of the property
- The fuel used to supply heating, ventilation and lighting
- Energy for providing cooling, if applicable
- Renewable energy technologies
- Household size

For each factor related to the individual occupying characteristics of the property, the rating is calculated independently, for instance, household size, efficiency of electric appliances and particular heating patterns and set-point temperature applied by the residents. These factors affect significantly to realistic domestic energy consumption [57].

The SAP ratings are within the range of 1 to 100, with A to G categories, seven levels (see Figure 2.9). The rating is calculated based on the energy cost spent per square meter and is linked with its post-construction running cost. It represents a forecast annual cost spent for space heating, domestic hot water and lighting of a residential property (£/m^2) [58]. Higher

SAP rating, such as an A-rated property, means it has better energy efficiency and lower running costs.

Rating	Band
1 to 20	G
21 to 38	F
39 to 54	E
55 to 68	D
69 to 80	C
81 to 91	B
92 or more	A

Figure 2.9 SAP rating bands.

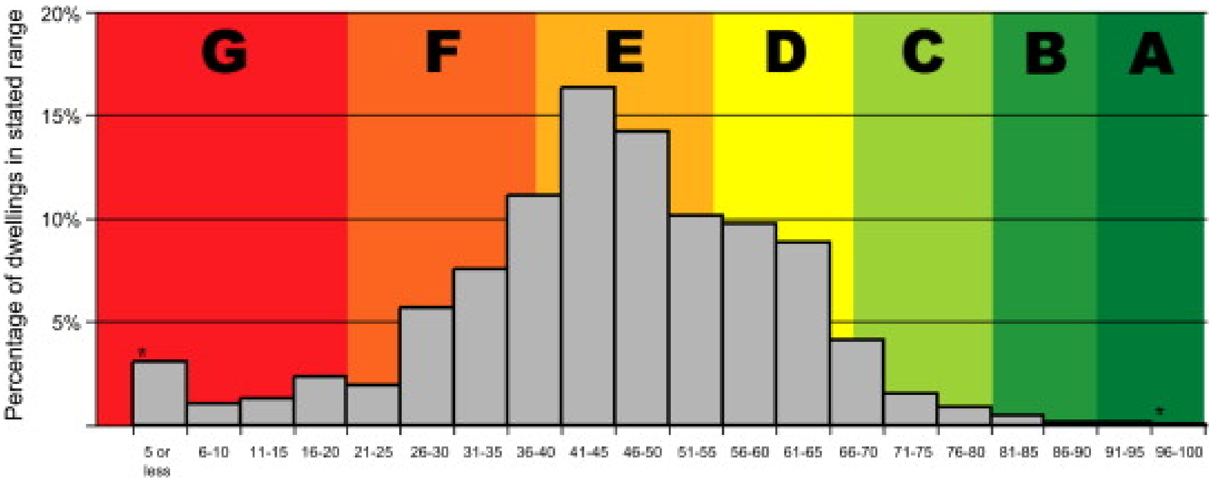


Figure 2.10 Distribution of UK SAP ratings in 1996 (Source: English House Condition Survey (EHCS) 1996).

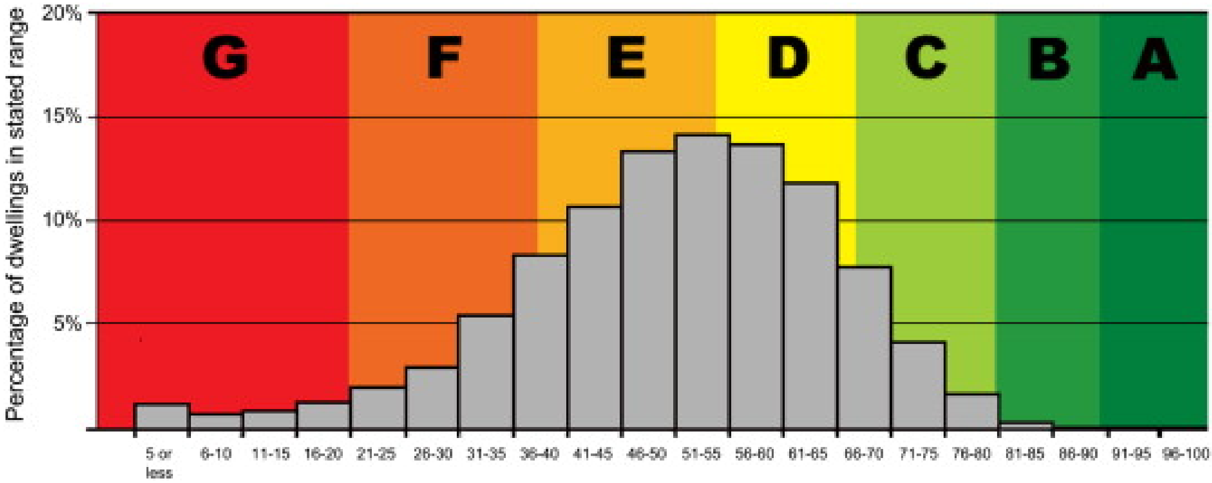


Figure 2.11 Distribution of UK SAP ratings in 2006 (Source: English House Condition Survey (EHCS) 2006).

There are very few A-rated residential dwellings in the UK and this represents the opportunity and need to improve the energy efficiency of national household. Most dwellings are E-rated properties and the average SAP rating in the country in 1996 was only 41 [59, 60]. As of 2016, the mean SAP rating increased to 47 over a 10 year period [61]. The performance and changing trend of the UK house stock from 1996 to 2006 was displayed in Figure 2.10 and Figure 2.11. It is clear that the overall energy performance of all national dwellings has been improved. The number of low performance properties (G-rated and F-rated) decreased but there was still little increase for high performance properties (A-rated and B-rated). The SAP rating in the UK has been mandatory for new build dwellings since 1995 and it has become compulsory for all dwellings on the market since 2007 [62]. In order to satisfy the energy consumption and CO_2 emissions reduction goals set by the government, especially for those existing old houses, specific considerations and strategies are needed to improve their energy performance to a relative acceptable level.

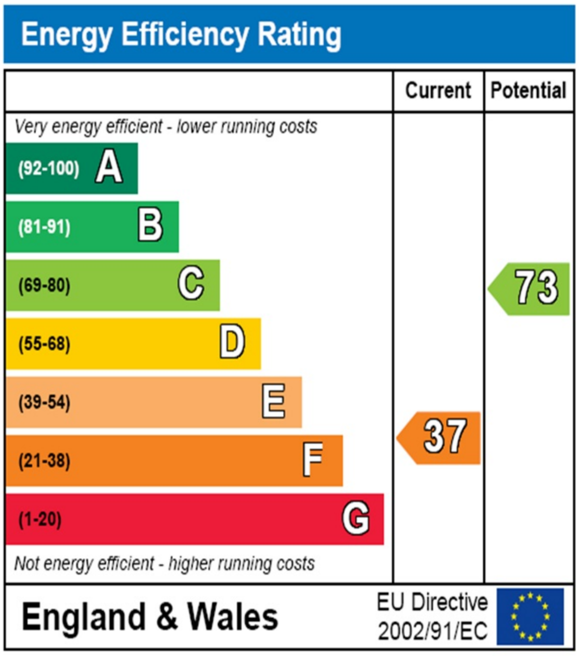


Figure 2.12 SAP rating for energy performance certificates (EPCs) in England and Wales.

In 2002, the Energy Performance of Buildings Directive (EPBD) was approved and its principle objective is to improve EU countries' building energy performance by cost effective methods [63]. Under such a circumstance, in the UK, Energy Performance Certificates (EPCs) were introduced as an important output of conducting building performance assessment, such as SAP rating. Figure 2.12 shows the layout of an EPC in England and Wales reflects the SAP rating.

The energy performance certificate is essential to restrict the energy consumption for existing or new build dwellings to meet the related building regulations and standards. There must be a valid energy performance certificate whenever the buildings are under construction, sales or rental stages. Loft insulation, external windows, boiler, and radiators etc. in the property will be examined by specific assessor and their performance would be recorded to generate the rating of energy efficiency. Moreover, EPC recommendations and potential improvement can be provided to enhance the energy performance of the dwelling and save future energy costs.

The Standard Assessment Procedure rating calculation is the method used to indicate the dwellings compliance well with the Building Regulations whereas the Energy Performance Certificate enables the residents in the properties to see how energy efficient the dwelling is. The EPC is very easy to understand from the rating figure and instructions while the SAP contains a lot of detailed figures and spreadsheets for calculations. These two are linked together as the EPC is calculated using the information contained within the SAP calculation.

Energy-efficiency boiler is one of the most important factors to determine the domestic heating demand. Since 2005, all new gas boilers installed in the dwellings within England and Wales must be high performance condensing boilers. Similar regulations were implemented in Scotland and Northern Ireland since 2007, unless some exceptional circumstances. Before 2005, condensing boilers were only account for 7% of the boilers in the UK. After six years' new regulation implementation, the percentage increased to 50% and led to a significant energy efficiency improvement.

Condensing boilers extract additional heat from the exhaust gases by condensing water vapour so recovering the latent heat of vaporisation, which would be wasted if unused. The typical increase of energy efficiency can be as much as 10-12%. The energy efficiency of modern condensing boilers reaches 90% as the result of laboratory tests, which is the highest energy efficiency for domestic central heating boiler category [64]. However, slightly lower energy efficiency of the boilers was demonstrated in practice but they still perform well in energy conservation [65]. The advantages and benefits for using condensing boilers have been investigated in the following research [66-73]. Significant energy consumption reduction is discovered by utilising high energy efficiency condensing boiler. The heating energy saving effect is also obvious if a traditional boiler is replaced by a condensing boiler in a retrofitted or refurbished building.

The household insulation is another important factor for reducing domestic heat demand. This includes but not limits in wall insulation, double glazing application, loft insulation and floor insulation. According to the Government report, it is known that the majority of the UK's residential buildings are not insulated well [74]. Most of the national existing dwellings will be used at least until 2050 [75-77], thus, to increase the energy efficiency of the domestic properties is very necessary to satisfy the UK carbon reduction targets set in the Climate Change Act 2008 [78].

In the UK, there are 9.2 million poor energy performance house having solid walls without wall insulation, no roof insulation, no gas central heating or those high rise buildings are defines as 'hard to treat' homes [79]. Within this number, 6.5 million are solid wall construction and due to technical and cost reasons, they have many difficulties to conduct those retrofitting actions [80]. There are two main methods to improve the performance of solid walls in general: retrofit insulation externally or retrofit insulation internally. In 2008, annual solid walls installations were predicted within the range of 25000 to 35000 [81]. Of these numbers, 60% were external insulation while 30-40% were internal insulation as estimated. Similar or even better thermal transmittances and performance can be achieve by utilising external insulation to those properties with solid walls compared to modern dwellings with cavity walls [82]. It also requires shorter construction duration than internal insulation and it can improve the dwellings' appearance if they have become deteriorated [83]. However, in terms of historic or heritage buildings, external insulation is not suitable for the retrofitting as it may change the appearance of the properties. Internal insulation retrofitting is implemented unavoidably under this circumstance [84].

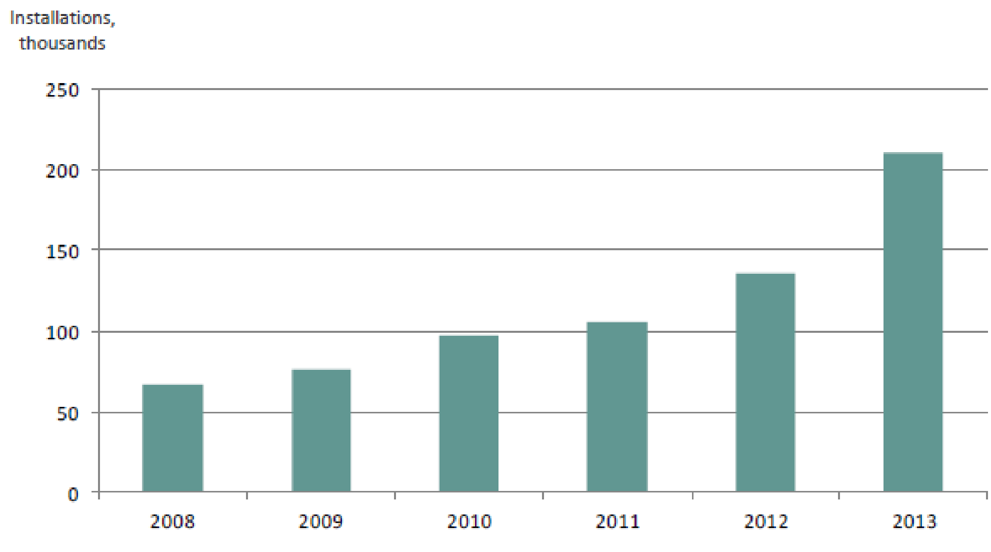


Figure 2.13 Solid wall insulation in the UK (Source: UK Housing Energy Fact File 2013).

By April 2013, the number of estimated solid wall insulations of UK household was about 211000 (see Figure 2.13). The installation rate of solid wall insulation has increased to around 75000 a year due to more insulation implement since 2012.

In the case studies conducted by Campbell et al. [84], the houses performance after retrofits show the advantage in receiving comfortable indoor temptation and relative humidity. The U-values for walls, glazing, roof and floor have been reduced greatly compared to their original status. Their post retrofit indoor temperature and relative humidity were within the CIBSE recommended guidance range [85]. But the lack of energy consumption information and original building performance of the two houses did not provide direct evidence that the insulation retrofitting work leads to enhanced building performance of the two target houses.

Over the last forty years, a significant growth in the number of household with double glazing was found. Since 1970 to 2011, the percentage of UK households with double glazing has increased 12-fold, from approximately 8% to 93% [48]. Double glazing windows refers to the excellent airtightness components, rather than simple windows with secondary glazing. They are designed to reduce heat loss and cut down the domestic heating demand. Over the last 10 year, research related to different double glazing windows has been investigated by a number of researchers [86], for instance, double glazing window with enclosed air layer [87-89] or inert gas layer [90-93], with thermal fluid layer using dynamic water [94, 95], with enclosed slats or blinds [96, 97], and those using phase change materials [98-100], etc. Due to the cost and performance factors, double glazing windows have been proved to be the best option for building energy conservation in most climates as the air or inert gas layer between the two glazing panels are superb thermal barriers. Many studies related to double glazing windows with air layer have been carried out [101-107]. It is known that heat loss from double glazing windows has been decreased by about 50% compared to single glazing windows [108].

2.3 Conventional domestic properties

The housing stock in the UK increases very slowly from then till now. As of 2013, there were 27.6 million dwellings in the nation and the 160000 new build households per year was more than the number of households were demolished annually [109]. The replacement of old homes in the UK is only approximately 1% per year due to the long lifetime of residential buildings [110]. A number of UK houses have very long history for more than 100 years as they were built during the Victorian era. As a result of this, many dwellings have very poor insulation and they consume much more energy but only maintain the properties at an unsatisfied comfort level. In order to meet the target of 80% carbon dioxide emissions reduction set by the Government, 70%-75% of the new build homes with energy efficiency improvements will be constructed by 2050 [111].

From the findings discussed in section 2.2.2, we know that two of the most necessary factors of space heating demand are insulation and energy efficiency of the heating system. And these two determinants are related to the age of a household closely. Older dwellings have relatively poorer insulation for the whole property and it would be more troublesome to retrofit to meet the current insulation standard if they have solid wall. Household heating system is easier to update compared to the building insulation. Its lifetime is shorter than the dwelling itself, and it can be changed due to low efficiency by different occupants live in the property at different stages. Because the low demolition rate for UK households, the numbers of existing dwellings, especially the houses build before 1976, stays almost the same.

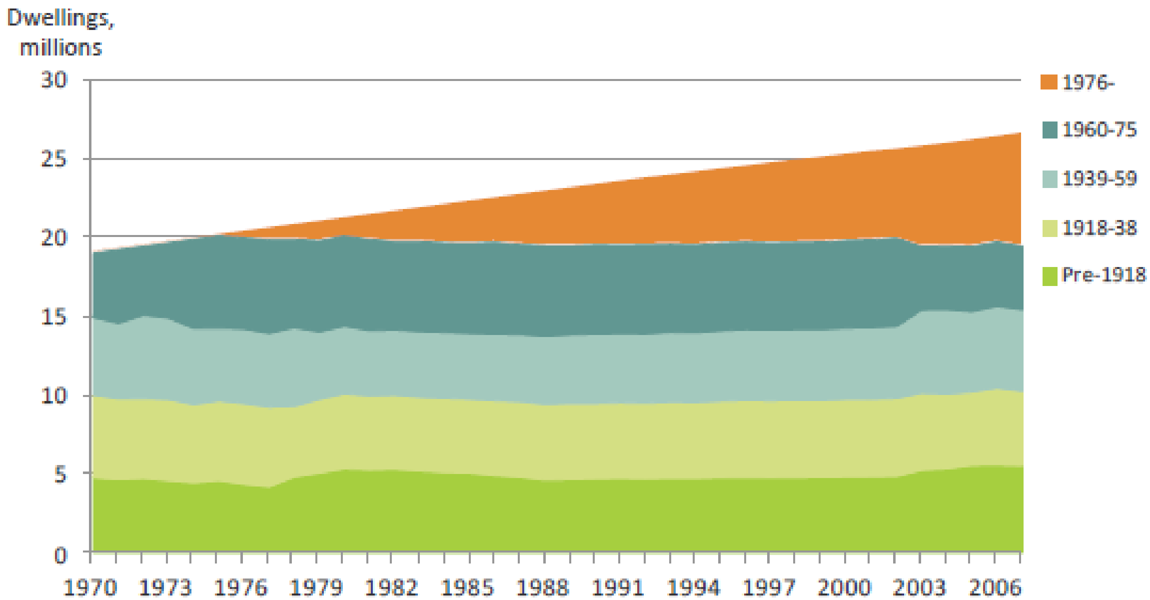


Figure 2.14 UK housing stock distribution by age to 2007 (Source: UK Housing Energy Fact File 2013).

Figure 2.14 shows the UK housing stock distribution by age to 2007. It can be seen from the figure that the number of households in 1970 were roughly divided by the four home age categories evenly (pre-war, inter-war, post-war and 1960s) [48]. The significant change of the UK housing stock in the age profile is the rising number of recent dwellings since 1976. The Building Regulations addressed energy conservation from 1965 and the limitations for the household energy consumption have been restricted in related version of the Regulations.

Thus, the new dwellings which were built after 1970s should be more energy efficiency than others built in the four age bands listed above.

Some regions of the UK experience very harsh weather in the winter. In addition, some parts of the country also have high rainfall and strong wind all the year round. For instance, North Ireland, Scotland and the North England are usually colder in winter than the South England with milder weather. Wales and West England are more humid because of the frequent rains while the East England is much drier compared to those parts. This leads to different heating requirements for the dwellings in different regions in the UK. The numbers of UK homes by regions are shown in Figure 2.15. The dwellings within England have been divided into nine regions and counting one each for Northern Ireland, Scotland and Wales, the total numbers of 12 regions' homes are presented. The total number of UK dwellings increased slightly since 1981.

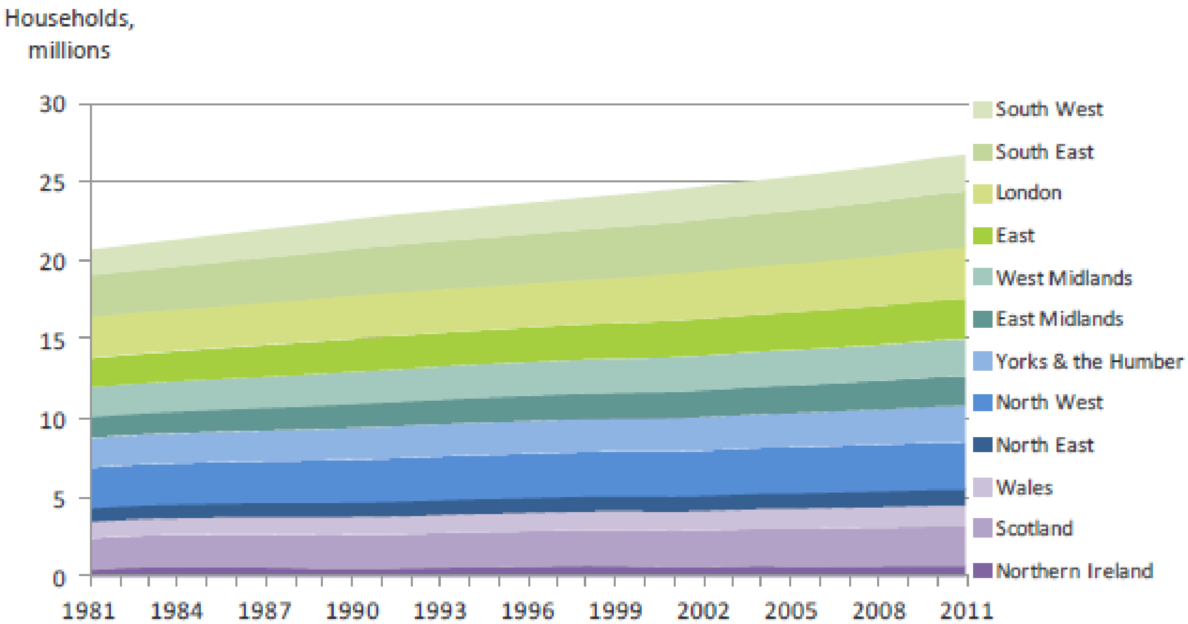


Figure 2.15 Number of UK homes by regions (Source: UK Housing Energy Fact File 2013).

Because of the different weather features in different regions, the household energy consumption in different regions varies from each other. This effects the space heating demand the most as colder regions require more heating during the winter. Figure 2.16 indicated the statistics data of average household energy consumption of nine regions in the England and one for Wales, in 2011 [49]. It doesn't contain the data for Scotland and Northern Ireland in this figure. In 2011, for the England and Wales dwellings, the average energy consumption was 16.1 MWh. Those regions in the North England including North

East, North West and Yorkshire and the Humber had very similar household energy usage level (16.9 MWh, 16.8 MWh and 17.0 MWh, respectively) and they consumed the most energy compared to other homes within England and Wales. The average household energy consumption of South West was only 13.4 MWh, which was the lowest one in the year.

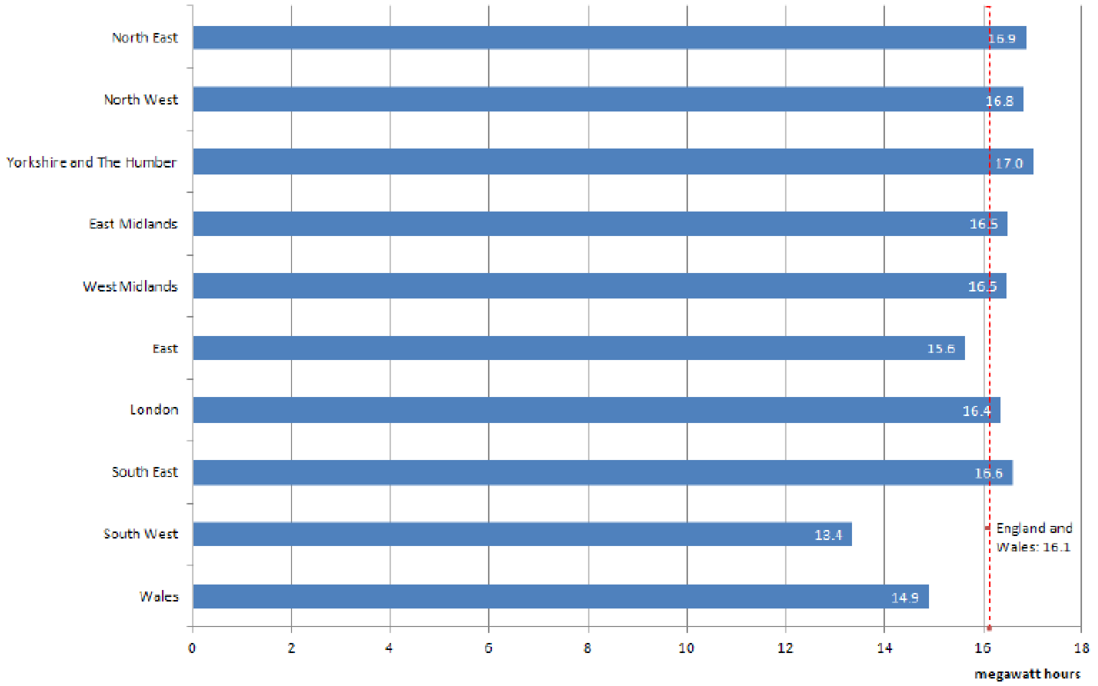


Figure 2.16 Average household energy consumption for England and Wales in 2011 (Source: Household Energy Consumption in England and Wales, 2005-11, Figure 1).

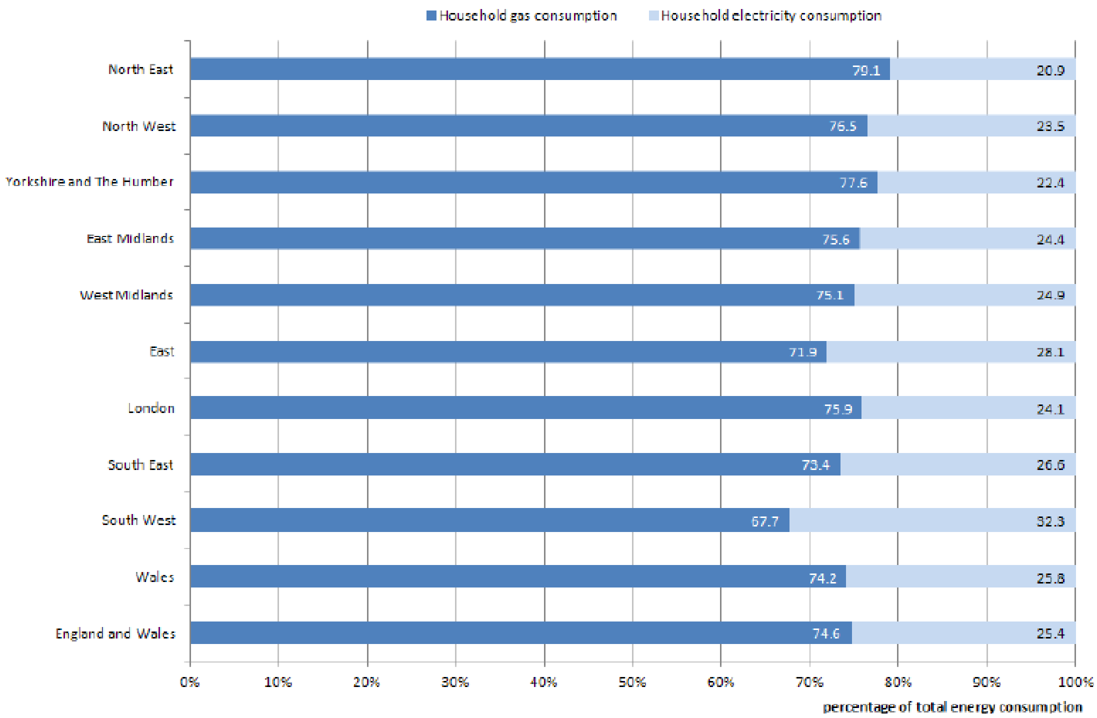


Figure 2.17 Average household energy consumption by type in 2011 (Source: Household Energy Consumption in England and Wales, 2005-11, Figure 4).

Figure 2.17 presents the average household energy consumption by type for nine regions in the England and one for Wales, in 2011 [49]. In this year, for the England and Wales housing, the proportion of total gas consumption and electricity consumption was 74.6% and 25.4%. Due to the cold weather in North England, homes in the North East consumed the most gas proportionally (79.1%). On the contrary, South West consumed the least gas not only because of the warmer weather, but also because of the dwellings in this region received less pipes gas and consumed less gas.

A number of publication focus on the improvement of UK conventional house performance aim to reduce the energy consumption and the environmental impacts from the properties [112-120, 12, 121]. Energy consumption and corresponding carbon dioxide emissions of a dwelling can be reduced through retrofitting. 66% of space heating demand can be saved by utilising superior property retrofitting technologies [48]. 40% of heat loss through the external walls can be reduced by applying cavity wall insulation [122]. 50-80% of heat loss can be prevented if to conduct the roof and external wall insulation retrofitting for the solid wall dwellings [83]. Despite the impacts of building fabric design, high performance condensing boiler [73], Mechanical Ventilation with Heat Recovery system [123], LED lightings [124] and low energy electric appliances [125] play important roles in saving energy of the domestic conventional properties. There are many approaches to mitigate the environmental impact by using low embodied energy materials (e.g. timber) [126, 127], and reducing the need for transportation by using local or regional construction materials [128].

2.4 Low energy domestic properties

Low energy domestic properties are the dwellings that consume less energy than conventional households from the views of design, technologies and building products. Not only because of the energy crisis and increasing environmental problems, the legislation and enforcement of energy efficiency building transformation leading by the government contribute significant development in building sector [13, 14].

The movement towards energy efficiency buildings from traditional properties since the 1970s [15]. There were a large amount of attempts to cut down the space heating demand of residential buildings began at that time. Some projects reached the goal of significant energy saving for heating demand and achieved “low energy house”, which enhanced the thermal mass of the building envelope, contained a mechanical ventilation system for high level indoor air quality, achieved low space heating demand between 50 to 70 kWh/(m^2a) successfully [129]. In the mid-1980s, the "low energy house" energy standard became a legal requirement for new buildings in some Northern Europe countries, e.g. Denmark and Sweden. Further improvements of "low energy house" principle were being considered at that time, for instance, airtightness and insulation materials of the building, a well-controlled mechanical ventilation system and the glazing for windows and doors [130]. Based on the discussions and considerations above, the concept for "Passive House" was launched by Dr Wolfgang Feist in Germany and Professor Bo Adamson in Sweden in May 1988.

Even though there are many advantages the low energy domestic properties hold, the shortage of these energy efficiency dwellings is still obvious. The main reasons for this phenomenon summarised from previous studies are listed below [131-133]:

- Lack of integrated design
- Lack of sustainable education
- Resistance to change
- Existing buildings improvement
- Lack of post occupancy evaluation
- Lack of transportation and related services development
- Split incentives for owner and tenant
- High cost investment

For developed countries, their progress for cutting down the energy consumption and carbon emissions in building sector have been accelerated by implementing those strict regulations issued by the government [13, 134-138]. For developing countries, the related guidance for sustainable buildings introduced by the government were only to create awareness at current stage [135, 139].

2.4.1 *The concepts of low energy domestic properties*

A low-energy building is any type of dwelling that from design, technologies and building products uses less energy, from any source, than a traditional property. In some countries the term relates to a specific building standard [16]. A number of terms or concepts have been defined by different organisations worldwide for sustainable buildings, with low energy consumption, comfortable indoor conditions and friendly impacts to the environment. These high performance buildings include Green Building (also known as Green Construction or Sustainable Building), Zero Energy Building (also known as Zero Net Energy Building, Net Zero Energy Building or Net Zero Building), nearly Zero Energy Building, Zero Carbon Homes, PlusEnergy House, Passive House, and so on. The definition for each type of high performance building may differ from each other and all the terms are summarised as follow:

- Green Building: "*Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Green building is also known as a sustainable or high-performance building*." [140, 141, 134, 142]
- Zero Energy Building: "*A zero-energy building is a building with zero net energy consumption, meaning the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site, or in other definitions by renewable energy sources elsewhere.*" [143, 144]
- nearly Zero Energy Building: *"A building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*." [4]
- Zero Carbon Homes: "*Requires all new homes from 2016 to mitigate, through various measures, all the carbon emissions produced on-site as a result of the regulated energy use. This includes energy used to provide space heating and cooling, hot water and fixed lighting, as outlined in Part L1A of the Building Regulations. Emissions resulting from cooking and 'plug-in' appliances such as computers and televisions are not being addressed as part of this policy.*" [145]
- PlusEnergy House: "*The PlusEnergy House fulfils a threefold objective: it will be supported exclusively by 100% renewable energy. It will operate CO2-neutral. Moreover, it reduces the energy consumption so extensively, that it will generate more energy than it will use. Additionally comes the selection of healthy building materials and a feasible market price*" [146]
- Passive House: "*A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air*." [147]

Although the terms of high performance buildings are widely introduced worldwide, the specific definition and energy demand for each country and the differences between different countries may vary greatly. For instance, the primary energy demands of nearly Zero Energy Buildings for every Member State are not the same. Table 2.3 shows the primary energy demands for nearly Zero Energy Buildings categorised by countries [4].

Country	Primary Energy demand (kWh/(m^2a))
Belgium	45 for residential buildings; 95 for non-residential buildings
Cyprus	180 for residential buildings; 210 for non-residential buildings
Denmark	20
Estonia	50-140
Ireland	45
Sweden	55-130 for residential buildings; 55-120 for non-residential buildings

Table 2.3 The primary energy demand for nearly Zero Energy Buildings categorised by countries (Source: Report from the commission to the European parliament and the council: Progress by Member States towards Nearly Zero-Energy Buildings, Annex 1).

Hence, each country has its own Green Building assessment standard to evaluate the building performance. For instance, Building Research Establishment Environmental Assessment Method (BREEAM) was launched in the UK in 1990. BREEAM is a foremost environmental assessment method and rating system for buildings which can be used not only in the UK, but also can be widely adapted to other regions and used worldwide. It sets the standards for the best performance of sustainable building design, construction and operation and has turned into one of the most accepted methods for building indoor environmental condition measurement. It focuses on reduce energy demand and carbon emissions of the target building and also minimize the impacts to building designs [148, 149].

Leadership in Energy and Environmental Design (LEED) discovered in the USA is another popular Green Building rating system and used widely in the world [150]. Moreover, Green Star (GS) in Australia [151], Green Mark (GM) in Singapore [152], Green Building Index (GBI) in Malaysia [153] and Building Environmental Assessment Method (BEAM) in Hong

Kong [154] are highly recognised rating tools in various countries or regions. The comparison of rating criteria and corresponding weighting between different rating systems are presented in Table 2.4.

	BREEAM [155]	LEED [156]	Green Mark [157]	GBI [158]
Management	11	-	8	3
Health and Wellbeing	19	-	9	-
Energy	**20**	**35**	**25**	**38**
Transport	6	-	-	2
Water	7	14	13	12
Materials	13	10	18	9
Waste	6	-	4	-
Land Use and Ecology	8	-	-	-
Pollution	10	-	-	
Innovation	10 (additional)	6	-	10
Sustainable Sites	-	26	10	5
Indoor Environmental Quality	-	15	8	21
Regional Priority Credits	-	4	17	-
Smart Building Operation	-	-	8	-
Advanced Green Efforts	-	-	20	-
Total	100 (110)	110	140	100

Table 2.4 The comparison of rating criteria and corresponding weighting between BREEAM, LEED, Green Mark and GBI.

Code for Sustainable Homes was one of the environmental and performance assessment methods for new build residential buildings in the UK. It was launched in 2006 and was built on the changes to national Building Regulations at that time. There were nine criteria to be measured to assess the overall performance of selected new dwellings: Energy and CO_2 emissions, Water, Materials, Surface water run-off, Waste, Pollution, Health and well-being, Management and Ecology, which were very similar to BREEAM rating system [159]. Code for Sustainable Homes was withdrawn by Government in March 2015 for new developments. But the Code continues to operate for "legacy developments" in England and in Wales and Northern Ireland [160].

HQM sections, category, assessment issues and available credits			
Section	**Category**	**Assessment Issue**	**No. Credits Available**
Our surroundings	Transport and Movement	01 Accessible Public Transport	16
		02 Alternative Sustainable Transport Options	15
		03 Local Amenities	19
	Outdoors	04 Ecology	30
		05 Recreational Space	20
	Safety and Resilience	06 Flood Risk	18
		07 Managing the Impact of Rainfall	16
		08 Security	10
My Home	Comfort	09 Indoor Pollutants	10
		10 Daylight	16
		11 Internal and External Noise	4
		12 Sound Insulation	8
		13 Temperature	20
		14 Ventilation	12
	Energy and Cost	15 Energy and cost	62
		16 Decentralised Energy	10
		17 Impact on Local Air Quality	11
	Materials	18 Responsible sourcing of construction products	31
		19 Environmental Impact from Construction Products	31
		20 Life Cycle Costing of Construction Products	18
		21 Durability of Construction Products	10
	Space	22 Drying Space	3
		23 Access and Space	10
		24 Recyclable Waste	10
	Water	25 Water Efficiency	10
Knowledge Sharing	Home Delivery	26 Commissioning and Performance	10
		27 Quality Improvement	10
		28 Considerate Construction	4
		29 Construction Energy Use	5
		30 Construction Water Use	5
		31 Site Waste	15
	User Experience	32 Aftercare	10
		33 Home Information	5
		34 Smart Homes	7
	Future Learning	35 Post-Occupancy Evaluation	9

Figure 2.18 Home Quality Mark assessment issues (Source: Home Quality Mark Technical Manual, page 5).

In the same time, with the withdrawal of Code for Sustainable Homes, the new Home Quality Mark (HQM) was launched by BRE. It provide a number of technical standards for the assessment of new build and existing dwellings [161]. The Home Quality Mark indicates to occupants the total expected costs, environmental impacts and health and wellbeing benefits living in the dwelling clearly. In general, the simple but reliable 5-star rating system helps everyone to understand the performance of a new build home easily and completely. There are 3 main sections including 35 assessment issues in total defined in the Home Quality Mark (shown in Figure 2.18) [162]. 'Our surroundings' includes issues of the dwellings' ability to fit with current and future surroundings. 'My Home' includes issues of the energy, cost, comfort and health demands of the living spaces. 'Knowledge Sharing' includes issues of the processes that improve the understanding and co-operation between the home designer, constructor and occupants. The minimum credits required for each Star Rating are shown in Figure 2.19.

	1 Star	2 Star	3 Star	4 Star	5 Star
Minimum total credits	150	225	275	375	400
Percentage	30	45	55	75	80

Figure 2.19 The minimum credits required for each Star Rating within Home Quality Mark (Source: Home Quality Mark Technical Manual, Table 43).

It can be observed that the 'My Home' section is the most important part for the home assessment as it contained the highest credits compared to the other two sections. The energy issues are also the decisive factors in the rating system. Not just for the UK residential buildings, the most important issue for every building assessment rating system corresponding different types of buildings in different regions is energy performance. It can be summarised from the current standards that energy performance and indoor environmental condition are the most essential criteria for an advanced housing.

2.4.2 *The concept and standards of Passive House*

1) Passive House Standard

The concept for "Passive House" was launched by Dr. Wolfgang Feist in Germany and Professor Bo Adamson in Sweden in May 1988. The concept was developed through eight research projects and the explanation was given by the two originators: *"Passive Houses" were defined as buildings which have an extremely small heating energy demand even in the*

Central European climate and therefore need no active heating. Such houses can be kept warm "passively", solely by using the existing internal heat sources and the solar energy entering through the windows as well as by the minimal heating of incoming fresh air [17]. The first Passive House dwelling was built in Darmstadt-Kranichstein, Germany, in 1990. The house has extremely good performance and was occupied by residents since 1991. Focus on the dwelling itself, mechanical ventilation heat recovery, thermal insulation, prevention of thermal bridges, airtightness and high quality glazing were the keys to minimise the Passive House's total energy demand [18]. In general, the building consumed less than 10% of the energy for heating compared to the German new-built building code at that time [19]. The Darmstadt Passive House still functions well as designed after more than twenty years since built: the annual energy consumption of space heating demand was under 15 kWh/m^2 yearly.

Since the first example had been validated in Kranichstein, the standard for Passive House was further elaborated and developed rapidly. The following CEPHEUS (Cost Efficient Passive Houses as EUropean Standards) project funded by the European Union certified the Passive House concept with more than 100 dwellings for 11 cases during 2000 to 2002. These projects presented that, normally, Passive Houses consumed 80 to 90% less energy for space heating than conventional buildings. Additionally, the building costs would increase by 5 to 10% [163, 164]. A building is required to meet these main criteria to obtain the Passive House certification [165-169]:

- Primary energy demand: maximum 120 kWh/(m^{2}a) of usable living space for all domestic applications, including electricity, domestic hot water, heating and cooling.
- Space heating/cooling demand: maximum 15 kWh/(m^{2}a) or 10 W/m^2 for peak demand of usable living space.
- Airtightness: maximum 0.6 air changes/h @50 Pa for the pressurisation test.
- Thermal Comfort: maximum 10% of the hours over 25 °C for all living areas in a year.

In Passive House Standard, the specific term used is Primary energy demand. It is worth noting that the concepts of Primary energy demand and Primary energy consumption are different. Both definitions for Primary energy demand and Primary energy consumption are stated as follow:

- Primary energy demand: the total energy to be used for all domestic applications (heating, hot water and domestic electricity) per square meter of treated floor area per year for Passive House Classic.

- Primary energy consumption: refers to the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process.

2) EnerPHit Standard

In existing old buildings, the Passive House Standard often cannot be achieved due to different technical difficulties. The use of Passive House Standard and technology for relevant building components in such buildings would lead to significant improvement in respect of thermal comfort, energy requirements, structural protection and cost-effectiveness. The EnerPHit Standard can be achieved through compliance with the criteria of the component method or the energy demand method (shown in Figure 2.20 and Figure 2.21, respectively). Only one of these two methods of the criteria must be met. The UK weather belongs to the Cool-temperate Climate Zone, thus, the detail criteria of the energy demand method of EnerPHit Standard can be summarised in Table 2.5.

Climate zone according to PHPP	Opaque envelope[1] against...				Windows (including exterior doors)					Ventilation	
	...ground	...ambient air			Overall[4]			Glazing[5]	Solar load[6]		
	Insulation	Exterior insulation	Interior insulation[2]	Exterior paint[3]							
	Max. heat transfer coefficient (U-value)			Cool colours	Max. heat transfer coefficient ($U_{D/W,installed}$)			Solar heat gain coefficient (g-value)	Max. specific solar load during cooling period	Min. heat recovery rate[7]	Min. humidity recovery rate[8]
	[W/(m²K)]			-	[W/(m²K)]			-	[kWh/m²a]	%	
Arctic	Determined in PHPP from project specific heating and cooling degree days against ground.	0.09	0.25	-	0.45	0.50	0.60	$U_g - g*0.7 \leq 0$	100	80%	-
Cold		0.12	0.30	-	0.65	0.70	0.80	$U_g - g*1.0 \leq 0$		80%	-
Cool-temperate		0.15	0.35	-	0.85	1.00	1.10	$U_g - g*1.6 \leq 0$		75%	-
Warm-temperate		0.30	0.50	-	1.05	1.10	1.20	$U_g - g*2.8 \leq -1$		75%	-
Warm		0.50	0.75	-	1.25	1.30	1.40	-		-	-
Hot		0.50	0.75	Yes	1.25	1.30	1.40	-		-	60 % (humid climate)
Very hot		0.25	0.45	Yes	1.05	1.10	1.20	-		-	60 % (humid climate)

Figure 2.20 EnerPHit criteria for the building component method (Source: Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard).

Climate zone according to PHPP	Heating	Cooling
	Max. heating demand	Max. cooling + dehumidification demand
	[kWh/(m^2a)]	[kWh/(m^2a)]
Arctic	35	equal to Passive House requirement
Cold	30	
Cool-temperate	25	
Warm-temperate	20	
Warm	15	
Hot	-	
Very hot	-	

Figure 2.21 EnerPHit criteria for the energy demand method (Source: Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard).

Criteria	EnerPHit
Specific Heat Demand (SHD)	$\leqslant$ 25 kWh/(m^2a)
Primary Energy (PE) Demand	$\leqslant$ 120 kWh/(m^2a) *
Limiting Value	n_{50} $\leqslant$1.0 air changes/h
** PE $\leqslant$ 120 kWh/*(m^2a) *+ ((SHD - 15 kWh/* (m^2a)*) x1.2)*	

Table 2.5 EnerPHit criteria for the energy demand method.

3) PHI Low Energy Building Standard

The PHI Low Energy Building Standard is suitable for the buildings which do not fully comply with the criteria of Passive House Standard due to various reasons. The criteria of PHI Low Energy Building Standard are summarised as follow:

- Space heating demand: maximum 30 kWh/(m^2a) of usable living space.
- Space cooling demand: maximum 30 kWh/(m^2a) of usable living space.
- Airtightness: maximum 1.0 air changes/h @50 Pa for the pressurisation test.
- Non-renewable primary energy demand: maximum 120 kWh/(m^2a) of usable living space for all domestic applications, including electricity, domestic hot water, heating and cooling.
- Renewable Primary Energy demand: maximum 75 kWh/(m^2a) of usable living space, moreover, exceeding the criteria up to +15 kWh/(m^2a) is permitted.

Criteria	Passive House Standard	EnerPHit Standard	PHI Low Energy Building Standard
Primary energy demand	120 kWh/(m^2a)	120 kWh/(m^2a)	120 kWh/(m^2a)
Space heating/ cooling demand	15 kWh/(m^2a)	25 kWh/(m^2a)	30 kWh/(m^2a)
Airtightness (maximum)	0.6 air changes/h @50 Pa	1.0 air changes/h @50 Pa	1.0 air changes/h @50 Pa

Table 2.6 Comparison of criteria for different standards.

The main criteria for the three standards were compared in Table 2.6. The Passive House standard is achievable for the selected Conventional House in expectation. Thus, in order to achieve the best performance of the retrofitted Conventional House, Passive House Standard was chosen and used for this research.

2.4.3 *Performance of Passive House*

Passive House is a well-recognized method to achieve low energy building with great indoor air quality, and it was first developed and spread in Europe through a number of project as it adapts the European climate very well. Passive House reduces building energy consumption significantly by its superb building fabrics and HVAC optimization. The cores of Passive House design include the four aspects as follows: 1) fabulous insulation with rarely thermal bridges; 2) outstanding airtightness level; 3) passive solar gains and internal heat gains; 4) excellent indoor environmental condition.

As of 2013, more than 50000 Passive House structures were built worldwide because the standard has been proven to be a reliable scheme to achieve extremely low energy demand dwellings that applicable to several different climates [170]. Most of them were located in Germany, Austria and Scandinavia, while others in various countries worldwide. In 2003, the first North American Passive House was built in Urbana, Illinois [171]. Ireland's first Passive House – Out of the Blue was built by Architect Tomas O'Leary, a Passive house designer, in 2005 [172].

What we need to be careful is, when applying the Passive House standard to other countries or regions with different climate conditions, the relative requirements such as glazing, insulation, ventilation and renewable energy system need to be reconsidered according to realistic situation. The solution for a Passive House has to be catered the climate and demand for each country and not just copy the original standard and use without careful consideration. A recent study conducted by Griego et al. shows the increased energy consumption of a Mexican office building was caused by the adding building insulation [173]. The excessive internal heat gains lead to higher indoor temperature and more cooling loads and increase the total building energy consumption.

Schnieders and Hermelink [164] delivered the detailed measurements and occupants' satisfaction of more than 100 Passive House dwelling units from the Cost Efficient Passive Houses as EUropean Standards (CEPHEUS) projects. A 2.5-year study was conduct in Germany, Austria and Switzerland in 11 sub-projects. The aim of this project is to provide evidence for Passive House being an option for sustainable building. Insulation, ventilation system and efficient appliances were considered in this study. Energy saving comparison and occupants' satisfaction were detailed described in the paper. The limitations, first, the floor area calculation method would lead to a bigger result and lower specific energy consumption. Second, how to adapt the principle to different climate conditions and building behaviours are required. For example, is triple glazing necessary in warmer regions?

McLeod et al. [174] investigated a revised definition of Zero Carbon Homes (ZCH) in the UK. The aim of the study is to discover a more robust "fabric first" approach are adapting with climate change and energy policies and strategies. In this study, the authors considered about the UK built environment, the role of the Passive House standards in the UK climate change and energy targets. The significant increases in the absolute number of UK households, hot water demand, appliance consumption and even cooling demand appear to have been overlooked during the recent review of UK zero carbon dwelling standards. Further research of health issues associated with internal airborne pollutants in airtight UK dwelling using mechanical ventilation is needed to strengthen UK domestic ventilation guidance and regulations.

The performance of Passive House apartmanets and low-energy apartments in Austria were indicated by Mahdavi and Doppelbauer [175]. The aim of this study is to discuss a comparison of low-energy and passive buildings based on empirical data based on a five-month monitoring. The main difference between the two blocks lies in the ventilation system: controlled ventilation for passive buildings whereas natural ventilation for low-energy buildings. The authors measured the indoor environmental conditions, and also considered the project from the view of operation and embodied energy use, CO_2 emissions and construction cost. Uncertainty for payback period: different source of energy and future energy price. In summary, Passive House uses less energy and offer better indoor conditions. And the construction cost does not appear to be prohibitive.

Blight and Coley [176] addressed the probable range of occupant behaviour and the influence on heating energy consumption for Passive House dwellings. In this paper, the authors aimed to examine the sensitivity of the required heating energy of the houses during the heating season (October to April). Integrated Environmental Solutions 'Virtual Environment' (IES VE) thermal modelling software was used to model the Passive House buildings. The thermal modelling results are validated by comparisons to monitored data from Passive House projects around central Europe. The model is limited to a single architectural design so it could be valuable to inspect the values of coefficients for other Passive House dwellings. However, many concerns about Passive House approach is overly sensitive to occupant behaviour hence not many sections of society are founded.

The first batch of certified Passive Houses in the United Kingdom has been built since 2010 [177-179]. Among them, the Camden Passive House was the first new-built dwelling certified to the Passive House standard in London. The case study showed the 12-month monitored thermal and energy performance of the building and aimed to provide standards and reference for UK low energy residential house from the views of energy efficient design and refurbishment, indoor comfort and occupants' health. Winter space heating, summer time over heating risk, and the mechanical ventilation with heat recovery (MVHR) system are the concerns in the paper. All the measured data were compared with the building performance assumed in Passive House Planning Package (PHPP). This study presented that the Camden Passive House was one of the lowest energy dwellings (65 $kWh/(m^2a)$) in the UK.

However, summer time overheating was observed in the project even the occupants didn't report it as a problem [180]. Ridley et al. presented the monitored performance of the first two Welsh side by side social Passive Houses in [181]. This two-year monitoring aimed to assess whether the novel building design and the whole systems were performing well as expected and to discover any unexpected building or occupant behaviours. The two dwellings are different in their design and are occupied by two families with different behaviours. The technical and performing differences resulted in significant discrepancy in space heating demand (one for 9.3 kWh/(m^2a) and another one was 25.6 kWh/(m^2a)), CO_2 emissions and the indoor environmental performance in summer, even both houses achieved the Passive House certification. The summer overheating in UK homes has been observed and reported in [182, 183]. The studies showed that overheating problem was more likely to happen in the UK houses with extremely high energy efficient than conventional households. Thus, it is necessary to find out whether overheating occurs in high energy efficient dwelling is the result of higher insulation applied to the building [184].

The implement of Passive House Standard always relies on energy efficient design. Thus, new techniques and technologies can generate difficulties and problems because of the design innovation. This can create technical barriers and risks, but also a number of social, cultural and economic non-technical barriers. The main concerns can be summarised as follow [239]:

- The Passive House methods are not fully embraced by current architectural practices associated with low energy design either because of pride or overconfident;
- The relative high Passive House construction budget would be cut down by using cheaper off-the-shelf systems for the MVHR or sealing tapes. However, these give Passive House a bad name because these replacements do not meet the requirement of Passive House design;
- Some concerns are about the overheating causes by the super-insulated Passive House design. Also, as a central European standard, is this Passive House methods suitable for the construction in their own country becomes a hot topic;
- Once a project began to use a plethora of subcontractors that the technical cohesion required for Passive House might be lost and was often the cause of failure to meet testing standards;
- Another major hurdle was the area of retrofitting technologies used for existing buildings. This can be more complicated when the ownership varies from property to property between owner occupiers to social rented to private rented. Further difficulties might result if health and safety risks result from the installation of inappropriate retrofit measures.

Because of these technical and non-technical barriers for Passive House, the large scale implements of this low energy design building cannot be achieved in a short time. More openness was required alongside an ability to be honest about these difficulties. An open mind is necessary for traditional designers, constructors and the public. Moreover, the Government, the building industry and the market could provide some strategies and supports for the spread of Passive House.

2.5 Improvement of building performance

Active methods [185-187, 37, 188-194], passive methods [195-208, 43, 209, 210] and integrated methods [211-219] are the three main ways to enhance building performance according to previous research and studies. Active methods mean the implementation of approaches to reduce energy consumption by improving the energy efficiency of mechanical ventilation system, gas boiler, lighting system, onsite renewable energy system and other relative equipment within the building. Passive methods, in the opposite direction, are defined as the methods to minimise energy consumption using state-of -art building design and advanced construction materials including high standard triple glazing, fabrics and insulation, orientation selection, passive heating, passive lighting and passive cooling. Lastly, the integrated methods combine both active methods and passive methods to cut down energy consumption. Implement of both methods provides the possibility to save more energy as the building performance is doubling enhanced.

In order to reduce the building energy consumption in traditional European countries, the implements of active methods, passive methods or integrated methods such as changing the set-point temperature of mechanical ventilation system, settings or working schedules of ventilation system during non-peak period, smart lighting control, improvement of boiler efficiency, building fabrics, glazing and insulation are very important. Previous studies also indicate that higher energy consumption can be achieved by optimising the mechanical ventilation than improvement of building fabrics and insulation. However, for those traditional residential dwellings without mechanical ventilation system, passive methods are the most efficient approach to reduce their energy consumption [220-224].

2.5.1 *Retrofitting of buildings*

In order to reduce energy consumption and emissions from the built environment, it is important to transform the existing building stock and develop retrofit strategies to achieve energy efficiency buildings. In general, there are four main retrofit strategies for existing dwellings and they are shown below.

1) The whole-house strategy

A whole-house approach (also known as whole-house systems approach) regards the building as an energy system with interdependent parts. The approach was used on one of the eight sample projects (Retrofit for the Future (R4tF) programme) [243] and considers the interaction between the occupant, building site, climate, and other elements or components of a building. In this approach the features and performance of any one component are strongly affected by the rest, and energy performance is considered a result of the whole system.

2) The “fabric first” strategy

This approach prioritises improvement of the thermal properties of the building fabric through the use of high levels of thermal insulation and airtightness. A range of measures is then employed to increase the efficiency of various systems (e.g. heating and hot water, lighting and electrical appliances). System re-sizing may be desirable as a consequence of reduced energy demand, but oversizing (e.g. of heat distribution systems) can significantly improve overall performance. Finally, renewables are installed to meet the remainder of the CO_2 and energy reduction requirements [243, 244].

3) The Passive House strategy

4) The “Insulate then generate” strategy

This strategy is very similar to the “fabric first” strategy. It aims to reduce energy demand from passive design strategies (for instance, building fabric, thermal mass and airtightness, ventilation and heat recovery), and then to meet the remaining demand through the use of micro-generation technologies [243].

Leardini et al. [225] presented problems, opportunities, strategies and predictable effects of retrofitting historic (1940–1960s) houses in New Zealand. This study aims to upgrade the energy consumption of the mid-century state housing to Passive House standard by retrofitting. The computer thermal simulation program Virtual Environment (VE) and PHPP were used in the simulation. R-values of envelope components used in VE and PHPP were compared in the paper. From this study, the standard can be theoretically achieved in the selected region using existing technology but further research is needed to develop feasible retrofit details and make a full cost benefit analysis.

The Building Regulations 2010 Part L1B is used for the evaluation of existing residential buildings' retrofitting in the UK. It provides the general guidance and requirements for the component's' U-values of retrofitted dwellings (see Figure 2.22). Reasonable provision should be implemented to upgrade those thermal elements whose U-values is worse than the threshold value stated in the table below. In general, these U-values should not be less than 0.7 $W/(m^2K)$.

Element[1]	(a) Threshold U-value $W/(m^2 \cdot K)$[8]	(b) Improved U-value $W/(m^2 \cdot K)$[8]
Wall – cavity insulation[2]	0.70	0.55
Wall – external or internal insulation[3]	0.70	0.30
Floor[4,5]	0.70	0.25
Pitched roof – insulation at ceiling level	0.35	0.16
Pitched roof – insulation between rafters[6]	0.35	0.18
Flat roof or roof with integral insulation[7]	0.35	0.18

1 'Roof' includes the roof parts of dormer windows and 'wall' includes the wall parts (cheeks) of dormer windows.

2 This applies only in the case of a wall suitable for the installation of cavity insulation. Where this is not the case, it should be treated as 'wall – external or internal insulation'.

3 A lesser provision may be appropriate where meeting such a standard would result in a reduction of more than 5% in the internal floor area of the room bounded by the wall.

4 The U-value of the floor of an extension can be calculated using the exposed perimeter and floor area of the whole enlarged building.

5 A lesser provision may be appropriate where meeting such a standard would create significant problems in relation to adjoining floor levels.

6 A lesser provision may be appropriate where meeting such a standard would create limitations on head room. In such cases, the depth of the insulation plus any required air gap should be at least to the depth of the rafters, and the thermal performance of the chosen insulant should be such as to achieve the best practicable U-value.

7 A lesser provision may be appropriate if there are particular problems associated with the load-bearing capacity of the frame or the upstand height.

8 Area-weighted average values.

Figure 2.22 U-values requirements for different elements in existing dwellings (Source: The Building Regulations 2010 Part L1B).

The demand of building refurbishment and retrofitting is increasing because of the large number of existing unsuitable buildings on the market [226]. The relative policies and regulations issued by the government highlight the importance to enhance the energy performance of existing buildings. Compare to demolition and rebuilding of a building, retrofitting is more cost efficient and environment friendly [227]. As leading institute in this aspect, US Department of Energy (US DOE) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have published some guidance for building retrofitting and energy efficient measures. Before applying relative energy efficient measures (EEM), calculation [228, 240] and computer simulation [229, 217] are the two main methods to predict the new energy performance of the target buildings. The retrofit procedures of the two methods are shown in Figure 2.23 and Figure 2.24.

The second retrofit procedure based on field studies and computer simulation (see Figure 2.24) was chosen as the main procedure for this research. Firstly, actual data of the target building including energy consumption and relative indoor environment condition are collected. An energy audit is conducted afterwards for the energy analysis and preparation for the model set up. While the building model is verified by actual monitored data, it can be used for the applications of EEMs and conduct the energy conduction analysis. Finally, a payback period should be taken into account as cost analysis is one of the biggest concerns of retrofitting.

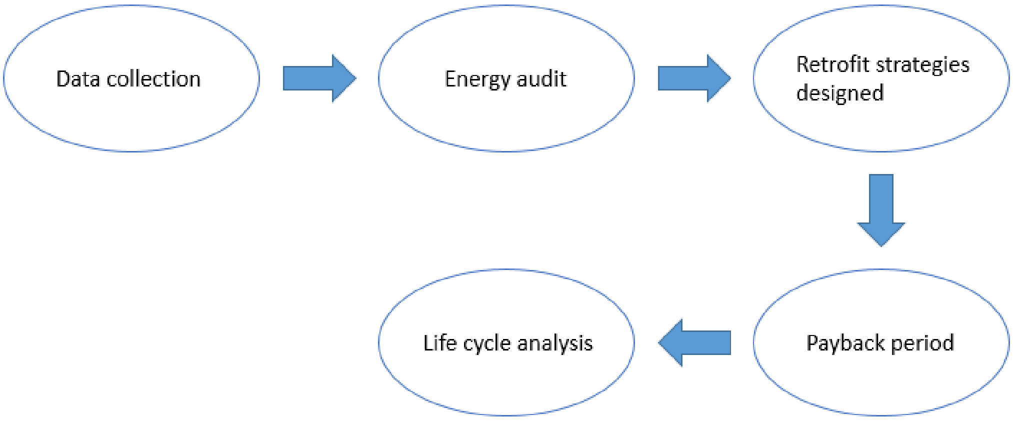


Figure 2.23 Retrofit procedures based on field audit and calculation.

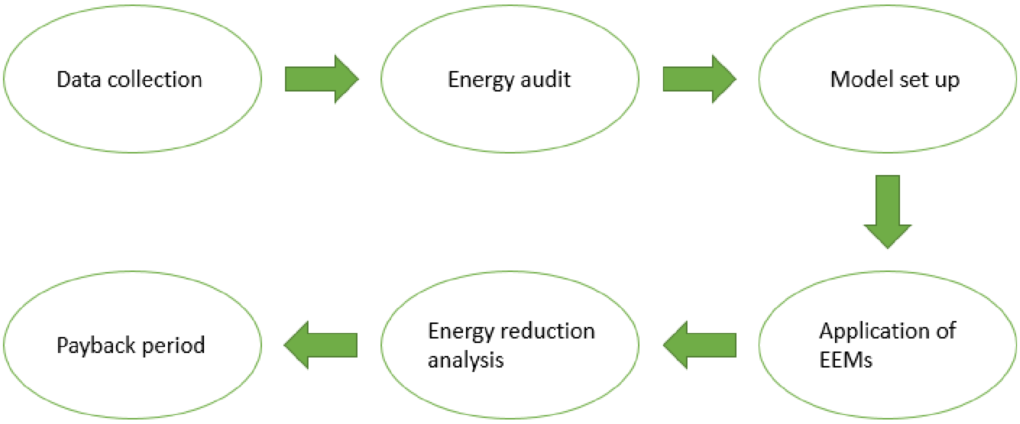


Figure 2.24 Retrofit procedures based on field audit and computer simulation.

A building energy performance analysis and simulation provides the essential information needed to detect and quantify possible solutions that decrease environmental footprint while keeping compliance with the national standards and regulations. For this reason, a detailed and accurate 3D model of the selected buildings were constructed using actual collected data and all the available information on materials and landscape usage was inserted into the DesignBuilder, as well as all respective energy needs was imported in the selected software. The goal of the simulation is to show the significant level of assistance provided to the research and the ability to lead to solutions that take into consideration all the respective technical, environmental and socio-economic issues involved. Occupant behaviour is critical to the energy performance of buildings, which can be an important supplement to the technology approach to improving building energy performance. The energy-saving potential of occupant behaviour in building energy performance ranges between 10% and 25% for residential buildings [245].

In order to achieve the Government's goal of reducing CO2 emissions, a life cycle approach is required. A life cycle assessment (LCA) quantifies the potential environmental impact of a product or a service and is defined in the British Standard of BS EN ISO 14040:2006 [260] and BS EN ISO 14044:2006+A1:2018 [261]. The life cycle assessment studies often show the relationship between the construction materials' embodied energy and the operational energy. Recent LCA research and studies indicate that the global tendency is to construct buildings with lower energy demands in the operation stage in order to achieve the international energy efficiency goals. Therefore, the relationship between the building materials' embodied energy and the operational energy is changing that 40% of the impact is associated with materials and 60% is associated with the operational stage [262].

The retrofitting of buildings relies on a new building life cycle assessment to discover the probable improvements that could reduce their impacts for the environment. Steel and concrete are the materials usually used in buildings and constructions that produce more environmental impacts, while timber frame buildings produces lower environmental impacts [263, 264]. In addition, some specific materials, such as insulation materials, can reduce the overall building environmental impacts throughout their life cycle [265–269]. Building materials should be decided and selected based on location and availability [270–272]. Moreover, their resource efficiency through material features such as recyclability of material, waste reduction and prefabrication should be considered [273–276].

The construction and demolition processes do not significantly impact the global life cycle [277]. During the building operation stage, the construction design with passive strategies is very important to reduce global energy demands [278–282]. The operation stage is often dominant in energy consumptions and greenhouse gas emissions [283–285]. Hence, some research and studies have investigated methodologies to optimise energy retrofits [286, 287]. In addition, buildings within colder climate have higher environmental impacts than those in hotter climate because of their greater energy requirements [288]. This factor should be taken into account because the over-glazed or over-insulated buildings applied to warm or hot climate countries (e.g. in southern Europe), leading to a risk of overheating that can increase air conditioning needs at an additional energy cost. Energy supply systems influences the carbon dioxide emissions and energy consumptions greatly [289]; energy managers using building energy management systems during the buildings operation stage can reduce massive energy consumption from the view of active energy saving method [290]. Lastly, at the end-of-life stage, reducing the waste materials and maximising recycling are the keys to reduce the overall LCA [291-294].

2.6 Summary

This chapter reviewed the domestic energy demand features (including electricity and gas demand), the characteristics of conventional domestic properties, the concept of low energy properties, the concept and performance of Passive House and the improvement of building performance by using retrofitting methods. The literature review indicated that energy consumption reduction and comfortable indoor environmental condition in the building are the goals we chase in the process of building development. The building energy consumption keeps increasing along with the rising thermal comfort demand of occupants, particularly in the domestic buildings. A number of low energy buildings were developed in recent decades to meet the requirements.

However, a number of questions arise. Firstly, how to reduce the energy consumption in existing domestic buildings? There are many assessment methods to evaluate the energy and indoor thermal comfort performance of buildings worldwide. Additionally, those methods are mainly focus on the evaluation of new build buildings' performance. Even in some developed countries, such as UK, most of its existing building standards and assessment methods only generate marks for the overall building performance, but they would not provide solutions for those buildings with poor energy performance or indoor environmental condition to improve their performance. What is the best approach to enhance the building performance of existing households?

Furthermore, is the Passive House concept suitable for the buildings in the UK? As we all know that the Passive House concept was developed in Germany and it is adaptable to cold climate and is widely applied in many central European countries. The climate of UK is milder than those European countries in cold regions, thus, is it applicable to the UK climate with warmer temperature? If the super-insulated buildings overqualified, what solutions can be utilised to deal with the new problems?

As more than 50000 Passive House structures were built worldwide, the Passive House concept has been proven to be a reliable scheme to achieve extremely low energy demand dwellings that applicable to several different climates. Recent studies and research indicate that a reduction of up to 90% energy consumption can be achieved by Passive House compared to those typical conventional households. The Passive House concept is under investigation by many organisations and researchers worldwide, showing its potential to become one of the most efficient “low energy building”. Along with the improvement of technology in the building industry, the diversity and flexibility of construction materials are driving the development of Passive House, and the performance of this type of building is expected to be in leading position in the future.

Chapter 3. Methodology

3.1 Introduction

The aim of this research is to investigate the energy demand and indoor environmental condition of different types of UK residential buildings and find out the optimised solutions for Conventional House retrofitting, overcome the summer overheating problem for Passive House, and then improve the building performance through case studies. To achieve the aim, the methodologies used in this work were explains in this chapter.

Building energy metering and environmental monitoring provide valuable and important information regarding how buildings are performing. Knowledge gained from previous research and analytics can also be used to improve the building performance further [255]. A robust energy metering and environmental monitoring system has the possibility to get everyone related to the building (including building owners, tenants and energy managers) to take energy-efficiency measures. Energy metering and monitoring can also help determine cost-reducing opportunities by detecting inefficiencies; evaluate the performance of buildings internally and externally; improving energy plans and consumption; and managing demand to minimise exposure to system reliability and price volatility risks [256].

There are currently huge numbers of metering and sensor technologies that are available on the market with different degrees of sophistication and functionality. Choosing a correct metering and sensor solution for a building is a challenging and essential task as it depends on many various factors. These factors need to be taken into account to ensure the metering and monitoring solution can meet the relevant quality (electricity consumption, gas consumption, indoor temperature, indoor relative humidity etc.). Therefore, it is very important to be aware of different factors that influence the selection of these technologies. In future, smart buildings infrastructure will support bi-directional communication standards, which will allow continuous interaction between the utility, the consumer and the controllable electrical load [257]. According to Rashed Mohassel's research [258], a highly reliable communication will be required to transfer a high volume of data. Therefore, communication and network technologies will play a significant role in the integration of smart buildings and grids.

There are three categories for building sensors and meters for measuring and sensing suggested by Fugate et al. [259]: 1) building performance parameters, 2) occupants comfort perception, 3) machinery characteristics. Temperature, relative humidity, CO_2 concentration, occupancy, and indoor air quality sensors are used to sense occupant comfort and activity. On the other hand; building energy meter, sub-metering, plug-load measurements, natural gas meters, and other sources of energy meters are used to measure energy consumption. Measurements of machinery characteristics can be done by using refrigerant temperature, machinery electrical current, machinery vibration, and return and supply airflows sensors. Different factors that influence the selection of sensing and metering solutions will be discussed. The key factors including sensor accuracy, ease of deployment, availability, cost, granularity and communication protocol.

3.2 Building audits

3.2.1 *General field study*

The general field study conducted in the target buildings before the monitoring period provides a preliminary knowledge of each property. Normally, the general information (e.g. floor plans and residents' occupancy) and the existing energy bills of the dwellings were gathered during the first field study as preparation for the work. The previous energy bills provided by the house owner are shown in Figure 3.1. The annual energy consumption was recorded by actual pre-payment meter readings but the monthly energy consumption was estimated by the energy companies. All information collected during the general field study became a solid basis for the work as it gave us a general understanding to the property and it helped decide the qualities and species of monitoring equipment in later stage of the study.

Figure 3.1 The previous electricity and gas bills for the Conventional House.

Under certain circumstances, the house information is incomplete and some field work including measurement and verification needs to be done in this stage. For the Conventional House case study, two different tap measures (8 m and 30 m long, respectively), shown in Figure 3.2, were used to verify the detailed house dimensions. Both precision of measurements of the tapes are 1 mm. According to the technical data, the accuracy for these two tapes are ±1.9 mm and ±6.3 mm.

Figure 3.2 The Rabone Chesterman (30 m) and CONTRACTOR (8 m) tape measures.

3.2.2 *Thermal study*

The thermal study of the target property was carried out as a part of each case study. One fully automatic FLIR i7 thermal imaging camera, shown in Figure 3.3, was used in this study.

Figure 3.3 FLIR i7 thermal imaging camera.

A series of thermal photographs taken by the thermal camera onsite was collected to analysis the performance of the dwelling. The features and specification of the thermal camera are listed in Table 3.1. The thermal imaging study of building fabric identifies where internal heat leaks in or out of buildings and shows thermal insulation defects. Using this thermal images we can highlight issues such as thermal bridging, assess the continuity of insulation and locate areas of moisture compromise. Moreover, suggestions can be provided to the residents to make informed decisions on needed repairs that can help them save energy bills and stay more comfortable.

Features /specification	Details
Total image capacity	5000 JPEG image files
Thermal image quality	140x140 pixels
Field of view	29°(H) x 29°(V)
Colour LCD resolution	71mm
Accuracy	Temperature accuracy calibrated within ±2°C or 2% of reading
Measures temperature range	–20 to 250°C
Thermal sensitivity	0.10°C
Measurement functions	Spotmeter, box with max./min. temperatures, isotherm above/below (depending on model)

Table 3.1 Features and specification of the FLIR i7 thermal imaging camera.

3.3 Actual data monitoring and collection

In order to monitor and evaluate the energy consumption of the selected building, it is necessary to collect the following data, including temperature, relative humidity, CO_2 concentration, electricity consumption and gas consumption (see Figure 3.4) [180, 181]. Therefore, sensors and instrument listed in this section are selected and used for data collecting and recording.

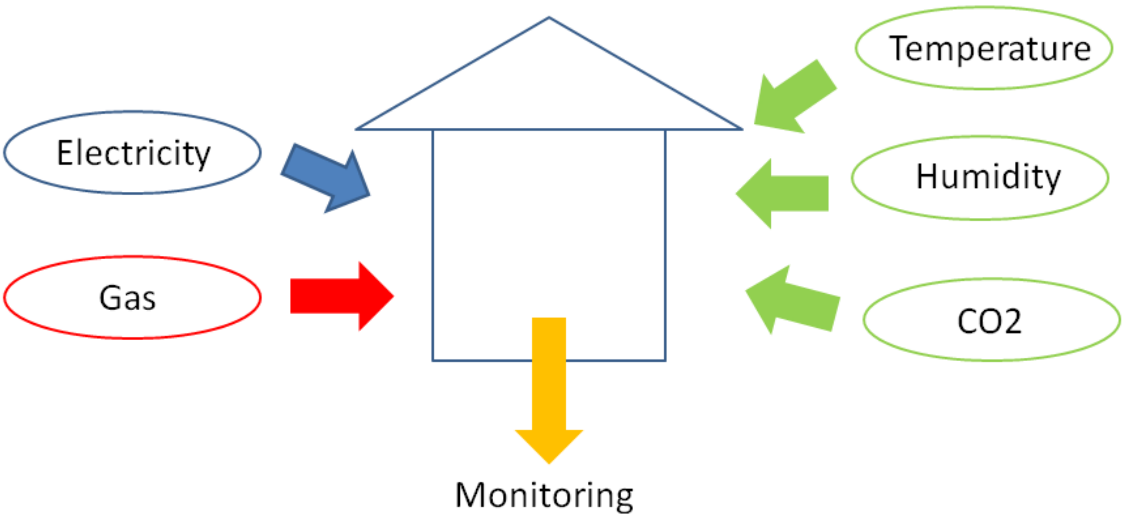


Figure 3.4 Data required for building monitoring.

3.3.1 *Data requirement*

For the purpose of understanding the building performance of each target property, energy consumption and indoor environmental condition of the dwellings need to be measured and recorded for further investigation. Electricity and gas consumption, indoor temperature and relative humidity of the house, and onsite outdoor temperature and relative humidity were the required data in this research. Besides, indoor CO_2 concertation in the Passive House was measured evaluate its indoor air quality. Hourly weather data of Newcastle upon Tyne including outdoor temperature, relative humidity, wind speed and direction etc. was gathered from Met Office as a reference for the studies. In order to achieve reliable and high quality data of the houses, a specific monitoring equipment package was deployed in each house to monitor its real time energy consumption and indoor environmental condition.

3.3.2 *Sensors and data loggers*

1) Case study of Conventional House

A. Temperature and humidity base-station (RFM12Pi V2)

The RFM12Pi adapter board is for the Raspberry Pi to receive wireless data from RFM12B wireless module such as emon TH energy temperature and humidity monitoring node. A Raspberry Pi is used to transmit data to an Emoncms sever and log data to an SD card or connected hard drive. The RFM12Pi V2 (shown in Figure 3.5) consists of an RFM12B wireless module and an ATmega328 microprocessor. The new RFM2Pi with ATmega328 allows programming directly from Raspberry Pi using avrdude (and OptiBoot).

Figure 3.5 RFM12Pi V2 base-station.

The technical overview of the RFM12Pi V2 are list below:

i. ATmega328 based, has more memory and hardware serial support
ii. Runs on the internal 8Mhz oscillator (to save unnecessary components)
iii. SMT used, board layout is optimized for pick-and-place assembly
iv. Lower profiles to fit inside most Raspberry Pi enclosures

B. Temperature and humidity wireless node (emon TH)

Figure 3.6 emon TH sensor.

The emon TH (shown in Figure 3.6) is a temperature and humidity wireless node powered by battery. It has been designed to monitor indoor temperature and humidity and the data could be used to feed into a building performance model easily. The data is transmitted through wireless to a web-connected base-station which posts the data onto a server for logging, processing and graphing. The sensor type used for the emon TH is DHT 22 temperature and humidity sensor. The features of the emon TH and DHT 22 are listed in Table 3.2 and Table 3.3 below, respectively.

Features	Details
Microcontroller	ATmega328
Radio	RFM69CW / RFM12B
Sensors	DHT 22 (temperature & humidity)
Power	2 × AA from on-board holder, LTC3525 3.3V DC-DC boost converter to extend battery life
Battery life	7-36 months depending on sensor choice
New version emon TH V1.5 (May 2015)	RF node ID DIP Switch selector

Table 3.2 Features of emon TH.

Features	Details
Power supply	3.3~6V DC
Operating range	Humidity: 0~100% RH
	Temperature: -40~80 Celsius
Accuracy	Humidity: ±2% RH (Max ±5% RH)
	Temperature: < ±0.5 Celsius
Resolution or sensitivity	Humidity: 0.1% RH
	Temperature: 0.1Celsius
Repeatability	Humidity: ±1% RH
	Temperature: ±0.2 Celsius
Humidity hysteresis	±0.3% RH
Sensing period average	2s
Long-term stability	±0.5% RH /year

Table 3.3 Features of DHT 22.

C. Electricity power monitoring node (emon Tx V3)

The emon Tx V3 is the newest electrical power monitoring product of the emon Tx Low Power Wireless Energy Monitoring Node series. This node could monitor up to four separate AC electrical powers by circuits using non- invasive clip on CT current sensors. Voltage signal is provided by an AC-AC voltage adaptor for full real power calculations. Figure 3.7 shows the emon Tx V3 with a non-invasive clip for monitoring the electricity in the Conventional House. The data from the emon Tx V3 is transmitted via wireless to a web-connected base-station. In this study, the Raspberry Pi with an RFM12Pi (RFM12Pi V2) mentioned above is recommended and used to post the electrical power data on the server for processing and graphing. There are four ways to power the emon Tx V3: USB to UART cable; 5V DC Mini-USB; 3 × AA Batteries and 9V AC-AC power adapter. For this study, the node is powered by the AC-AC power adapter. The features of the emon Tx V3 are listed in Table 3.4 as follow.

Figure 3.7 emon Tx V3 with a non-invasive clip.

The readings of emon Tx are affected by normal manufacturing tolerances just like other equipment assembled using different components. The ‘worst-case’ error of the device is, all errors add up together if every component meets the greatest possible error. But this case is rarely to happen in practice because some errors of different components could cancel each other. According to the calculation, for the emon Tx V3, before calibration, the error might be approximately 11.7% in the worst case. With careful calibration, the energy consumption of emon Tx is within 1% of the value compared to the energy supplier’s meter.

Features	Details
Microcontroller	ATmega328 with Arduino Uno bootloader
RF Radio	HopeRF RFM69CW 433Mhz
Sensors	3 × standard (23kW max) CT sensor 3.5mm jack input 1 × high sensitivity (4.5kW max) CT sensor 3.5mm jack input 1 × 9V AC-AC 2.1mm barrel jack plug in adapter input for powering the unit and AC voltage sample
Power supply	5V mini-USB / 3 × AA batteries / 9V AC-AC adapter
Battery life	At least one year expected from 3 × AA batteries
Accuracy	< 11.7% (worst case); < 1% (calibrated)

Table 3.4 Features of the emon Tx V3.

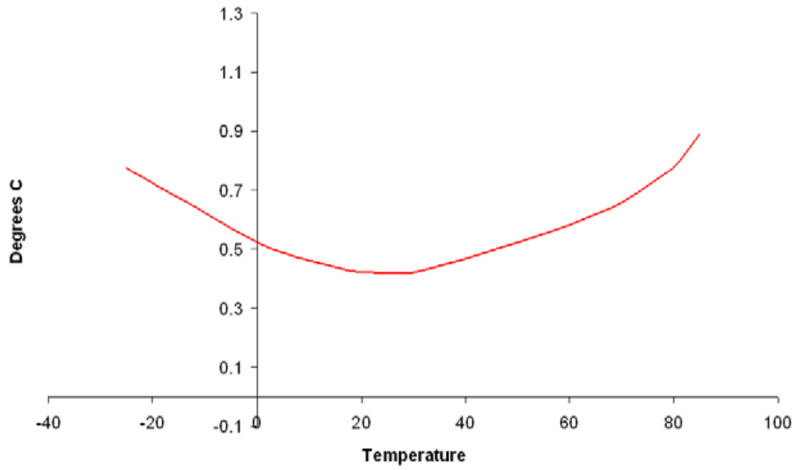
D. Tinytag Plus 2 (TGP-4500)

The Tinytag Plus 2 TGP-4500 (shown in Figure 3.8 below) is rugged, waterproof temperature and relative humidity logger with built-in sensors.

Figure 3.8 Tinytag Plus 2 TGP-4500.

The coated relative humidity sensor provides excellent resistance to condensation and moisture. This reliable and accurate unit is not restricted for monitoring indoor environment, it is even ideal for monitoring in outdoor conditions and industrial applications. The features and specification of the data logger are listed in Table 3.5 below.

<table>
<tr><td>Features /specification</td><td>Details</td></tr>
<tr><td>Total reading capacity</td><td>32000 readings</td></tr>
<tr><td>Reading types</td><td>Actual, Min, Max</td></tr>
<tr><td>Logging interval</td><td>1 second to 10 days</td></tr>
<tr><td rowspan="2">Reading range</td><td>Humidity: 0% to 100% RH</td></tr>
<tr><td>Temperature: -25°C to +85°C (-13°F to +185°F)</td></tr>
<tr><td rowspan="2">Sensor type</td><td>Humidity: Capacitive (externally mounted)</td></tr>
<tr><td>Temperature: 10K NTC Thermistor (internally mounted)</td></tr>
<tr><td rowspan="2">Response time</td><td>Humidity: 40 seconds to 90% FSD</td></tr>
<tr><td>Temperature: 25 mins to 90% FSD in moving air</td></tr>
<tr><td rowspan="2">Reading Resolution</td><td>Humidity: Better than 0.3% RH</td></tr>
<tr><td>Temperature: 0.01°C or better</td></tr>
<tr><td rowspan="2">Accuracy</td><td>Humidity: ±3.0% RH at 25°C / 77 °F</td></tr>
<tr><td>Temperature:



</td></tr>
</table>

Table 3.5 Features and specification of Tinytag Plus 2 TGP-4500.

E. Tinytag Talk 2 (TK-4014)

Figure 3.9 Tinytag Talk 2 TK-4014.

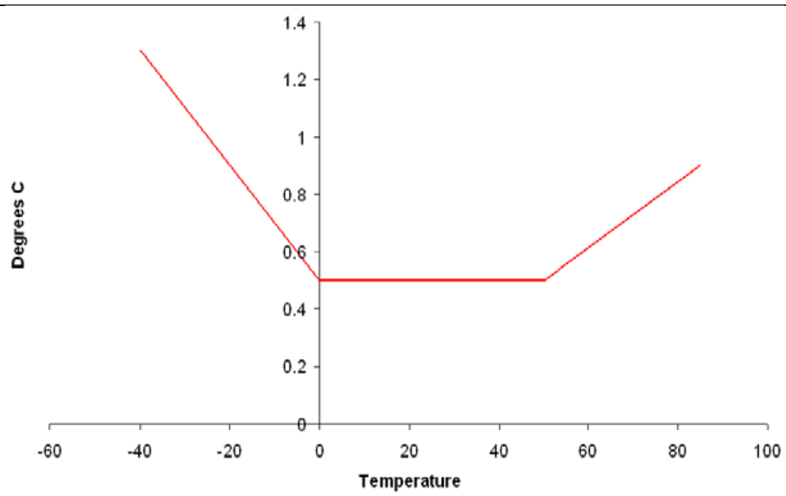
Features /specification	Details
Total reading capacity	16000 readings
Reading types	Actual, Min, Max
Logging interval	1 second to 10 days
Reading range	-40°C to +85°C (-40°F to +185°F)
Sensor type	Temperature: 10K NTC Thermistor (internally mounted)
Response time	Temperature: 25 mins to 90% FSD in moving air
Reading Resolution	Temperature: 0.05°C or better
Accuracy	

Table 3.6 Features and specification of Tinytag Talk 2 TK-4014.

The Tinytag Talk 2 TK-4014 is cost-effective indoor temperature data logger with built-in sensor. It is shown in Figure 3.9. The lightweight and compact design of the data logger makes it easy to deploy wherever it is placed. Tinytag Talk 2 data loggers are used in a wide range of applications such as building condition monitoring, fridge monitoring, academia etc. This type of loggers is designed for indoor use mainly. The features and specification of the data logger are listed in Table 3.6.

2) Case study of Passive House

A. Electricity meter optical pulse sensor (T7311)

The T7311 electricity meter optical pulse sensor with magnetic cup is coupling with 1 metre lead to connect to T3519-A pulse counters. The sensor head is incorporating a light guide, photo diode sensor and repeater LED for user feedback that the pulse has been counted. Pulse counting of pulses with a duration of > 100ms and a gap between pulses of > 20ms. Product Dimension: width: 19 mm; depth: 14 mm; length: 28 mm. T7311 LED lamp pulse (flashing LED lamp) sensor with magnetic steel attachment to the meter for easy attachment and detachment with the meter (see Figure 3.10).

Figure 3.10 T7311 LED lamp pulse sensor with the electricity meter.

B. Zigbee-HA wireless based 2 channel pulse counter (T3519-A)

The T3519-A counts pulses either via wired volt-free contacts or using a T7311 LED light sensor to count flashing LED lights on electricity or similar meters (shown in Figure 3.11). In this case study, this pulse counter is used for monitoring the main electricity consumption and PV electricity generation. Dual channel pulse counting of pulses with a duration of > 100ms and a gap between pulses of > 20ms. Product Dimension: width: 120 mm; depth: 60 mm; length: 110 mm, grey wall mounted enclosure. The features and specification of the pulse counter are listed in Table 3.7 as follow.

Figure 3.11 Zigbee T3519-A electricity pulse counter.

Features /specification	Details
Working voltage	2 × AA, low battery alert
Transmitting Current	< 40 mA
Receiving Current	< 40 mA
Standby Current	< 20 μA

Table 3.7 Features and specification of Zigbee pulse counter (T3519-A).

C. Electromagnetic pulse sensor for Sensus U6 Gas Meters (T7320SE)

The T7320SE electromagnetic pulse sensor, shown in Figure 3.12, is a magnetic sensing head with duel reed switches; one for permanent continuity, one for pulse sensing from a passing magnet within the meter. Design to work with the Sensus U6 gas meters, the T7320SE is housed in an encapsulated case that is affixed to the meter case via a strong adhesive pad. The T7320SE comes with a 1 meter flying lead designed to connect to a Zig 2.4 Mhz wireless mesh network pulse counter.

Figure 3.12 Pulse Block for Sensus U6 Gas Meters (T7320SE).

D. Wireless temperature and humidity sensor (T3534)

The T3534 is a temperature and humidity detecting device that uses the Zigbee HA protocol, shown in Figure 3.13. It is used for measuring internal ambient temperatures and humidity. The features and specification of the data logger are listed in Table 3.8 below.

Figure 3.13 Wireless temperature and humidity sensor (T3534).

Features /specification	Details
Communication range	50 m internal
Working voltage	1 × CR2 Lithium, low battery alert
Temperature Range	-10°C to 60°C
Humidity Range	10 to 90%
Transmitting Current	< 40 mA

Receiving Current	< 40 mA
Standby Current	< 2 μA
Accuracy	Humidity: ±1%
	Temperature: • ± 1°C at temperatures > -20°C < -10°C; • ± 0.7°C at temperatures > -10°C < 25°C; • 25°C ± 0.5°C; • ± 0.85°C at temperatures > 25°C < 90°C.

Table 3.8 Features and specification of temperature and humidity sensor (T3534).

E. Zigbee-HA wireless sensor for room carbon dioxide (T3571)

The T3571 wireless carbon dioxide detector is based on ZigBee HA protocol, shown in Figure 3.14. It is used for detecting indoor CO_2 concentration in the air and sending this information to the T3521 controller. It is mains powered, 230VAC, at an average of 10 mA. It measures CO_2 from 20ppm to 5,000 ppm with ± 30ppm or ± 5% tolerance (typical). Product Dimension: diameter: 95 mm; height: 68 mm; cable: 190 mm, white wall mounted enclosure.

Figure 3.14 Zigbee-HA wireless room carbon dioxide sensor (T3571).

F. External temperature sensor (T3528)

The external temperature sensor is mounted within a grey IP65 enclosure, shown in Figure 3.15. Product Dimension: width: 120 mm; depth: 60 mm; length: 110mm. The features and specification of the data logger are listed in Table 3.9 as follow.

Figure 3.15 External temperature sensor (T3528).

Features /specification	Details
Resolution	0.1°C
Working voltage	1 × CR2 Lithium, low battery alert
Temperature Range	-20°C to 90°C
Transmitting Current	< 40 mA
Receiving Current	< 40 mA
Standby Current	< 2 µA
Accuracy	• ± 0.7°C at temperatures > -20°C < 25°C; • 25°C ± 0.5°C; • ± 0.75°C at temperatures > 25°C < 90°C.

Table 3.9 Features and specification of external temperature sensor (T3528).

G. Zigbee Wireless Occupancy Sensor (T3524-B)

The occupancy sensor using passive IR detection with feral lens providing 120° detection around the centre point at a distance up to 6 metres. The sensor is shown in Figure 3.16. Product Dimension: diameter: 65 mm; height: 35 mm, white wall or ceiling mounted enclosure. The features and specification of the data logger are listed in Table 3.10 as follow.

Figure 3.16 Zigbee Wireless Occupancy Sensor (T3524-B).

Features /specification	Details
Detection range	6 meters
Working voltage	2 × AA, low battery alert
Spread	120°
Transmitting Current	< 40 mA
Receiving Current	< 40 mA
Standby Current	< 2 µA
Time	The T3524-B PIR scans its local environment in 10 second intervals. If no movement is recorded within the 10 second time frame the PIR will assume no one is present.

Table 3.10 Features and specification of Zigbee Wireless Occupancy Sensor (T3524-B).

H. Energy monitor hub (T3521)

The T3521 Energy Monitor Hub (shown in Figure 3.17) uses a high performance, low-power 1GHz Samsung ARM Cortex-A8 processor to provide the computing power for the Linux based software system. Its compact design has a variety of peripherals and interfaces which include Ethernet, USB Host & OTG, Serial ports, class 10 micro 8 GB SD card and manual control/reset switches. External communications to and from the Hub may be via the Internet using a standard router, Wi-Fi or wirelessly using an optional integral 3G module, SIM card and aerial. Product Dimension: width: 162 mm; depth: 132 mm; height: 36 mm. The features and specification of the data logger are listed in Table 3.11.

Figure 3.17 Energy monitor hub (T3521).

Features /specification	Details
Processor	Samsung ARM 1GHz Cortex-A8
Memory	512MB DDR2
Flash	• 256MB SLC NAND Flash • 8GB micro SDHC class 10
Energy Saving	Monolithic integrated power management chip
WiFi	• 802.11 b/g/n • Zigbee Wireless Technology
OS	Supporting Linux 2.6.32
Supporting capacity	Supports 64 wireless monitoring devices (add 20 more with each wireless plug in repeater)

Table 3.11 Features and specification of Energy monitor hub (T3521).

3.3.3 *Data record and collection*

All the monitored data needs to be collected and backed up at least once a month in order to minimise the risk of losing data caused by unforeseen factors. Generally, the beginning of each month is for collecting the latest month's recorded data and summarising the house performance.

For the Conventional House, the indoor temperature and relative humidity recorded by emon TH and electricity consumption measured by emon Tx V3 can be accessed via the OpenEnergyMonitor online system (shown in Figure 3.18). The data is updated every 5 minute automatically. The remaining monitored data gathered by the Tinytag Plus 2 and Tinytag Talk 2 data loggers has to be exported to the Tinytag software manually using specified cables. Thus, a monthly visit to the Conventional House is necessary for collecting all recorded data by those sensors. Otherwise, when the capacity of the data loggers is full, the sensor would stop collecting the latest data. Usually, the first Saturday of each month would be the onsite data collecting day decided with the house residents. For the Passive House, all the monitoring data measured by the Zigbee system can be accessed via the HeatingSave online system (shown in Figure 3.19).

Feeds Feed API Help

Id	Name	Tag	Datatype	Engine	Public	Size	Updated	Value
Node:10								
80320	CT1 Power	Node:10	REALTIME	PHPFINA		22Mb	10s ago	79
80321	CT1 kWh	Node:10	REALTIME	PHPFINA		22Mb	10s ago	3670
80322	CT1 kWhd	Node:10	DAILY	PHPTIMESERIES		5.3kb	10s ago	2.2
80323	VRMS AC Voltage	Node:10	REALTIME	PHPFINA		22Mb	10s ago	243
Node:21								
83070	Node21:DHT22 Temperature	Node:21	REALTIME	PHPFINA		716kb	9s ago	17.6
83073	Node21:DHT22 Humidity	Node:21	REALTIME	PHPFINA		716kb	9s ago	50.2
83075	Node21:Battery Voltage	Node:21	REALTIME	PHPFINA		716kb	9s ago	2.4
Node:22								
83071	Node22:DHT22 Temperature	Node:22	REALTIME	PHPFINA		716kb	3 mins ago	18.4
83072	Node22:DHT22 Humidity	Node:22	REALTIME	PHPFINA		716kb	3 mins ago	44.4
83074	Node22:Battery Voltage	Node:22	REALTIME	PHPFINA		716kb	3 mins ago	2.4
Node:19								
83076	Node19:DHT22 Temperature	Node:19	REALTIME	PHPFINA		716kb	4 mins ago	19.1
83077	Node19:DHT22 Humidity	Node:19	REALTIME	PHPFINA		716kb	4 mins ago	50.9
83078	Node19:Battery Voltage	Node:19	REALTIME	PHPFINA		716kb	4 mins ago	2.4
Node:20								
83079	Node20:DHT22 Temperature	Node:20	REALTIME	PHPFINA		716kb	47s ago	18.8
83080	Node20:DHT22 Humidity	Node:20	REALTIME	PHPFINA		716kb	47s ago	51.8
83081	Node20:Battery Voltage	Node:20	REALTIME	PHPFINA		716kb	47s ago	2.4

Figure 3.18 The OpenEnergyMonitor online system interface.

Actions	Device Name		Mac Address	Battery	Signal	Edit
	Master Bedroom - CO2		00:12:4B:00:04:F8:E2:C0	--	-59dBm	Edit
	Basic	--	--	--		
	Co2	Co2 measured value	425ppm	15th May, 2017 16:28:45		
	Living Room - CO2		00:12:4B:00:04:FB:3C:4B	--	-71dBm	Edit
	Basic	--	--	--		
	Co2	Co2 measured value	531ppm	15th May, 2017 16:28:38		
	Office - CO2		00:12:4B:00:04:DE:E1:B6	--	-70dBm	Edit
	Basic	--	--	--		
	Co2	Co2 measured value	441ppm	15th May, 2017 16:28:58		
	Double Height Family Room - CO2		00:12:4B:00:04:EA:92:38	--	-60dBm	Edit
	Basic	--	--	--		
	Co2	Co2 measured value	465ppm	15th May, 2017 16:27:15		

(a)

Range Extender DHFR	00:13:7A:00:00:02:68:85	--	-67dBm	Edit
Range Extender Master Bedroom	00:13:7A:00:00:02:68:7D	--	-55dBm	Edit
Range Extender Gas	00:13:7A:00:00:02:51:0F	--	-53dBm	Edit
Living Room - PIR	00:12:4B:00:05:B6:27:5D	3.0V	-43dBm	Edit
Living Room - T/RH	00:12:4B:00:04:EA:95:D4	3.3V	-61dBm	Edit
Basic	--	--	--	
Humidity Measurement	Relative humidity measured value	48.99%	15th May, 2017 16:30:31	
Power Config	Battery voltage	3.3V	15th May, 2017 16:30:36	
Temp Measurement	Temp measured value	24.46°C	15th May, 2017 16:30:30	
Office T/RH	00:12:4B:00:04:EB:3C:F5	3.0V	-59dBm	Edit
Basic	--	--	--	
Humidity Measurement	Relative humidity measured value	45.93%	03rd Mar, 2017 18:45:26	
Power Config	Battery voltage	3.0V	03rd Mar, 2017 18:45:27	
Temp Measurement	Temp measured value	20.90°C	03rd Mar, 2017 18:45:26	
Master Bedroom T/RH	00:12:4B:00:04:EB:36:82	3.3V	-68dBm	Edit
Basic	--	--	--	
Humidity Measurement	Relative humidity measured value	52.46%	15th May, 2017 16:31:45	
Power Config	Battery voltage	3.3V	15th May, 2017 16:31:46	
Temp Measurement	Temp measured value	22.02°C	15th May, 2017 16:31:45	
Double height family room-PIR	00:12:4B:00:05:B6:29:A1	3.0V	-43dBm	Edit
Double hight family room-T+RH	00:12:4B:00:04:EB:46:DE	3.2V	-44dBm	Edit
Basic	--	--	--	
Humidity Measurement	Relative humidity measured value	56.66%	15th May, 2017 16:29:37	
Power Config	Battery voltage	3.2V	15th May, 2017 16:29:42	
Temp Measurement	Temp measured value	21.04°C	15th May, 2017 16:29:36	
Electricity Meter	00:0D:6F:00:03:E2:42:07	2.3V	-42dBm	Edit
Basic	SW build id	4.0.1.0	05th May, 2017 15:18:49	
Power Config	Battery voltage	2.3V	15th May, 2017 16:30:19	
Simple Metering	Current summation delivered Current max demand received	5818941 1186201609	15th May, 2017 16:32:16 09th Apr, 2016 18:42:34	
Simple Metering	Current summation delivered	8365176	15th May, 2017 16:32:16	
External Temperature (sn177272)	00:0D:6F:00:03:C1:63:C0	2.9V	-43dBm	Edit
Basic	Version SW build id	1 3.0.1.0	01st Sep, 2016 14:59:51 02nd Mar, 2017 21:56:04	
Power Config	Battery voltage	2.9V	15th May, 2017 16:30:00	
Temp Measurement	Temp measured value	14.19°C	15th May, 2017 16:30:21	
Temp Measurement	Temp measured value	14.26°C	15th May, 2017 16:30:12	
Temp Measurement	Temp measured value	--	15th May, 2017 16:31:14	
Gas Meter	00:0D:6F:00:03:E2:3B:7C	2.6V	-43dBm	Edit
Basic	SW build id	4.0.1.0	14th May, 2017 22:04:43	
Power Config	Battery voltage	2.6V	15th May, 2017 16:31:54	
Simple Metering	Current summation delivered Current max demand received	119932 1186201609	15th May, 2017 16:31:54 11th Apr, 2016 22:18:41	
Simple Metering	Current summation delivered	0	15th May, 2017 16:30:08	

(b)

Figure 3.19 The HeatingSave online system: (a) CO_2 network, (b) other sensors network.

3.4 Computational modelling and simulation

20 main building energy simulation software regarding their features and capabilities were compared by Crawley, D. B. et al [242]. Based on the information published in the paper, it was found that EnergyPlus offered the highest number of features in terms of:

1) Zone loads;

2) Building envelope, daylighting and solar (BDS);
3) Infiltration, ventilation and multi-zones airflow (IVAAF);
4) HVAC systems (HVAC);
5) Economic evaluation.

The comparison of the number of features in each software compared to the total features is shown in Table 3.12. In addition, Table 3.13 compares a number of renewable energy (RE) systems, pre-configured systems and discrete HVAC components in the each software.

Software	Zone loads	BDS	IVAAF	HVAC	Economic Evaluation	Total features
BLAST	4	2	1	1	0	8
BSim	4	3	6	1	3	17
DeST	6	3	7	2	3	21
DOE-2.1	5	1	1	0	4	11
ECOTECT	3	1	1	1	1	7
Ener-Win	4	1	3	1	1	10
Energy Express	6	0	1	1	2	10
Energy-10	2	1	1	0	1	5
EnergyPlus	8	8	6	2	4	28
eQUEST	4	2	2	0	4	12
ESP-r	5	6	8	2	1	22
IDA-ICE	7	4	4	2	2	19
IES<VE>	9	0	7	2	3	21
HAP	4	5	1	1	3	14
HEED	6	1	1	1	4	13
PowerDomus	4	2	5	1	4	16
SUNREL	3	2	5	1	0	11
Tas	8	4	6	1	2	21
TRACE	5	6	1	1	4	17

TRNSYS	5	3	6	2	4	20
Total features	1.1. 9	1.2. 9	1.3. 9	1.4. 2	1.5. 4	1.6. 33

Table 3.12 The comparison of the number of features in each software.

Software	RE systems	Pre-configured systems	Discrete HVAC components	Total available
BLAST	1	14	51	66
BSim	2	14	24	40
DeST	2	20	34	56
DOE-2.1	1	16	39	56
ECOTECT	4	0	0	4
Ener-Win	0	16	24	40
Energy Express	0	5	8	13
Energy-10	2	7	15	24
EnergyPlus	4	28	66	98
eQUEST	2	24	61	87
ESP-r	7	23	40	70
IDA-ICE	1	32	52	85
IES<VE>	3	28	38	69
HAP	0	28	43	71
HEED	0	10	7	17
PowerDomus	1	8	15	24
SUNREL	2	1	3	6
Tas	2	23	26	51
TRACE	0	26	63	89
TRNSYS	12	20	82	114
Total systems	1.7. 12	1.8. 34	1.9. 98	1.10. 144

Table 3.13 The comparison of the number of systems in the each software.

In this study, the five main features listed in Table 3.12 are the main priority. Hence EnergyPlus was chosen as the simulation tool and DesignBuilder software was used as the user interface software for EnergyPlus.

3.4.1 *Software description*

Nowadays, many different criteria must be balanced in order to provide high quality, comfortable buildings that also comply with building regulations, minimise upfront costs to the client, optimise on-going energy costs and reduce environmental impact. DesignBuilder is the first comprehensive user interface to the EnergyPlus dynamic thermal simulation engine [230, 231]. Accurate environmental performance data and stunning rendered images or movies could be generated at any stage in the design process. DesignBuilder enables users to: easily compare design alternatives; optimise your design at any stage with client's variable objectives; model even complex buildings quickly; effortlessly import existing BIM and CAD design data; generate impressive rendered images and movies and simplify Energy Plus thermal simulation. Thus, the DesignBuilder software has been chosen for this study.

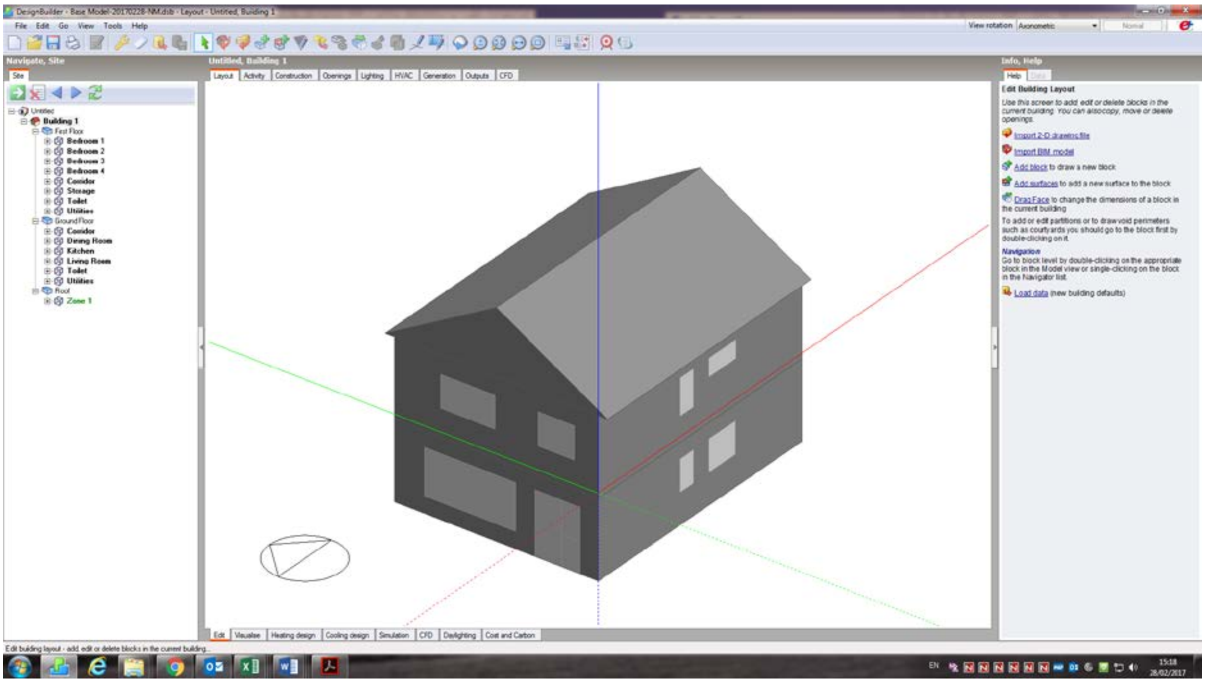


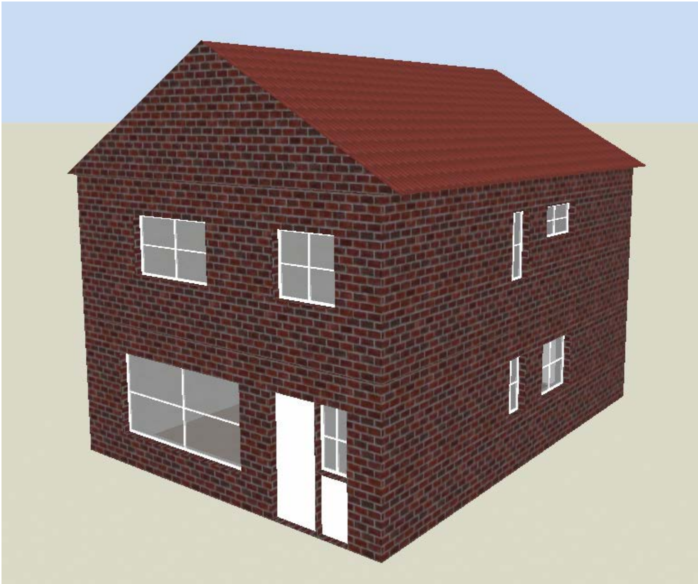
Figure 3.20 DesignBuilder software user interface.

One of the methodologies of this case study is to develop a DesignBuilder model for the Conventional House. It is used in the study to simulate the house energy consumption and indoor environmental condition. While the model is validated by actual monitoring data, it would help evaluate the energy performance of this Conventional House and recommend the most efficient energy saving plan. The DesignBuilder software user interface is shown in the following Figure 3.20.

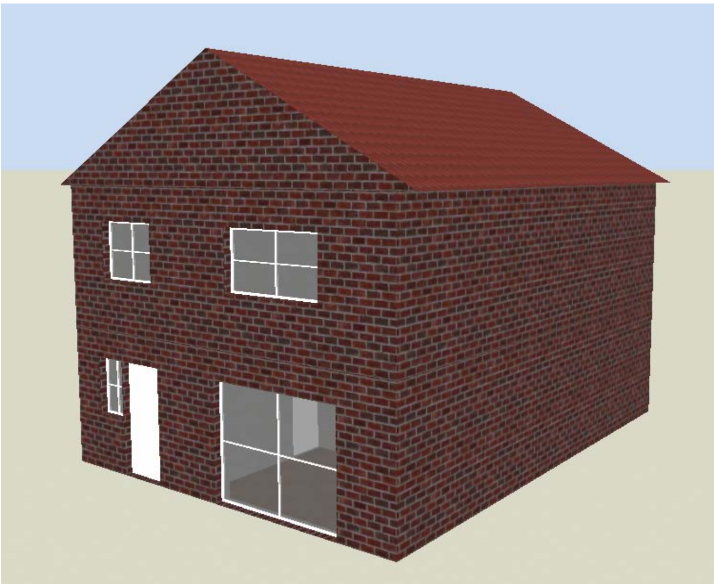
The Layout tab in the edit screen is where we create the model geometry using the drawing tools. The menu option and tool bar display at the top of the screen in the familiar windows format. The remaining tabs including Activities, Construction, Openings, Lighting, HVAC and Generation at the top of the edit screen are where the data is entered for each aspects of the model. To the left of the edit screen, is another navigation panel, which allows you to identify and select specific areas of the model. To the right of the edit screen, is info panel, which is only visible when learning mode is switched on. It provide useful options and guidance relevant to the selected operation. Below the edit screen, clicking the visualise tab, we can see the render view of the model. This is a very useful tool helping us to check things like internal geometry and shading from external object. The Heating design, Cooling design, Simulation and CFD tabs below the edit screen enable us to calculate heating and cooling plant sizes and to take simulation to determine thermal energy performance and to take CFD analysis on the building of specific part of it. The Daylighting tab can calculate daylight illuminance, average daylight factor and uniformity output for each zone using the advanced Radiance simulation engine. Construction cost, utility tariffs and life cycle analysis of buildings are able to be calculated in the Cost and Carbon tab below the edit screen. Moreover, DesignBuilder Optimisation module is the first fully-featured optimisation and cost-benefit analysis tool for building design. It helps to identify the design options with the very best combinations of cost, energy and comfort performance.

3.4.2 *Model construction*

The first step to set up the energy model in DesignBuilder, was to select the exact location and corresponding weather file for the selected property. The related building regulations may affect the performance of the target building chosen for the study. For instance, the national regulations of UK and China are different for the construction methods and material selection to satisfy their minimum indoor winter heating temperatures under different climate conditions. Thus, this step is one of the most important phases for the model construction. The second step was to import the house floor plan drawn by AutoCAD into the software. After that, entered the floor height and roof parameter of the dwelling so the building envelop could be formed through the software. Next step was to add the internal walls, windows and doors according to the floor plans. The layout of the house had been created via the steps stated above. The following stage was to input the actual detailed settings of the target building in Activities, Construction, Openings, Lighting and HVAC tabs for simulation. For the Conventional House, the following Figure 3.21 shows the external facade of the dwelling modelled by DesignBuilder.



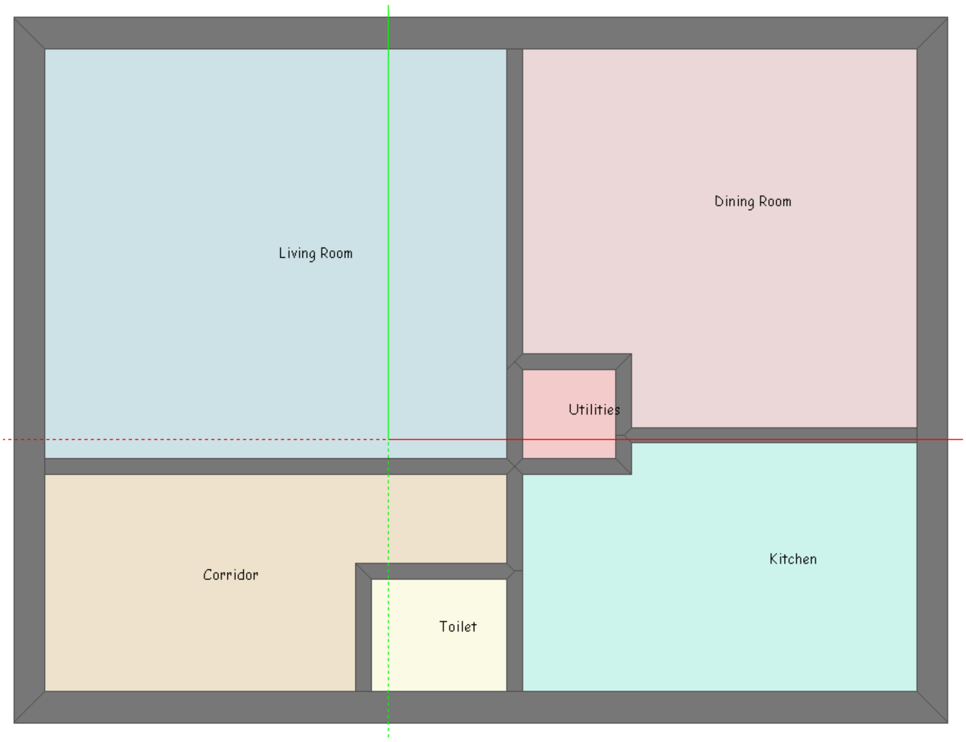
(a)



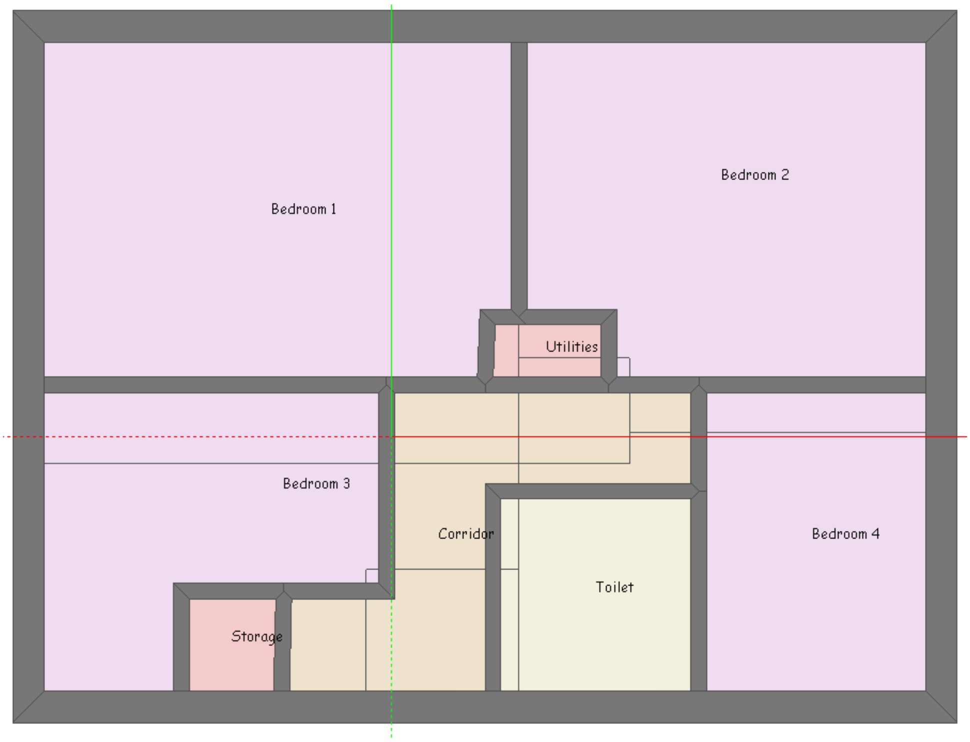
(b)

Figure 3.21 Conventional House facades generated by DesignBuilder: (a) South west façade, (b) North east façade.

Two different floor plans of the DesignBuilder model that include living room, dining room, kitchen, toilets, bedrooms, etc. are shown in Figure 3.22.



(a)

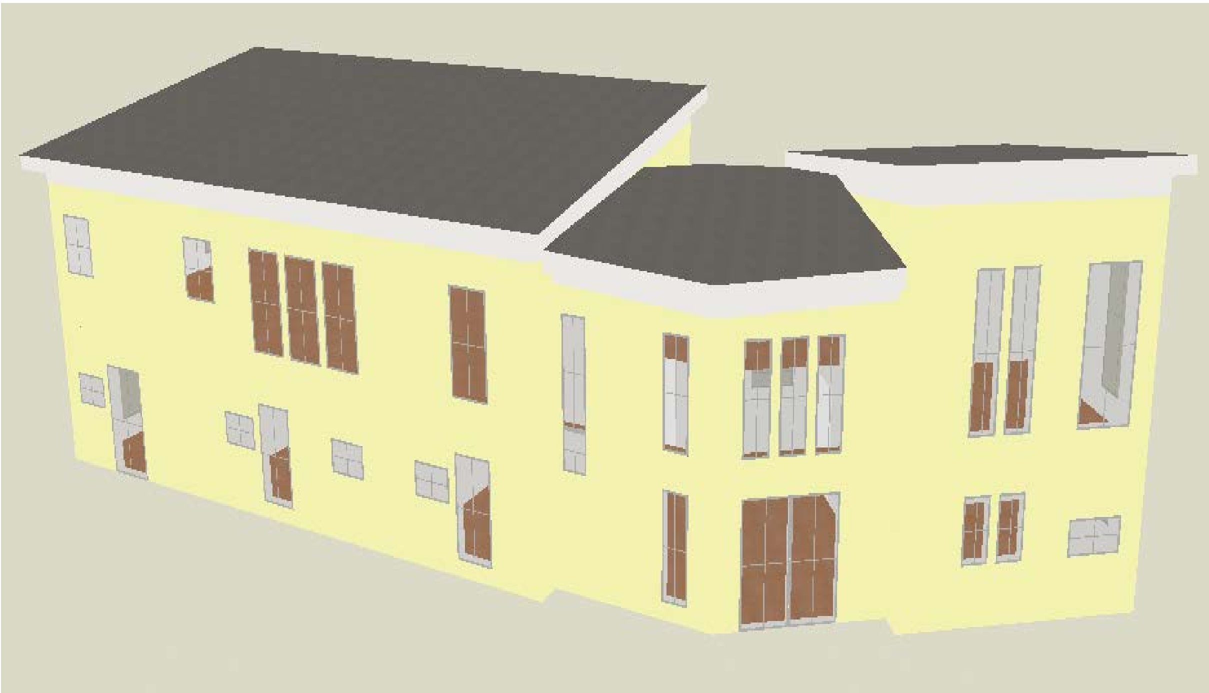


(b)

Figure 3.22 Conventional House floor plans generated by DesignBuilder: (a) Ground floor plan, (b) First floor plan.

For the Passive House, the following Figure 3.23 shows the external facade of the dwelling modelled by DesignBuilder.

(a)

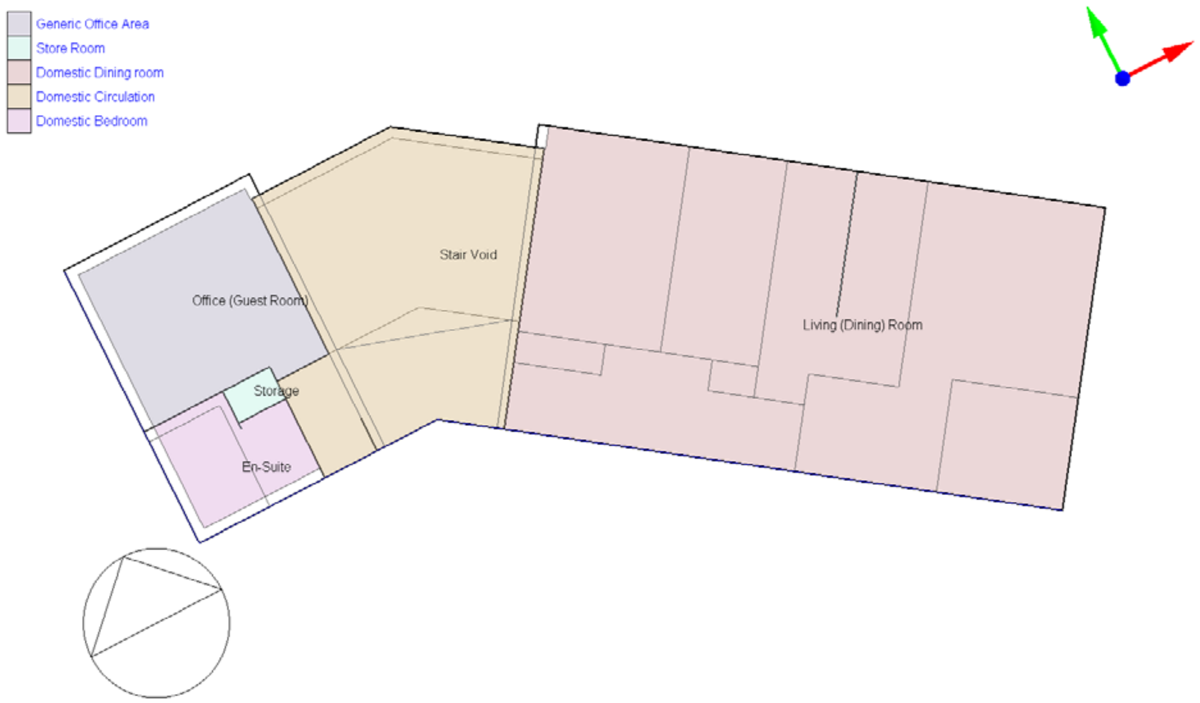


(b)

Figure 3.23 Passive House facades generated by DesignBuilder: (a) front façade, (b) rear façade.

Two different floor plans of the DesignBuilder model that include living room, dining room, kitchen, toilets, bedrooms, etc. are shown in Figure 3.24.

(a)



(b)

Figure 3.24 Passive House floor plans generated by DesignBuilder: (a) Ground floor plan, (b) First floor plan.

3.4.3 *Parameter input*

After the initial DesignBuilder models setting up, the actual building construction information and their bespoke operation schedules needs to be created and implemented in the software. The following three sections describe the parameter input in the DesignBuilder to achieve the accurate simulation models.

A. Construction information

Table 3.14 describes the detailed construction information for both Conventional House and Passive House selected for this research. Layers for the components are all described from the outer to inner surface.

Components' U-value (W/m^2K)	Conventional House (CH) model	Passive House (PH) model
External wall	0.54 [1]	0.123 [5]
Floor slab	0.25 [2]	0.090 [6]
Roof	2.93 [3]	0.064 [7]
Glazing	1.96 [4]	0.600 [8]

Table 3.14 Description of the construction information for both target buildings.

[1]	Layer 1:	102 mm Brickwork
	Layer 2:	50 mm Air layer
	Layer 3:	35 mm Glass fibre quilt
	Layer 4:	100 mm Concrete blocks
	Layer 5:	13 mm Plaster
[2]	Layer 1:	100 mm Urea formaldehyde foam (ground floor)
	Layer 2:	100 mm Cast concrete (ground floor)
	Layer 3 (1):	70 mm Floor screed
	Layer 4 (2):	30 mm Timber flooring
[3]	Layer 1:	25 mm Clay tile

Layer 2: 20 mm Air gap

Layer 3: 5 mm Roofing felt

[4] Generic clear, double 19 mm 3PYR B/13Air/3

[5] Layer 1: 10 mm Parvatex flexible render system

Layer 2: 60 mm Diffutherm

Layer 3: Breathable membrane

Layer 4: 235 mm Knauf Frametherm 32

Layer 5: 9.5 mm OSB

Layer 6: Siga Majpell fully taped

Layer 7: 25 mm PIR (Celotex/ Thermix)

Layer 8: 12.5 mm plasterboard

Layer 9: Plaster skim

[6] Layer 1: 50 mm blinding sand (ground floor)

Layer 2: 200 mm EPS laid with offset joints to above (ground floor)

Layer 3: 200 mm EPS (ground floor)

Layer 4: 1200 g waterproof membrane (ground floor)

Layer 5 (1): 100 mm reinforced concrete

Layer 6 (2): 22 mm engineered Oak /carpet and underlay/ tiled

[7] Layer 1: 120 mm PIR insulation (Celotex) laid with offset joints to the above

Layer 2: 130 mm PIR insulation (Celotex)

Layer 3: Waterproof membrane

Layer 4: 18 mm OSB type 3 deck

Layer 5: 160 mm acoustic/ thermal insulation

Layer 6: 140 mm air gap

Layer 7: 12.5 mm plasterboard with all joints taped using Siga products

Layer 8: Plaster skim

[8] Internorm HF 300, triple 48mm coated clear 4b/18Ar/4/18Ar/b4 (3N2); U-value for the stainless steel spacers frame: 0.8 W/ (m^2K); thermal insulation value of window: 0.79 W/m^2K

B. Activity and operation

Table 3.15 describes the detailed typical activity and operation for both Conventional House and Passive House selected for this research.

Activity	CH model	PH model
Occupancy density (People/m^2)	0.033	0.009
Heating set back temperature (°C)	16	20
Cooling set back temperature (°C)	N/A	N/A
Computer gains (W/m2)	3	3
Miscellaneous	3	3
Luminaire Type	Suspended	Suspended
Lighting consumption (W/m2)	2.5	2.5
Radiant fraction	0.42	0.42
Convective fraction	0.40	0.40
Visible fraction	0.18	0.18

Table 3.15 Description of the activity and operation for both target buildings.

C. HVAC

The model setting under the HVAC tab was one of the most important section for the energy models. As heating is the biggest energy consumer for a residential building, the heating type, heating schedules and the energy efficiency decide the thermal performance of the properties. Besides, the arrangement for ventilation and domestic hot water can also be set in the HVAC tab. The HVAC for each dwelling is different and it is affected by its own occupancy and residents' requirements. For instance, the number of residents, the time each resident stays in the dwelling, the type of heating system, ventilation methods, the expected winter indoor temperature and energy supplier will all lead to different energy consumption. Normally, in residential buildings, the energy consumption of DHW and winter heating is based on their own demands. A pre-set working schedule for gas boiler or electrical water tank to meet the demand can be known during the field study stage. Table 3.16 describes the detailed heating, ventilation and air conditioning (HVAC) settings for both Conventional House and Passive

House selected for this research. Occupancy has been taken into account for the HVAC settings.

HVAC	CH model	PH model
Heating system type	Radiator heating, Boiler HW, Nat Vent	Heating and Ventilation Ducted Supply + Extract
Heating schedule	Conventional House Heating Schedule: Compact, Conventional House Heating and DHW, Fraction, Through: 4 May, For: AllDays, Until: 06:30, 0, Until: 07:45, 1, Until: 18:00, 0, Until: 20:30, 1, Until: 24:00, 0, Through: 3 Nov, For: AllDays, Until: 24:00, 0, Through: 31 Dec, For: AllDays, Until: 06:30, 0, Until: 07:45, 1, Until: 18:00, 0, Until: 20:30, 1, Until: 24:00, 0;	Heating set point schedule Schedule: Compact, On, Any Number, Through: 12/31, For: AllDays, Until: 24:00, 20 ;
Prime mover	Floor mounted fan assisted gas boiler	Condensing gas boiler
Boiler Seasonal CoP	0.45	0.90
DHW Type	Instantaneous	Instantaneous
DHW CoP	0.45	0.90

Ventilation	Natural ventilation	Mechanical ventilation with heat recovery system (MVHR), 92% efficiency

Table 3.16 Description of the HVAC for both target buildings.

3.5 Model validation

ASHRAE Guideline 14-2002 [232] is used to validate the building models in this research [218, 241]. This entails cumulative variation of the coefficient of variation of root mean square error (CV(RMSE)) and determining mean bias error (MBE) results for energy consumption and indoor environmental condition using hourly monitored data. ASHRAE Guide 14 considers a building model calibrated if hourly CV(RMSE) and MBE values fall within 15% and ±5% spectrums respectively. In addition, histograms of residuals are constructed for closer examination of model deviations from actual figures.

Equation (1) were used to calculate the errors between actual monitoring data and simulation results. Following the convention of using the measured values as the reference point, percentage error results were generated for energy and indoor climate predictions of the model by Equation (2). CV(RMSE) and MBE between actual and simulated results were calculated by Equation (3) and (4) to validate the building model.

$$\varepsilon_i = M_i - S_i \quad (1)$$

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

$$CV(RMSE) = \frac{\sqrt{\sum_{i=0}^{N_i}[(M_i - S_i)^2/N_i]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \quad (3)$$

$$MBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \quad (4)$$

Where M_i and S_i are respective measured and simulated data at time instance i; and ε_i is the error at instance i.

3.6 Application of the validated models for further studies

While the building models are validated, they are used to conduct further model development to improve building performance and solve the real problems. For the Conventional House, the case study aims to reduce its energy demand by utilizing passive retrofitting methods. Apply the Passive House building fabric materials and high efficiency domestic gas boiler in the simulation model to analyse the building improvements (including energy saving and achieving comfortable indoor environmental condition) compare to its current status. Discuss the estimated results and the feasibility for Conventional House retrofitting using passive energy saving methods. For the Passive House, the energy consumption and indoor environmental condition of the property were excellent for most of time. The case study aims to improve the dwelling's performance in summer to solve the problem of overheating. Apply the Conventional House building fabric materials and regular domestic utilities in the simulation model to find out its superiority of building performance. Discover the optimised solutions to overcome the summer overheating problem for the Passive House.

3.7 Summary

The methodology adopted for the research, i.e. building audits, actual data monitoring and collection, models set up using DesignBuilder software for simulation, model validation and the validated models for further studies were introduced and discussed in detail in this chapter. The equipment and monitoring sensors and data loggers used for the case studies were also presented.

Chapter 4. Case Study of a Conventional House

4.1 Introduction

A residential dwelling selected for this case study is a two-story detached Conventional House located in Newcastle upon Tyne, United Kingdom, built in 1970s (shown in Figure 4.1). Newcastle upon Tyne is situated in the North East England, which is believed to be the coldest region of England and its climate is oceanic one. Compare to other British cities, Newcastle upon Tyne has cooler summer but colder winter. Generally, the residential buildings within this region require more heating energy during the winter heating season. This 90 m^2 property comprises an entrance hall, a living room, a dining room, a kitchen, a toilet, four bedrooms and a bathroom. Externally there is a pleasant forecourt garden to the front and a mature garden to the rear. There is a garage which is accessed via the front lane. The house benefits from double glazing windows, cavity wall with insulation and gas central heating for keeping the dwelling warm in winter. But this is a house that without cooling and mechanical ventilation systems. For most of the time during the research period, the house was occupied by three adults before September 2016. Since then, there are three residents in total living in the house, including one professional who do not work from home, one housewife and one child.

Mains electricity and gas are the two main energy sources supplied to this Conventional House. Electricity is consumed for providing household lighting and appliance while gas is for supplying domestic hot water, space heating and cooking. Domestic hot water and space heating for this house was provided by a low efficiency non-condensing conventional gas boiler: POTTERTON Kingfisher Mf CFL 50, which discontinued in 2007. A hot water storage tank was installed to store hot water for space heating or domestic use. The summer and winter working schedules of the boiler were different depending on the different seasonal residents' demands.

The aim of this work was to carry out an investigation of the dwelling's energy consumption and indoor environmental condition by day to day data measurements and recording; set up a computational model for the house; and then use the measured data to validate the model; use the validated model to find out which retrofitting methods can reduce the energy consumptions of the house. A general methodology for retrofitting found from this case study, which would be deployed for other target buildings in later stage of my research. Several general field studies and a thermal study of this property were carried out to help understand the house performance.

(a)

(b)

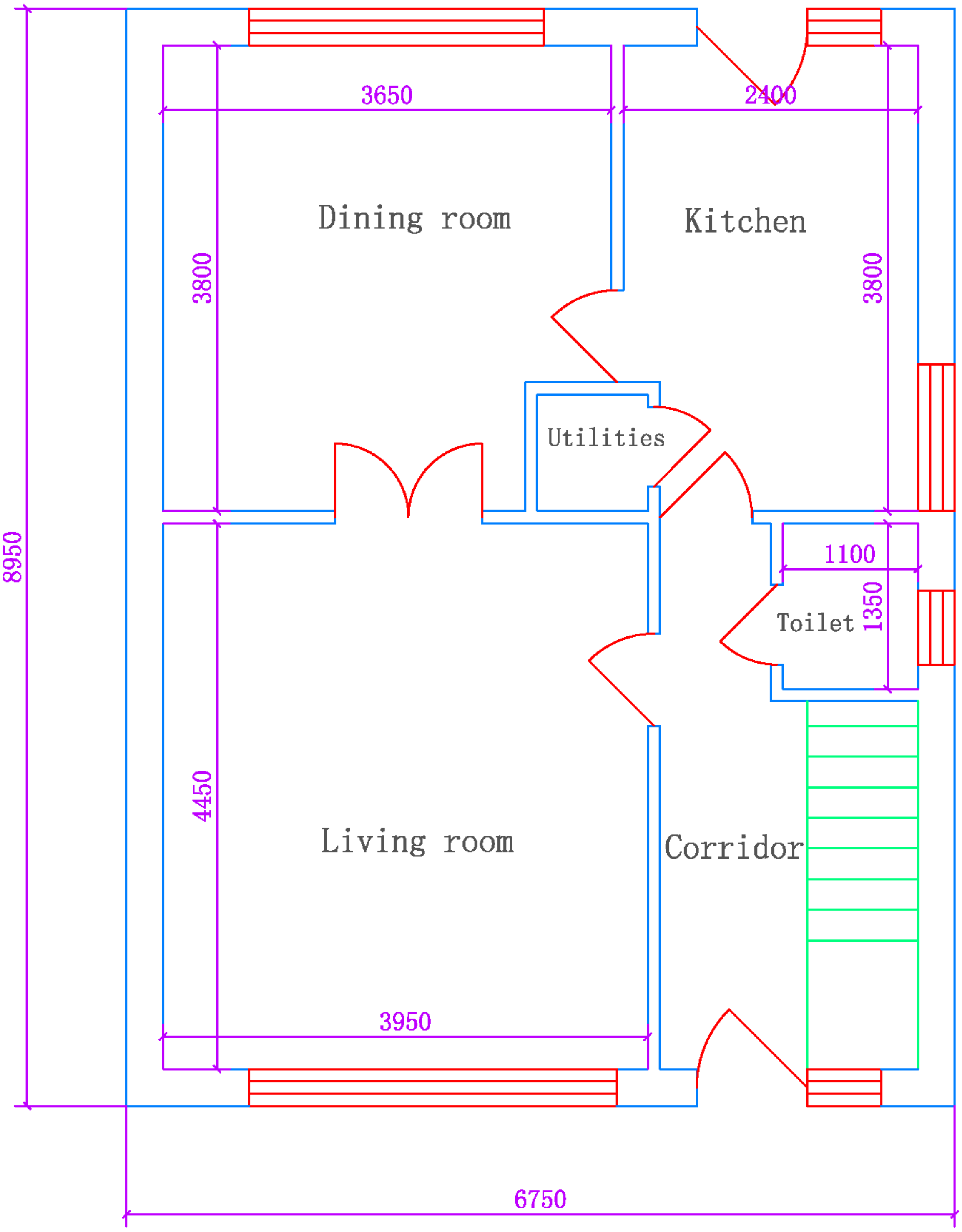
Figure 4.1 Photographs of building facedes of the selected detached house: (a) West (front) façade, (b) East (rear) façade.

4.1.1 *Measurement of the house structure*

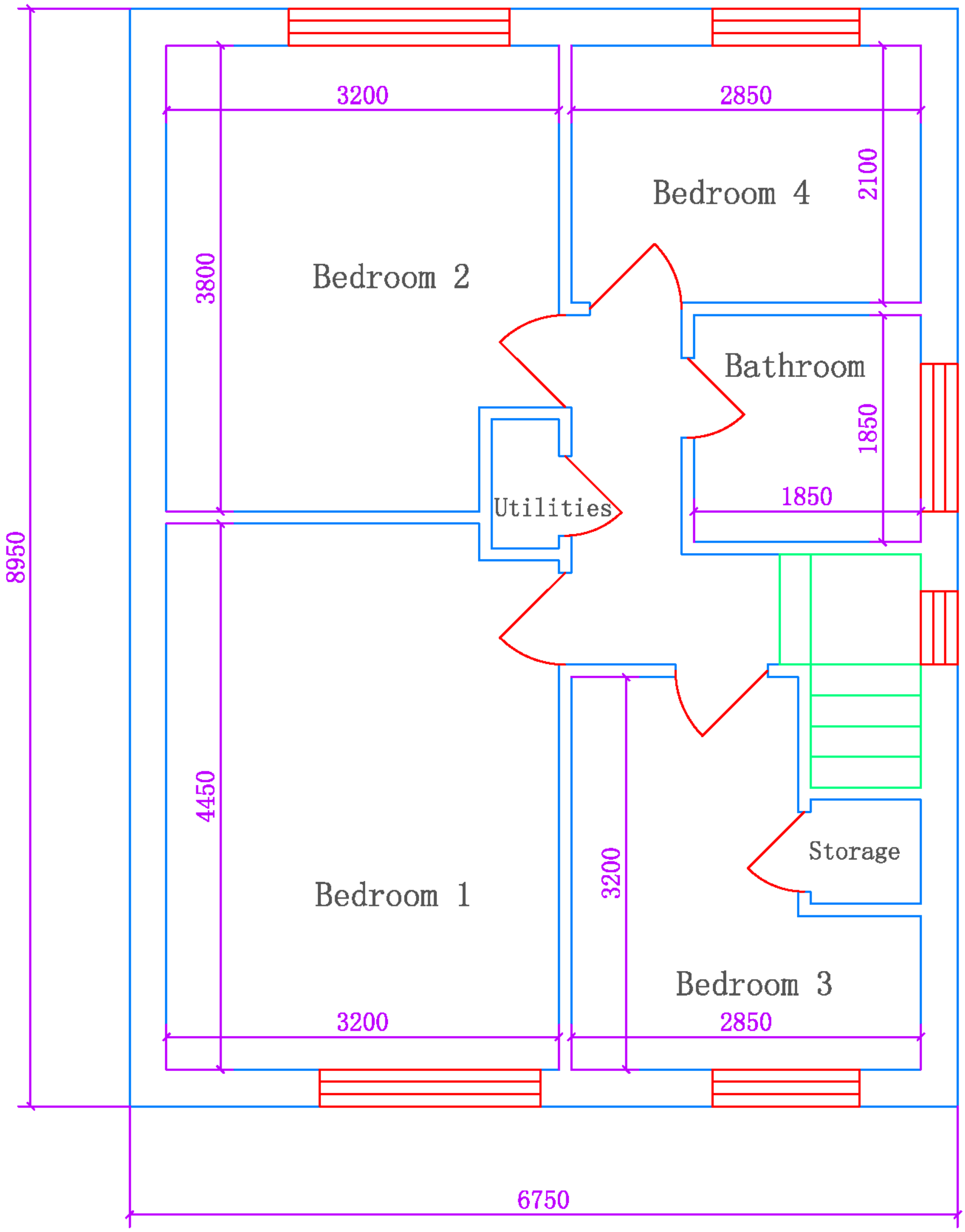
The first audit was conducted in April 2014 for the preparation work of this study. The house general information (e.g. floor plans, residents' occupancy and space heating schedules) and also the annual electricity and gas bills were gathered during the first field study. However, there were no detailed information about the floor plans of this dwelling provided by the house owner or house builders. The detailed house dimensions measurements were conducted by myself in order to set up an accurate building model of this Conventional House. The dimensions of the house were measured by two different tape measures (8 m and 30 m long, respectively). Both precision of measurements of the tapes are 1 mm. As the measured results indicated, the whole property's dimension is 6.75 m × 8.95 m and the building area of the house is about 120.80 m^2 and the usable floor area of this Conventional House is calculated to 90 m^2. Storey heights of ground floor and first floor are both 2.55 m. Thicknesses of external and internal walls are 300 mm and 100 mm, respectively. The room dimensions of the property have been measured and list in Table 4.1. Floor plans and elevations of the house have been drawn by Auto CAD software and they are shown in Figure 4.2 and Figure 4.3.

Floor	Zones	Measured dimensions (m)	Floor areas (m^2)
Ground floor	Entrance hall	1.20 × 4.45	5.34
	Living room	3.95 × 4.45	17.58
	Dining room	3.65 × 3.80	13.87
	Kitchen	2.40 × 3.80	9.12
	Toilet	1.10 × 1.35	1.49
First floor	Bedroom 1	3.20 × 4.45	14.24
	Bedroom 2	3.20 × 3.80	12.16
	Bedroom 3	2.85 × 3.20	9.12
	Bedroom 4	2.85 × 2.10	5.99
	Bathroom	1.85 × 1.85	3.42

Table 4.1 Room dimensions of the house.

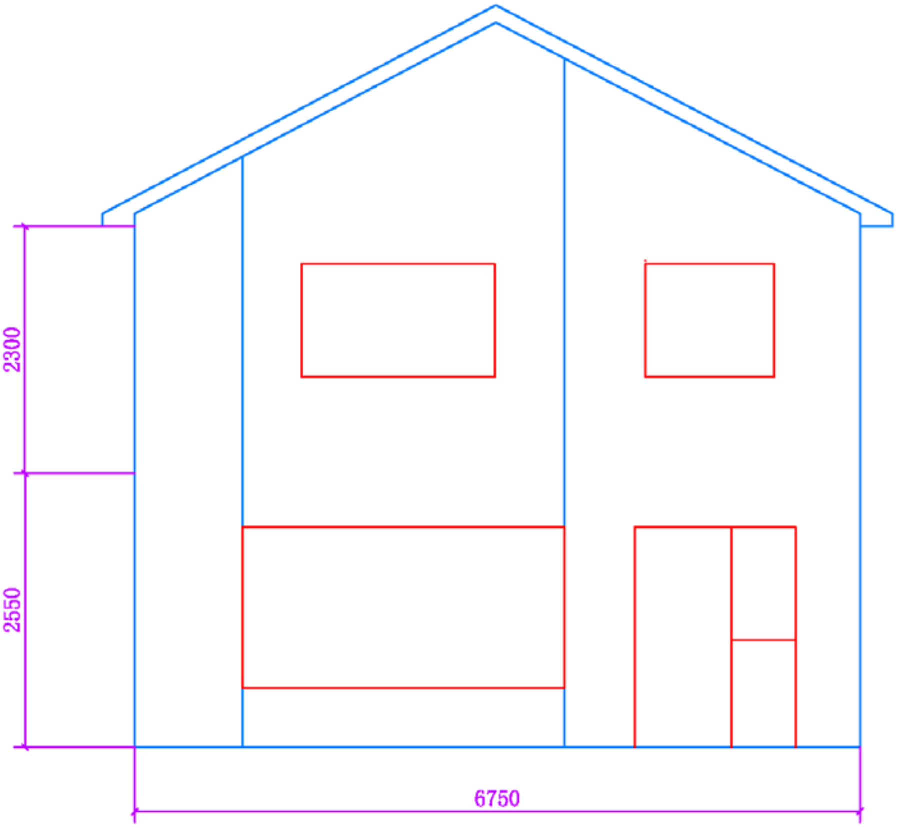

3650
2400
Dining room
Kitchen
3800
3800
Utilities
1100
Toilet
1350
8950
4450
Living room
Corridor
3950
6750

(a)

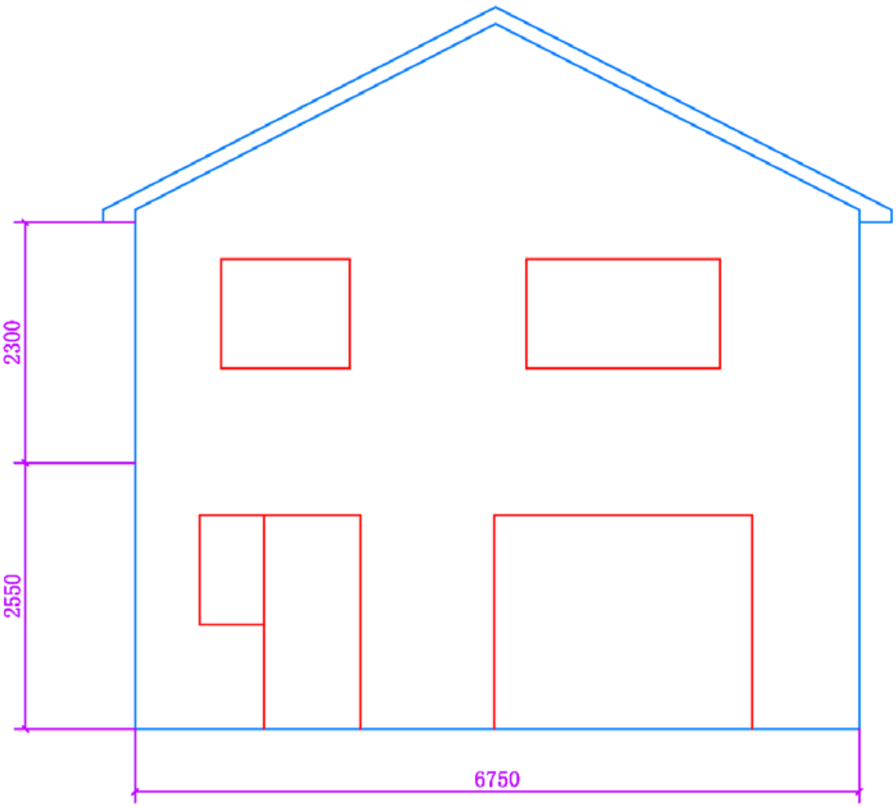


(b)

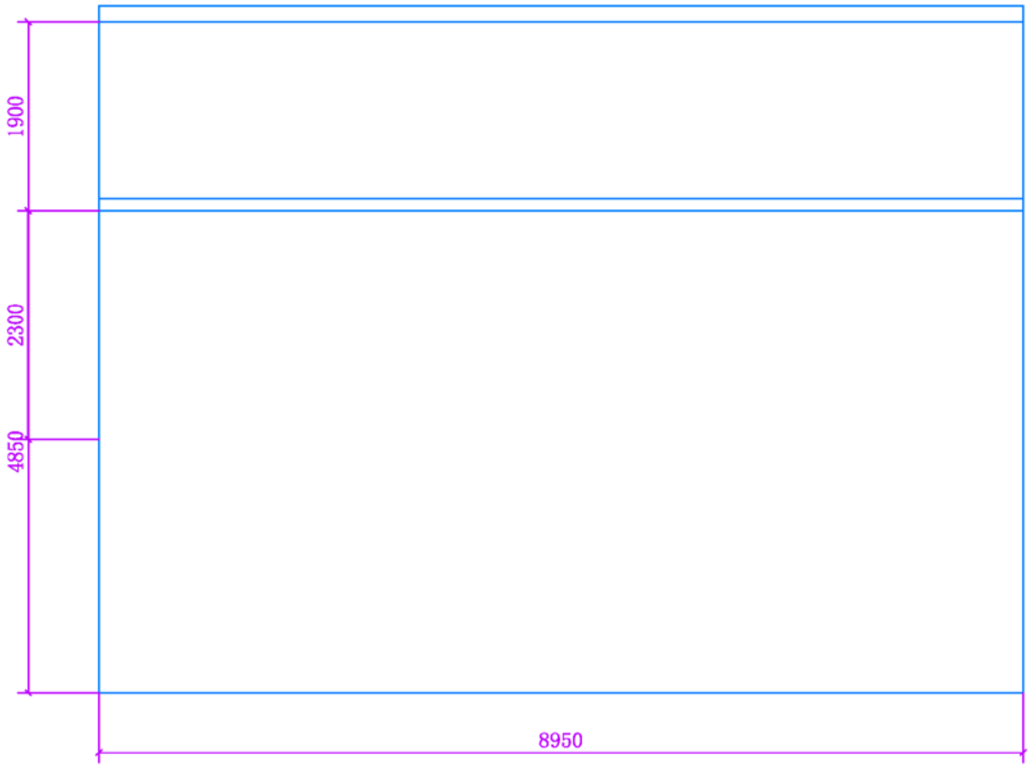
Figure 4.2 House floor plans drawn by Auto CAD: (a) Ground floor plan, (b) First floor plan.



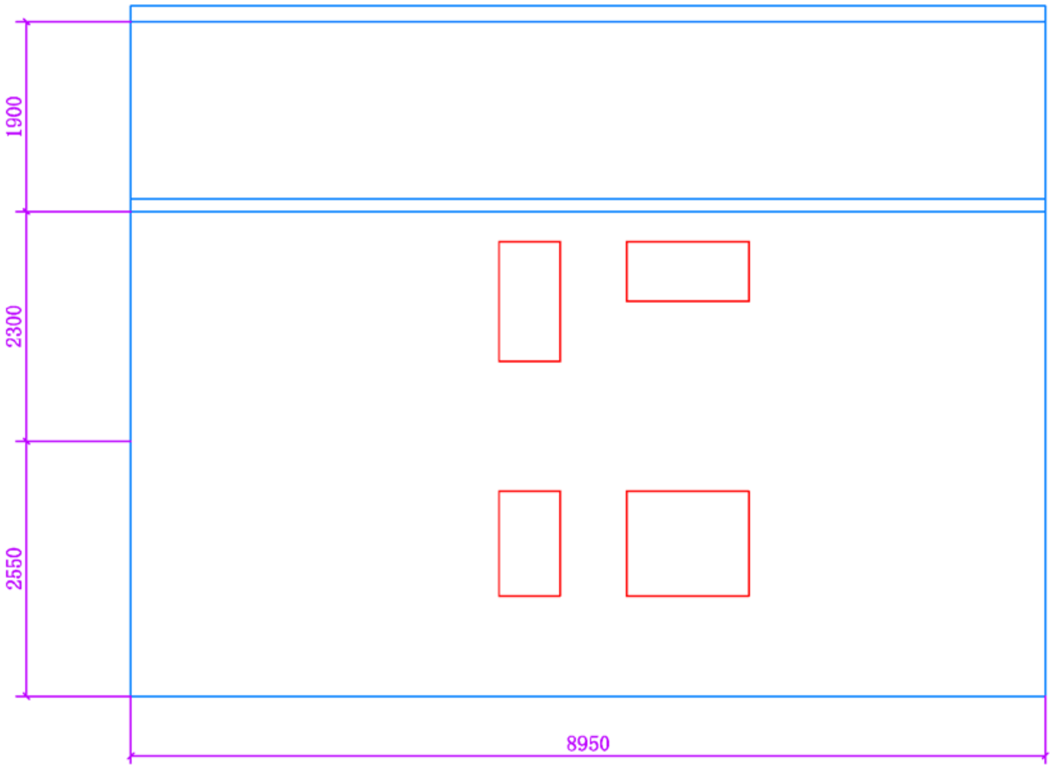
(a)



(b)



(c)



(d)

Figure 4.3 House elevations drawn by Auto CAD: (a) West (front) elevation, (b) East (rear) elevation, (c) North elevation, (d) South elevation.

4.1.2 *Audits of energy consumption*

Prepayment electricity (from October 2012 to September 2013) and gas (from February 2013 to January 2014) statements for 12 months, were provided by the house owner. During those bill periods, for electricity consumption, total usage was 2110.64 kWh and the average usage per month was about 175.89 kWh. For gas consumption, total gas usage was 7650.04 kWh and average monthly usage was about 637.50 kWh. The monthly electricity and gas consumption during the bill period was shows in Table 4.2.

Electricity consumption		Gas consumption	
Month	Usage (kWh)	Month	Usage (kWh)
October 2012	162.36	-	-
November 2012	185.55	-	-
December 2012	208.74	-	-
January 2013	208.74	-	-
February 2013	185.55	February 2013	1215.82
March 2013	185.55	March 2013	697.98
April 2013	170.48	April 2013	697.98
May 2013	170.48	May 2013	450.40
June 2013	162.36	June 2013	251.96
July 2013	154.24	July 2013	251.96
August 2013	154.24	August 2013	251.96
September 2013	162.36	September 2013	251.96
-	-	October 2013	450.40
	-	November 2013	697.98
-	-	December 2013	1215.82
-	-	January 2014	1215.82
Total usage	2110.64	Total usage	7650.04
Monthly average	175.89	Monthly average	637.50

Table 4.2 Monthly energy consumption of 2013.

Monthly weather and temperature data is also a factor to affect the energy consumption of each month. The weather data shown in Table 4.3 was obtained from NASA Surface meteorology and Solar Energy: RETScreen database by inputting the latitude and longitude of Newcastle upon Tyne. These data were gathered and provided by over 200 satellite-derived meteorology and solar energy parameters and was monthly averaged from 22 years data.

		Unit		Climate data location	
Latitude		°N		54.974	
Longitude		°E		-1.613	
Elevation		m		90	
Earth temperature amplitude		°C		9.37	
Frost days at site		day		13	
Month	Air temperature	Relative humidity	Atmospheric pressure	Wind speed	Earth temperature
	°C	%	kPa	m/s	°C
Jan	4.5	79.4	100.1	5.8	4.2
Feb	4.5	77.0	100.3	5.5	4.2
Mar	5.7	76.0	100.2	5.5	5.6
Apr	7.2	74.1	100.2	4.7	7.5
May	10.2	70.8	100.5	4.3	10.7
Jun	13.3	68.2	100.4	4.0	13.8
Jul	15.8	68.0	100.4	3.9	16.4
Aug	16.0	68.5	100.4	4.1	16.9
Sep	13.7	70.2	100.3	4.7	14.2
Oct	10.7	74.9	100.0	5.1	10.7
Nov	7.3	80.3	100.0	5.3	7.2
Dec	5.4	80.5	100.2	5.6	5.2
Annual	9.5	74.0	100.3	4.9	9.7
Measured at (m)	-	-	-	10.0	0.0

Table 4.3 Annual weather data of Newcastle upon Tyne.

In terms of the house energy bills, the initial electricity and gas consumption of the detached house for a whole calendar year were summarised and combined with the monthly temperature shown in Figure 4.4 below. It can be seen clearly from the figure that electricity usages of each month were relatively stable during a year. The electricity consumption in winter time were a little bit higher than the ones in summer time. But the gap between the highest consumption (208.74 kWh) and the lowest (154.24 kWh) was just about 54.50 kWh which was less than 2kWh difference for winter and summer electricity consumption per day. The weather and temperature affect the gas demand dramatically in different months because majority of gas is for heating purpose in winter. Thus, the gas usages from January to December are obviously different. From January to March, the gas consumption falls down dramatically and keeps dropping down until June. During summer time, the gas usage remains steady and it begins to rise to the peak from October.

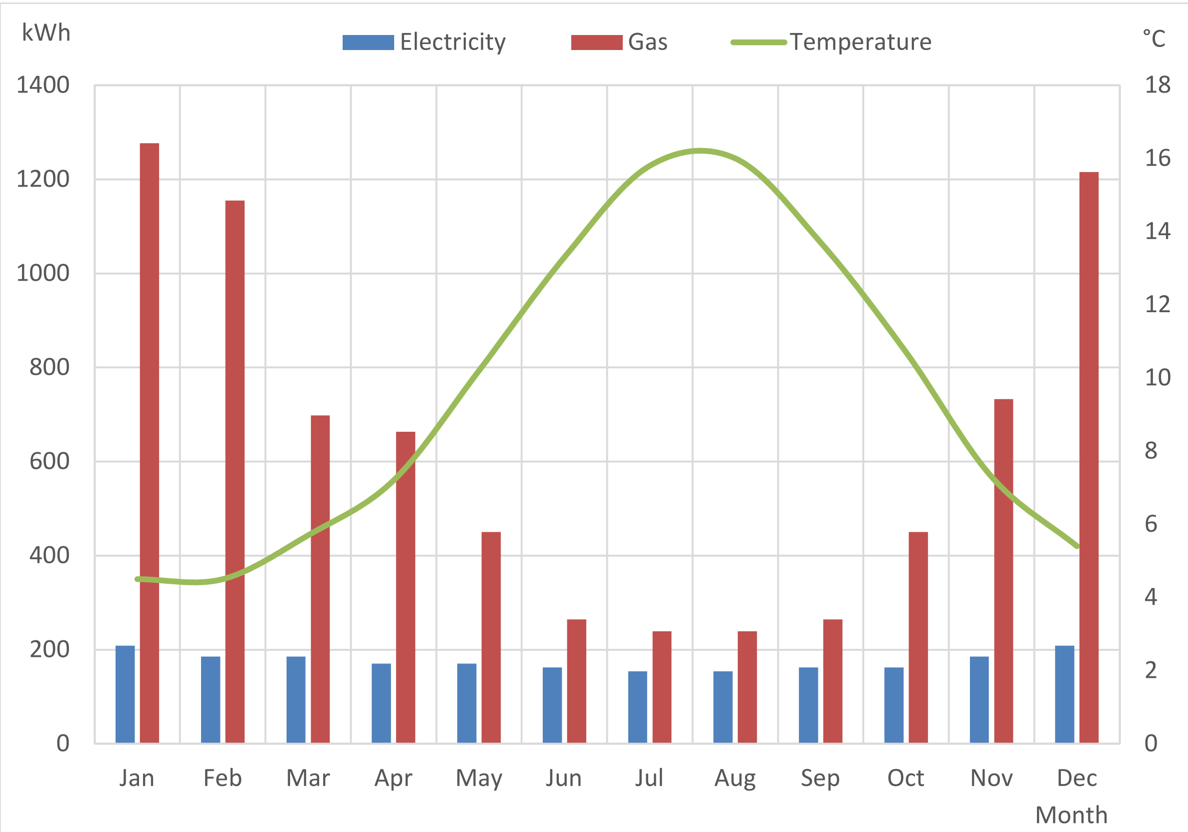


Figure 4.4 Relationship between energy consumption and outdoor temperature.

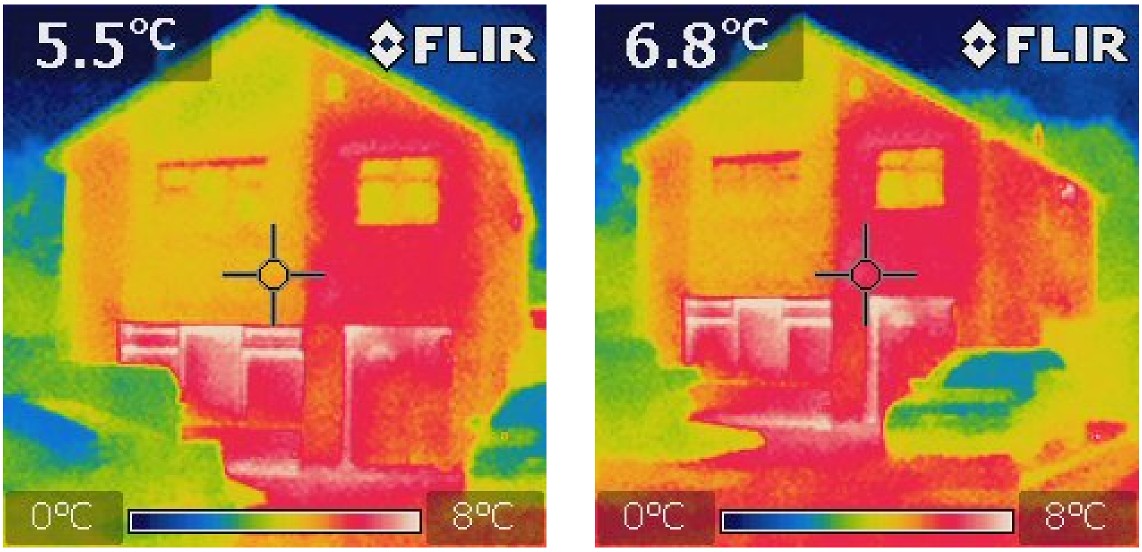
The activities and occupancy of the house residents could influence the energy consumption of the house obviously. Normally, there were only two residents (adults) lived in the target property during the initial bills collection periods. Hence, only two bedrooms of four were in occupancy. The two residents are all full time employees so during the working hours in weekdays, the electricity consumption of the Conventional House was at low level and nearly zero gas usage. In this property, gas is used for two main purposes: heating and domestic hot water (DHW). The schedule of the gas boiler for heating and non-heating seasons are different. During the heating season of a year, the gas boiler supplies both space heating and DHW for the house. But in the non-heating season, only DHW is supplied by the gas boiler and the boiler's working hour is shorter than the one compares to heating season. According to actual situation, the initial boiler schedule has been summarized and shown in Table 4.4.

	Heating season (Space heating + DWH)	Non-heating season (DHW)
Period	November - March	April - October
Operating time	6:00 - 8:00, 18:00 - 21:00	6:15 - 7:30, 19:15 - 20:30
Total operating hours	5	2.5

Table 4.4 Initial schedule of the gas boiler.

4.1.3 *Thermal study of property envelop*

Figure 4.5 indicates the infrared images of the front envelope of the Conventional House taken in a spring day of 2014. The external air temperature was about 4 °C. The two images above show the temperatures of different selected external surfaces of the house.

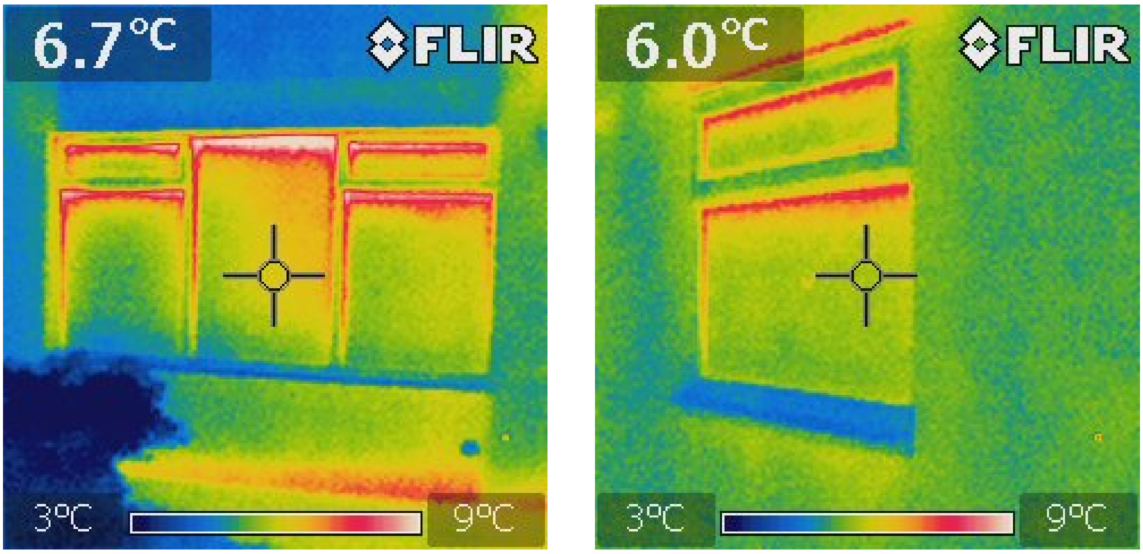


(a) (b)

Figure 4.5 Infrared images of the Conventional House external wall: (a) Bedroom 1, (b) Bedroom 3.

The left figure indicated the temperature for the surface of bedroom 3's external wall was 6.8°C, which was higher than the temperature of bedroom 1 (5.5°C). The reason for causing these two deferent temperatures was because the construction materials for these two surfaces are different, bricks for bedroom 3 and plastic panels for bedroom 1. Due to the materials characteristics, the brick wall may lose more heat compares to the external wall with plastic panel surface and this has been confirmed by Figure 4.5 above. Thus, the performance of external wall plays an important role for keeping house warm during the winter heating season.

Figure 4.6 shows the infrared images of the external windows of the Conventional House taken in the same day. The figure indicates the heat loss from upper window frame is the main point that losing heat of the Conventional House. The external window sizes for the living room and kitchen are 3m × 1.5m and 1.2m × 1m, respectively. And the outside temperatures for the corresponding main part of the external window are 6.7°C and 6.0°C. Hence, the bigger the external window size is, the more heat loses of the house envelop would occur.



(a) (b)

Figure 4.6 Infrared images of the Conventional House external windows: (a) Living room, (b) Kitchen.

Overall, the thermal study indicates the building construction and materials would affect the level of heat loss of a whole building. The types of windows, doors, external wall and insulation influence the energy performance of the property. Thus, these should be considered in further study of this research.

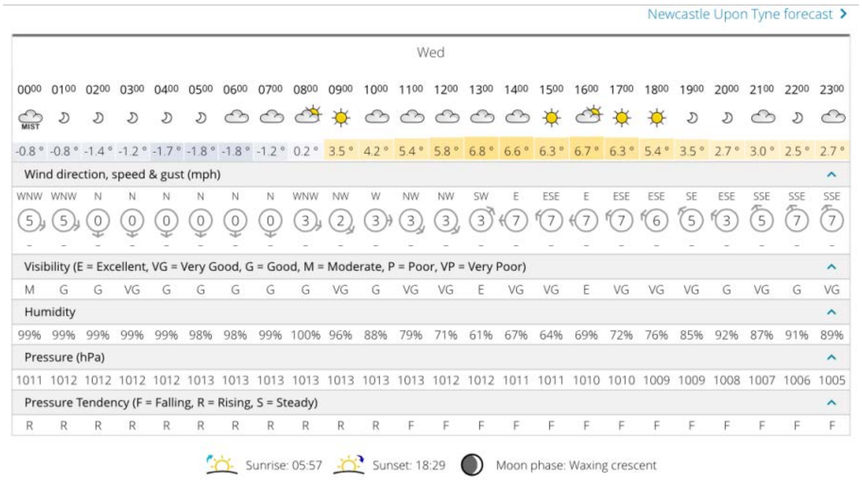
4.2 Actual monitoring data collection

4.2.1 *Pre-monitoring data collection*

Before the monitoring sensors installation, energy consumption was read and recorded manually as no smart meter was set up in this house. Monthly electricity and gas consumption was read through the meters since July 2014 and daily energy consumption readings was recorded since mid-March 2015. The differences of the energy meter readings for two consecutive days were the daily energy consumption for the house. The meter readings were recorded by taking photos at midnight or before all residents were ready for sleeping every day. Figure 4.7 shows the pictures of meter readings of the Conventional House recorded on 25th Mach, 2015. The local hourly weather data was collected every day from Met Office website since energy consumption of the house was collected (see Figure 4.8).

(a) (b)

Figure 4.7 Meter readings recording during pre-monitoring period: (a) Electricity meter, (b) Gas meter.



	0000	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300
	-0.8 °	-0.8 °	-1.4 °	-1.2 °	-1.7 °	-1.8 °	-1.8 °	-1.2 °	0.2 °	3.5 °	4.2 °	5.4 °	5.8 °	6.8 °	6.6 °	6.3 °	6.7 °	6.3 °	5.4 °	3.5 °	2.7 °	3.0 °	2.5 °	2.7 °
Wind direction, speed & gust (mph)	WNW	WNW	N	N	N	N	N	N	WNW	NW	W	NW	NW	SW	E	ESE	E	ESE	ESE	SE	ESE	SSE	SSE	SSE
	5	5	0	0	0	0	0	0	3	2	3	3	3	3	7	7	7	7	6	5	3	5	7	7
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Visibility (E = Excellent, VG = Very Good, G = Good, M = Moderate, P = Poor, VP = Very Poor)	M	G	G	VG	G	G	G	G	G	VG	G	VG	VG	E	VG	VG	E	VG	VG	VG	G	VG	G	VG
Humidity	99%	99%	99%	99%	99%	98%	98%	99%	100%	96%	88%	79%	71%	61%	67%	64%	69%	72%	76%	85%	92%	87%	91%	89%
Pressure (hPa)	1011	1012	1012	1012	1012	1013	1013	1013	1013	1013	1013	1013	1012	1012	1011	1011	1010	1010	1009	1009	1008	1007	1006	1005
Pressure Tendency (F = Falling, R = Rising, S = Steady)	R	R	R	R	R	R	R	R	R	R	R	F	F	F	F	F	F	F	F	F	F	F	F	F

Figure 4.8 Local weather data collected from the Met Office website.

4.2.2 *Installation of monitoring equipment*

There were two stages of the installation of monitoring equipment. The first stage began in July 2015: one emon Tx V3 electrical power monitoring node, four emon TH indoor temperature and relative humidity wireless nodes and two Tinytag Plus 2 TGP-4500 indoor/outdoor waterproof temperature and relative humidity data loggers were deployed in this Conventional House for the monitoring work after calibration. Electricity consumption, indoor temperature and relative humidity of Bedroom 1, Bedroom 3, Living room, Kitchen, Dining room and outdoor temperature and relative humidity were monitored by the sensors. Electricity consumption was recorded in 10 second interval and the sensors interval for indoor environment conditions were 5 minutes or 15 minutes. Due to some technique problems, real time gas consumption couldn't be monitored by the sensors. The second stage started before October 2015: four Tinytag Talk 2 TK-4014 indoor temperature data loggers joined the monitoring system after calibration to gather more indoor temperature data from different zones in the house. Indoor temperature of Bedroom 2, Bedroom 4 and second floor corridor were monitored by the sensors. Moreover, a better position for deploying the onsite outdoor temperature and relative humidity sensor was chosen, and one Tinytag Talk 2 TK-4014 indoor temperature data logger was placed in Bedroom 3 as a back-up sensor for recording the indoor environmental condition.

4.2.3 *Sensors and data loggers deployment*

Figure 4.9 Four emon TH sensors and the base-station.

There are four emon TH temperature and humidity wireless nodes and a base-station used in the Conventional House for indoor environment monitoring. The serial numbers of the four emon TH are node 19, 20, 21 and 22. An SD card has been inserted in the base-station for data collection. The system of the emon TH wireless nodes and base-station is shown in Figure 4.9. The four emon TH wireless nodes are placed in four different rooms to monitor the temperature and humidity of different places in the house or calibration purpose. Their corresponding rooms (zones) are listed below in Table 4.5.

Serial number	Room	Position
210/19 (Node:19)	Bedroom 1	Top of storage trolley
210/20 (Node:20)	Bedroom 3	Top of wardrobe
210/21 (Node:21)	Living room	Top of bookcase
210/22 (Node:22)	Kitchen	Top of cupboards
Base-station	Bedroom 3	On the floor

Table 4.5 Corresponding rooms of the emon TH.

Figure 4.10 Location of the Tinytag Plus 2 Sensor 2.

There are two Tinytag Plus 2 temperature and relative humidity data loggers used in the Conventional House for indoor environment monitoring. The serial numbers of the two Tinytag Plus 2 are Sensor 1 and 2. Those two data loggers are placed in different places for monitoring the onsite indoor or outdoor temperature and relative humidity. The initial position for deploying the outdoor data logger was not good and it has been changed to the

Northwest outer corner of the Conventional House at the beginning of second stage of sensor installation (see Figure 4.10). Their corresponding rooms (zones) are listed in Table 4.6.

Serial number	Zone	Position
Sensor 1	Outdoor	Northwest outer corner of the house
Sensor 2	Dining room	Top of tall cabinet

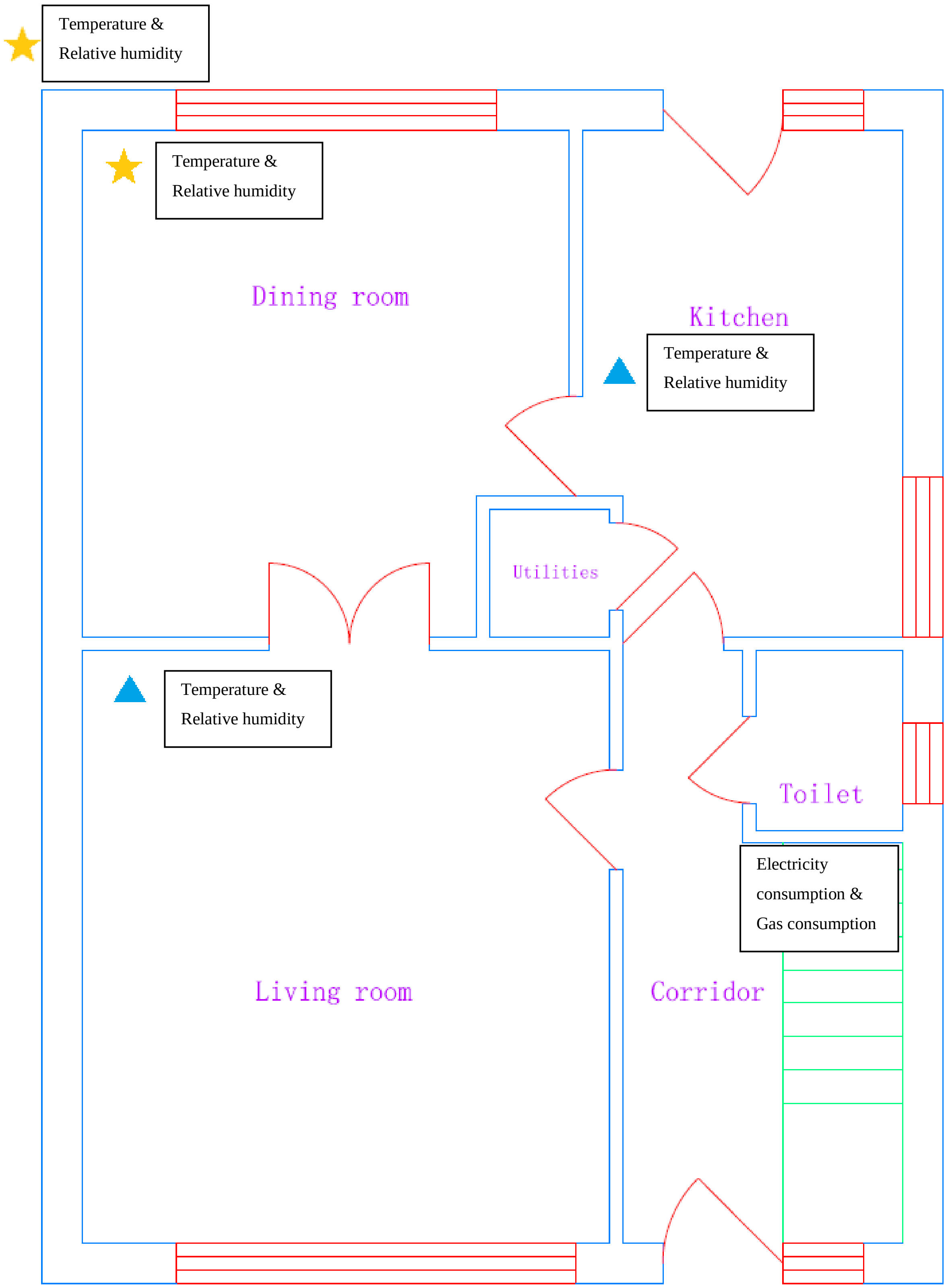
Table 4.6 Corresponding rooms of the Tinytag Plus 2.

There are four Tinytag Talk 2 indoor temperature data loggers used in the Conventional House for indoor environment monitoring. The serial numbers of the four Tinytag Talk 2 are Talk 4, 6, 10 and 11. Figure 4.11 indicates the four Tinytag Talk 2 used in the Conventional House monitoring. The four data loggers are placed in four different rooms in the house to monitor the indoor temperature. Their corresponding rooms (zones) are list in Table 4.7. All the positions of the indoor temperature, relative humidity sensors (data loggers), outdoor temperature sensor (data loggers) and the pulse counter for electricity consumption could be gathered and indicated in the room or floor plans as shown in Figure 4.12.

Figure 4.11 Four Tinytag Talk 2.

Serial number	Room	Position
Talk 4	Second floor corridor	Beside the window
Talk 6	Bedroom 2	Top of wardrobe
Talk 10	Bedroom 4	Top of wardrobe
Talk 11	Bedroom 3	Top of wardrobe

Table 4.7 Corresponding positons of the Tinytag Talk 2.


Temperature &
Relative humidity
Temperature &
Relative humidity
Dining room
Kitchen
Temperature &
Relative humidity
Utilities
Temperature &
Relative humidity
Toilet
Electricity
consumption &
Gas consumption
Living room
Corridor

(a)

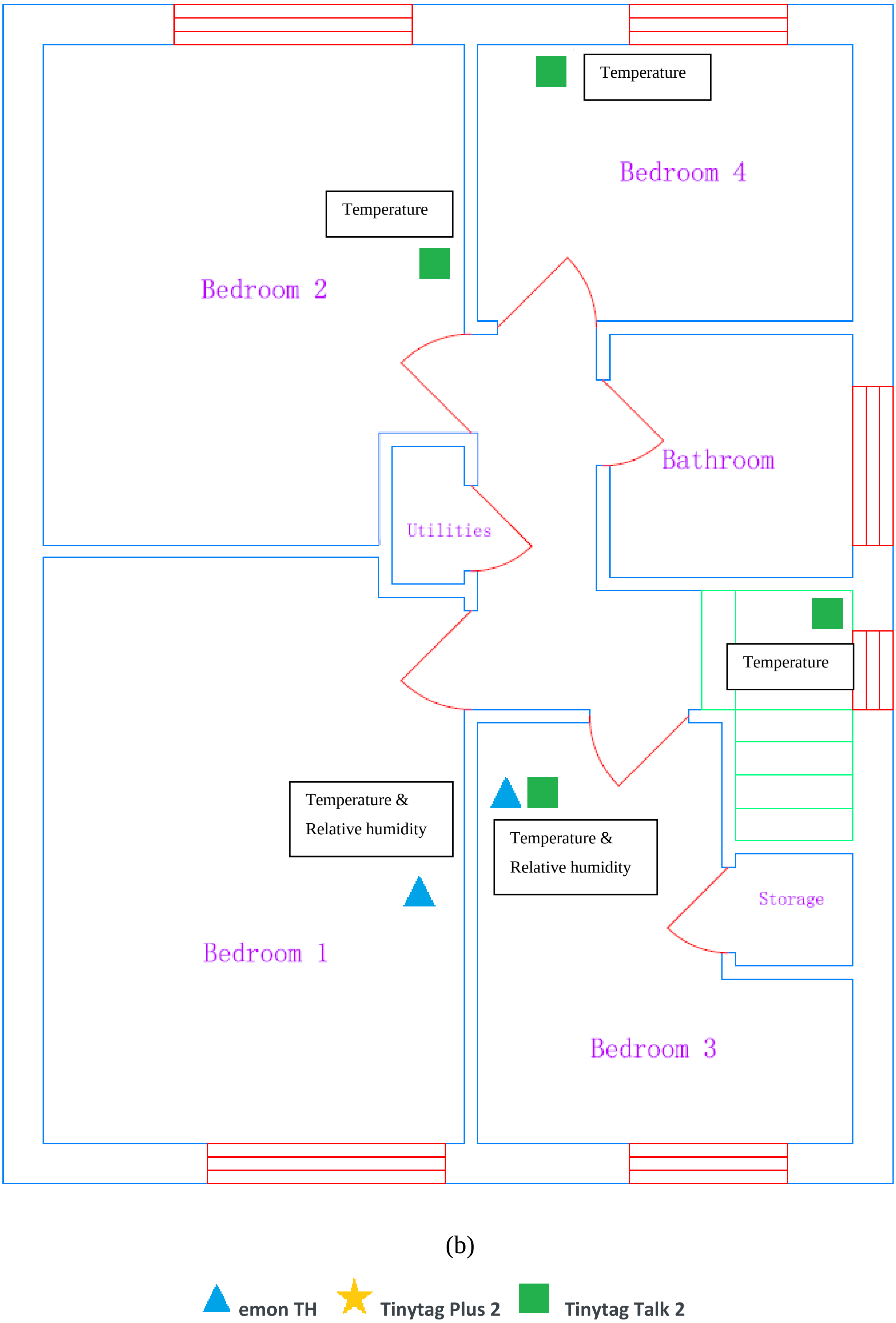


Figure 4.12 Sensors/data loggers distribution in the Conventional House: (a) Ground floor, (b) First floor.

4.2.4 *Calibration of sensors and data loggers*

There are three different types of indoor temperature and humidity sensors used in the Conventional House monitoring and the quantity of all the sensors is ten in total. But only the two Tinytag Plus 2 data loggers were calibrated by a reference meter that has been calibrated in a UKAS (United Kingdom Accreditation Service) approved laboratory. Thus, calibration for all the sensors is essential for monitoring the indoor environmental conditions. There were two phases of sensors calibration: (a) before monitoring; (b) during monitoring. The calibration instrument was applied in this study during the ongoing monitoring period due to some technical reasons. Thus, before monitoring, the sensors and data loggers were compared and calibrated by the Tinytag Plus 2 data loggers.

A. Before monitoring period

According to Table 3.3, Table 3.5 and Table 3.6, the temperature accuracy of the three different types of sensors could be summarised in Table 4.8. In addition, the relative humidity accuracy of emon TH and Tinytag Plus 2 are listed in Table 4.9.

	Temperature range	Accuracy
emon TH	-40°C ~ 80°C	< ±0.5°C
Tinytag Plus 2	0°C ~ 50°C	< ±0.4°C ~ 0.5°C
Tinytag Talk 2	0°C ~ 50°C	< ±0.5°C

Table 4.8 Temperature accuracy comparison of the three types of sensors.

	Humidity range	Accuracy
emon TH	0~100% RH	±2% RH (Max ±5% RH)
Tinytag Plus 2	0~100% RH	±3.0% RH at 25°C

Table 4.9 Relative humidity accuracy comparison between emon TH and Tinytag Plus 2.

The four Tinytag Talk 2 data loggers (Talk 4, Talk 6, Talk 10 and Talk 11), emon TH Node 20 and Tinytag Plus 2 Sensor 1 were put together on the top of wardrobe in Bedroom 3 for calibration purpose. A 10-hour calibration was conduct to validate if all those sensors work well before the monitoring of the house indoor environmental condition. Some sensors during calibration stage were shown in Figure 4.13. Figure 4.14 and Figure 4.15 respectively demonstrate the performance of the sensors for indoor temperature and relative humidity calibration.

Figure 4.13 Node 20, Sensor 1 and Talk 10 in calibration stage.

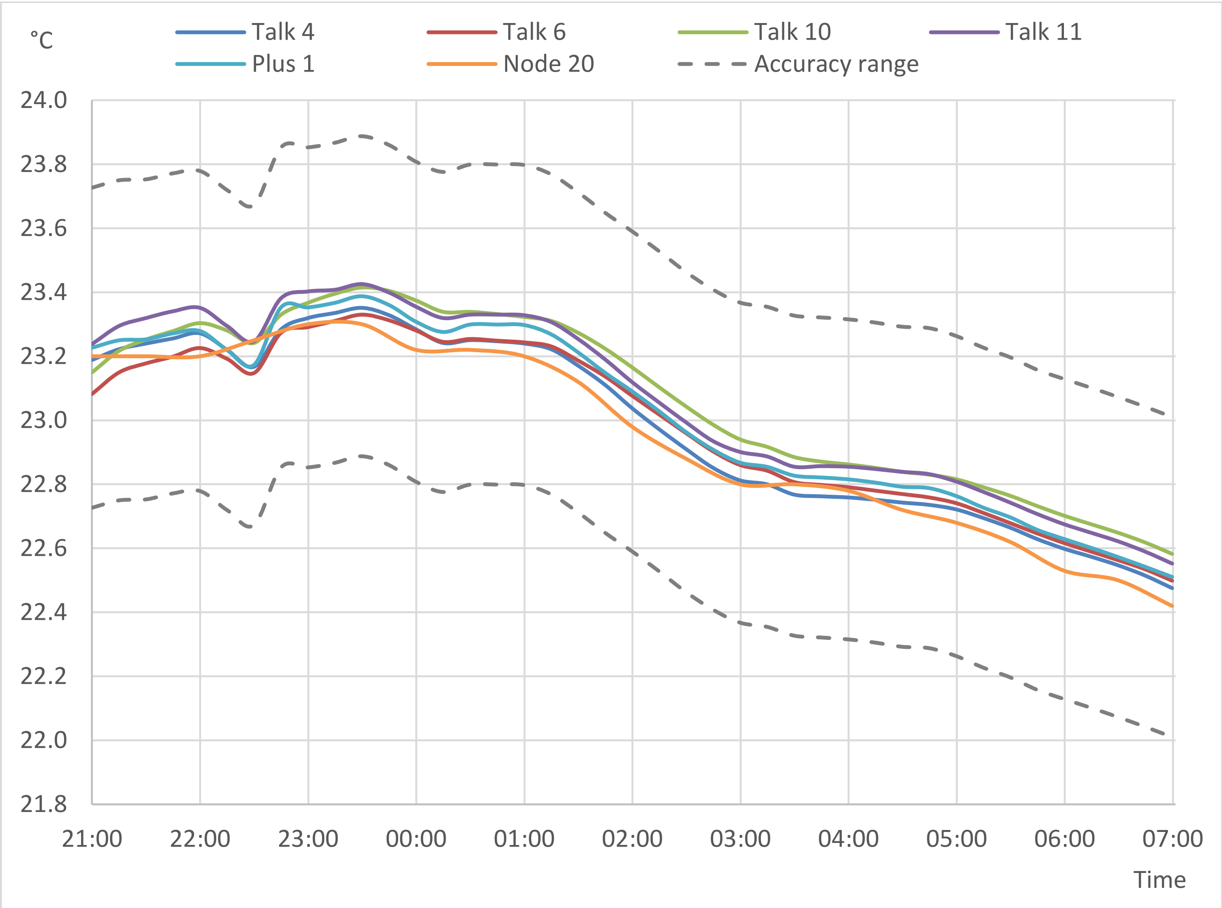


Figure 4.14 Sensors indoor temperature calibration.

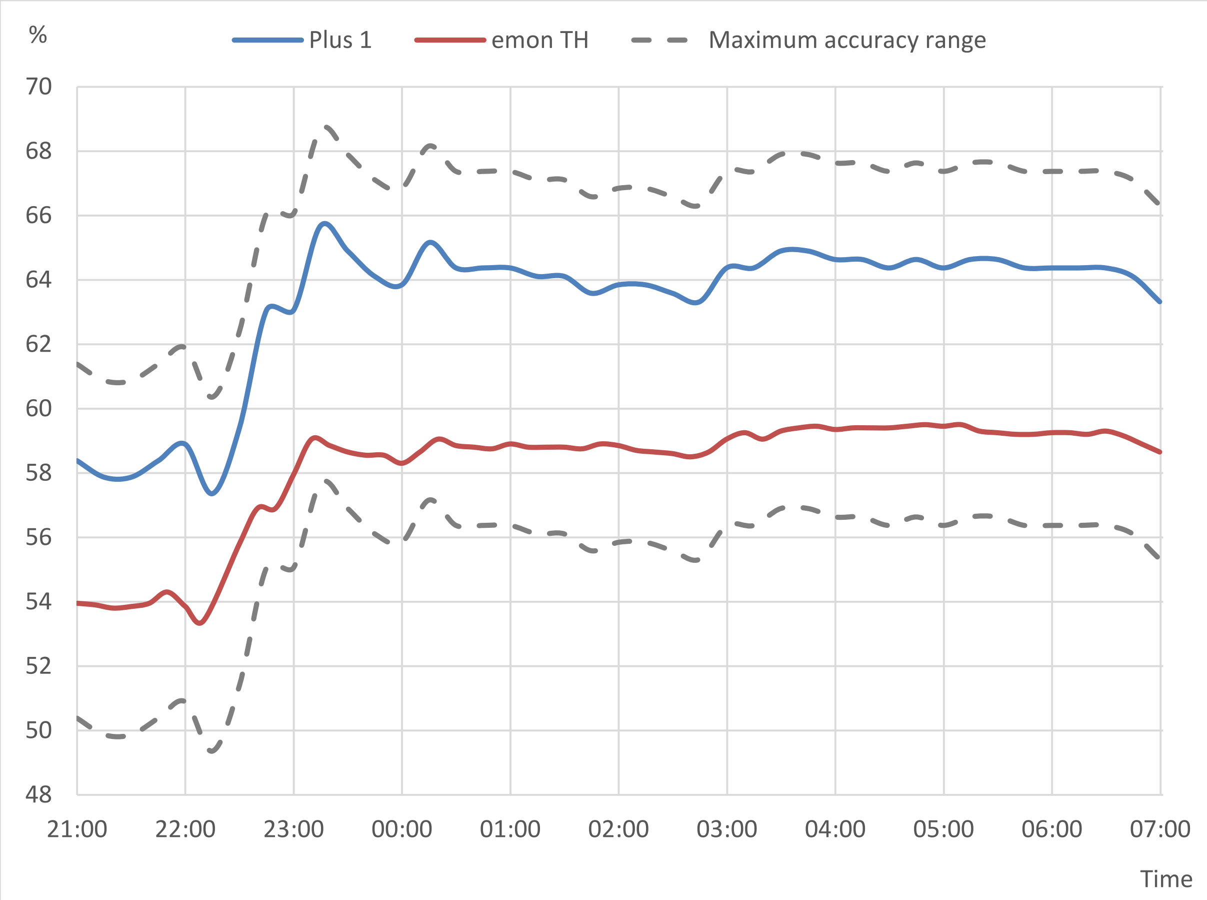


Figure 4.15 Sensors relative humidity calibration.

It could be seen from Figure 4.14 that the maximum temperature difference among these six sensors is approximately 0.2°C. The trends of change of all the sensors are similar. According to the technical data in Table 4.8, the deviations among these sensors are in the acceptable accuracy range and work well. Figure 4.15 indicates the performance of the relative humidity sensors during the calibration. It shows the maximum humidity difference between emon TH (Node 20) and Tinytag Plus 2 (Sensor 1) is about 5% RH. The trends of the change of the two sensors are similar as well. Considering the accuracy differences between these two types sensors, the error of the two relative humidity sensors are still within the accuracy range calculated based on the technical data and are passable for the monitoring stage.

The calibration results show that the relative humidity sensors are not as sensitive as the temperature sensors. The reason may be there were only two humidity sensors, one of each type was selected for the calibration, and the monitoring time was not long enough. However, the sensors are qualified for further monitoring because they are in the accuracy range for both temperature and humidity detected.

B. During monitoring period

A Q-TRACK Multi-function Indoor Air Quality Monitor 7575 (shown in Figure 4.16) was used to conduct a two-month sensors and data loggers' calibration since January to March 2016. This monitor is a handheld, multi-function test instrument which features a menu-driven user interface for easy operation and provides quick, accurate information to measure and assess key indoor air quality parameters including temperature, relative humidity, CO_2 and CO concentration, etc. The instrument was calibrated on 25th June 2015. Its logging interval was 5 minutes during the whole monitoring calibration period. The features and specification of the monitor are listed in Table 4.10.

Figure 4.16 Q-TRACK Multi-function Indoor Air Quality Monitor 7575.

Features /specification	Details
Logging capability	Logs up to 56,035 data points measured parameters enabled, 39 days at 1-minute log intervals
Logging Intervals	1 second to 1 hour
Operating temperature	5 to 45°C (40 to 113°F)
Reading range	Relative humidity: 5% to 95% RH
	Temperature: 0°C to +60°C (32°F to +140°F)
	CO_2: 0-5000 ppm
	CO: 0-500 ppm

Sensor type	Humidity: Thin-film capacitive
	Temperature: Thermistor
	CO_2: Dual-wavelength NDIR (non-dispersive infrared)
	CO: Electro-chemical
Response time	Humidity: 20 seconds (for 63% of final value)
	Temperature: 30 seconds (90% of final value, air velocity at 2 m/s [400 ft/min])
	CO_2: 20 seconds
	CO: < 60 seconds to 90% step change
Resolution	Humidity: 0.1% RH
	Temperature: 0.1°C (0.1°F)
	CO_2: 1 ppm
	CO: 0.1 ppm
Accuracy	Humidity: ±3% RH
	Temperature: ±0.5°C (1.0°F)
	CO_2: ± 3.0% of reading or ±50 ppm, whichever is greater
	CO: ± 3% of reading or 3 ppm, whichever is greater

Table 4.10 Features of Q-TRACK Multi-function Indoor Air Quality Monitor 7575.

Eight Tinytag Talk 2 data loggers and emonTH sensors in total were calibrated by the instrument in this stage. The monitoring data collected by the sensors was used to compare with the indoor environmental condition recorded by the Q-TRACK monitor at the same time. The calibration positons chosen for each sensor were as closed to the sensor as possible. Figure 4.17 shows the calibration process in the second floor corridor.

Using the errors calculation equations, the MBE and CV(RMSE) for each sensors were calculated and summarised in Table 4.11. The maximum value for MBE is ±5% while CV(RMSE) is 15%. It can be seen from the table that the Talk 4 and Node 19 are the most accurate sensor for monitoring temperature and relative humidity, respectively, with minimum calculated errors. Node 21 owns the maximum MBE and CV(RMSE) values for both indoor temperature and relative humidity sensors, -4.91%, 4.92%, 4.69% and 4.69%, correspondingly, but those error values are still within the requirements range. All sensors' performance was great during the two-month calibration period and it can be verified that these sensors have been calibrated. Thus, the data recorded by all sensors deployed in this Conventional House are reliable and can be used for further analysis.

Figure 4.17 Calibration process in the Conventional House.

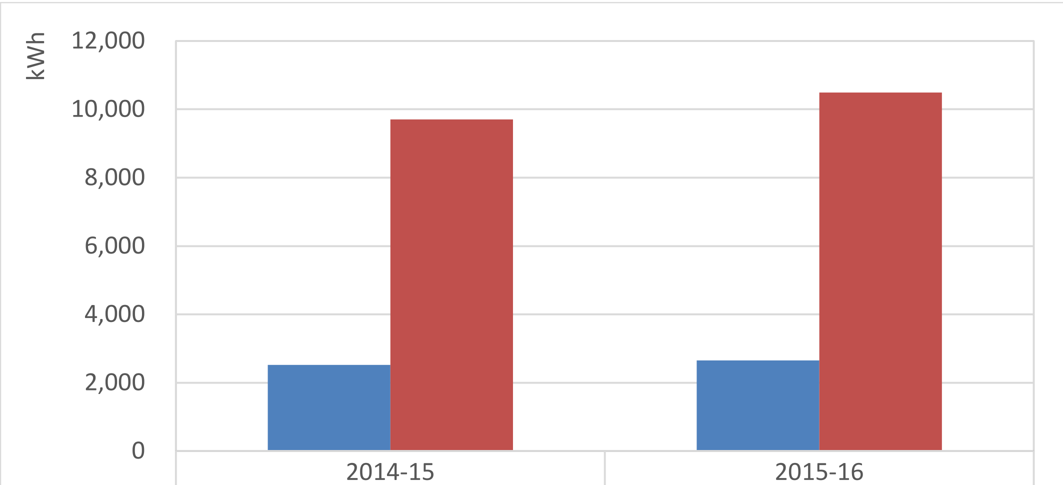
Sensor	Temperature sensor		Relative humidity sensor	
	MBE (%)	CV(RMSE) (%)	MBE (%)	CV(RMSE) (%)
Talk 4	0.12	0.89	-	-
Talk 6	2.08	2.20	-	-
Talk 10	2.41	2.00	-	-
Talk 11	2.52	5.00	-	-
Node 19	3.05	3.21	-0.55	3.32
Node 20	2.11	2.33	-3.79	4.78
Node 21	-4.91	4.92	4.69	4.69
Node 22	-4.03	4.15	3.10	3.43

Table 4.11 Calculated errors for the monitoring sensors.

4.3 Analysis of house performance

4.3.1 *Analysis of energy performance*

The monitoring work of the energy consumption conducted by the sensors and data loggers for this Conventional House began in July 2015. Combine the recorded meter readings since July 2014, the first two years' annual energy consumptions of the Conventional House are summarised in Figure 4.18. Both electricity and gas demand of the house increased (5.21% and 8.05%, respectively) but the energy consumption was competitively stable in general. The conditioned space of this Conventional House is calculated as 90m^2 according to the actual measured data. For the first monitoring year, the annual main electricity and gas consumption were 2521.06 kWh and 9708.82 kWh, respectively. Thus, the total energy consumption of dwelling was 12229.88 kWh and the primary energy demand was 135.89 kWh/(m^{2}a). For the second monitoring year, the annual main electricity and gas consumption were 2652.52 kWh and 10490.12 kWh, respectively. Hence, the total energy consumption of dwelling was 13142.64 kWh and the primary energy demand was 146.03 kWh/(m^{2}a).



	2014-15	2015-16
Electricity	2521.06	2652.52
Gas	9708.82	10490.12

Figure 4.18 Annual energy consumption of the Conventional House.

At most time of a year, the electricity consumption is stable for each month. However, residents' occupancy may affect the monthly electricity consumption obviously. It can be seen from Figure 4.19 that the average monthly electricity consumption for July 2014 to June 2015 (the first monitoring year) was 210.09 kWh. In August, September and December 2014, residents went away for holidays or business trips. Thus, the electricity consumption was lower than other normal months. And for the second monitoring year, from July 2015 to June 2016, the average electricity consumption was 221.04 kWh. Moreover, the electric shower of the house was broken since mid-June 2016. Hence, the electricity consumption was not as high as other typical months. Overall, the winter electricity consumption was higher than summer's under the same residents' occupancy.

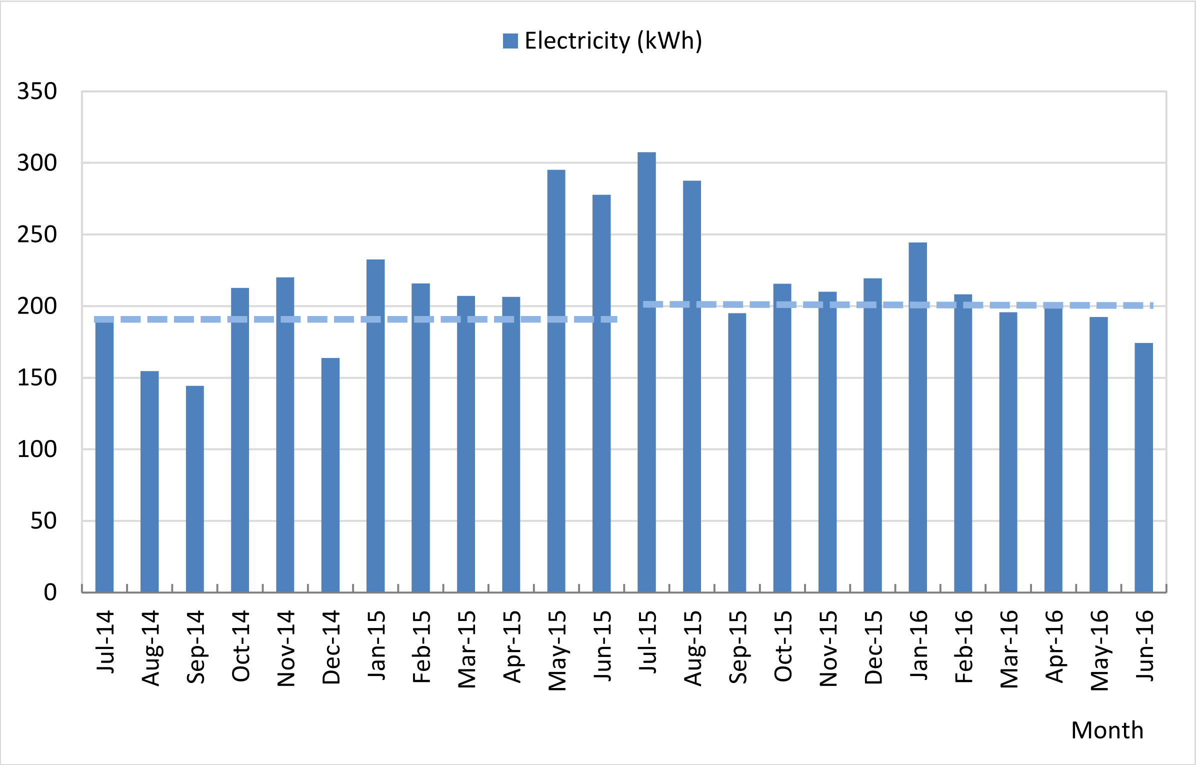


Figure 4.19 Monthly monitoring electricity consumption of the Conventional House.

Monthly monitoring gas consumption of the Conventional House was shown in Figure 4.20. In the two years' monitoring period, it is clear that the winter heating season starts from November to April of next year and non-heating season begins in May and ends in October. And the gas consumption for each month is related to the weather conditions (outdoor air temperature). The monthly gas consumption of non-heating season remained stable and not very different from month to month. In this period the gas was supplied for cooking and domestic hot water (DHW) only. The gas consumption of July or August may be the lowest because the hot water demand reduces during these two hottest months of a year. The trend line of the gas consumption shows the peak demand of the gas consumption appears in January every year because that is the coldest month of Newcastle upon Tyne. It can be seen from the figure that the winter of 2015 was colder the winter of 2014 and the gas consumption match with trend line.

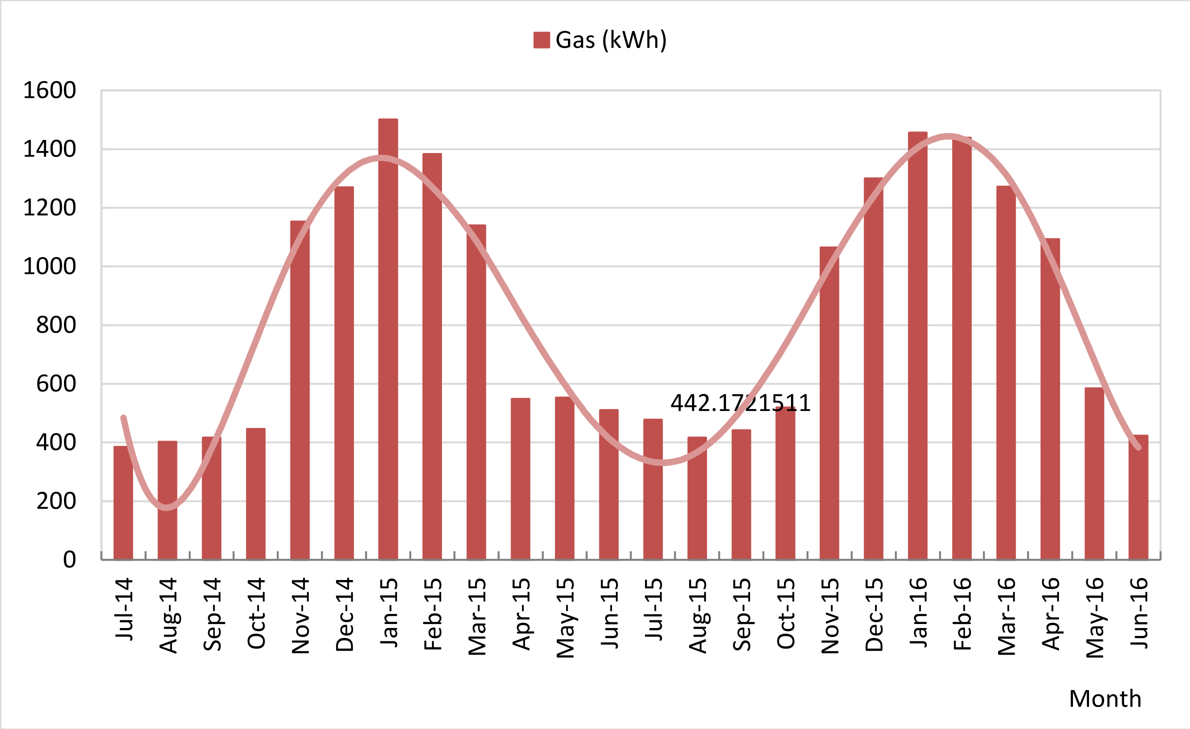


Figure 4.20 Monthly monitoring gas consumption of the Conventional House.

Considering the real time monitoring sensors were installed and began collecting data of the Conventional House performance since July 2015, the second year's house monitoring data is used for the following study.

Due to the network disruption and technical problems, the electricity data for 1st to 10th July and 9th November to 15th December, 2016 has not been recorded by the monitoring system. The whole year's electricity consumption recorded by the monitoring kit except these days were compared with electricity meter readings for calibration purpose. For the rest of the year, the monitored electricity consumption was 2277.56 kWh while the meter recorded electricity consumption was 2304.35 kWh. The electricity consumption error between system monitoring and real time meter recording was 1.36% according to Equation (1) and (2), which was within the acceptable range. The CV(RMSE) was calculated as 1.49% (maximum value is 15%) and the MBE was -1.36% (within the ±5% requirement) according to Equation (3) and (4).

The comparison of monthly system monitored electricity consumption and meter recorded usage and their percentage errors are shown in Figure 4.21. It is clear from the figure that, the electricity consumption monitored by the kit was always lower than the actual usage. This is because the monitoring kit applies the pulse counter to record and convert the electricity imported from main grid and it may lose some counting occasionally and lead to lower data. But the calculation results still shows the high accurate of the electricity monitoring kit and the data generated by it is within the acceptable range and can be used for further analysis.

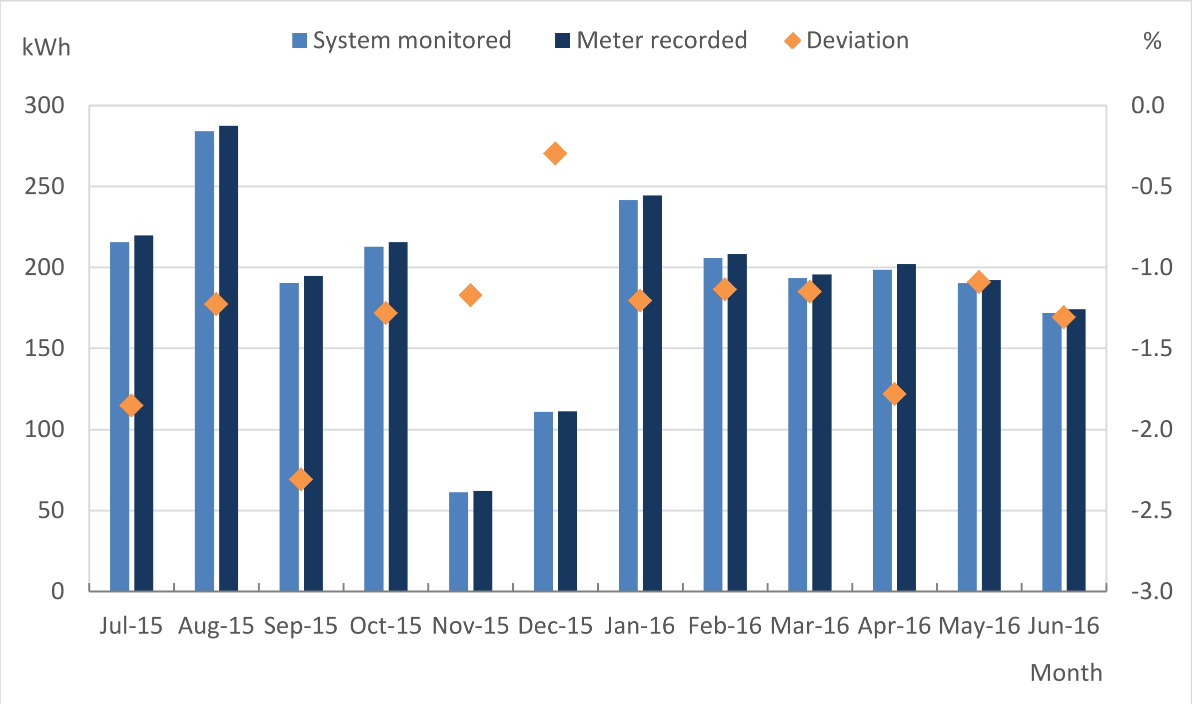


Figure 4.21 Comparison of monthly system monitored electricity consumption and meter recorded usage.

Figure 4.22 and Figure 4.23 indicate the daily monitoring electricity and gas consumption of the Conventional House during July 2015 and June 2016, respectively. The average daily electricity consumption for this year was 7.25 kWh. The house was fully occupied by 5 residents in July and August 2015. Thus, the electricity consumption during these two months was around one third higher than other normal months, shown in Figure 4.22 clearly. There was one week at the beginning of April that the residents went for holidays and only one person stayed in the house. The house electricity consumption of that week dropped down obviously, which was below half demand compared to other normal months.

It can be seen form Figure 4.23 that there were some days with low gas consumption during the heating season because the residents shut down the house space heating system due to warm weather or going out for holidays. The gas consumption was relatively stable during the non-heating season. The average daily gas consumption for heating season and non-heating season for this year were 41.90 kWh and 15.56 kWh, respectively.

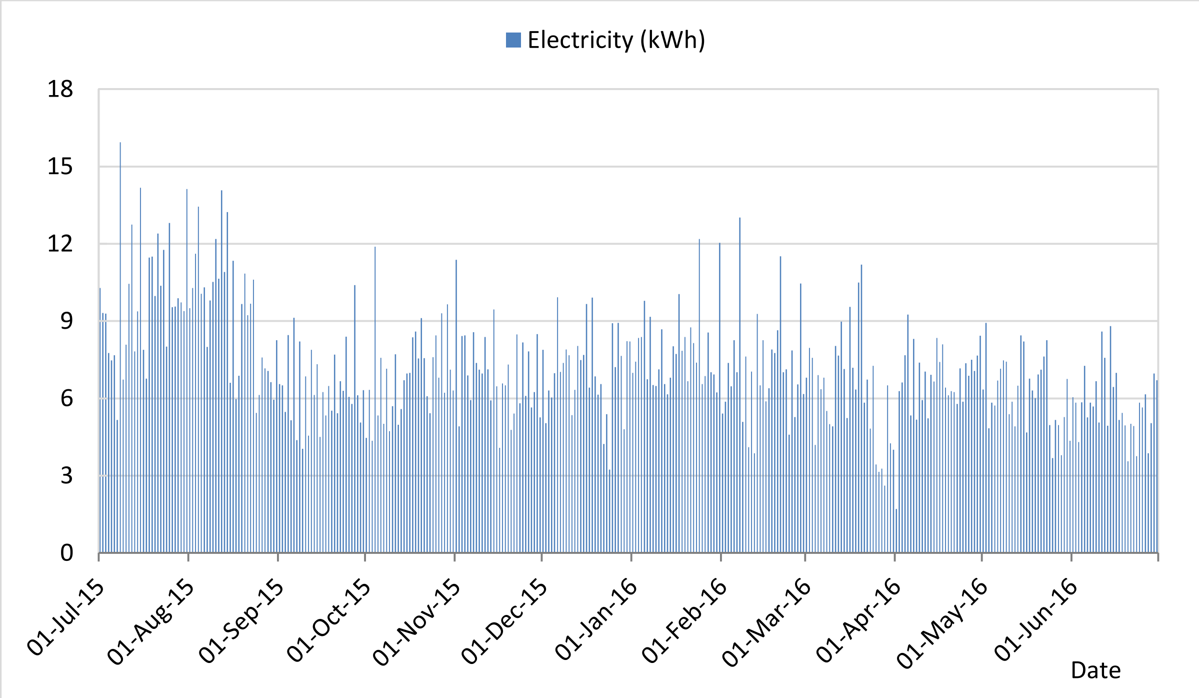


Figure 4.22 Daily monitoring electricity consumption of the Conventional House.

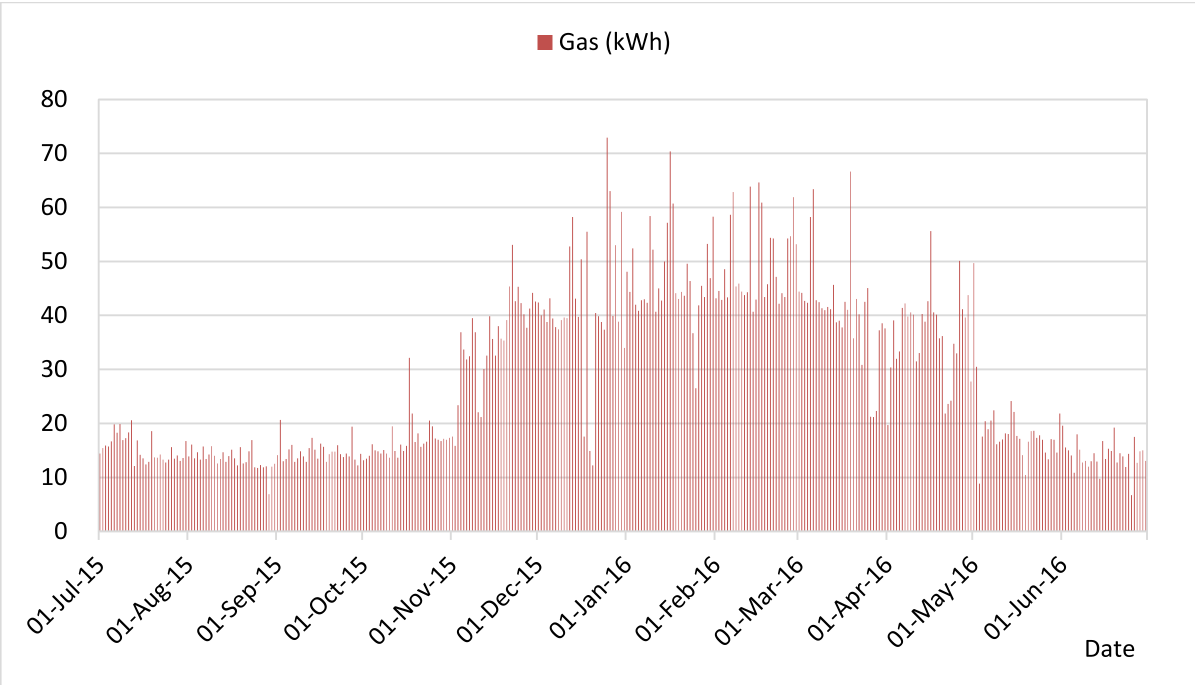


Figure 4.23 Daily monitoring gas consumption of the Conventional House.

According to the monitoring results, the 10 second interval (real time) electricity consumption in a typical heating day in winter and a non-heating day in summer could be demonstrated in Figure 4.24 and Figure 4.25, respectively. The electricity consumption for these two days were 7.64 kWh and 6.98 kWh and the electricity demand in winter was slightly higher than summer demand. From the figures, it could be seen that both peak time of electricity demand in winter and summer were in the evening. The main reason was the residents always took showers in the evening and the 6 kW electric shower was the biggest electricity consumer in the Conventional House.

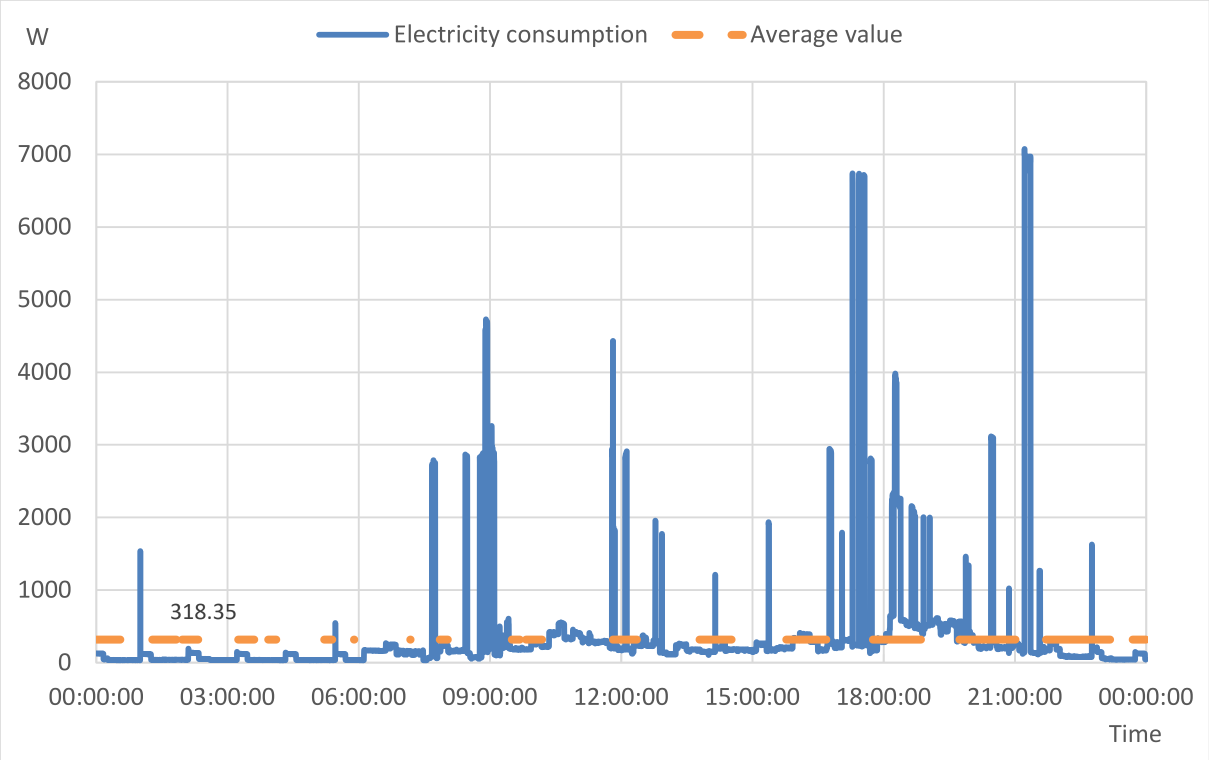


Figure 4.24 Dynamic electricity consumption for the Conventional House on 16th Jan, 2016.

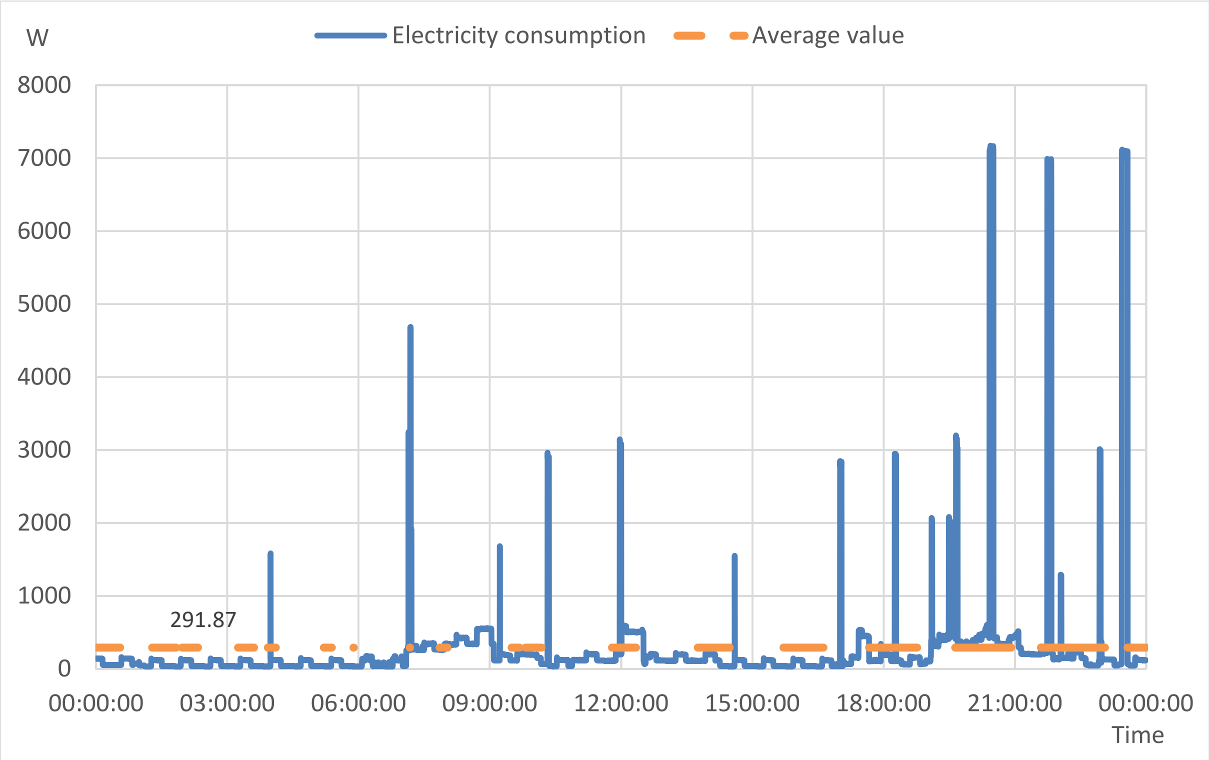


Figure 4.25 Dynamic electricity consumption for the Conventional House on 16th Jun, 2016.

The monitoring of gas consumption is a difficult problem to be solved in this study. There were no suitable equipment and techniques for the gas meter of this Conventional House to record the dynamic gas consumption. In summer time, the gas is supplied for the domestic hot water and cooking. Thus, at this moment, the feasible plan was to record the gas meter readings three times a day to separate the gas consumption for domestic hot water and cooking. Considering the gas boiler's working time and daily cooking hour, the first gas meter reading should be taken after 9 am, second reading should be conducted at around 9 pm and the final one should be done between 11 pm and midnight. Hence, the difference of first and second gas meter readings was the gas consumption for cooking, and the other two meter readings add together would be the gas consumption for daily domestic hot water.

A 45-day gas monitoring to distinguish the actual gas consumption for domestic hot water and cooking in non-heating season was conducted from August to October 2015. Figure 4.26 indicates the gas distribution for domestic hot water and cooking during the period. According to the monitoring data, the average daily gas consumption for domestic hot water and cooking were 12.41 kWh and 1.56 kWh, respectively. The cooking habits of the house residents were analogous in a year thus, the 1.56 kWh gas consumption for cooking could be assumed as an average value yearly. It is known from the results that the percentage gas consumption for domestic hot water and cooking during non-heating season were approximately 89.2% and 10.8%. However, long term monitoring is recommended for more accurate data.

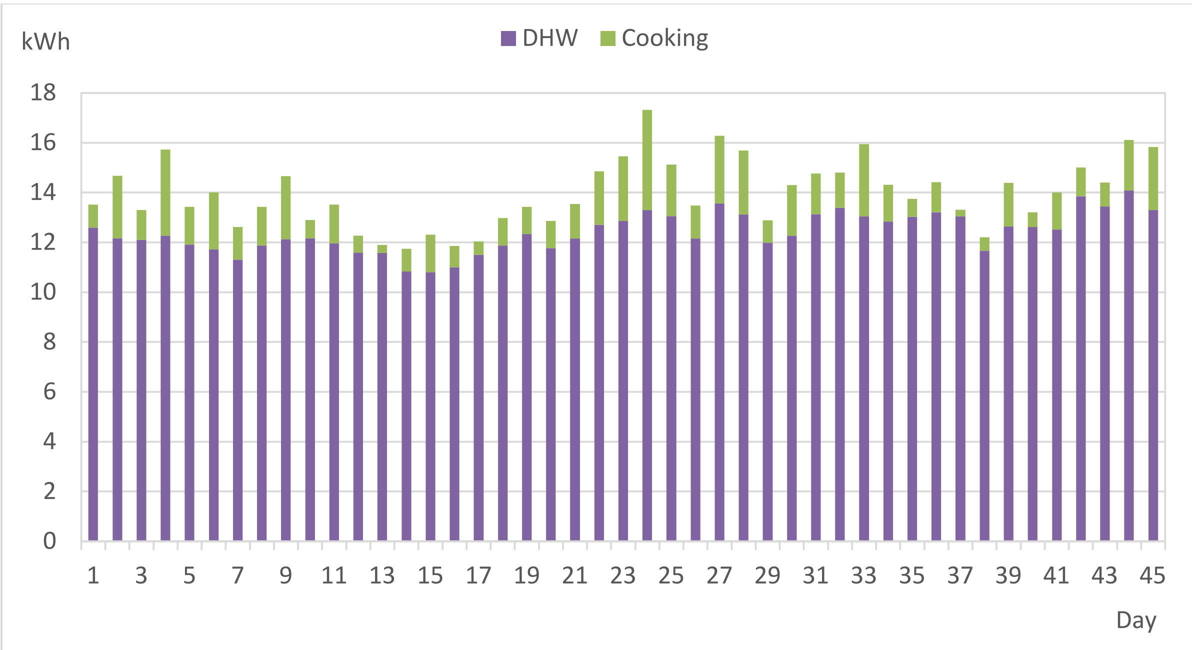


Figure 4.26 Gas consumption monitoring for domestic hot water and cooking.

4.3.2 *Analysis of indoor environmental condition*

The indoor environmental condition monitoring in this Conventional House including temperature and relative humidity began in July 2015, since the second study year. In addition, a two-month CO_2 concentration monitoring was conducted from January to March 2016 mainly in Bedroom 3 to understand the trend of carbon dioxide concentration in the bedroom of this typical Conventional House.

A. Temperature

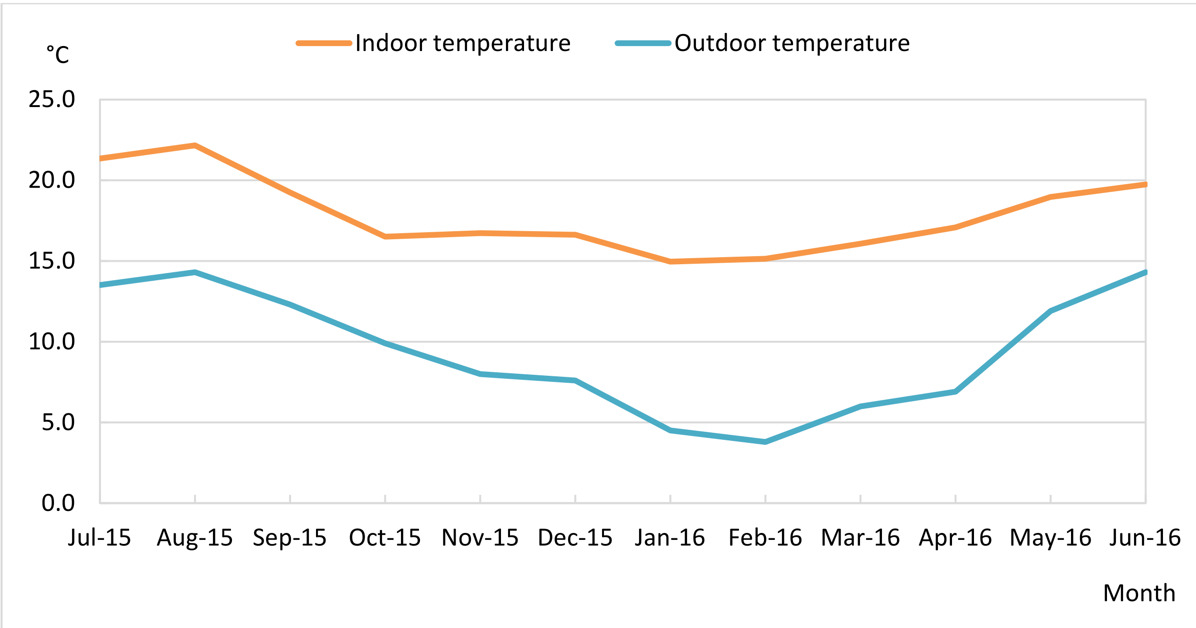


Figure 4.27 Monthly monitoring onsite temperature for the Conventional House.

Figure 4.27 shows the monthly monitored indoor temperature of the Conventional House and onsite outdoor temperature during the second monitoring year. There were 8 zones' indoor temperature recoded by the data loggers and sensors in the house including Bedroom 1, Bedroom 3, Living room, Kitchen, Dining room, Bedroom 2, Bedroom 4 and 2^{nd} floor corridor. Thus, the indoor temperature shown in the figure was the average temperature of the 8 zones in the property. From the monitoring data, it can be seen that the average indoor temperature for the whole monitoring year was 17.7°C. The average monthly indoor temperature during the heating season (Nov-15 to Apr-16) was 16.1°C while the onsite outdoor temperature was 6.1°C. The difference between indoor and outdoor temperature was 10.0°C. The average indoor temperature of the Conventional House during non-heating season was 19.7°C summarised from the monitoring data. The coldest month was February in a year and the indoor temperature dropped down to approximately 15.0°C with heating while the hottest month in summer was August and the indoor temperature increased to 22.1°C.

As an example, indoor temperature of July 2015 (a typical month in summer time) is shown in Figure 4.28 to display the monitored daily indoor room temperature. This month's house average temperature was 21.3°C. It can be seen from the figure that, in most cases, the range of daily house temperature was between 18°C and 25°C. The temperature of bedrooms were usually higher than living room and dining room. The reason is these two bedrooms are in upper floor and received solar radiation directly from the windows in the afternoon. The kitchen is quite special because cooking could generate heat during the daytime and it is a comparatively small room with fixed opening. Hence, its temperature would be higher than normal ground floor zones. In general, the temperature of first floor was about 1°C higher than ground floor in summer time.

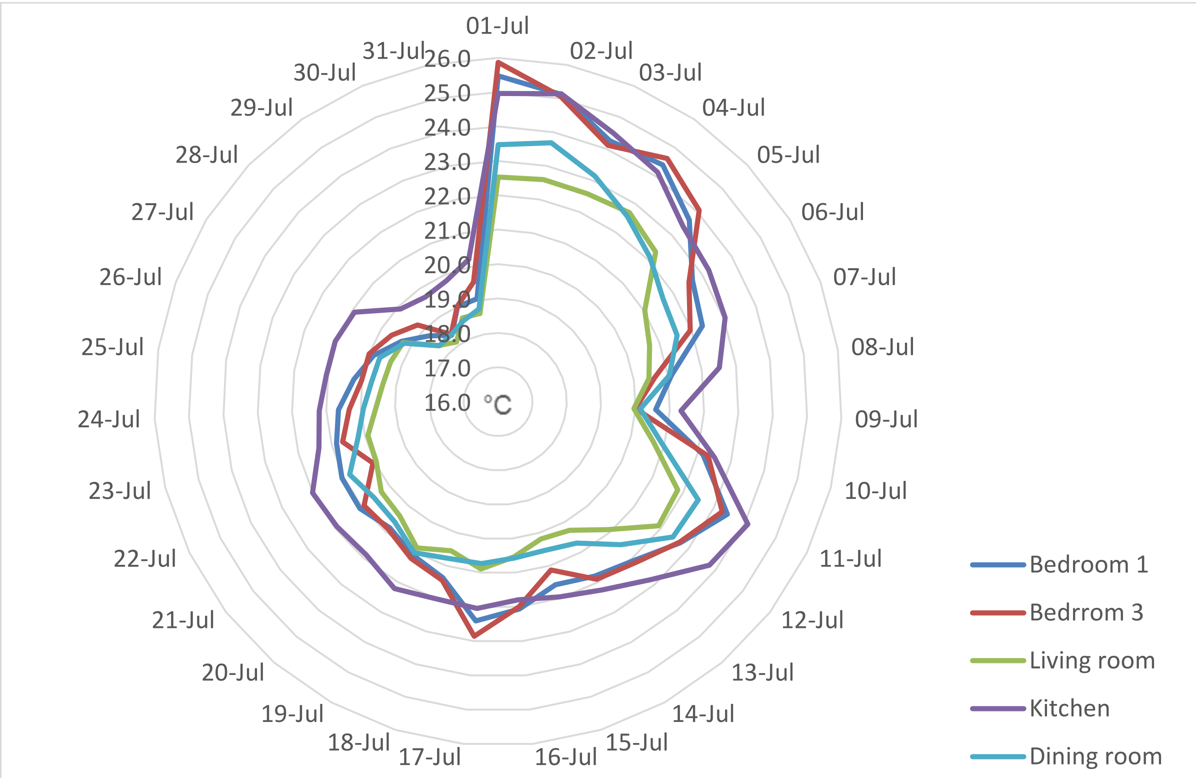


Figure 4.28 Monitored daily room temperature in July 2015.

As 1st July 2015 was the hottest day in 2015 with 20.6°C, according to the data gathered from Met Office, the house average indoor temperature reached 24.5°C on that day. The highest daily room temperature was about 25.9°C appeared in Bedroom 3. Figure 4.29 shows the hourly temperature on 1st July, 2015. It can be seen from the figure that the temperature of Bedroom 3 was over 25°C all the day. The resident in the room keep the room door closed in the evening made the room temperature remain high (over 26°C) and the differences between Bedroom 1 and it can be found in the figure. Compare to the coolest room, the temperature of Living room on that day was 22.5°C. There were no many residents' activities in the room in a day and there was good shading outside the window of the Living room. Thus, the temperature of the room was not very high and it stayed more than 3°C lower than the hottest room. The temperature of Kitchen in the evening affected obviously by the cooking. Within 20 minutes, the temperature grew from 25.4°C to 26.2°C and dropped down afterwards.

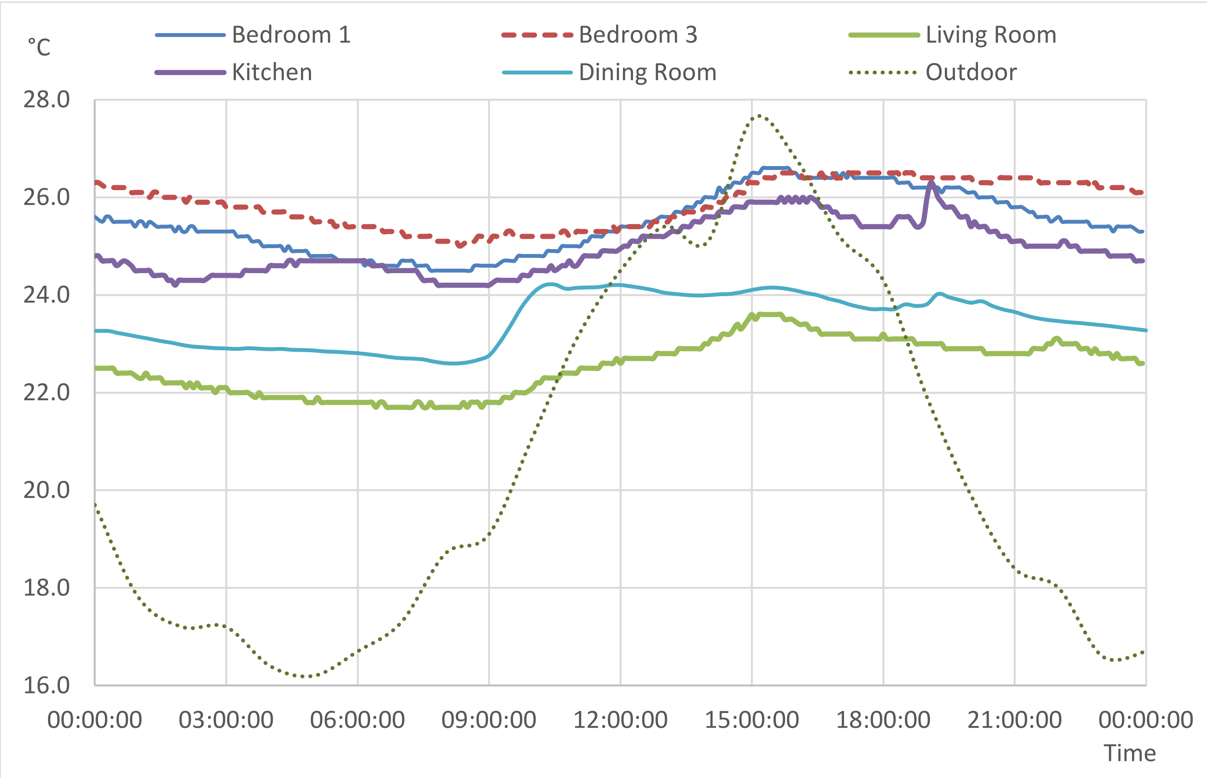


Figure 4.29 Monitored real time temperature of the Conventional House on 1st July 2015.

Similarly, indoor temperature of January 2016 (a typical month in winter time) is shown in Figure 4.30 to display the monitored daily indoor room temperature. This month's house average temperature was only 15.0°C. It can be seen from the figure that, in most cases, the range of daily house temperature was between 11°C and 17°C. The temperature of Bedroom 2 and Living room were usually higher than other rooms because the residents, especially the kid mainly stayed in these two rooms. Thus, the space heating demand of these rooms were higher compared to others and led to higher room temperature. The kitchen's temperature was still relatively high in winter because cooking could generate heat during the daytime. There were no obviously differences for each room's indoor temperature except the situation of turning off heating, i.e. 9th to 12th January in Bedroom 3.

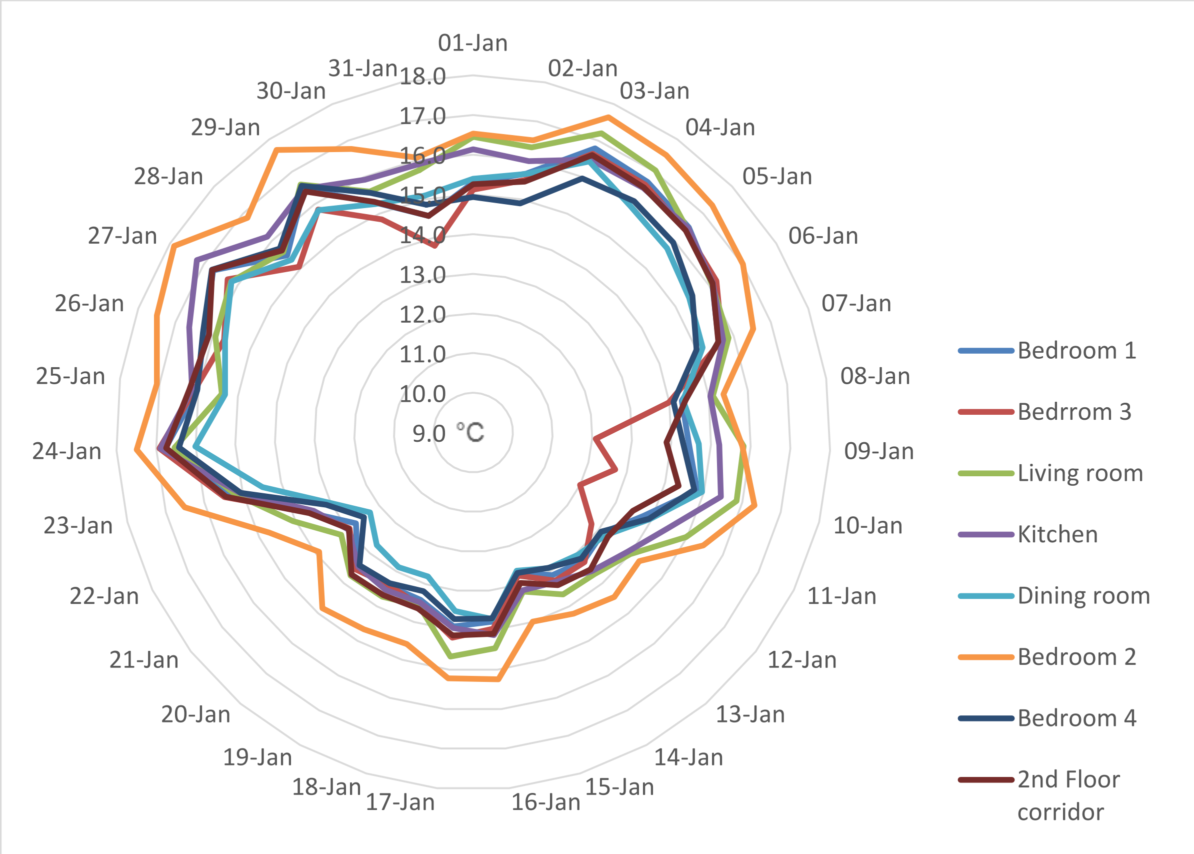


Figure 4.30 Monitored daily room temperature of the Conventional House in January 2016.

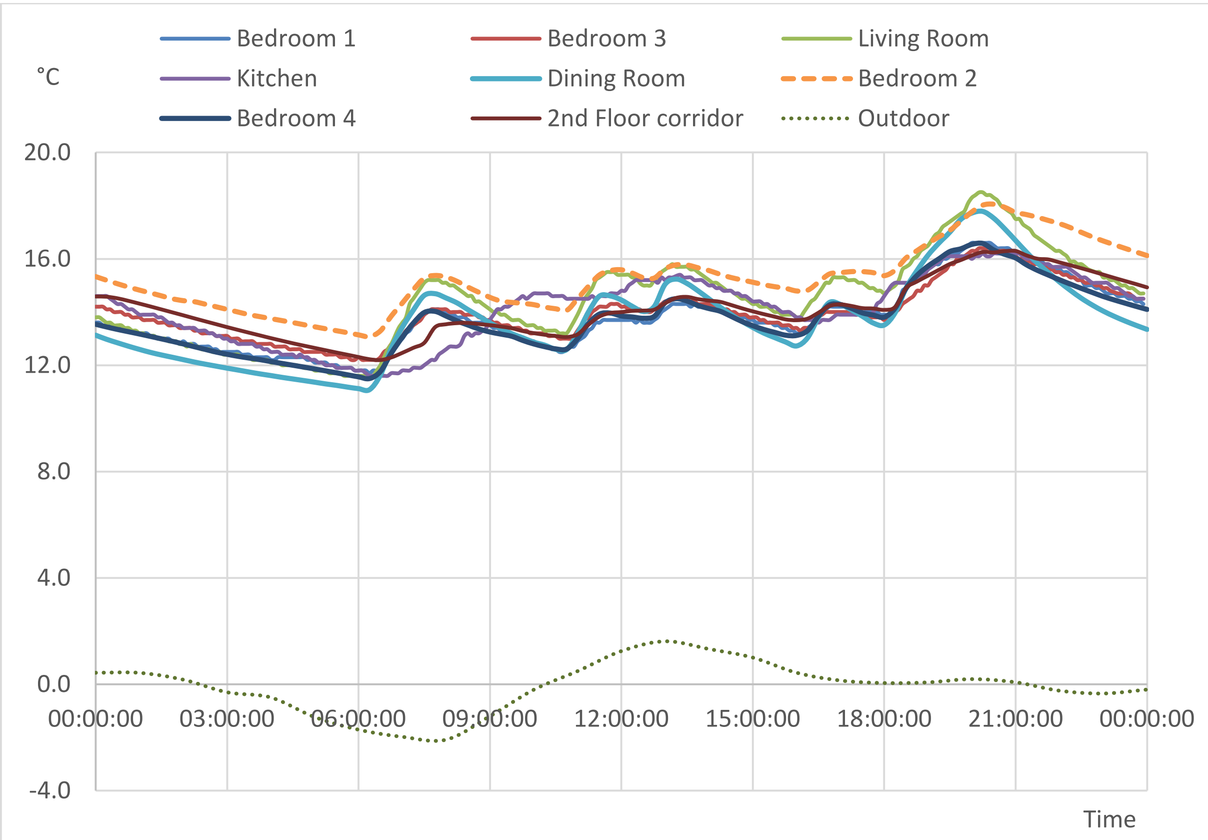


Figure 4.31 Monitored real time temperature of the Conventional House on 16th January 2016.

As 16th January 2016 was the coldest day in 2016 with -0.6°C, according to the data gathered from Met Office, the house average indoor temperature remained at 14.1°C on that day. The lowest daily room temperature was about 13.7°C appeared in Dining room and Bedroom 4. Figure 4.31 shows the hourly temperature on 16th January 2016. It can be seen from the figure that the Dining room became the coldest room in the house during the night time. But when the heating was on in the day time, its temperature grew up very fast. There is a big glazing door on the northern wall of the Dining room so it was assumed that the heat released through the opening led to the reducing temperature. Bedroom 4 was not in occupancy so less heating was needed to meet the basic space heating requirement for the room. And the room door kept opened all the time made the room temperature lower than normal bedrooms. Compare to the warmest room, the temperature of Bedroom 2 on that day was 15.3°C, approximately 1.6°C higher than the coldest Bedroom 4. The room is the place for the kid's activity so the heating demand was higher to keep the child warm.

B. Relative humidity

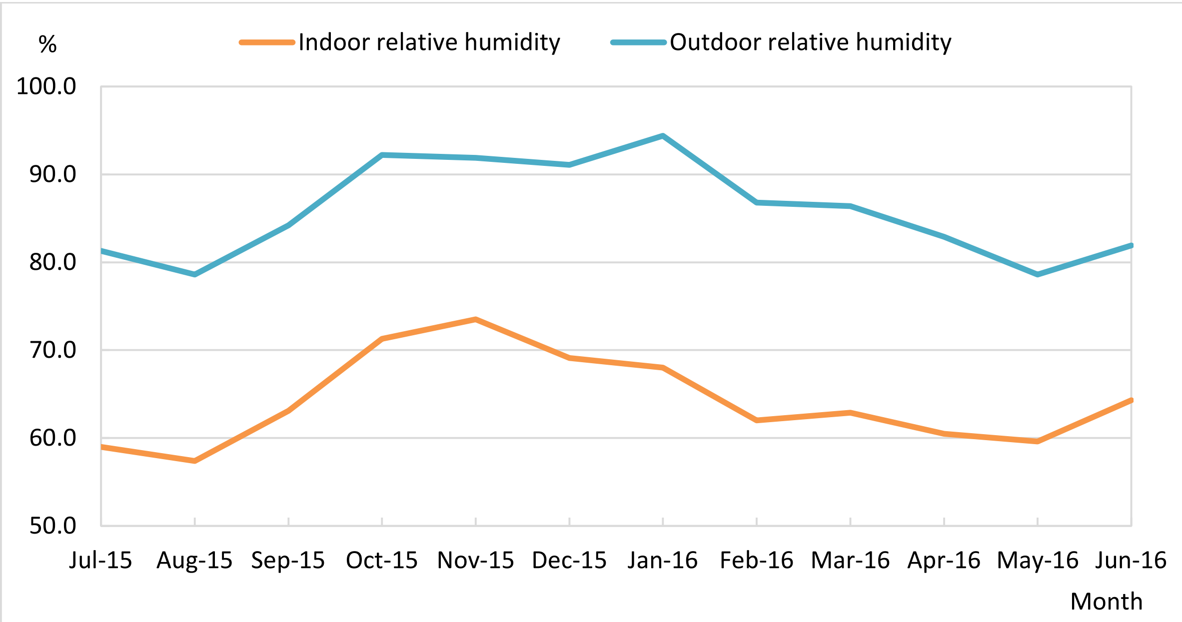


Figure 4.32 Monthly monitoring onsite relative humidity.

Figure 4.32 shows the monthly monitored indoor relative humidity of the Conventional House and onsite outdoor relative humidity during the second monitoring year. There were 5 zones' indoor relative humidity recoded by the data loggers and sensor in the house including Bedroom 1, Bedroom 3, Living room, Kitchen and Dining room. Thus, the indoor relative humidity shown in the figure was the average relative humidity of the 5 zones in the property.

From the data monitoring, it can be seen that the average indoor relative humidity for the whole monitoring year was 64.2%. The average monthly indoor relative humidity during the heating season (Nov-15 to Apr-16) reached 66.0% while the onsite outdoor relative humidity rose to about 90%. The difference between indoor and outdoor relative humidity was more than 20%. Once the outdoor relative humidity achieved 90% and the house indoor relative humidity increased to about 70.0%. The average indoor relative humidity of non-heating season of the Conventional House was 62.5% summarised from the monitoring data.

Corresponding to the indoor temperature analysis, indoor relative humidity of July 2015 (a typical month in summer time) is shown in Figure 4.33 to display the monitored daily indoor room relative humidity. This month's house average relative humidity was 59.0%. It can be seen from the figure that, the range of daily house relative humidity was between 50% and 70% in majority cases. The relative humidity of Bedroom 3 and Kitchen were usually lower than other rooms. The reasons were these two bedrooms' temperatures were always the highest and the window or door in these two rooms were always kept opened by the residents for more natural ventilation. In general, the relative humidity of these two rooms would be around 5% lower than all other rooms in summer time.

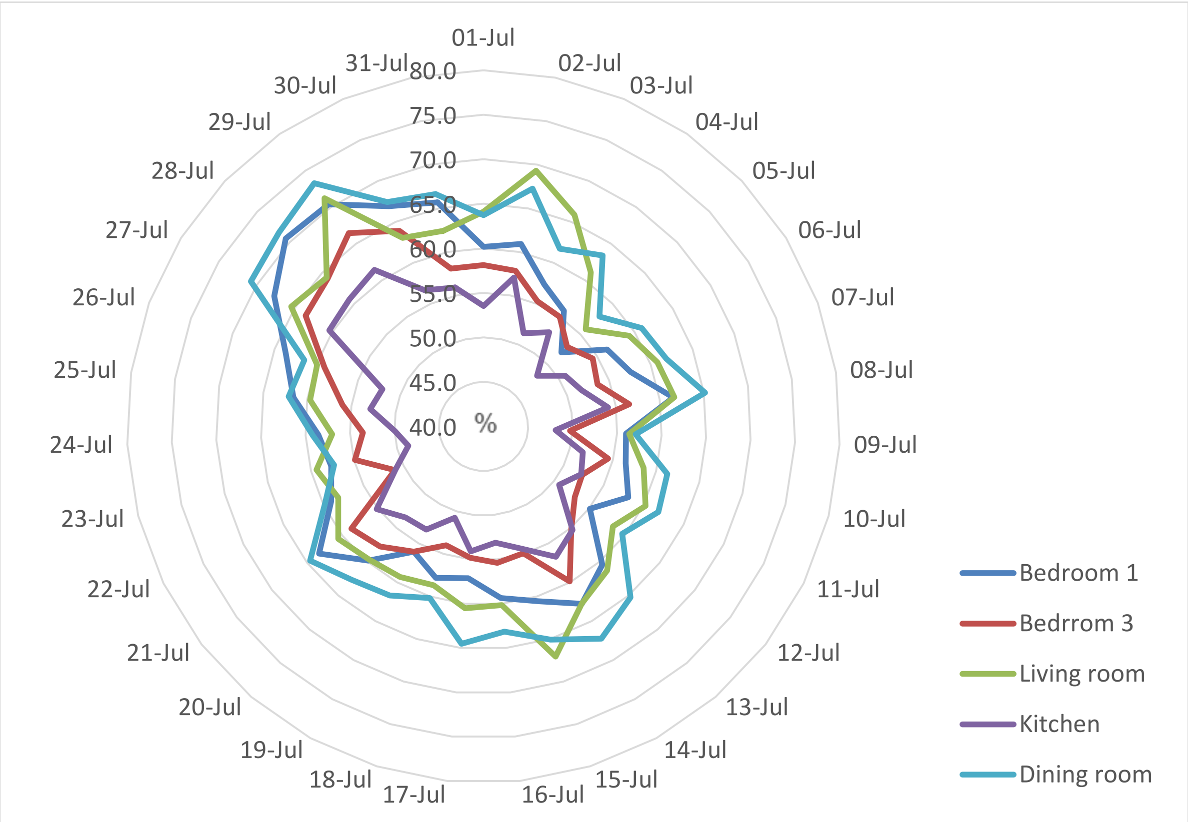


Figure 4.33 Monitored daily room relative humidity in July 2015.

On 1st July 2015, the hottest day in 2015, the house average indoor relative humidity was 59.9%. The highest daily room relative humidity was about 64.2% appeared in Living room while the lowest relative humidity was about 53.6% of Kitchen. Figure 4.34 shows the hourly relative humidity on 1st July, 2015. At most time of a day in summer, the relative humidity was stable. But it can be seen from the figure that the relative humidity of Kitchen was affected obviously by cooking. Within 15 minutes, the relative humidity grew dramatically from 53.5% to 59.3% at noon and 56.4% to 73.5% in the evening and dropped down afterwards. Because the Dining room is just next to the Kitchen, its relative humidity performance was also influenced by the cooking. If residents in the bedroom keep the window closed at night would make the room relative humidity grew slowly until they woke up in the morning (e.g. Bedroom 1). The performance was different if compare it to Bedroom 3, which was opened window all the day. As the Living room was very cool in summer and residents usually kept its window closed, the relative humidity of the room was slightly higher than all other rooms.

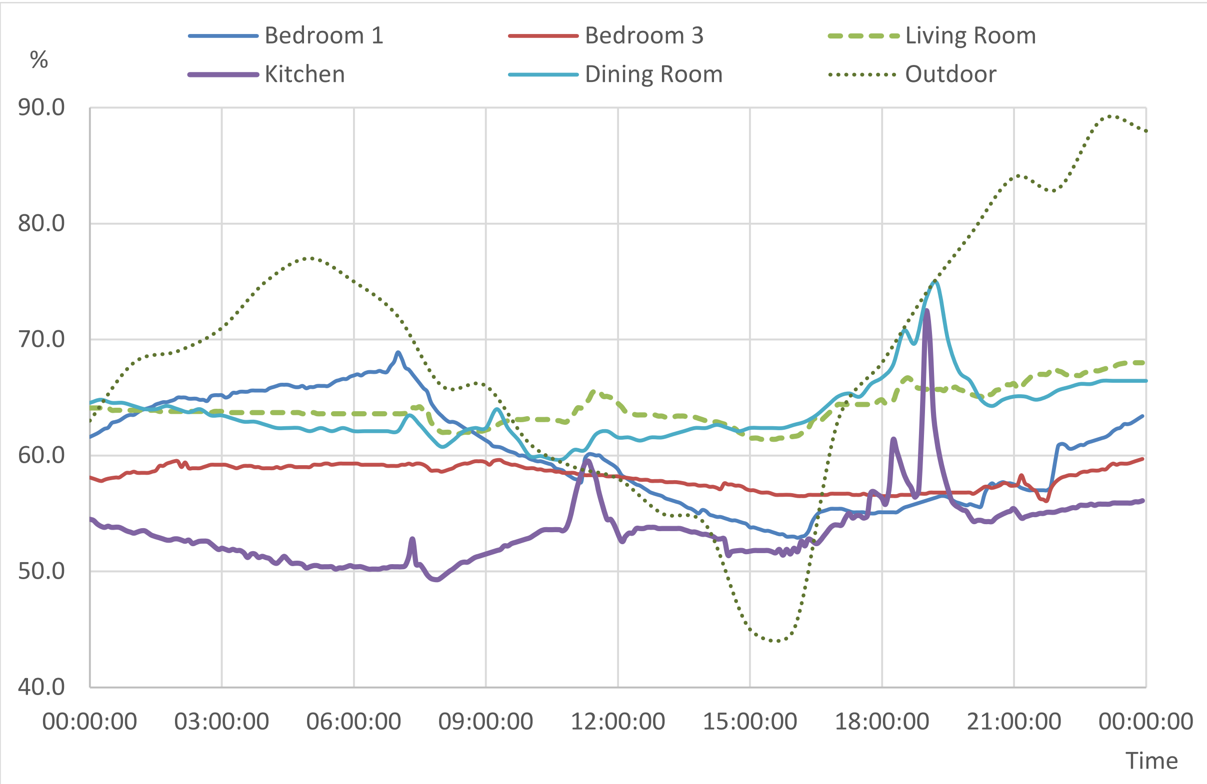


Figure 4.34 Monitored real time indoor and outdoor relative humidity of 1st July 2015.

Analogously, indoor relative humidity of January 2016 (a typical month in winter time) is shown in Figure 4.35 to display the monitored daily indoor room relative humidity. This month's house average relative humidity reached 68.0%. It can be seen from the figure that, the range of daily house relative humidity was between 60% and 80% in most of the time in the month. The relative humidity of bedrooms were usually the highest compared with other rooms. The reason was the windows and doors of bedrooms were always kept shut by the residents for keeping the bedroom warm with limit space heating during winter. In general, the relative humidity of these two rooms would be around 8% higher than other rooms in winter time.

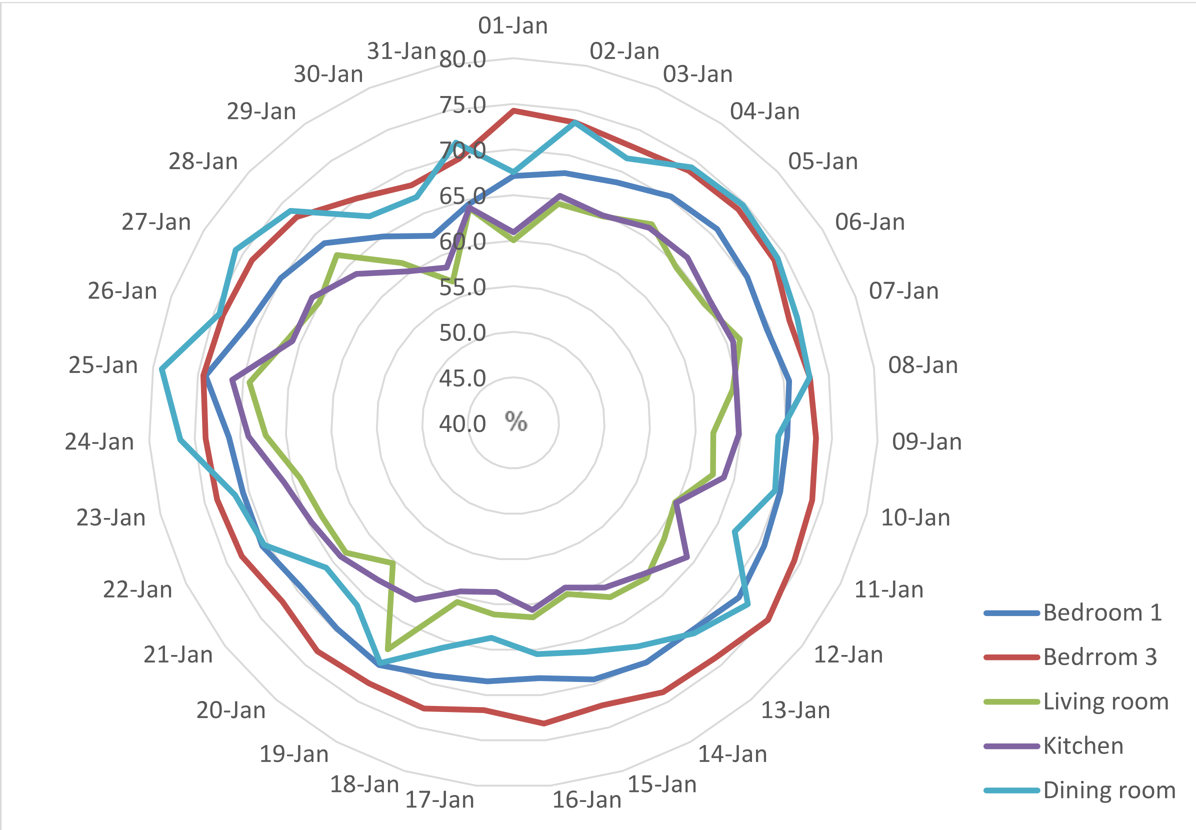


Figure 4.35 Monitored daily room relative humidity in January 2016.

On 16th January 2016, the coldest day in 2016, the house average indoor relative humidity was 59.9%. The highest daily room relative humidity was about 73.2% appeared in Bedroom 3 while the lowest relative humidity was about 60.6% of Kitchen. Figure 4.36 shows the hourly relative humidity on 16th January, 2016. During winter time, especially in the heating season, the indoor relative humidity would vary with the working time of central gas heating. It can be seen from the figure that the relative humidity of Kitchen was still affected obviously by cooking. This day was a family dinner day so the Kitchen was fully occupied in the day time. An interesting finding was, during the heating hours in the morning from 6:00am to 7:30am, the relative humidity of Living room and Dining room dropped down but for the bedrooms, the relative humidity rose up. The trend in the evening's heating hours for this rooms were the same so it can be assumed that because the Living room and Dining room were not occupied by residents in the morning working hours. While the space heating was on, as the indoor temperature grew up, the relative humidity decreased. On the contrary, the relative humidity of the bedrooms increased with the rising temperature was the results of residents' occupancy.

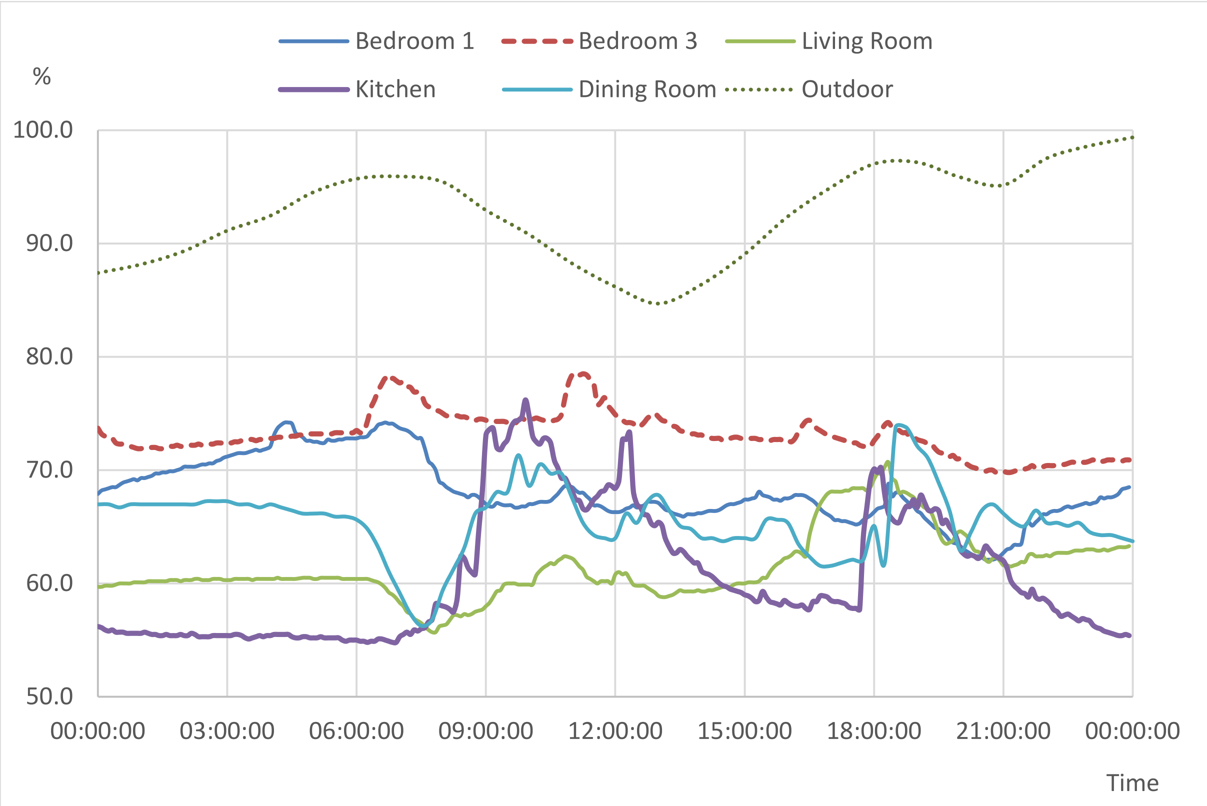


Figure 4.36 Monitored real time indoor and outdoor relative humidity of 16th January 2016.

C. CO_2 concentration

The CO_2 concentration monitoring was conducted from January to March 2016 at the same time with the data loggers and sensors' calibration work. It mainly recorded the performance of carbon dioxide concentration in Bedroom 3. The average CO_2 concentration reached a very high level of 1798 ppm since 25th January to 17th March 2016. The peak value of the average daily CO_2 concentration was 2981 ppm on 12th March 2016 (shown in Figure 4.37). It was a Saturday and the resident occupied the bedroom for a full day. Without ventilation and the window and door of Bedroom 3 were shut during the heating season, the CO_2 concentration maintained at an extremely high level on that day. There were only six days' monitored CO_2 concentration under 1200 ppm, the top value for moderate indoor air quality standard (IDA3 category) associated with CEN indoor air quality standards (BS EN 13779). It meant only 11.3% of all the monitoring results met the requirement of great indoor air quality. Among them, the Bedroom 3 was not in occupancy from 8th to 10th March 2016 and average CO_2 concentration for an empty bedroom in this Conventional House would be about 929 ppm.

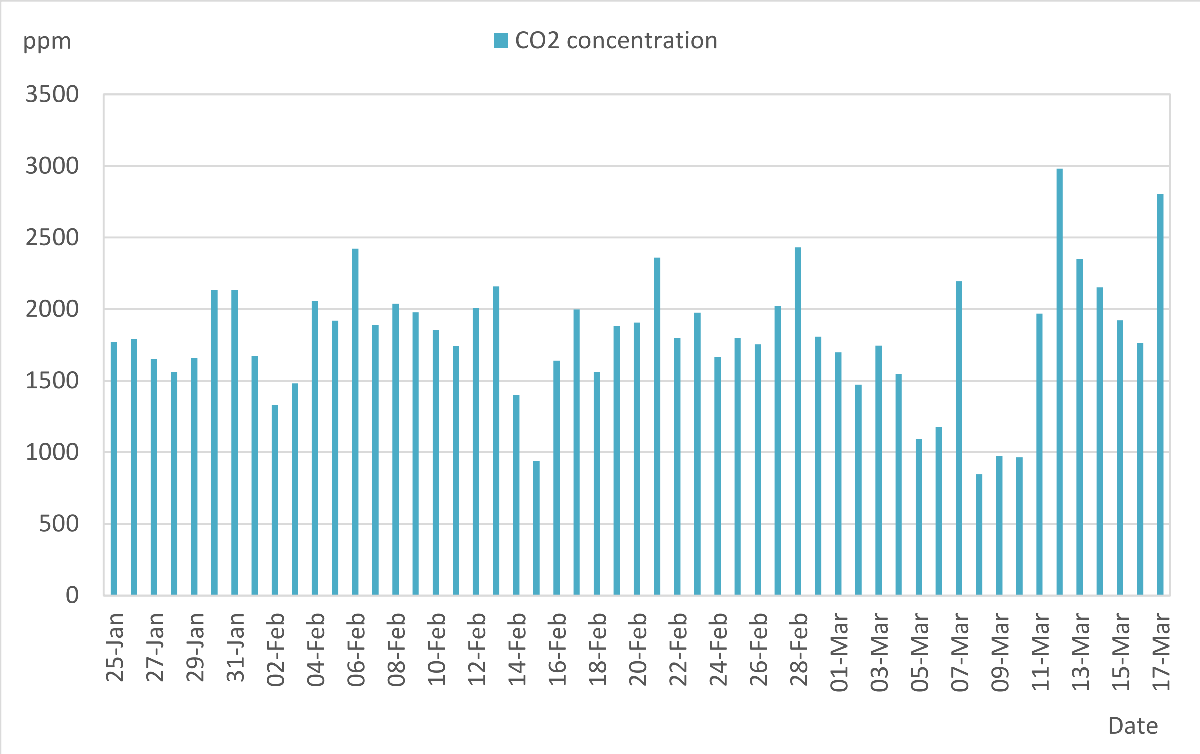


Figure 4.37 Monitored daily CO_2 concentration in Bedroom 3.

The monitored real time CO_2 concentration in Bedroom 3 on 25th February 2016 was shown in Figure 4.38. Its daily average CO_2 concentration was 1798 ppm so it was chosen to represent the typical carbon dioxide concentration performance of the bedroom in this Conventional House. It can be seen from the figure that the CO_2 concentration in this room increased dramatically while the resident was sleeping during the night time. The CO_2 concentration grew up from approximately 1000 ppm before the resident went to bed and it began to drop down from 3762 ppm to normal level since the resident got up in the morning. The peak of CO_2 concentration in this room was more than three times of the maximum value of IDA3 category (1200 ppm). In this case, it needed about 4 hours to cut down the room's CO_2 concentration from the peak to acceptable range. Without occupancy in the room, while the CO_2 concentration dropped down to normal level, it could maintain at around 870 ppm for 11 hours as the best performance of this room. In addition, the resident in this bedroom indicated it was not very comfortable when woke up in the morning in winter and in very few cases, felt hard to breath. Thus, the extremely high CO_2 concentration generated during night time would be the reason.

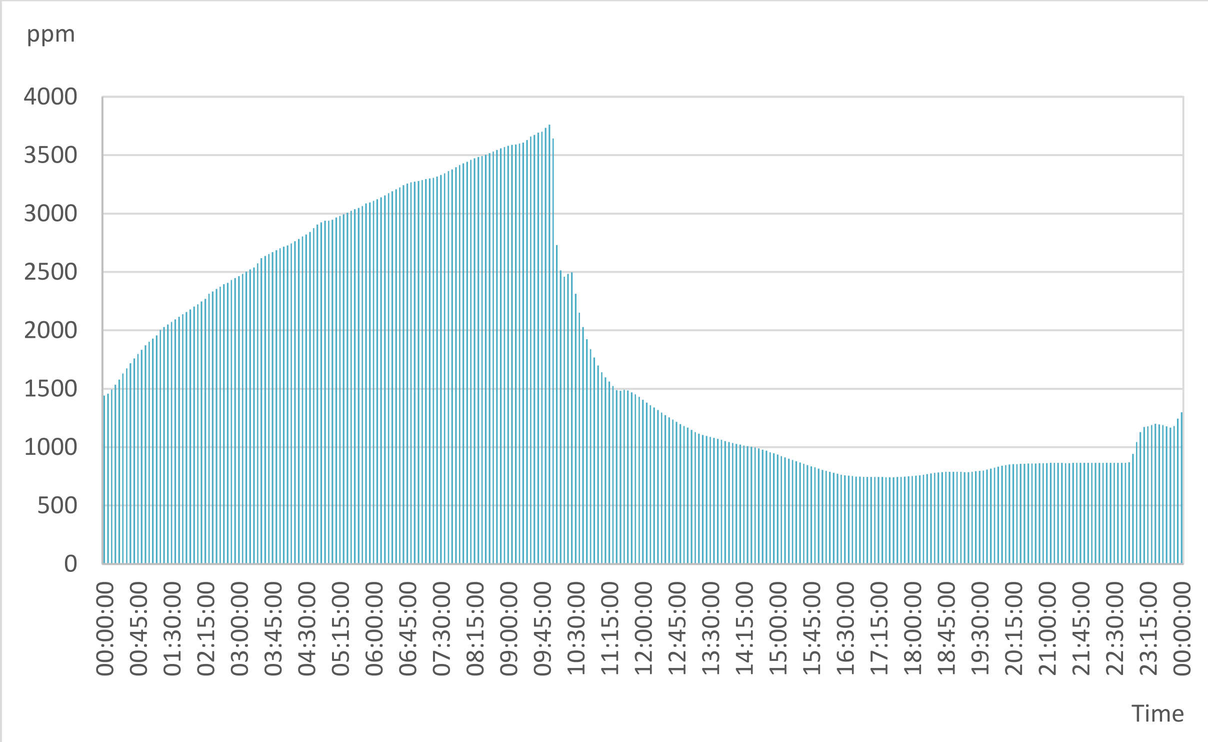


Figure 4.38 Monitored real time CO_2 concentration in Bedroom 3 on 25th February 2016.

4.4 Building modelling and simulation

4.4.1 *Model simulation and validation*

The simulation results generated by DesignBuilder indicate that the annual electricity and gas consumption of the Conventional House were 2457.21 kWh and 10348.53 kWh, respectively. The total building area and net conditioned building area of this Conventional House estimated in the model was 120m^2 and 90m^2, respectively. Hence, the total simulated energy consumption was 12805.74 kWh and the primary energy demand was 174.47 kWh/(m^{2}a).

Figure 4.39 shows the simulated monthly electricity and gas consumption of the Conventional House for a whole calendar year. It can be seen from the figure that both electricity and gas consumption in summer were lower than the energy consumption in winter due to the high energy demand for heating during the coldest months in a year. For electricity consumption, the highest and lowest monthly demands were 216.11 kWh in December, and 195.01 kWh in February. For gas consumption, the usages during non-heating period maintained at the same level. The average monthly consumption of 423.24 kWh was supplied to domestic hot water and cooking only. Considering the heating energy, it can be known from the simulation results that the colder the weather was, the more heating energy it consumed. The biggest gas consumption appeared in January with 1493.08 kWh in order to keep the whole house warm in the winter. As weather was getting warm in April, the demand for space heating of the last heating month reduced and the monthly gas consumption dropped down to 1028.65 kWh.

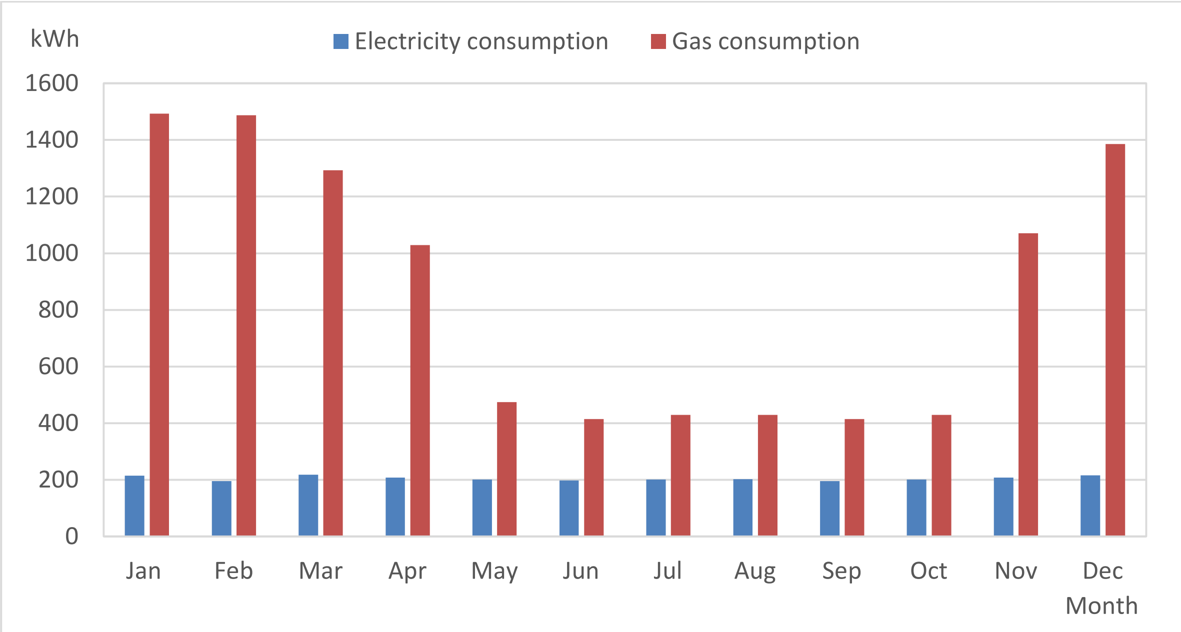


Figure 4.39 Simulated monthly electricity and gas consumption of the Conventional House.

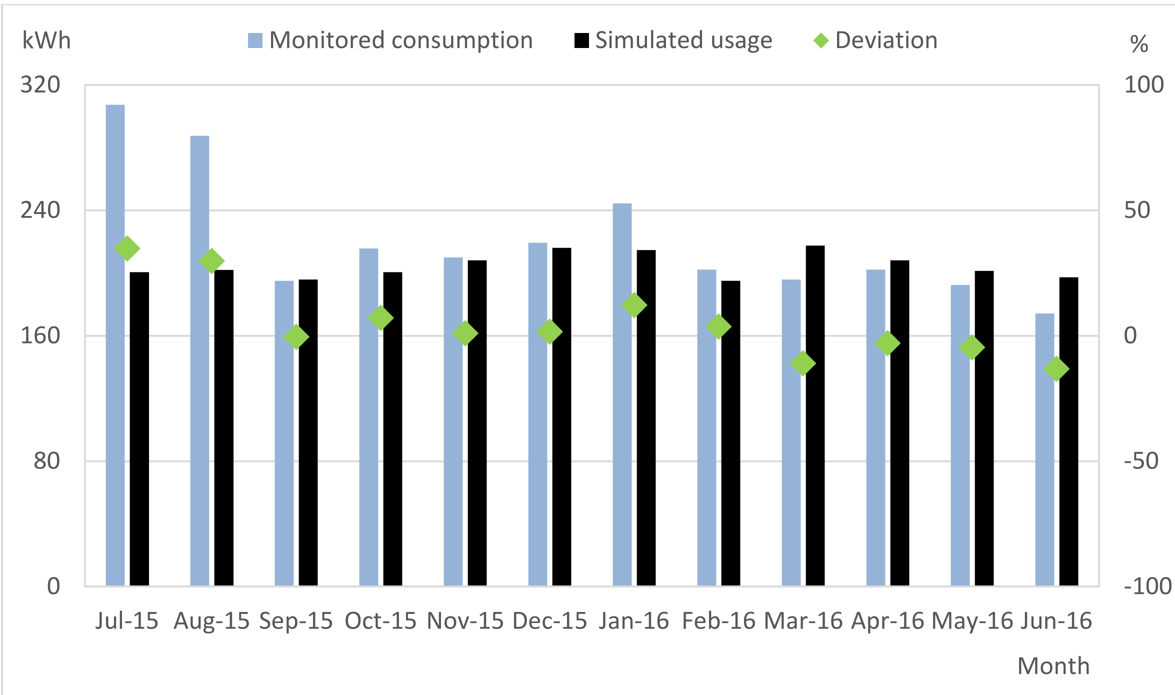
The simulation results generated by this DesignBuilder model including electricity consumption of appliances and lighting, gas consumption of space heating, domestic hot water (DHW) and cooking are listed in Table 4.12. As the consistent schedule for energy consuming was set in the simulation model, the simulated energy consumption was relative stable compared to the actual usages.

Month	Electricity consumption		Gas consumption		
	Appliances (kWh)	Lighting (kWh)	Heating (kWh)	DHW (kWh)	Cooking (kWh)
Jan	162.16	52.55	778.73	666.36	48.00
Feb	147.30	47.72	842.42	601.87	43.35
Mar	164.29	53.21	578.69	666.36	48.00
Apr	157.21	50.94	337.34	644.86	46.45
May	148.91	52.55	27.25	399.20	48.00
Jun	145.63	51.60	0	368.49	46.45

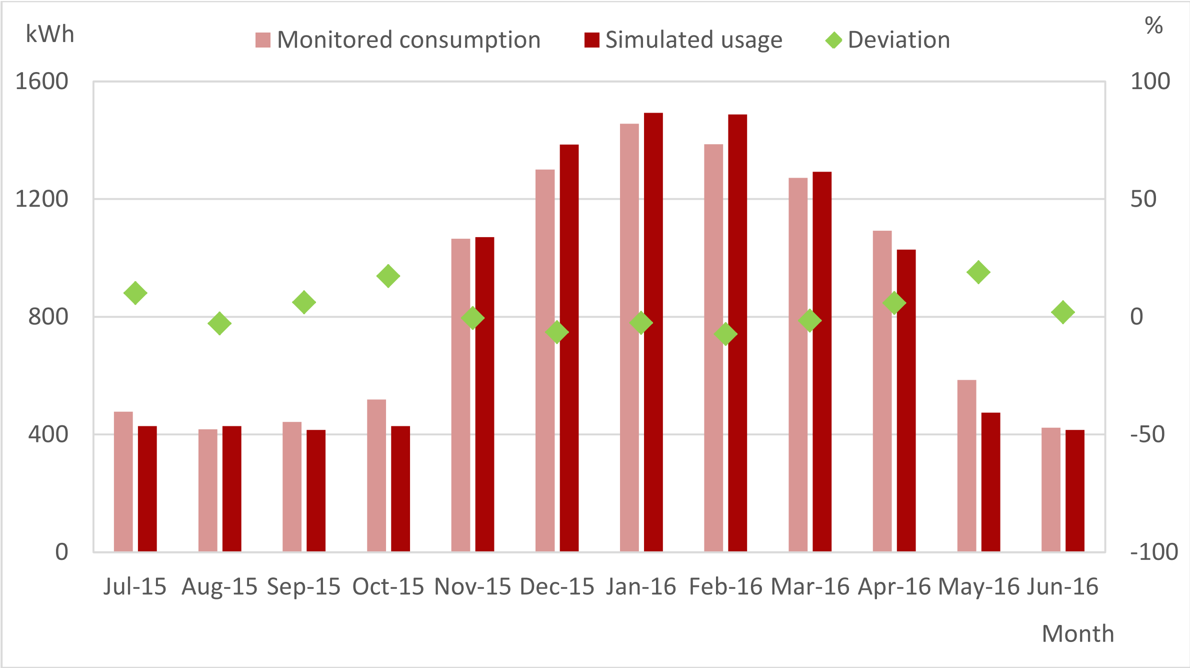
Jul	148.00	52.55	0	380.77	48.00
Aug	149.06	52.88	0	380.77	48.00
Sep	144.56	51.27	0	368.49	46.45
Oct	148.00	52.55	0	380.77	48.00
Nov	156.90	51.27	406.63	617.22	46.45
Dec	163.23	52.88	670.79	666.36	48.00

Table 4.12 Monthly energy consumption by sector simulated by DesignBuilder.

As the second monitoring year was 366 days, excluding the electricity and gas consumption of 29th February 2016, the annual actual electricity usage was 2646.35 kWh while the gas usage was 10436.92 kWh. Thus the annual actual total energy for a year was 13083.27 kWh. The comparison for actual monitoring data and simulation results. The total energy consumption error between actual measurement and simulation was 2.12% according to Equation (1) and (2), which was within the acceptable range. The CV(RMSE) was calculated as 7.14% (maximum value is 15%) and the MBE was +2.12% (within the ±5% requirement) according to Equation (3) and (4).



(a)



(b)

Figure 4.40 Comparison of the Conventional House's monthly monitored energy consumption and simulated usage: (a) Electricity consumption, (b) Gas consumption.

The comparison of monthly monitored energy consumption and simulated usage and their percentage errors are shown in Figure 4.40. For electricity consumption, it is clear from the figure that, except the consumption in July and August, the deviations between monitored and simulated results were moderate and within the acceptable range. The reason for the abnormal values of the errors appeared in July and August was because the change of house occupancy. First, all residents were in holiday in July and the electricity demand must increase than other normal month. Moreover, two guests was visiting the family and stayed with them in the summer holiday. The actual electricity consumption rose about 50% compared to the simulated usage but the monthly electricity consumption per person for monitored and simulated usage in those two months were very closed, 49.59 kWh and 50.31 kWh, respectively. From the view of this point, the model was still accurate. Besides, the electricity consumption error between actual measurement and simulation of the remaining ten months was 0.17% according to Equation (1) and (2), which was within the acceptable range. The CV(RMSE) was calculated as 7.40% (maximum value is 15%) and the MBE was -0.17% (within the ±5% requirement) according to Equation (3) and (4). For gas consumption, the CV(RMSE) and MBE were 7.20% and 0.85%, correspondingly. The biggest deviation between actual measured and simulated usage appeared in May of 18.89%. Similarly, the error in October was also bigger than usual level and over 15%. This was because the two months were within the boundary of heating and non-heating seasons. As it was a cold winter, the temperature of October and May was lower than regular years. Thus, the heating of the house was turned on occasionally in these two months and this led to the increasing of gas demand.

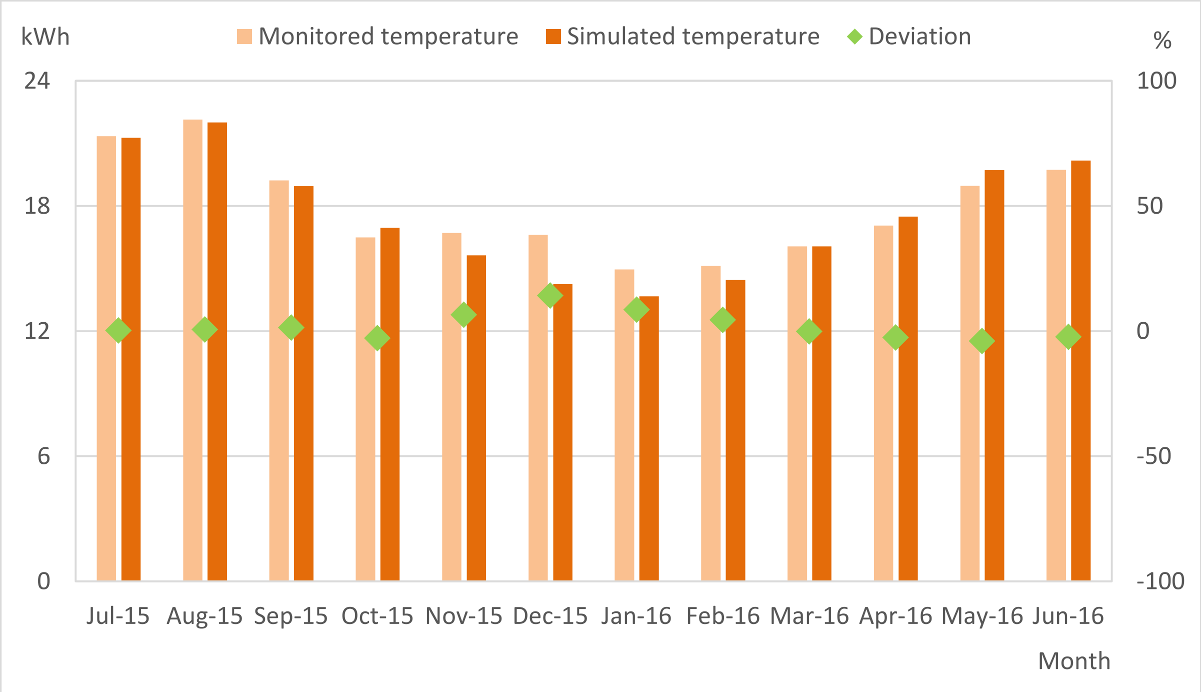


Figure 4.41 Comparison of monthly monitored and simulated indoor temperature.

Figure 4.41 indicates the comparison of monthly monitored and simulated indoor temperature and their percentage errors. The annual monitored average indoor temperature was 17.7°C while the simulated indoor temperature in the model was 17.6°C. The CV(RMSE) and MBE were 5.15% and 1.76%, respectively. The relative large deviations occurred in December and January, the coldest winter time. The indoor temperature difference was near 2°C in the heating season. There were two reasons for leading to this situation: firstly, the 8 indoor temperature monitoring sensors had their own measure accuracy range and the average readings of the sensors may offset some specify data in winter time; another consideration for this case should be the incomprehensive sensors deploy plan in the house. The simulated indoor temperature represented the average temperature of all zones of this Conventional House. However, the monitored indoor temperature indicated the measured thermal condition of the main occupant zones in the house. These zones were warmer than other rooms e.g. toilet, storage room and the unoccupied Bedroom 4 because those rooms were not heated in the winter. Hence, the monitored indoor temperature should be slightly higher than simulated results due to the two reasons stated above.

In general, the comparison results above between actual and estimated energy consumption of this Conventional House show the high accurate of the DesignBuilder model. Considering the indoor temperature with the energy demand especially in the heating season, the thermal condition was still correct compared with the onsite measured data. The simulation model has been validated by the actual measured energy consumption and indoor temperature and it can be used for further analysis.

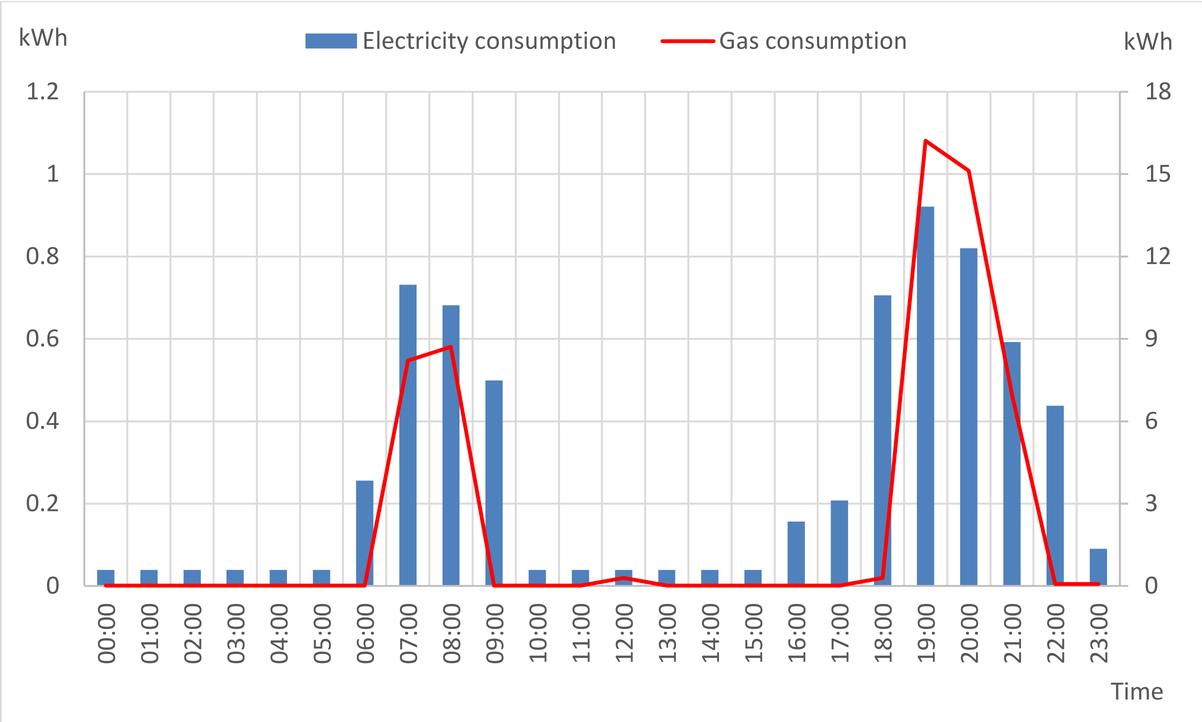


Figure 4.42 Average hourly energy consumption in heating season.

Estimated average hourly energy consumption in 24 hours in winter time (heating season) is shown in Figure 4.42. It demonstrated that there were two peaks of energy demand appear in a day, 6:00-9:00 and 18:00-22:00, for both electricity and coal consumption. The energy trends matched with the actual situation well. The residents got up at around 6:30am and went to work before 9:30am and they came back home from work at around 6pm and went to bed at 10pm in the evening. The space heating was supplied by a gas boiler about 4 hours a day, one and a half hour in the early morning when they wake up and two and a half hour in the evening when they come back home. The peak value of gas consumption in the morning is lower than the other in the evening is due to the longer gas boiler operation time and the main cooking gas demand from the residents. The trend of electricity demand is similar to the heating. But the electricity demand in the evening is slightly higher because the increasing of residents occupancy after 6pm. When the residents were away from home to work and at sleeping period, the electricity consumption remained at a minimum standard. In general, the energy consumption during non-peak hours is below 20% of the energy demand of peak hours. Besides these high energy demand hours, the energy consumption for other time of a day remained at a relative low level.

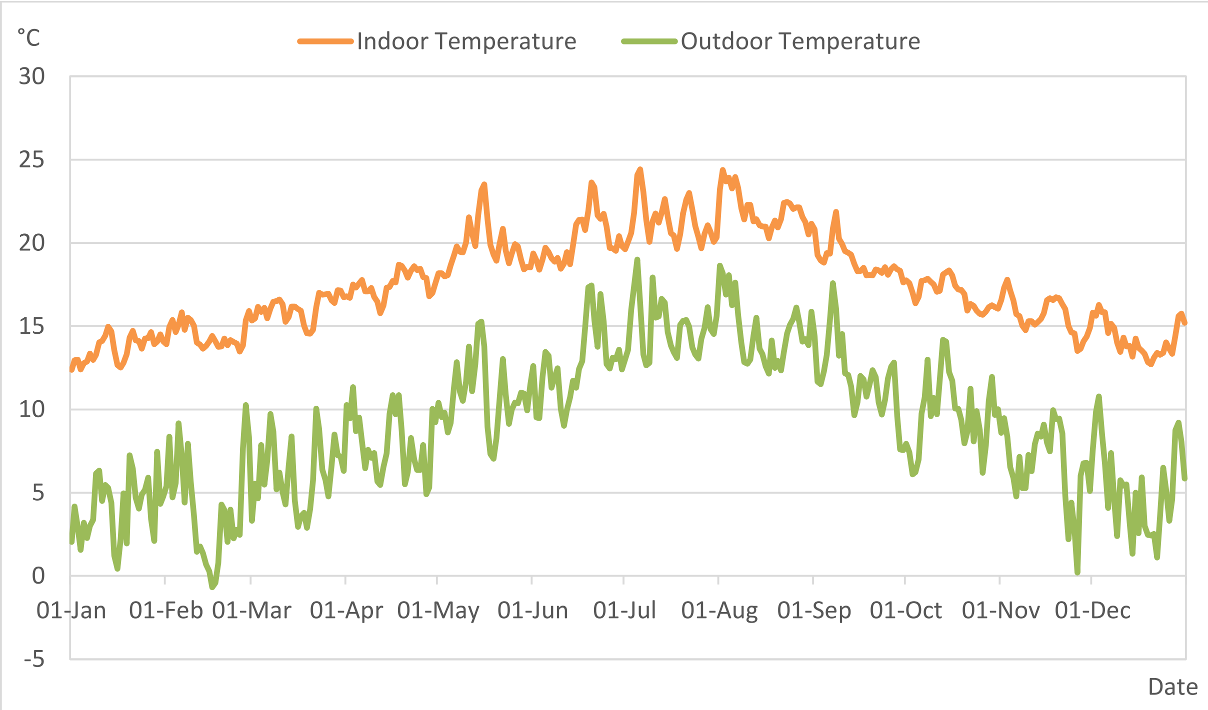


Figure 4.43 Comparison of daily indoor temperature and outdoor temperature.

The comparison of daily indoor and outdoor temperature estimated from the DesignBuilder model is shown in Figure 4.43. It can be seen from the simulation results that the indoor temperature during the whole heating season was 15.6°C, which is 0.5°C lower than the onsite monitored data. The temperature error between actual measurement and simulation was 3.11% according to Equation (1) and (2), which was within the acceptable range.

4.4.2 ***Analysis of property performance***

For this selected Conventional House, the realistic usage of electricity and gas consumption in the first monitoring year were 2646.35 kWh and 10436.92 kWh, respectively and the total energy consumption could be calculated as 13083.27 kWh. The simulated energy usage in a calendar year generated by the DesignBuilder software were listed as follows: electricity consumption was 2457.21 kWh; gas consumption was 10348.53 kWh; and the annual energy consumption was 12805.74 kWh. Compare to the data from National Statistics in 2011, the total energy consumption of this detached house (13.09 MWh) was approximately 20% lower than the average house household energy consumption of North East (16.90 MWh) and Northumberland (15.70 MWh) in North East region.

The comparison of the energy consumption for these three different cases is summarised in Table 4.13. Household energy consumption could be divided by the proportion of electricity and gas consumed. In North East, the average household energy consumption consisted of 20.9% electricity and 79.1% gas consumption. Thus, the electricity and gas usages were about 3.53 MWh and 13.37 MWh, respectively. According to the simulation results, electricity consumption accounted for about 19.2% of the total energy consumption. And the rest was gas consumption which represented 80.8% of the house energy consumption. Based on the measured energy data, the realistic proportion of the electricity and gas usage were about 20.2% and 79.8%. From the table, it can be seen that the ratio of electricity and gas consumption were approximately 20:80.

Case	Electricity consumption (MWh)		Gas consumption (MWh)		Total energy consumption (MWh)	
(1) Actual consumption	2.65	20.2%	10.44	79.8%	13.09	100%
(2) Simulated usage	2.46	19.2%	10.35	80.8%	12.81	100%
(3) Statistics data	3.53	20.9%	13.37	79.1%	16.90	100%

Table 4.13 Comparison of the energy consumption in different cases.

As this house was not fully occupied (Bedroom 4 was not used at most of the time), the energy consumption was slightly under the national average level. In addition, in order to save money on paying energy bills, the daily heating hours of this Conventional House was set less than 4 hours during the whole winter by the residents. Thus, although the energy demand of this house was lower than the national average level published on the statistics data, the approximate ratio of electricity and gas consumption indicated this Conventional House represented the typical house performance in the UK.

Reducing the heating hour in the winter help save the money for paying energy bills. However, the indoor temperature for the house could not be guaranteed to remain at a comfort level if heating hours were less than the requirement. The annual monitored average indoor temperature of this Conventional House was 17.7°C while the simulated indoor temperature in the model was 17.6°C. Moreover, during the winter heating period, the measured average indoor temperature was only 16.1°C. According to the report published by West Midlands Public Health Observatory (UK), an adequate level of wintertime indoor temperature is 21°C for a living room, and a minimum of 18°C for other occupied rooms, giving 24 °C as a maximum comfortable room temperature. In the Passive House standard, it is required to achieve 20 °C indoor temperature, which is the most comfortable indoor temperature in winter.

Besides, the house residents live in this Conventional House also complained about the cold winter indoor environmental condition. Improving the indoor environmental condition especially the room temperature in winter time and reduce the space heating demand attract people’s attention now. As this house represents a type of Conventional House in the UK, it means a large number of houses are facing the same problem in the country. According to the simulation results, the highest room temperature during the heating season could achieve 16.4°C based on the current building fabric, heating schedule and residents’ occupancy. Thus, an investigation of retrofitting to improve the property performance was conducted in the validated DesignBuilder model, which is shown in the following section.

4.5 Exploration of retrofitting measures to improve property performance

4.5.1 *Building fabric retrofitting*

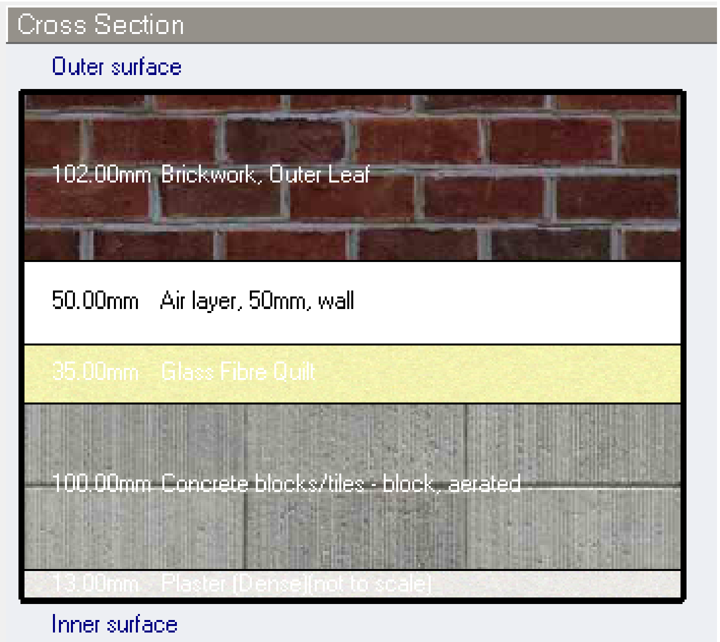
From the view of passive methods of building energy saving, advanced building construction technologies and materials can enhance the thermal mass of building envelop and reducing the energy consumption for heating of the building by utilising the existing internal heat effectively. From the simulation, it is found that the external wall, roof, floor and glazed windows were the four main parts, which resulted in internal heat lost.

A house retrofitting using advanced materials certified by Passive House standard, which is one of the most effective and rigid passive energy saving regulations are applied to this Conventional House. Table 4.14 shows the recommended limits for building fabric’s U-values in the Passive House standard and it also indicates the current U-values of the property and the suggested retrofitting U-values calculated by the simulation model.

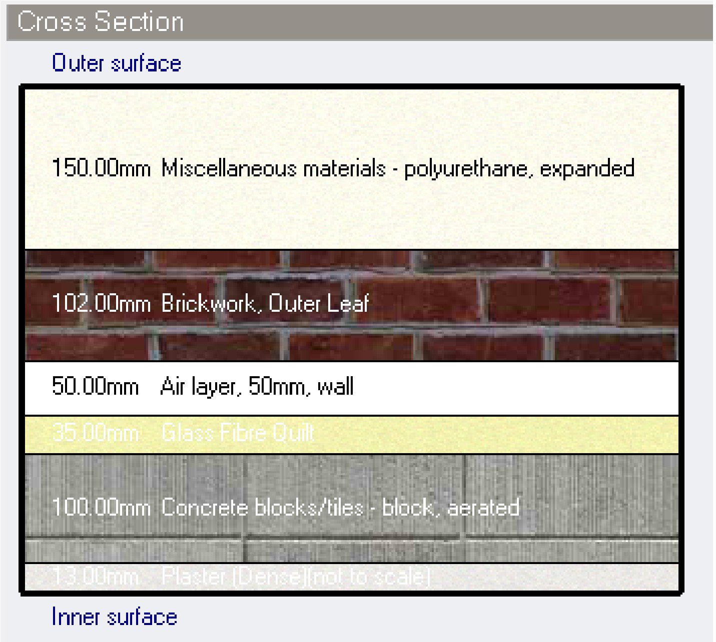
Elements	Passive House standard U-values (W/m²K)	Current U-values (W/m²K)	Retrofit U-values (W/m²K)
Walls	0.15	0.54	0.12
Floors	0.15	0.25	0.10
Roofs	0.15	2.93	0.13
Windows	0.85	1.96	0.78

Table 4.14 Comparison of U-values for different envelop elements.

For external walls, floors and roofs, the U-values should be lower than 0.15 W/m²K. For complete window installation, the maximum U-value is 0.85 W/m²K. It can be seen from the table that the current U-values for all building elements are greater than the recommended limits of Passive House, which is one of the best energy efficiency building. Among them, the unoccupied pitched roof of this house is the place that losing heat and people may ignore it easily. Compare to the Passive House standard, the U-value is about 20 times greater according to the calculation generated from the DesignBuilder model. For the remaining elements, all the U-values are approximately within 3 times of the Passive House standard. All the U-values of the four fabric elements could be reduced to recommended range by adding insulation materials and their performance would be improved significantly.



(a)



(b)

Figure 4.44 Comparison of external wall structure for different cases: (a) Current construction, (b) Estimated retrofitting construction.

In the simulation, 150 mm thickness expanded polyurethane board was chosen to add to the outer surface of external wall, and inner surface of floor slab and roof level; the double glazing for windows and doors have been replaced by good quality triple glazing. The estimated U-values of the four fabric elements are listed in the table below and they are all within limitation of the Passive House standard. As an example, the comparison of external wall structure for current construction and recommended retrofitting construction is shown in Figure 4.44.

To compare the house performance for current status and after retrofitting, indoor temperature was set at 16°C in the model and the annual heating gas consumption of current status is 3641.85 kWh and the annual heating consumption after retrofitting is 812.30 kWh known from the simulation. Thus, at 16°C indoor environmental condition level, the heating demand of this Conventional House can reduce about 77.7% because of the building fabric retrofitting.

By retrofitting the building fabrics, this Conventional House is able to be heated to 20°C, which is the average indoor temperature during heating season based on the DesignBuilder model simulation. The house electricity consumption (2457.21 kWh) after retrofitting is not different compares to current status, but the annual gas consumption grows up from 10348.53 kWh to 13724.86 kWh, leading by the rising heating demand. Thus, the primary energy demand after retrofitting is 152.50 kWh/(m^2a). The annual gas consumption for heating is 4561.06 kWh in this case, and the heating energy demand is 50.68 kWh/(m^2a).

4.5.2 *Improvement of house utility*

Figure 4.45 The old floor mounted fan assisted gas boiler in the Conventional House.

The old fashion gas boiler in this Conventional House has worked for more than 10 years already. Its original seasonal efficiency was 78.5% and this value was used in the UK Government's Standard Assessment Procedure (SAP) for energy rating of dwellings. However, the efficiency of the boiler decreased as the time went on. According to the statistics data, the efficiency of this type of gas boiler (shown in Figure 4.45) could be reduced to 45% after 10 years' working scheme. In the DesignBuilder model, the 0.45 boiler working efficiency was set and the simulation results for both energy consumption and indoor environmental condition have been validated. Thus, it can be known that the efficiency of this boiler has dropped down for approximately 42.7% after more than a decade's service.

A new condensing gas boiler with 90% efficiency is considered to replace the old boiler in the simulation. Combine the effects of the retrofitted building fabric, to keep the whole house at 16°C, the heating energy demand is only 406.15 kWh per year and the gas consumption for DHW also decreases to around 3070.76 kWh. Hence, the gas consumption after replacing the old boiler would be 3476.91kWh. In order to heat the Conventional House to 20°C, the annual estimated gas consumption for space heating simulated in the DesignBuilder model is only 2280.53 kWh. Hence, the total energy consumption of this Conventional House would reduce to 8373.66 kWh in a year. The primary energy demand and space heating demand for this case are 93.04 kWh/(m^2a) and 25.34 kWh/(m^2a), respectively.

Indoor temperature (°C)	Gas consumption (kWh)	Case 1	Case 2	Case 3
16	Heating demand	3641.85	812.30	406.15
	DHW demand	6141.52	6141.52	3070.76
20	Heating demand	-	4561.06	2280.53
	DHW demand	-	6141.52	3070.76

Table 4.15 Comparison of gas consumption for different cases.

Table 4.15 shows the comparison of gas consumption of space heating and DHW for different cases of this Conventional House. Among them, Case 1, Case 2 and Case 3 represents the gas consumption of current status, after building fabric retrofitting and after both building fabric retrofitting and boiler replacement, respectively. 16°C and 20°C are chosen as two typical indoor temperature to compare the performance of the gas consumption under different situations. It can be seen from the simulation results that to maintain the house temperature at 16°C, Case 3 save the most energy for space heating, of 88.8% gas consumption reduction. Moreover, the gas consumption of DHW is half of the current demand. At 20°C, the standard indoor temperature, the estimate heating demand of this house is only 2280.53 kWh for a year. Compare to the Passive House standard, the 93.04 kWh/(m^2a) primary energy demand of this house is within the 120 kWh/(m^2a) limit. Although the 25.34 kWh/(m^2a) space heating demand nearly reaches twice consumption of the criteria, it has been reduced significantly from its original status. The consequent of retrofitting for both building fabric and the improvement of low efficiency gas boiler is great for reducing house energy and provide a direction for future Conventional House retrofitting.

4.6 Summary

The case study of a Conventional House was investigated in this chapter, by undertaking field audits, house structure measurement, actual energy and indoor environment data measurements, collection, house performance analysis, building modelling and the prediction of property performance after retrofitting.

The energy performance and indoor environmental condition of this Conventional House have been monitored for more than two years by a series of calibrated data loggers and sensors, and the actual data of the second monitoring year was analysed in this study. The DesignBuilder model was validated by actual energy consumption and onsite indoor temperature recorded by the monitoring kits.

The validated model was used to explore the property performance from the view of applying passive energy saving retrofitting methods. The actual annual energy consumption for this house was 13142.64 kWh. The primary energy demand was 146.03 kWh/(m^2a). With 3641.85 kWh heating gas consumption in winter, the house indoor temperature remained at 16.1°C. The building fabric retrofitted model indicated the gas consumption for space heating in a year could be reduced by 77.7% to 812.30 kWh to keep the house at the same indoor temperature during the heating season.

By replacing the low efficiency gas boiler to a high standard condensing boiler, the gas demand for space heating and DHW decreased to half of the simulation results in the building fabric retrofitted model, with 88.8% and 50% reduction compared to the actual gas consumption.

As the recommended indoor temperature of 20°C during the heating season was set in the compound retrofitting model, the estimated results indicated the primary energy demand and the space heating demand of the house were 93.04 kWh/(m^2a) and 25.34 kWh/(m^2a), respectively. From the simulation model, it can be seen that the energy performance and indoor environmental condition of this Conventional House can be improved to a high energy-saving one by using the passive retrofitting methods.

Overall, this case study indicates the advantages and benefits of house retrofitting by using passive energy methods in achieving lower energy consumption, which resulted in low carbon dioxide emissions and good thermal comfort. It provides a better quality environment for living in this type of Conventional House. The methodology developed from the study can be used as a reference for the future Conventional Household retrofitting.

Chapter 5. Case Study of a Passive House

5.1 Introduction

The selected property for this case study is a two-storey Passive House located in Durham, United Kingdom (shown in Figure 5.1). Durham is also located in the North East England, which is believed to be one of the coldest regions of England with cooler summer but colder winter. This dwelling was designed and built to achieve minimum energy demand and high quality of living environment. The house is a new build timber framed detached family house that meets the Passive House construction standards and is included in the Passive House database (ID: 4186) of International Passive House Association.

Figure 5.1 North façade of the Passive House.

The treated floor area of the house is 219 m^2 based on the calculation of Passive House Planning Package (PHPP). The first floor (upper level) of this house comprises an entrance hall, a guest bedroom (changed from an office room), a shower room, a living room, a dining room and a kitchen. The ground floor (lower level) consists of a family room, a utility room, a cloakroom, a bathroom, two bedrooms and a master bedroom with an en-suite. This dwelling benefits from its advanced building envelop design and construction materials (e.g. high performance insulations and triple glazing), a mechanical ventilation with heat recovery system (with 92% heat recovery efficiency), a 6 kW photovoltaics array and a high efficiency condensing gas boiler supplied to a thermal store for providing domestic hot water and space heating. Due to the personal preferences of the Passive House owner who appreciates outdoor scenery through the openings of the house, there are 4 external doors and 43 windows installed in this dwelling. However, this became one of the biggest challenges for the housing design and construction. Previously, the number of openings in a Passive House dwelling was limited in order to keep the house super-airtight and reduce the windows installation thermal bridges as close to zero as possible. Thus, it took about three years to finish all stages construction works of this contemporary property since 2012.

The aim of this work was to investigate the energy performance and indoor environmental condition of this super-insulated dwelling by day to day data measurements and recording; set up a computational model for the house; and then use the measured data to validate the model; use the validated model to find out potential optimised operation solutions for Passive Houses; and overcome their overheating problem during summer time and further to reduce the overall energy consumption of this house. Moreover, set up a Conventional House model with same dimensions and compare the energy consumption with the Passive House's to find out how much energy could Passive House save more than the traditional house in a calendar year. Then the methodology would be deployed for further application about the energy consumption analysis. Several field studies and a thermal study of this property were carried out to help understand the house performance.

5.1.1 *Field study*

The first audit was conducted in November 2014 for the preparation work of this study. 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 gathered from the house owner during the field study. A thermal study of the dwelling was carried out as a part of this case study. A series of thermal photographs taken by thermal camera of the windows and frames was used to analyse the performance of energy conversation and compare it with a Conventional House. We can see from the top view of this Passive House (shown in Figure 5.2) that this dwelling could be divided to Part A, Part B and Part C from west to east. PV solar panels were installed on the roof of the Part A dwelling so the pattern in the figure is different from others. Storey heights of ground floor for all three parts are 2.7 m. And the storey heights of first floor for Part A, Part B and Part C are 2.65 m, 2.10 m and 2.65 m, respectively.

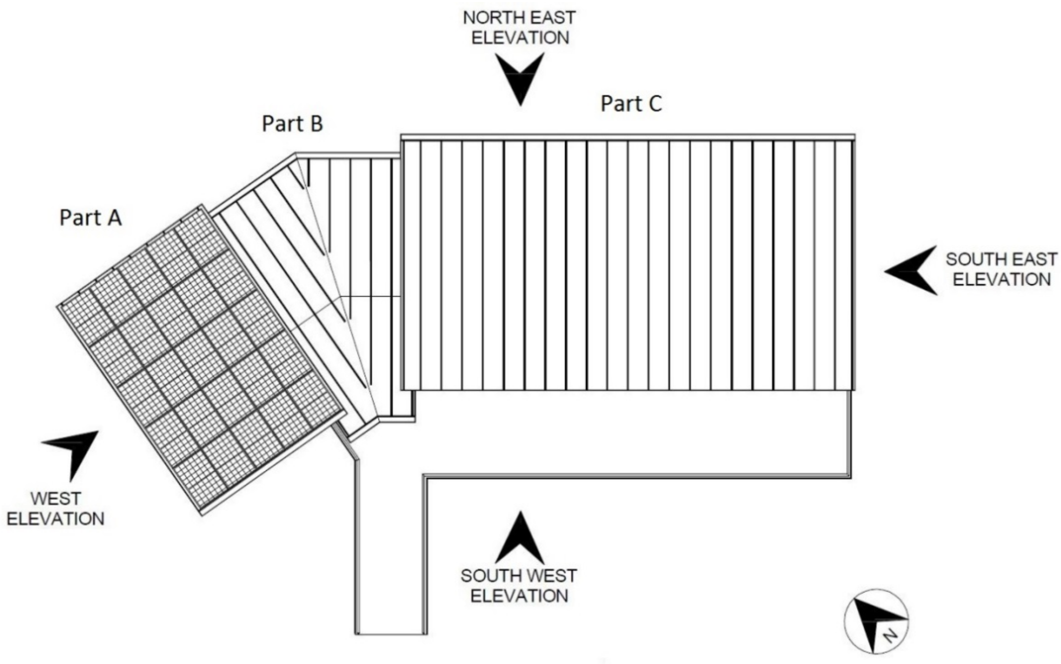
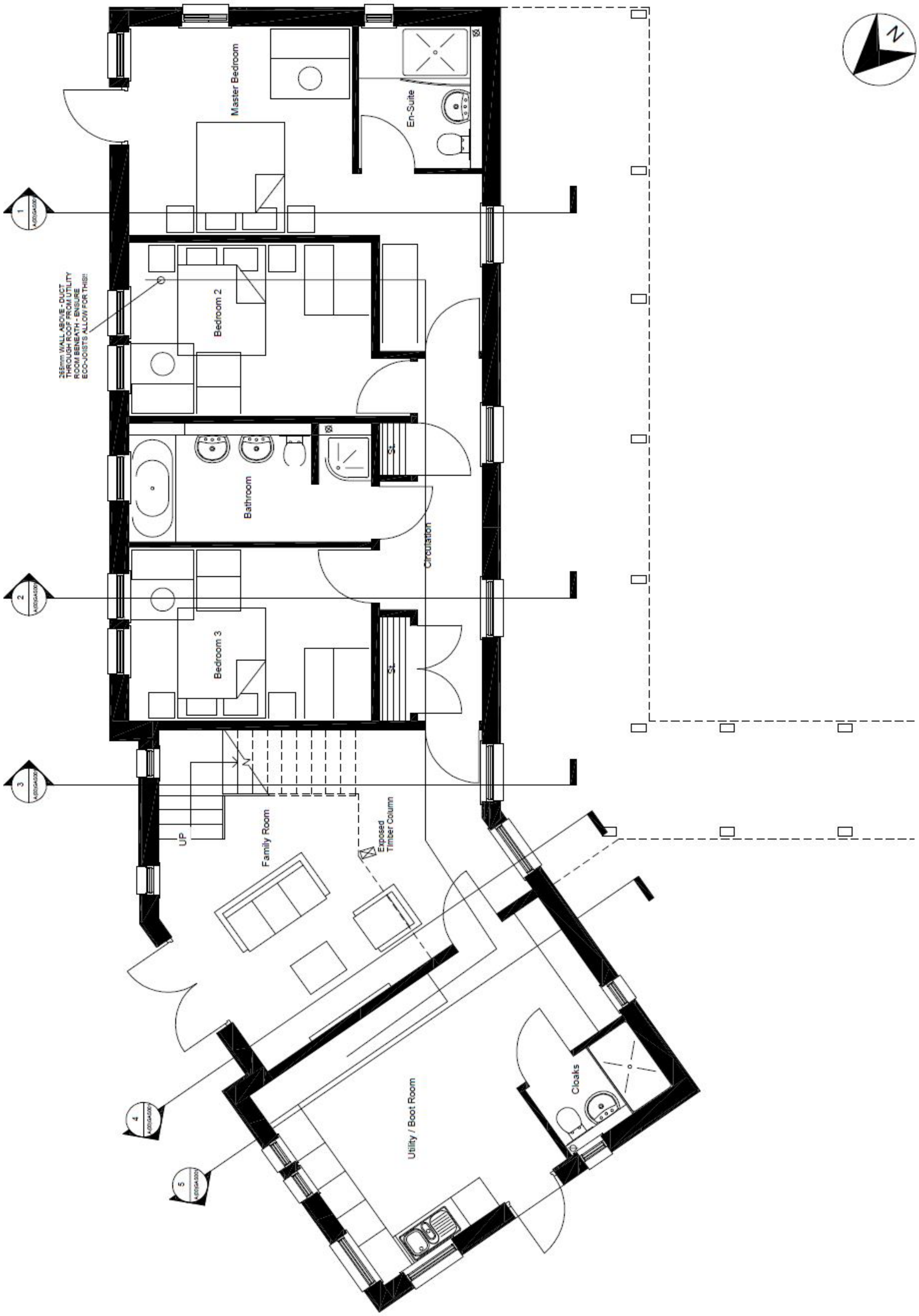


Figure 5.2 Top view of the Passive House. (Source: Roger Lindley.)

According to the information provided by the house owner, the detailed areas for each room of the dwelling are listed in Table 5.1.

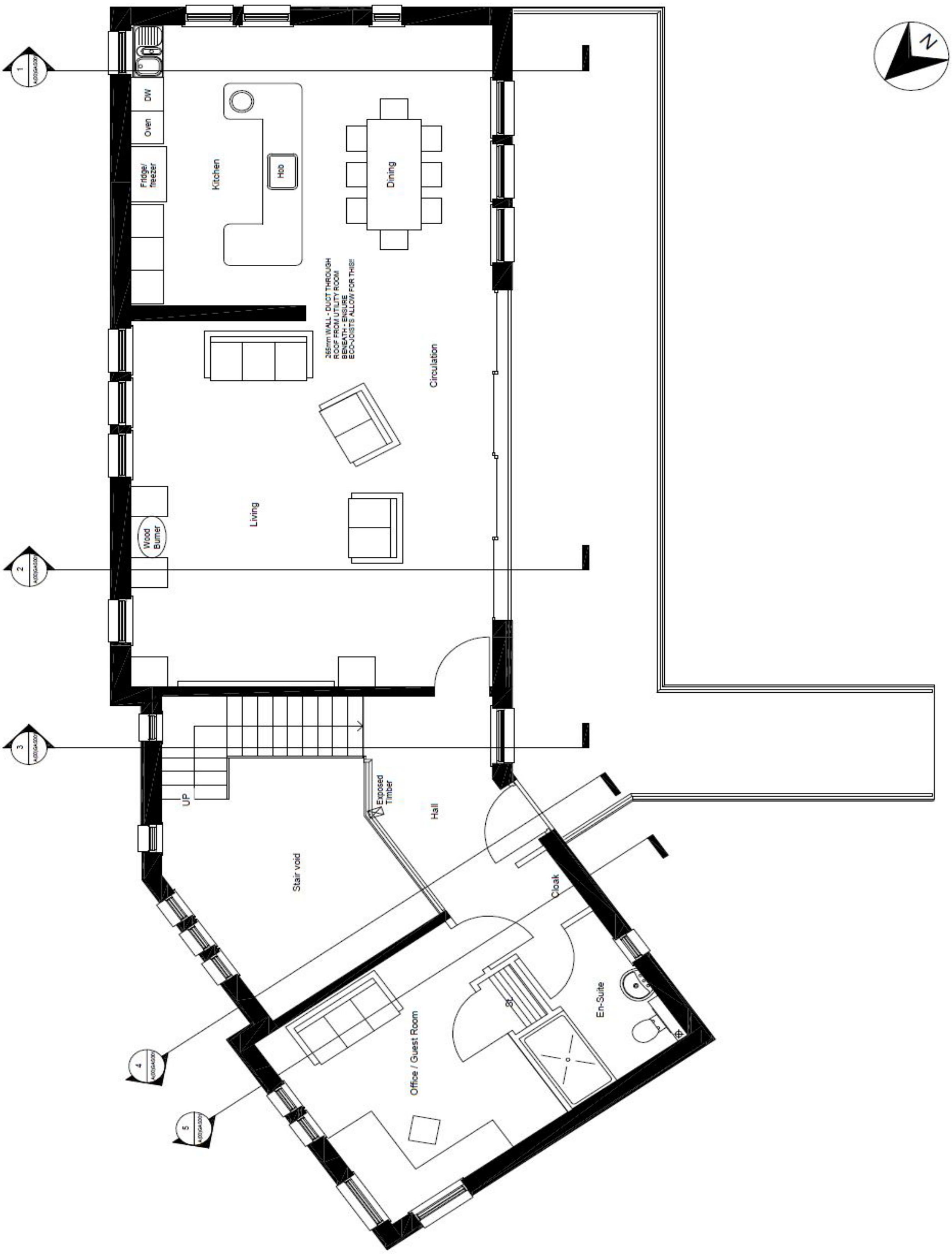
Floor	Room type	Room area (m^2)
Ground floor	Utility room	25.24
	Family room	27.42
	Bedroom 3	13.32
	Bathroom	9.17
	Bedroom 2	13.91
	Master bedroom	26.33
First floor	Office room	15.58
	En-suite	6.08
	Living room	40.97
	Kitchen	15.78
	Dining room	17.84

Table 5.1 Areas for main rooms of the Passive House.



Master Bedroom
En-Suite
Bedroom 2
Bathroom
Circulation
Bedroom 3
St.
St.
UP
Family Room
Exposed
Timber Column
Utility / Boot Room
Cloaks

(a)



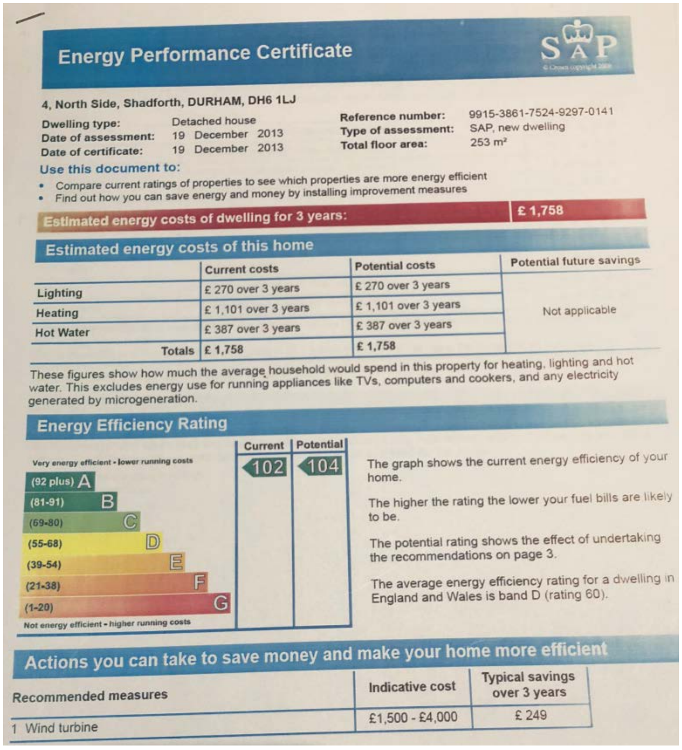
(b)

Figure 5.3 Floor plans of the Passive House: (a) ground (lower) floor, (b) first (upper) floor.

The floor plans of the Passive House are shown in Figure 5.3 above.

5.1.2 *Audits of energy consumption*

The Energy Performance Certificate (EPC) of the Passive House was gathered during the audit and it is shown in Figure 5.4 below. The graph shows the current energy efficiency of the property, and the higher the rating means the lower the energy bills that needs to be paid. The Energy Efficiency Rating of the dwelling is band A (rating 102), which is much higher than the average energy efficiency rating for a dwelling in England and Wales (band D, rating 60). From the EPC we can know that the Passive House is very energy efficient with very low running cost. For all the elements of the house, including walls, roof, floor, windows, heating control, lighting and airtightness, the energy efficiency are rated at the best level. According to the EPC, wind turbine is the recommended measure for this house to improve its performance furthermore. And the rating can be increased to 104 within band A and save £83 per year. However, the performance of the current Passive House is fabulous and the improvement after the recommended measure is not so much as expectation. Thus, the EPC shows the performance of the Passive House maintains at the best level and it is not necessary to conduct further improvement.



Energy Performance Certificate

4, North Side, Shadforth, DURHAM, DH6 1LJ

Dwelling type: Detached house
Date of assessment: 19 December 2013
Date of certificate: 19 December 2013
Reference number: 9915-3861-7524-9297-0141
Type of assessment: SAP, new dwelling
Total floor area: 253 m²

Use this document to:
- Compare current ratings of properties to see which properties are more energy efficient
- Find out how you can save energy and money by installing improvement measures

Estimated energy costs of dwelling for 3 years: £ 1,758

Estimated energy costs of this home

	Current costs	Potential costs	Potential future savings
Lighting	£ 270 over 3 years	£ 270 over 3 years	Not applicable
Heating	£ 1,101 over 3 years	£ 1,101 over 3 years	
Hot Water	£ 387 over 3 years	£ 387 over 3 years	
Totals	£ 1,758	£ 1,758	

These figures show how much the average household would spend in this property for heating, lighting and hot water. This excludes energy use for running appliances like TVs, computers and cookers, and any electricity generated by microgeneration.

Energy Efficiency Rating

The graph shows the current energy efficiency of your home.

The higher the rating the lower your fuel bills are likely to be.

The potential rating shows the effect of undertaking the recommendations on page 3.

The average energy efficiency rating for a dwelling in England and Wales is band D (rating 60).

Actions you can take to save money and make your home more efficient

Recommended measures	Indicative cost	Typical savings over 3 years
1 Wind turbine	£1,500 - £4,000	£ 249

Figure 5.4 Energy Performance Certificate of the Passive House.

It can be known from the initial field audit that there are three different types of energy resources supplied to this Passive House: electricity from main grid, onsite solar PV generation and gas. Among them, electricity from grid is used for cooking, lighting and all appliances in the property; solar PV also provides electricity to the household appliances and to the thermal store for domestic hot water and space heating; the main heating and domestic hot water supplier is a high efficiency gas boiler in this property. Besides, the solar PV electricity would have priority to be used to supply the Passive House directly rather than the grid electricity. This is due to the low cost operation management as the solar PV generation is 'free' energy for this dwelling. The general energy flow diagram of this Passive House is shown in Figure 5.5.

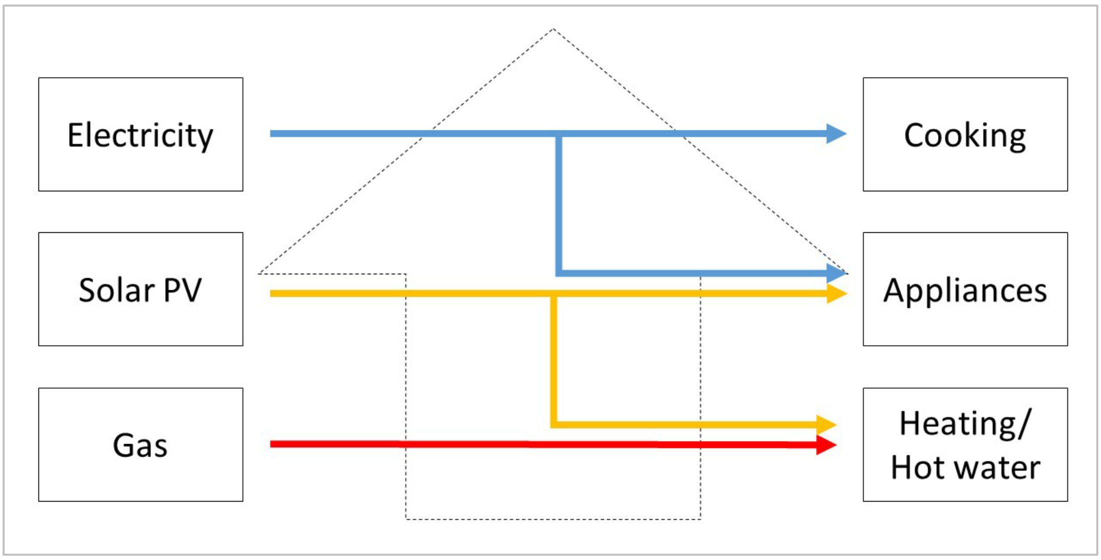
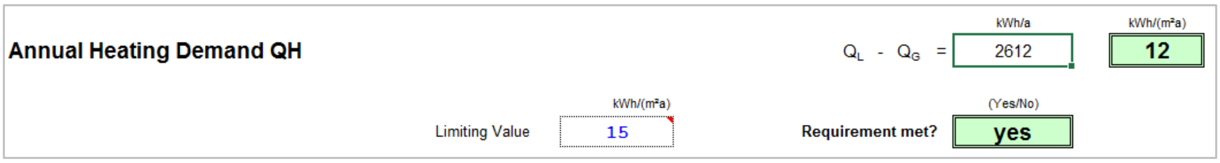


Figure 5.5 Energy flow diagram of the Passive House.

As this Passive House is a new build property and the residents moved in the dwelling in September 2014, there was no enough actual energy information while we conducted the first field study in early November 2014. However, the house owner provided the simulated data of primary energy demand and space heating demand of this house generated by PHPP (see Figure 5.6). It can be seen from the figures that the estimated primary energy demand and space heating demand of this house are 81.9 kWh/(m^{2}a) and 12 kWh/(m^{2}a), respectively. And the values for both energy demand of this Passive House are within the Passive House standard before occupancy.

Heating, Cooling, DHW, Auxiliary and Household Electricity		54.2	81.9	19.9
Total PE Value	81.9	kWh/(m²a)		
Total Emissions CO_2-Equivalent	19.9	kg/(m²a)		(Yes/No)
Primary Energy Requirement		120	kWh/(m²a)	yes

(a)



(b)

Figure 5.6 Energy information simulated by PHPP: (a) Primary energy demand, (b) Space heating demand.

5.2 Actual monitoring data collection

5.2.1 *Installation of monitoring equipment*

The installation of all the monitoring equipment for this case study was conducted at the beginning of November 2015: one T3519-A Zigbee wireless pulse counter for both main electricity and solar PV meters, one T7320SE electromagnetic pulse sensor for Sensus U6 gas meter, four T3534 wireless internal temperature and humidity sensors, four T3571 ZigBee wireless sensors for room carbon dioxide, one T3528 external temperature sensor and two T3524-B Zigbee wireless occupancy sensors were deployed in this Passive House for the monitoring work. All sensors were calibrated by their manufacturers. Electricity consumption from main grid, solar PV electricity generation, gas consumption, indoor temperature, relative humidity and CO_2 concentration of Double Height Family Room (DHFR), Master Bedroom (MB), Office Room (OR), Living Room (LR), indoor occupancy situation of Double Height Family Room and Living Room and outdoor temperature were monitored by the sensors. The sensors intervals for all energy meters and indoor environment conditions were 1 minute.

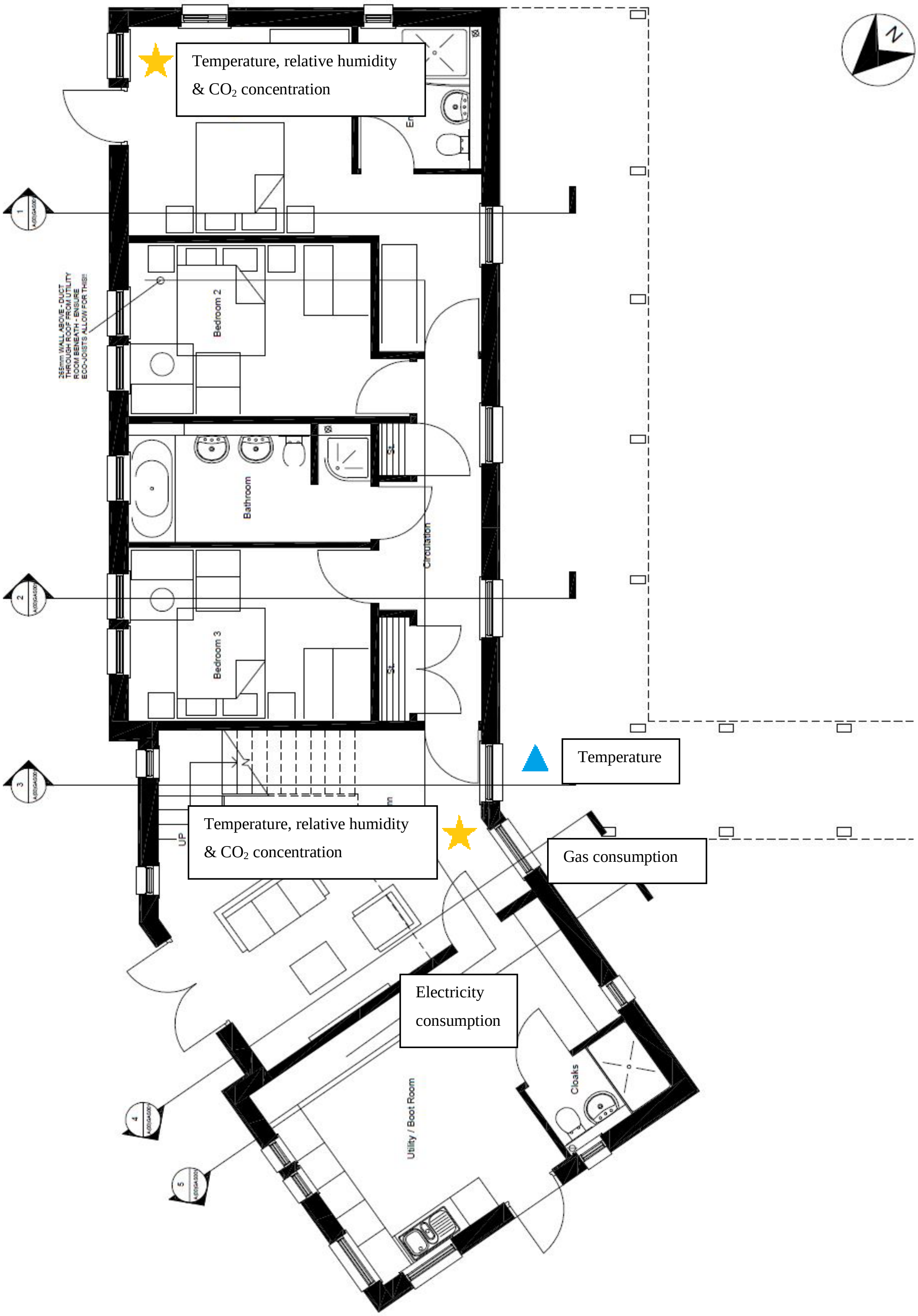
5.2.2 *Sensors deployment*

Four different rooms in the property were chosen for sensors deployment to measure the indoor environmental conditions: Living Room, Double Height Family Room, Master Bedroom and Office Room. One temperature and relative humidity sensor (T3534) and one CO_2 concertation monitor (T3571) were deployed together in each selected room. One PIR occupancy sensor (T3524-B) was put in Living Room and Double Height Family Room, the two communal rooms in the house. The external temperature sensor (T3528) was placed outside the south external wall and it is under the first floor's balcony. Their corresponding positions are listed in Table 5.2. All the positions of the indoor temperature, relative humidity,

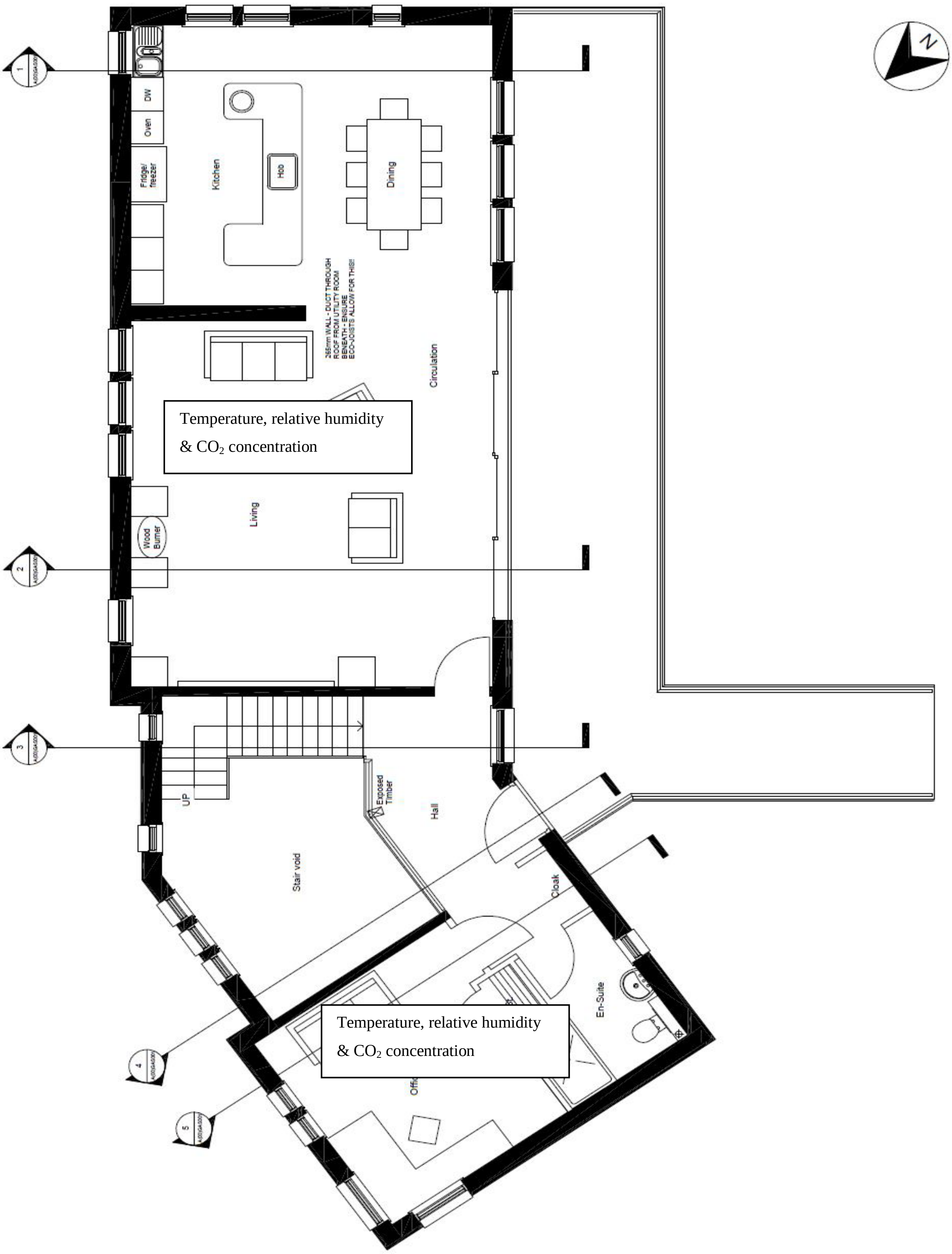
CO_2 concentration sensors, outdoor temperature sensor and also the pulse counters for energy consumption could be gathered and indicated in the floor plans as shown in Figure 5.7.

Sensor number	Room/Zone	Sensors position
TH1 & C1	Living Room	Top of TV stand
TH2 & C2	Double Height Family Room	Top of cabinet
TH3 & C3	Master Bedroom	Top of wardrobe
TH4 & C4	Office Room	Top of bookcase
O1	Living Room	Top of TV stand
O2	Double Height Family Room	Top of cabinet
ET1	South external wall of the house	Under the first floor’s balcony

Table 5.2 Corresponding positons of the monitoring sensors.


Temperature, relative humidity
& CO_2 concentration
Bedroom 2
Bathroom
Circulation
Bedroom 3
Temperature
Temperature, relative humidity
& CO_2 concentration
Gas consumption
Electricity
consumption
Utility / Boot Room
Cloaks
UP
N

(a)



(b)

Figure 5.7 Sensors distribution in the Passive House: (a) Ground floor, (b) First floor.

5.2.3 *Calibration of sensors*

The entire monitoring kit was calibrated after it was purchased. In order to maintain the reliability of actual data collected by the monitoring system, the sensors calibration during the first monitoring year was conducted twice in January and June 2016. Within them, the accuracy of instant indoor environmental conditions sensors (including indoor temperature, relative humidity, CO2 concentration and outdoor temperature) were calibrated by using the Q-TRACK Multi-function Indoor Air Quality Monitor 7575. The calibration monitor was placed at the same position of all target sensors for approximately 30 seconds. And the measurements were recorded and compared with the sensor readings. Solar PV generation, electricity and gas consumption calibration were carried out by the energy meter recording.

Table 5.3 shows the average errors for all sensors between monitored data and calibrated results. In general, the sensors performed very well and the measurement errors for all temperature sensors were within the acceptable range. Only one CO_2 concentration and two relative humidity calibration results were slightly higher than the limits. Because of the time restrict of every onsite field study, the calibration time for each sensor was not long enough to get the most stable measurement. The calibration errors for the indoor relative humidity and CO_2 concentration may increase due to this reason. The calibration results for all the energy meters were excellent and the errors met the requirements. The sensors recorded energy were lower than the meter readings may affected by rare missed counted pulses. As all the sensors were calibrated before deployment, and the measured errors for the onsite investigation were still of high quality, the monitoring sensors are reliable and can be used for further analysis.

Sensor	Temperature sensor	Relative Humidity sensor
Accuracy	± 0.7°C	± 1.0%
TH1	0.30	-0.10
TH2	-0.64	1.45
TH3	0.35	0.11
TH4	0.38	1.80
ET1	0.09	-

(a)

Sensor	CO_2 concentration sensor
Accuracy	± 30ppm or ± 5%
C1	6.24%
C2	4.89%
C3	-2.73%
C4	-0.65%

(b)

Sensor	Error
Accuracy	± 5%
Electricity meter	-0.46
Gas meter	-3.38
Solar PV electricity meter	-2.73

(c)

Table 5.3 Calculated errors for the monitoring sensors (a) CO_2 concentration sensors, (b) temperature and relative humidity sensors, (c) energy meter sensors.

5.3 Analysis of house performance

5.3.1 *Analysis of energy performance*

The monitoring work of the Passive House's performance began since early November 2015. In order to analysis the monitoring data for a calendar year, all the data used in this case study were recorded since January to December 2016, the first monitoring year. The monitoring intervals for all sensors were 1 minute except the CO_2 concentration detectors, which were 3 minute. Due to the network disruption and dead batteries problems, electricity consumption and solar PV generation for 13th to 18th January, 30th October to 2nd November and 29th to 31st December, 2016 and gas consumption for 20th to 30th July, 30th October to 2nd November and 15th to 31st December, 2016 have not been recorded by the sensors. Based on the measured data, the annual net electricity and gas consumption (see Figure 5.8) were 5059.86 kWh and 9396.80 kWh, respectively. Thus, the total energy consumption (excludes the electricity provided by local solar PV) of dwelling was 14456.66 kWh and the primary energy demand was 66.01 kWh/(m^{2}a), which was nearly half value compared to the Passive House standard.

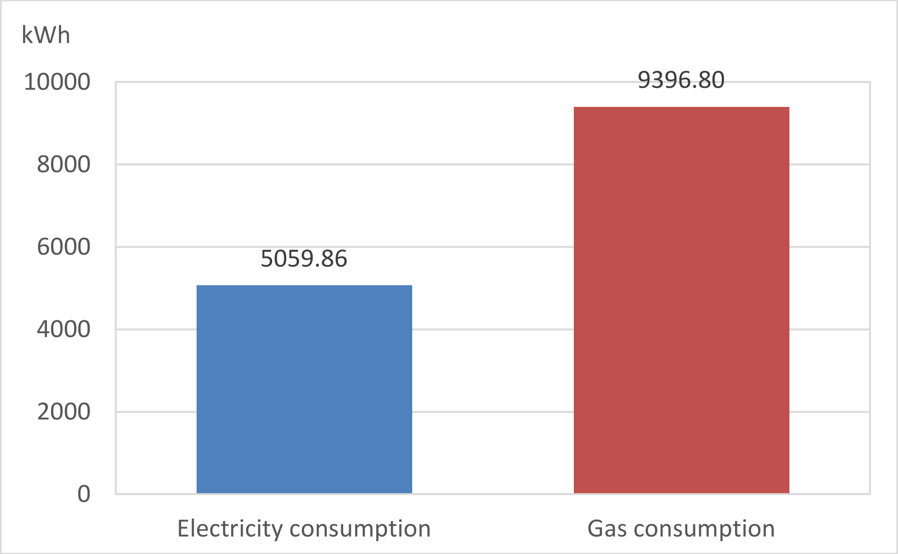


Figure 5.8 Annual energy consumption of the Passive House.

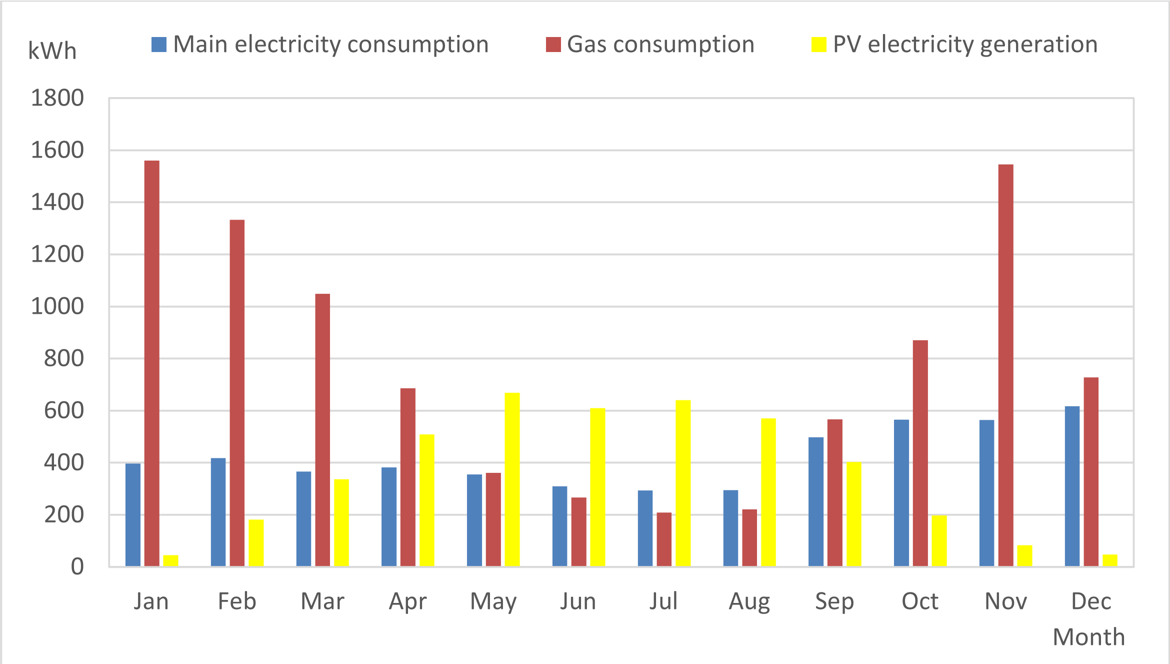


Figure 5.9 Monthly monitoring energy information of the Passive House.

Figure 5.9 above indicates the monthly energy consumption recorded onsite of the Passive House. It shows the differences of energy requirements within summer and winter, especially the gas demand. From the figure, it can be seen that the gas demand increased significantly (approximately 600%) from approximately 200 kWh in summer to 1560 kWh in winter and then began to decrease after January, the coldest month in a year. On the other hand, solar PV electricity generated by onsite station rose from bottom line to the peak since January and dropped down again to the valley value after the hottest summer time. The electricity consumption in a year remained at a stable level except the change of residents' occupancy since September last year. Moreover, because the solar PV electricity would have priority to be used to supply the Passive House directly, the main grid electricity consumption was comparatively lower in summer period compared to winter demand. The increased electricity consumption from September to December was due to the growth of the family members, i.e. changed from two adults to two adults and three children.

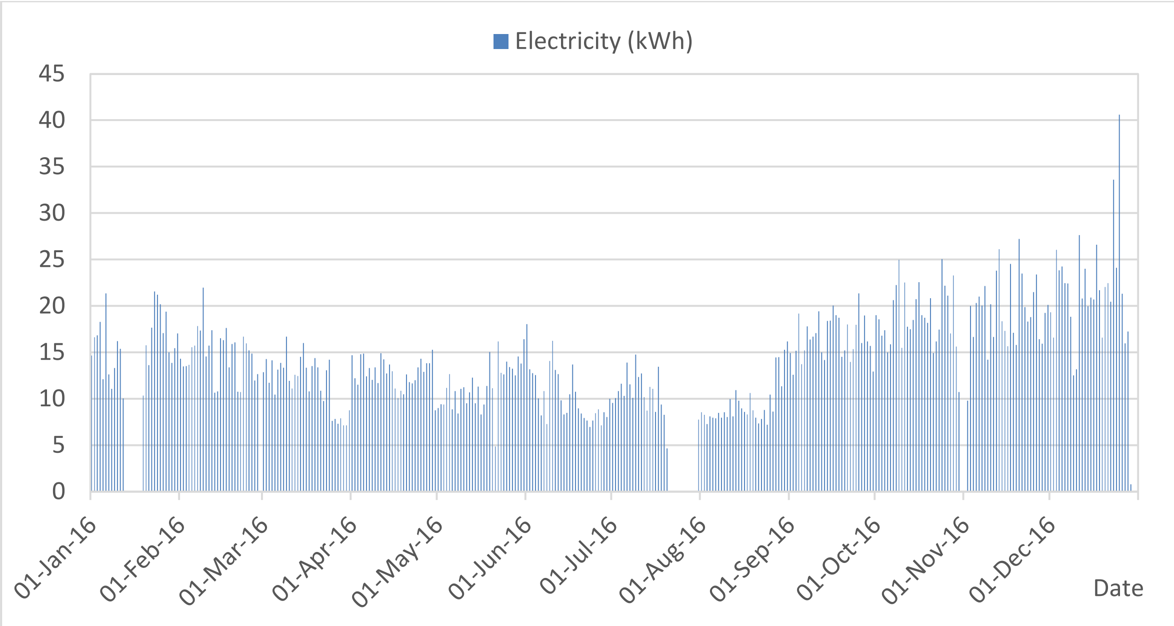


Figure 5.10 Daily monitoring electricity consumption of the Passive House.

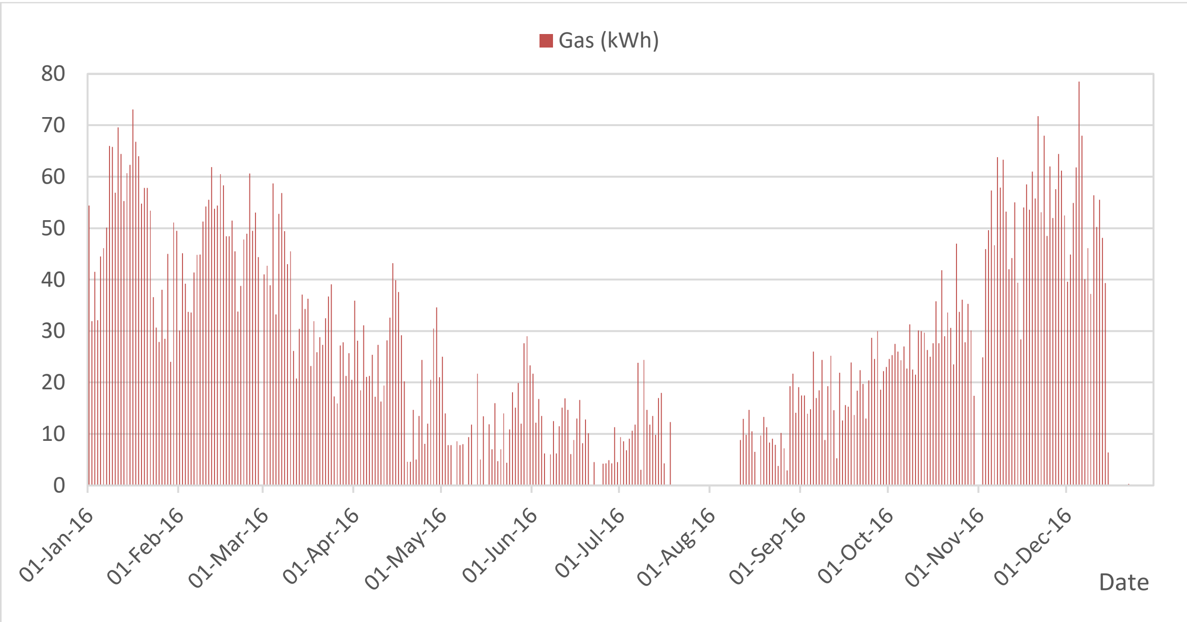


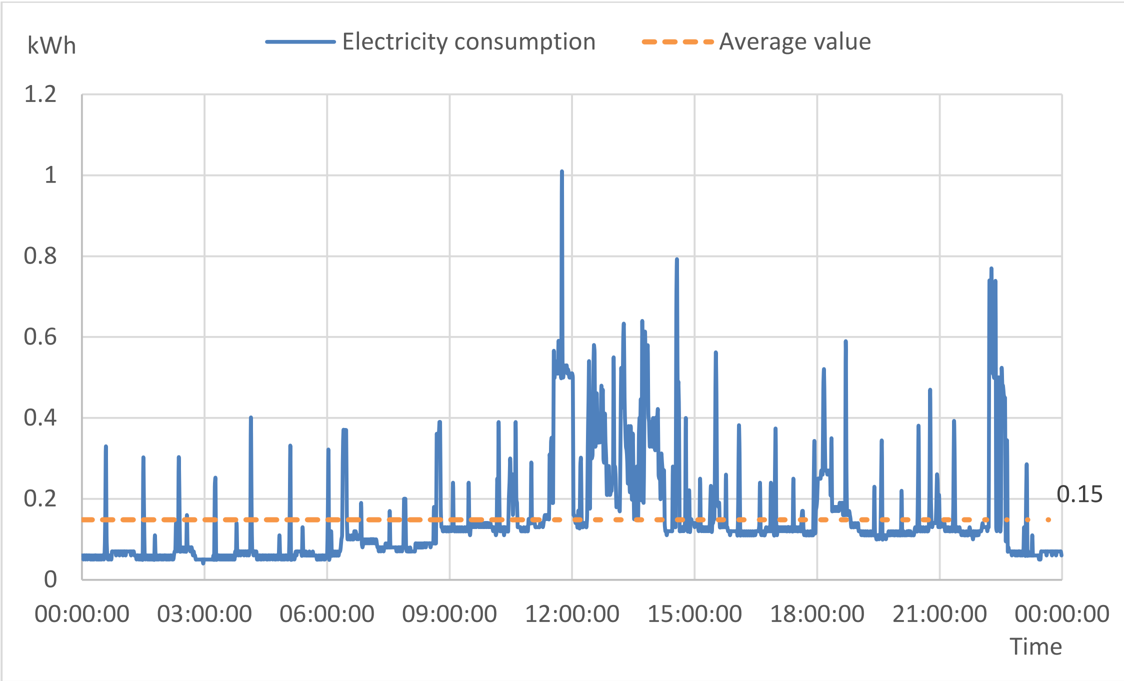
Figure 5.11 Daily monitoring gas consumption of the Passive House.

Figure 5.10 and Figure 5.11 indicate the daily monitoring electricity and gas consumption of the Passive House during January 2016 and December 2016, respectively. Despite the data missing days, the average daily electricity consumption for this year was 14.59 kWh. The house was fully occupied by 5 residents (2 adults and 3 children) since September 2016. Thus, the monthly electricity consumption from September was around one third higher than the first 8 months' operation by two residents, shown in Figure 5.10 clearly. There was one week during Easter in March and one month in August that the residents went for holidays and no person stayed in the house. The house electricity consumption of those periods dropped down obviously, which was nearly half demand compared to other normal months. We can know that 8 kWh was the average basic electricity demand for the Passive House operation to supply power to those mechanical ventilation system, fridges, garden water pumps and etc. that working 24 hours per day.

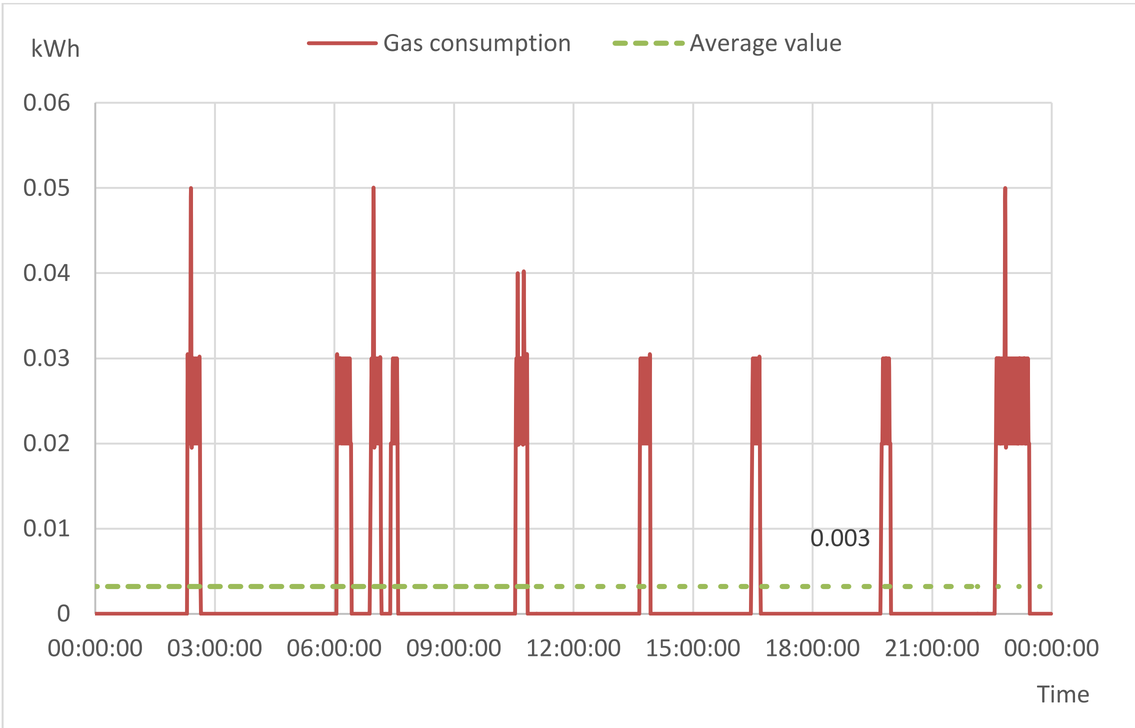
It can be seen form Figure 5.11 that there were some days with low gas consumption during the heating season because the residents adjusted or shut down the house space heating system due to warm weather or going out for holidays. Despite the data missing days, the average daily gas consumption for heating season and non-heating season for this year were 42.40 kWh and 14.58 kWh, respectively. The gas consumption was relatively stable during the non-heating season as the gas demand was only for providing domestic hot water. In the winter heating season, the gas consumption increased along with the decrease of actual weather temperature.

According to the monitoring results, the 1 minute interval (real time) electricity and gas consumption in a typical heating day in winter (6th January, 2016) and a non-heating day in summer (16th June, 2016) could be demonstrated in Figure 5.12 and Figure 5.13, respectively. The electricity consumption for these two days was 21.34 kWh and 10.47 kWh and the gas consumption were 46.10 kWh and 13.00 kWh, correspondingly. It is clear that the summer energy consumption was much lower than those winter demand as the solar PV provided power to the house and nearly no heating demand was required.

From the figures, it could be seen that the main grid electricity was replaces by solar PV power since 6:30am to 7:30pm. In addition, from 11am to 6pm, the basic household electricity could be fully satisfied by solar PV and there was rarely grid electricity input. From 8pm to 6am next day, the electricity behaviour was similar between summer and winter days. Along with the different appliances were occupied by the residents, the electricity consumption may be slightly dissimilar. The gas boiler only worked for about one hour in the typical summer day and the gas was mainly supplied to the domestic hot water. But in the winter, the boiler worked for at least four hour per day and the energy was provided to the house space heating majorly. Thus, we can assume that the gas demand for domestic hot water is around 25% of the heating energy for this Passive House for further investigation.

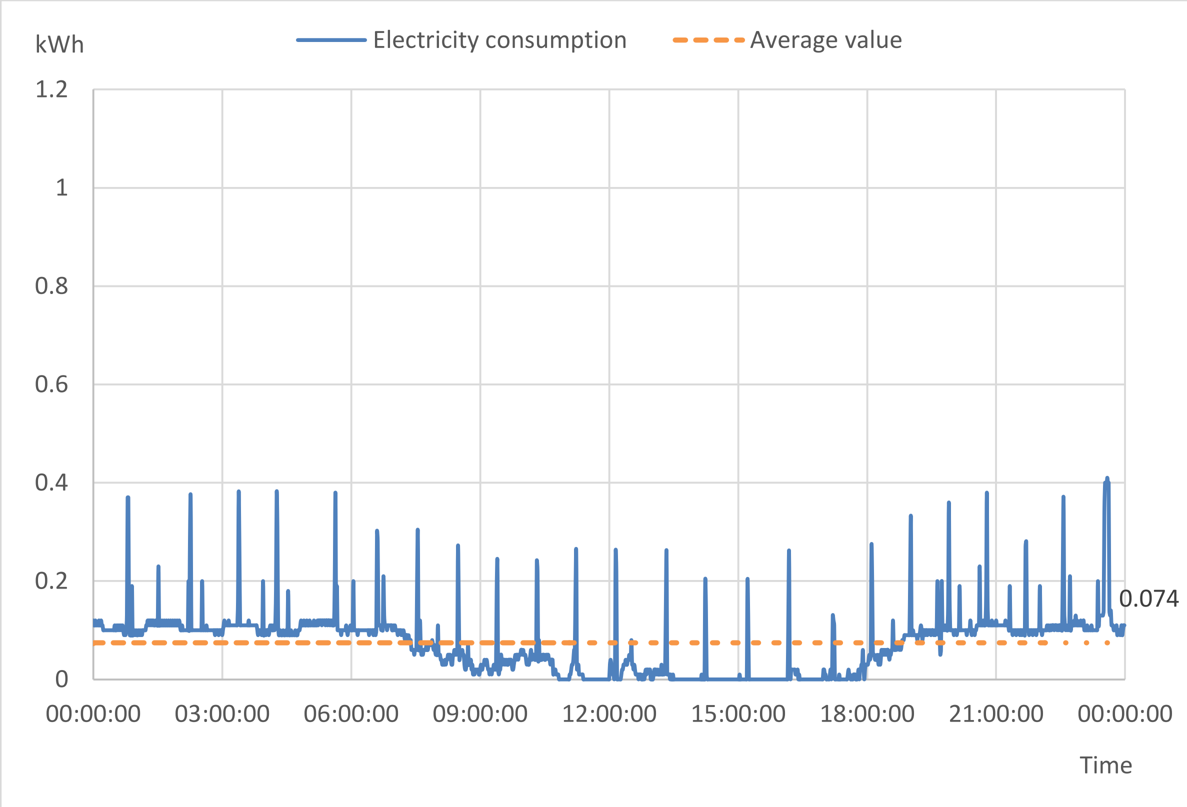


(a)

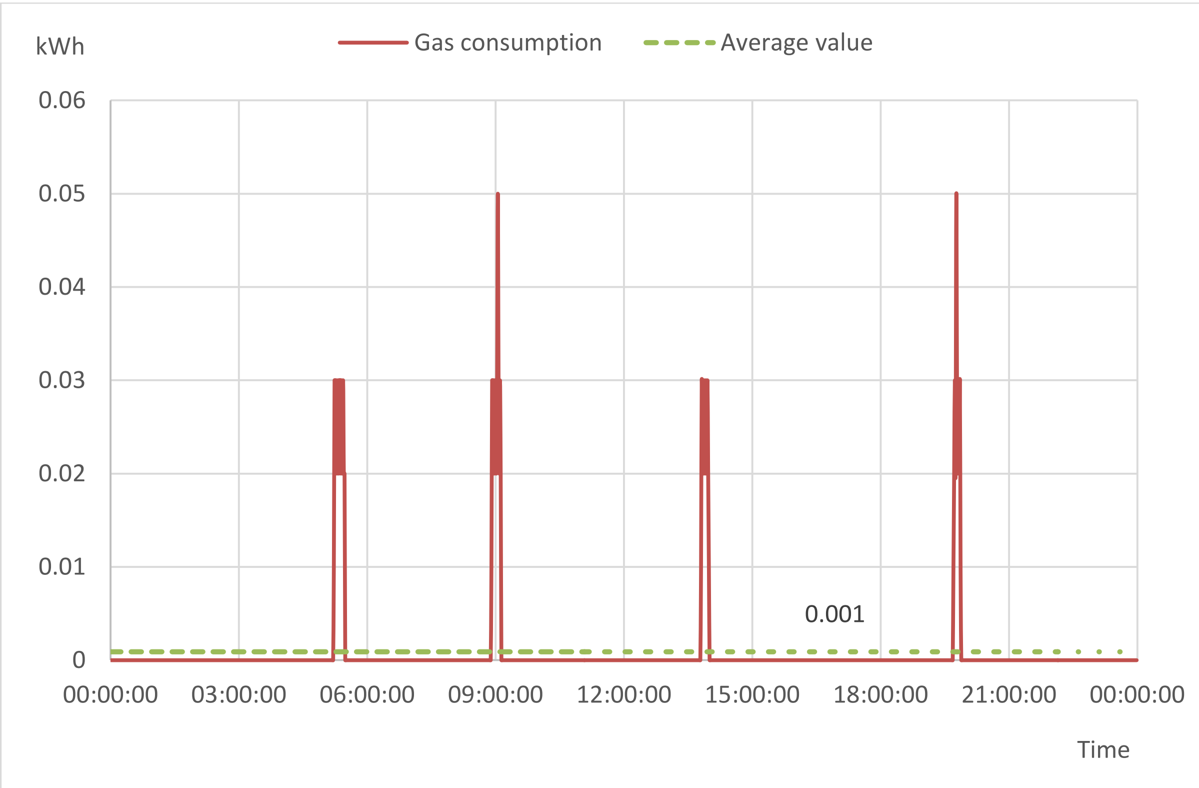


(b)

Figure 5.12 Dynamic energy consumption for the Passive House on 6th January, 2016: (a) Electricity consumption, (b) Gas consumption.



(a)



(b)

Figure 5.13 Dynamic energy consumption for the Passive House on 16th June, 2016: (a) Electricity consumption, (b) Gas consumption.

The solar PV electricity generation is an important energy resource for the whole Passive House and it plays an essential role in energy saving. To calculate the actual total energy consumed by this dwelling, we must know the generated solar PV electricity flow of this property. According to the measured data, despite the data missing days, the solar PV generation during the first monitoring year was 4292.63 kWh. Based on the measured data, the annual (365 days) generated solar PV electricity calculated by using average values was 4325.06 kWh in assumption.

In total, 85% of the solar PV electricity generated onsite (3655.45 kWh) was utilized in the Passive House and 15% of electricity generated by the onsite solar PV panels were feeding back to the main grid. Among them, about 45% of the annual solar PV electricity generation (1918.38 kWh) was supplied to the household appliances preferentially. Secondly, 40% of the total generated solar PV (1737.07 kWh) was provided to the thermal store for the space heating and domestic hot water energy. The map of the solar PV generation during the first monitoring year is summarised in Figure 5.14 below.

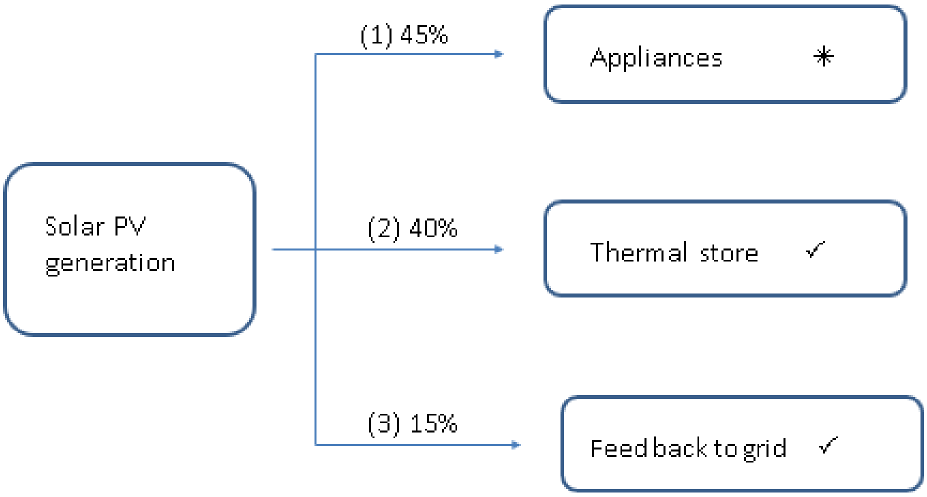


Figure 5.14 The flow of solar PV power generation.

Similarly, those missing energy consumption data in the first monitoring year were estimated by average values and the exact electricity and gas consumption were calculated as 5281.19 kWh and 10522.02 kWh, respectively. Count with the solar PV power generation, the final electricity demand of this Passive House was 7199.57 kWh and the gas demand was 12259.09 kWh. Thus, the final annual energy consumption for this house was 19458.66 kWh and the primary energy demand was 88.85 kWh/(m^2a). It is clear that the application of solar PV array to this Passive House reduced approximately 18.8% of the primary energy consumption (i.e. the electricity and the natural gas supply from the national grids were saved).

Month	Solar PV generation	Solar PV power consumed		Solar PV converted to thermal store		Solar PV feedback to main grid	
	kWh	kWh	%	kWh	%	kWh	%
Jan	59.21	50.02	84	4.89	8	4.30	7
Feb	181.93	94.36	52	66.22	36	21.35	12
Mar	336.99	149.36	44	146.54	43	41.09	12
Apr	508.90	214.56	42	213.83	42	80.51	16
May	668.69	251.87	38	290.17	43	126.65	19
Jun	609.55	304.89	50	213.34	35	91.32	15
Jul	640.80	211.90	33	220.04	49	114.90	18
Aug	570.18	193.19	34	280.06	49	96.93	17
Sep	403.24	198.44	49	144.31	36	60.49	15
Oct	209.90	142.82	68	45.53	22	21.55	10
Nov	84.25	62.01	74	14.41	17	7.83	9
Dec	51.42	44.94	87	3.80	7	2.69	5

Table 5.4 Monthly solar PV flow of the Passive House.

The monthly solar PV power flow of this Passive House is summarised in Table 5.4. It can be seen from Table 5.4 that the monthly utilization rates of solar PV electricity in winter time were higher than those in summer time. Over 90% solar PV electricity generated onsite in winter was used and supplied to the Passive House while approximately 85% of the total generation was consumed by the property in summer. In addition, the percentage of solar PV power consumed by the household appliances dropped down from peak value in January to the bottom in July and then rose again to the highest value in December. And the changing trend for the solar PV converted the thermal store was opposite. The reason is the onsite winter solar PV generation was much lower than the summer generation, only approximately 15% compared to the summer's productivity. Usually, the domestic energy consumption in winter is slightly higher than summer consumption because of the increased demand for space heating. Therefore, the utilization rate of solar PV power in winter was as high as 95%. But there is no energy storage to store extra generated solar PV power, although the solar PV array produced much more energy in summer month, the percentage of solar PV utilization was under the winter level. However, the 85% total solar PV utilization rate was higher than the 50% energy tariff estimate value. But the further investigation could be carried out to fully use the free solar PV power to supply the property.

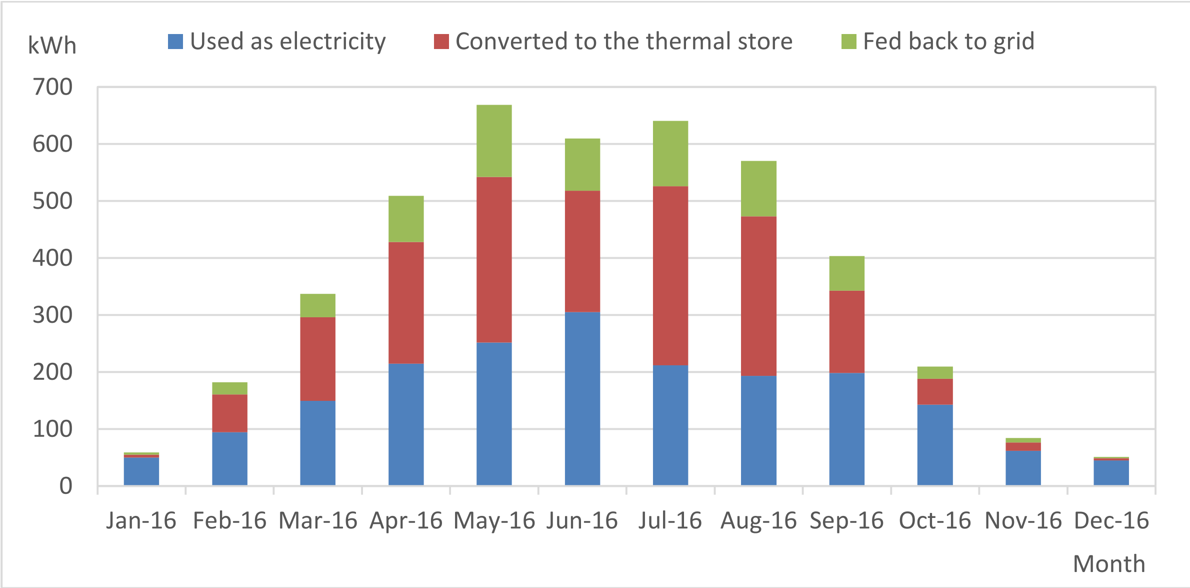


Figure 5.15 Solar PV generated power distribution to the Passive House.

The solar PV generated power distribution to the Passive House during the first monitoring year was shown in the Figure 5.15. Theoretically, the proportion of solar PV converted to the thermal store in July and August should be about half of existing values and the power used by the appliances could reach at least 350 kWh. But because of the house residents went away for holidays in those two months and the electricity demand was maintained at the basic usage level, more solar PV power was converted to the thermal store before they fed back to the main grid. Overall, it is known that the total energy consumption of this property would be 19458.66 kWh if no solar PV supplied to this Passive House and the primary energy demand could reach 88.85 kWh/(m^2a). The use of 6 kW solar PV array reduced about 18.8% primary energy demand for this Passive House. For electricity and gas consumption, it helped to save 26.6% and 14.2%, respectively, compared with the net usage.

5.3.2 *Analysis of indoor environmental condition*

The indoor environmental condition monitoring in this Passive House including temperature, relative humidity and CO_2 concentration began in November 2015. In order to analysis the monitoring data for a calendar year, all the data used in this case study were recorded since January to December 2016, the first monitoring year.

D. Temperature

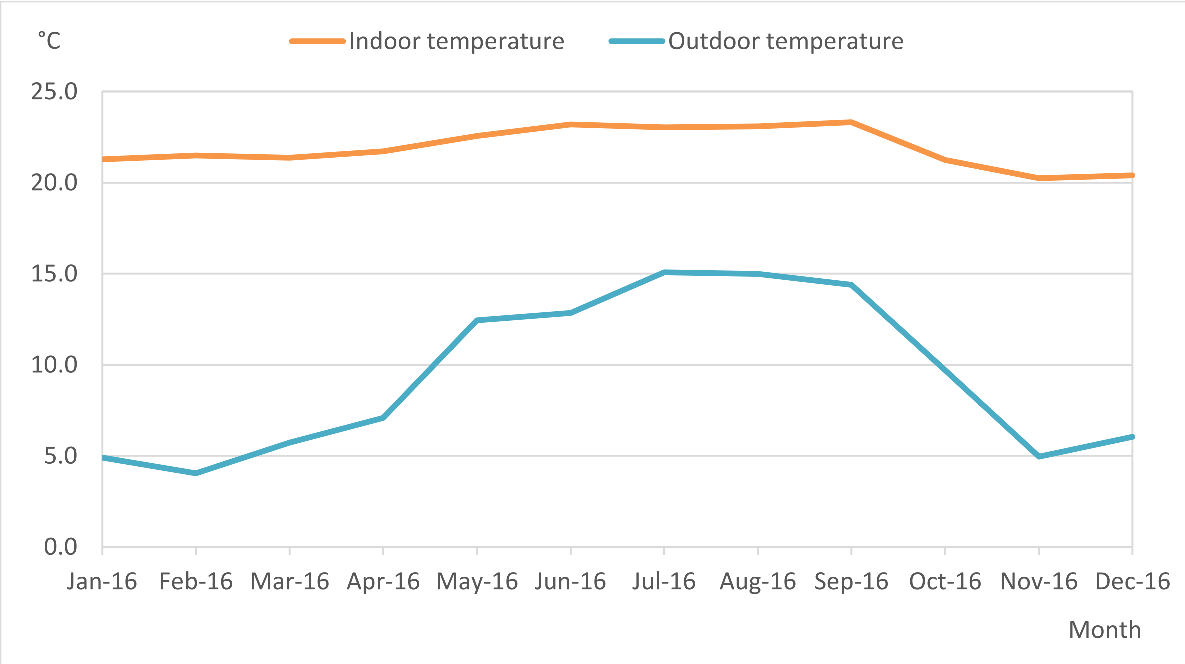


Figure 5.16 Monthly monitoring onsite temperature for the Passive House.

Figure 5.16 shows the monthly monitored indoor temperature of the Passive House and onsite outdoor temperature during the first monitoring year. There were 4 zones' indoor temperature recoded by the sensors in the house including Double Height Family Room, Master Bedroom, Office Room and Living room. Thus, the indoor temperature shown in the figure was the average temperature of the 4 zones in the property. From the monitoring data, it can be seen that the average indoor temperature for the whole monitoring year was 21.9°C. The average monthly indoor temperature during the traditional heating season (from January to April and November to December) was 21.1 °C while the onsite outdoor temperature was 6.2°C. The difference between indoor and outdoor temperature was 15.0°C. The average indoor temperature of this Passive House during the non-heating season (from May to October) was 22.7 °C summarised from the monitoring data. In the coldest month in a year, February, the indoor temperature could still be maintained at 21.5°C by high efficiency heating system. The hottest month in summer was August and the indoor temperature can be kept at 23.1 °C.

The indoor temperature from September to December was not as high as the first eight months of the monitoring year. As I mentioned before that the house occupancy changed since September and the indoor heating set point temperature reduced from 22°C to 20°C set by the new residents. They thought the 20°C house temperature was comfortable enough for them and wanted to save more energy at the same time. Therefore, the average indoor temperature for November (20.3°C) was the lowest but it still satisfied both Passive House standard and the residents' requirement. The recorded data indicated that there were no apparent differences for the winter and summer house temperature because of the intelligent mechanical ventilation with heat recovery controlled the set point indoor temperature accurately. The indoor temperature of the Passive House were always very stable.

As an example, indoor temperature of June 2016 (a typical month in summer time) is shown in Figure 5.17 to display the monitored daily indoor room temperature. This month's house average temperature was 23.2°C. It can be seen from the figure that, in most cases, the range of daily house temperature was between 21°C and 24°C. The temperature of Living Room and Office were usually higher than Double Height Family Room and Master Bedroom. The reason is these two rooms are in upper floor and received solar radiation directly from the windows all the day. The Double Height Family Room is an open zone that through upper and lower level in the Passive House. The wide space is not beneficial for heat accumulation. Hence, its temperature would be lower than normal upper floor zones. In general, the temperature of upper floor was about 2°C higher than lower floor in summer time.

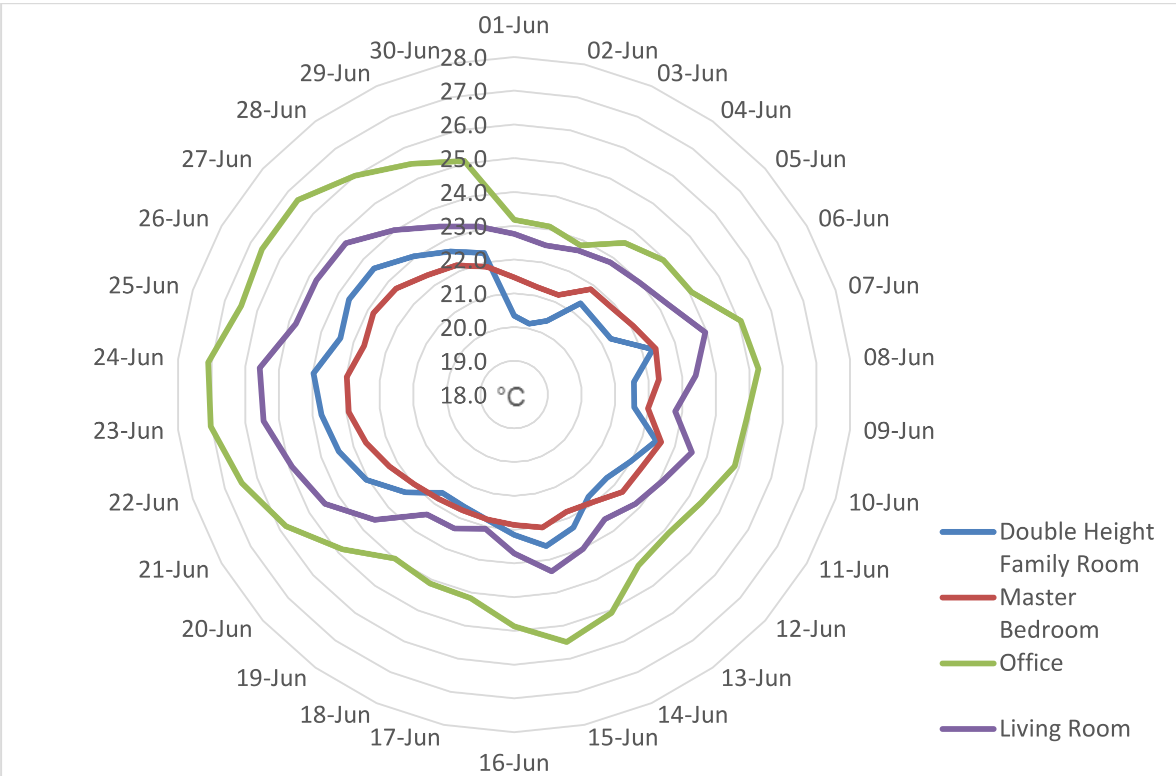


Figure 5.17 Monitored daily room temperature of the Passive House in June 2016.

As 19th July 2016 was the hottest day in 2016 with 21.5°C, according to the data gathered from Met Office, the house average indoor temperature reached 25.0°C on that day. The highest daily room temperature was about 27.4°C appeared in Living Room. Figure 5.18 shows the hourly temperature on 19th July 2016. It can be seen from the figure that the temperature of Living Room was over 25.5°C all the day and the peak temperature reached 30.1°C at 18:00 on that day. The residents of the Passive House went out for holiday on the day so all windows and doors were closed and no extra natural ventilation made the Living Room's temperature remain very high. This showed the super insulated dwelling may occur the overheating problem, especially on the upper floor with strong solar radiation. The Office is also located on the upper floor, but its temperature was relatively stable and kept at 24.1°C, even 0.2°C lower than those two rooms on the lower floor. The reason is the house owner has found that there was overheating problem happened in the upper level including Living Room and Office due to the large west facing window when the evening sun is out. And they install a small wall mounted split unit in the Office room as the window in the room are fixed and cannot be opened for achieving extra natural ventilation. The cooling system helped keep the Office's temperature at comfortable level in summer. However, the residents thought that to keep the Living Room's windows and doors opened could reduce the risk of overheating so they don't install a cooling system in that space. But when the residents are away, closed windows and doors cause the room temperature increased significantly and the heat can't release from the little thermal mass upstairs room.

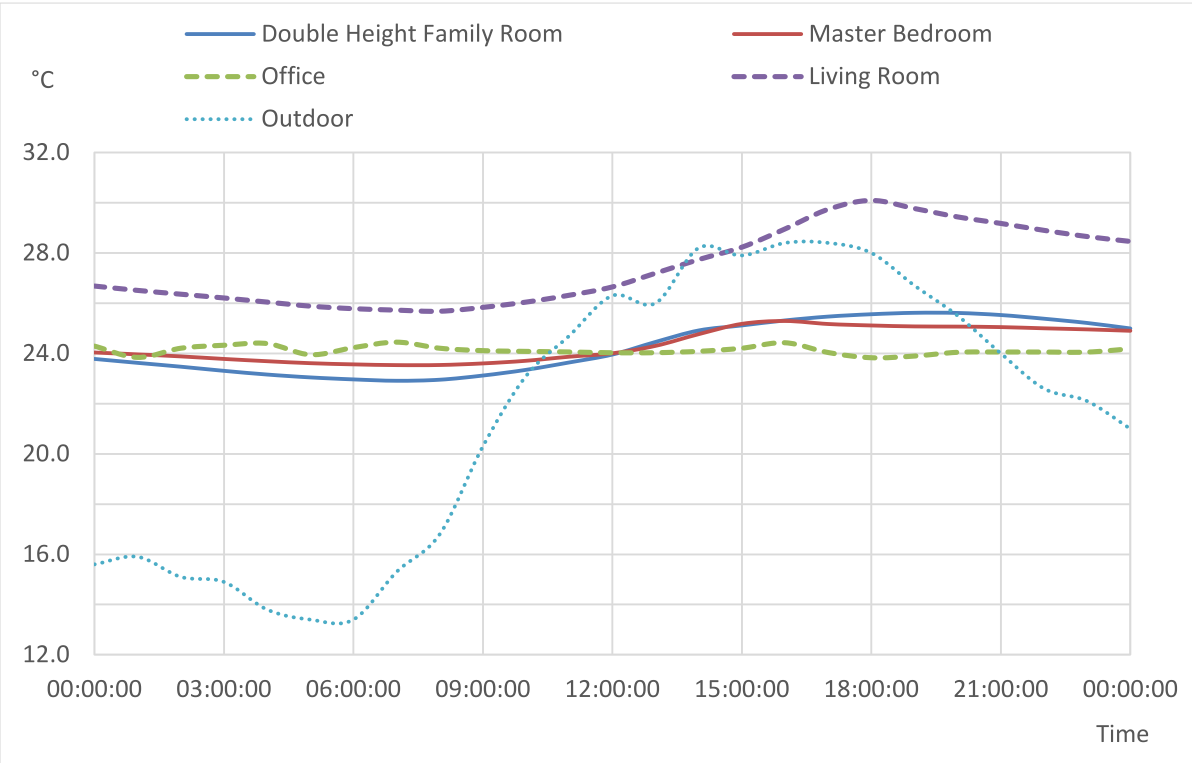


Figure 5.18 Monitored real time temperature of the Passive House on 19th July 2016.

Similarly, indoor temperature of February 2016 (a typical month in winter time) is shown in Figure 5.19 to display the monitored daily indoor room temperature. This month's house average temperature was 21.5°C. It can be seen from the figure that, in most cases, the range of daily house temperature was between 20°C and 23°C. The temperature of Master Bedroom (22.0°C) and Living room (22.4°C) were usually slightly higher than other rooms because the residents mainly stayed in these two rooms in winter time. Thus, the space heating demand of these rooms were higher compared to others and led to relatively higher room temperatures. The Double Height Family Room's temperature in this month was 20.4°C, the lowest monitored room temperature in the property. But this temperature was still above 20°C, which is the indoor temperature required in the Passive House standard and it is comfortable enough for living space.

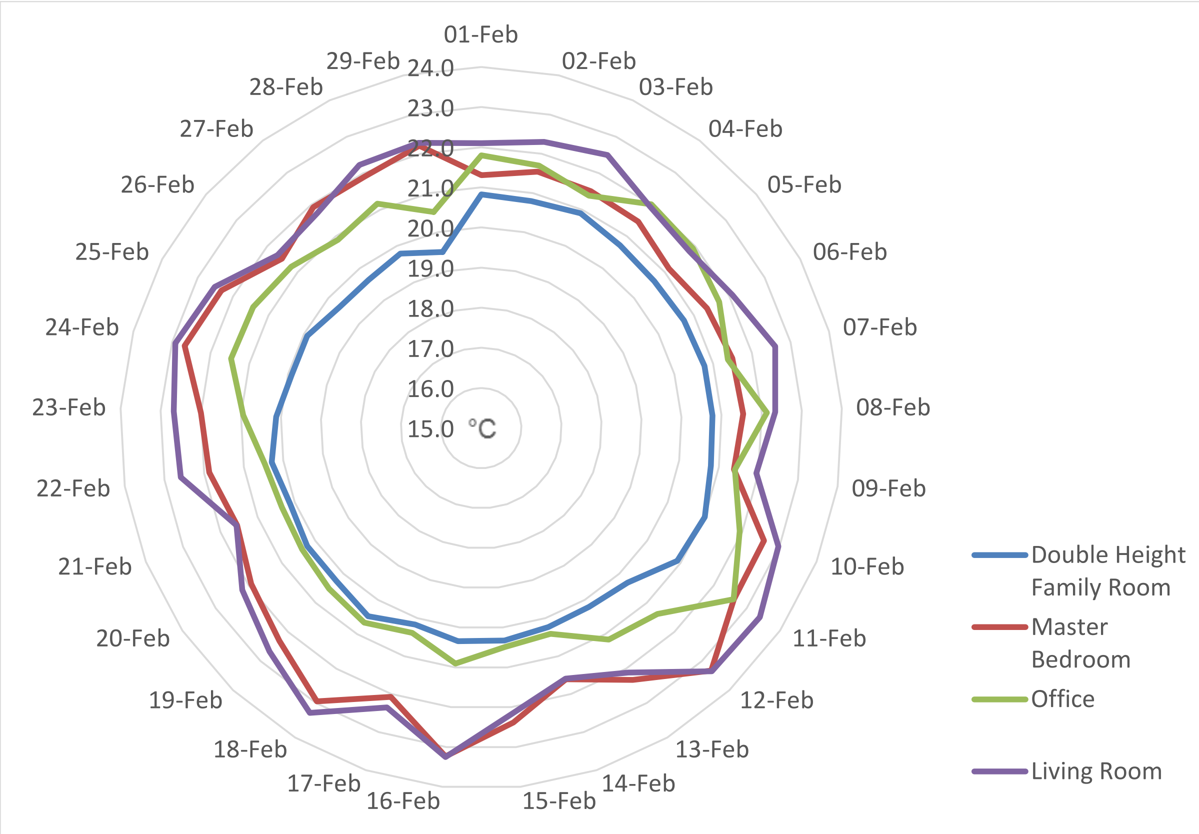


Figure 5.19 Monitored daily room temperature of the Passive House in February 2016.

As 16th January 2016 was the coldest day in 2016 with -0.6°C, according to the data gathered from Met Office, the house average indoor temperature remained at 21.8°C on that day, only 0.2°C lower than the heating set point temperature. The battery of the Office's sensor died and didn't be changed in time so all other three rooms indoor environmental condition represented the whole house performance. Figure 5.20 shows the hourly temperature on 16th January 2016. It can be seen from the figure that the temperature for all the rooms was above

20°C during the day. The lowest daily room temperature was about 20.8°C appeared in Double Height Family Room. The temperature of Master Bedroom and Living Room were the same and maintained at 22.3°C. There was a significant temperature increasing in the Living Room from 21.9°C to 25.6°C within one hour in the evening. The reason was the fireplace was used in the coldest day of a year. The wood burning made the specify room's temperature grow up very fast within a short period of time and last for several hours and will not affect other rooms' heating demand.

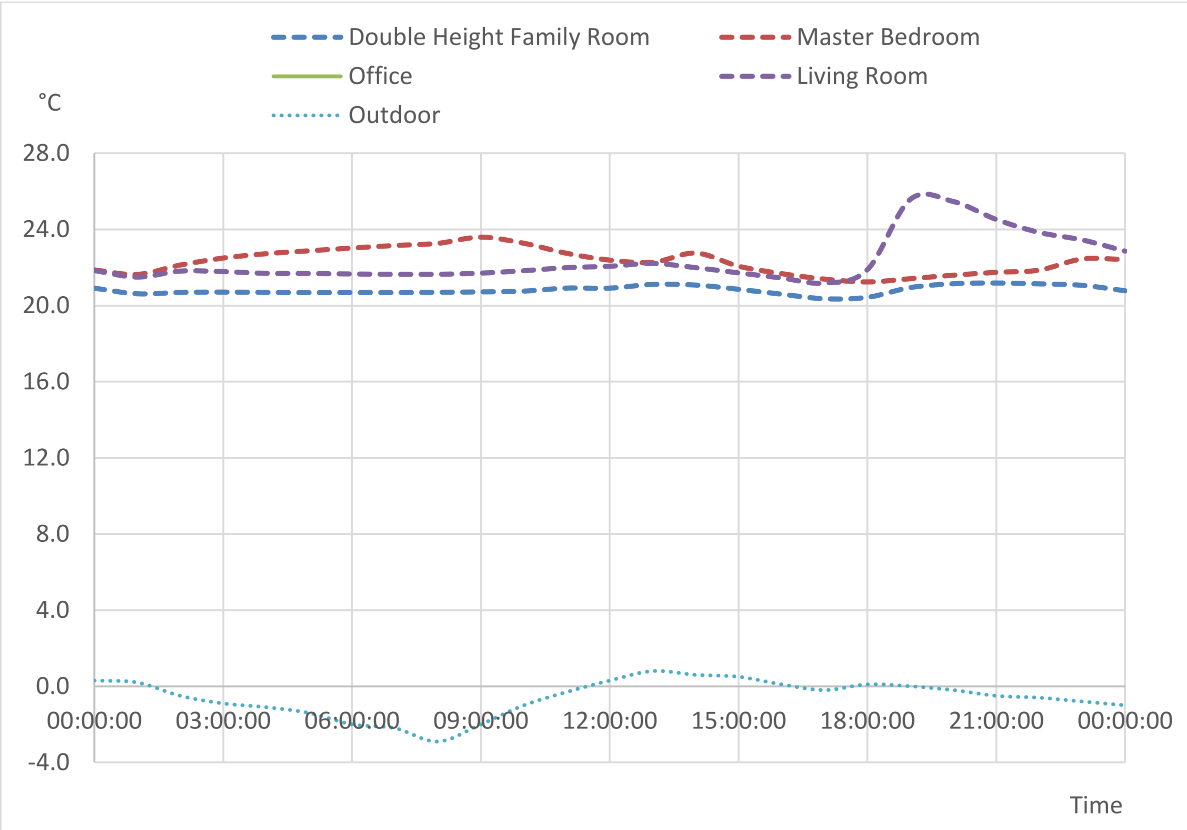


Figure 5.20 Monitored real time temperature of the Passive House on 16th January 2016.

E. Relative humidity

Figure 5.21 shows the monthly monitored indoor relative humidity of the Passive House and outdoor relative humidity gathered from Met Office during the first monitoring year. There were 4 zones' indoor relative humidity recoded by the sensors in the house including Double Height Family Room, Master Bedroom, Office Room and Living room. Thus, the indoor relative humidity shown in the figure was the average relative humidity of the 4 zones in the property. From the data monitoring, it can be seen that the average indoor relative humidity for the whole monitoring year was 45.5%. The average monthly indoor relative humidity during the traditional heating season (from January to April and November to December) was only 40.3% while the recorded outdoor relative humidity reached about 87.3%. The average indoor relative humidity of this Passive House during the non-heating season (from May to October) was 50.8% summarised from the monitoring data. The outdoor relative humidity reduced to 84.9% during that period. It is clear that the indoor relative humidity value monitored in the first year was nearly half of the outdoor relative humidity. All of the indoor relative humidity in the Passive House was between 30% and 60%, within the most comfortable indoor relative humidity range. The reason that the summer indoor relative humidity was slightly higher than winter's was because most of the windows and doors of the property kept closed all the time in winter but opened in summer for internal heat release. Thus, natural ventilation through the house made the relative humidity increased around 10%.

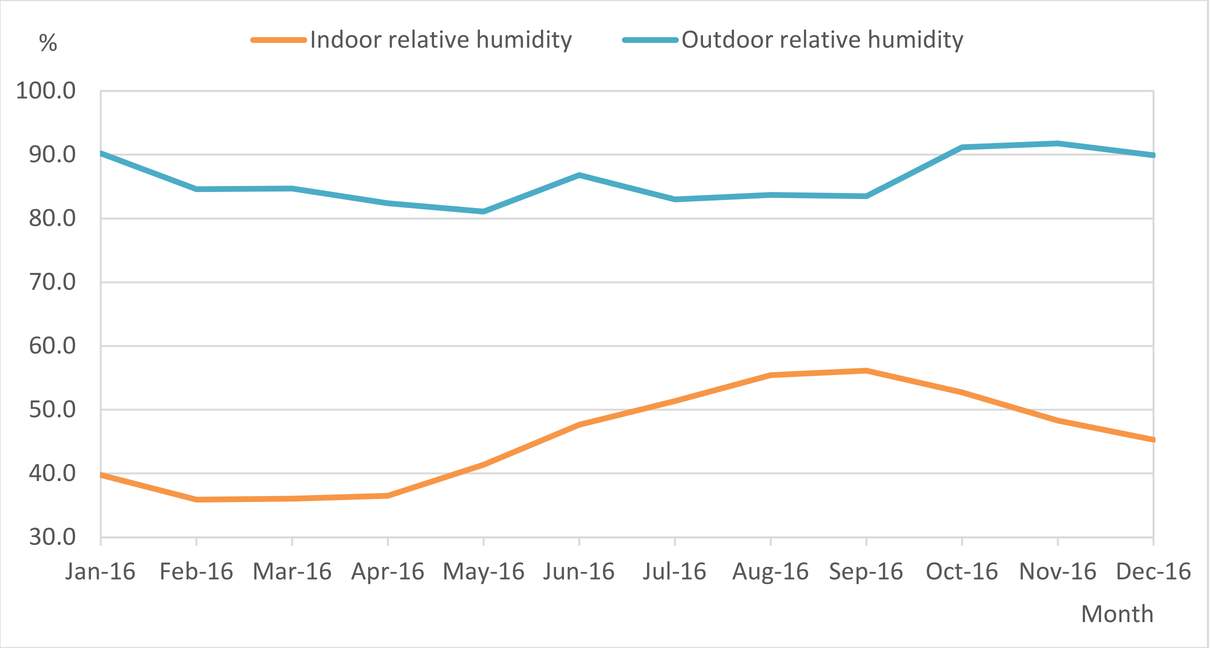


Figure 5.21 Monthly monitoring onsite relative humidity for the Passive House.

Corresponding to the indoor temperature analysis, indoor relative humidity of June 2016 (a typical month in summer time) for this Passive House is shown in Figure 5.22 to display the monitored daily indoor room relative humidity. This month's house average relative humidity was 47.7%. It can be seen from the figure that, the range of daily house relative humidity was between 40% and 50% in majority cases. The relative humidity of Office and Living Room were usually lower than other rooms. The reasons were these two rooms' temperatures were always the highest and the window or door in these two rooms were always kept opened by the residents for more natural ventilation. In general, the relative humidity of these two rooms would be around 5% lower than other rooms in summer time.

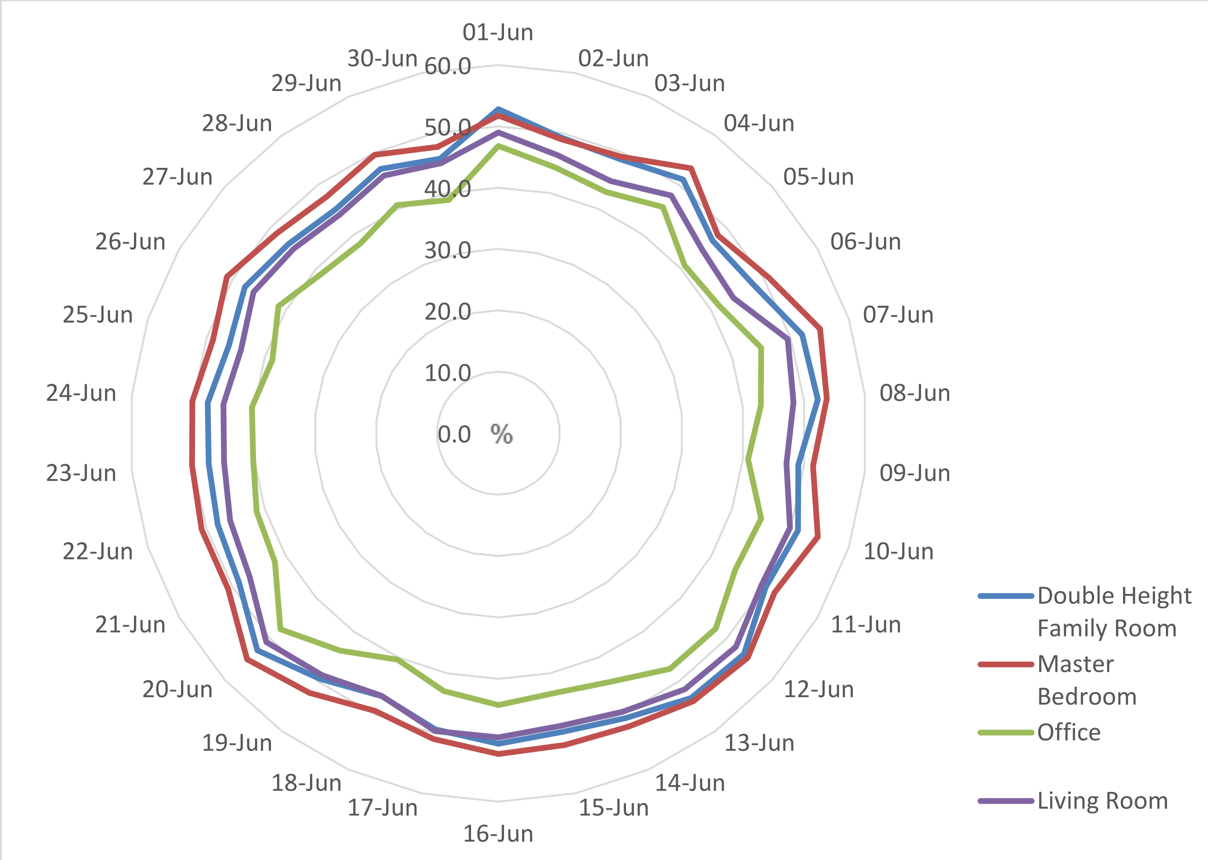


Figure 5.22 Monitored daily room relative humidity of the Passive House in June 2016.

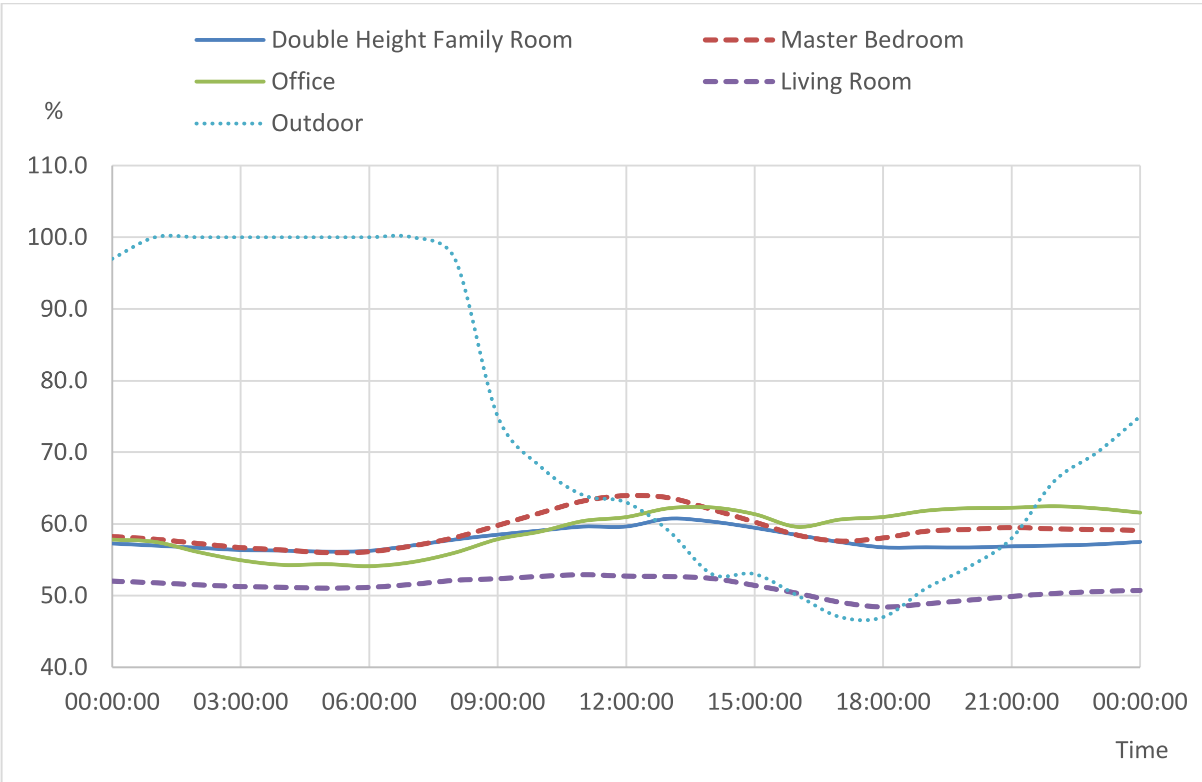


Figure 5.23 Monitored real time relative humidity of the Passive House on 19th July 2016.

On 19th July 2016, the hottest day in 2016, the house average indoor relative humidity was 56.7%. The highest daily room relative humidity was about 59.1% appeared in Master Bedroom while the lowest relative humidity was about 51.1% of Living Room. Figure 5.23 shows the hourly relative humidity on 19th July 2016. It can be seen from the figure that the relative humidity of Living Room maintained at around 50% all the day and its value was the lowest one compared to other three rooms. The residents of the Passive House went out for holiday on the day so all windows and doors were closed and no extra natural ventilation made the Living Room's temperature remain very high and this also led to relatively lower room humidity. It didn't happen in the same level's Office because the mechanical ventilation and air conditioning kept the indoor environmental condition as normal as possible. At most time of a day in summer, the relative humidity was stable. The fluctuation of the indoor relative humidity for each room in the day was within 10%.

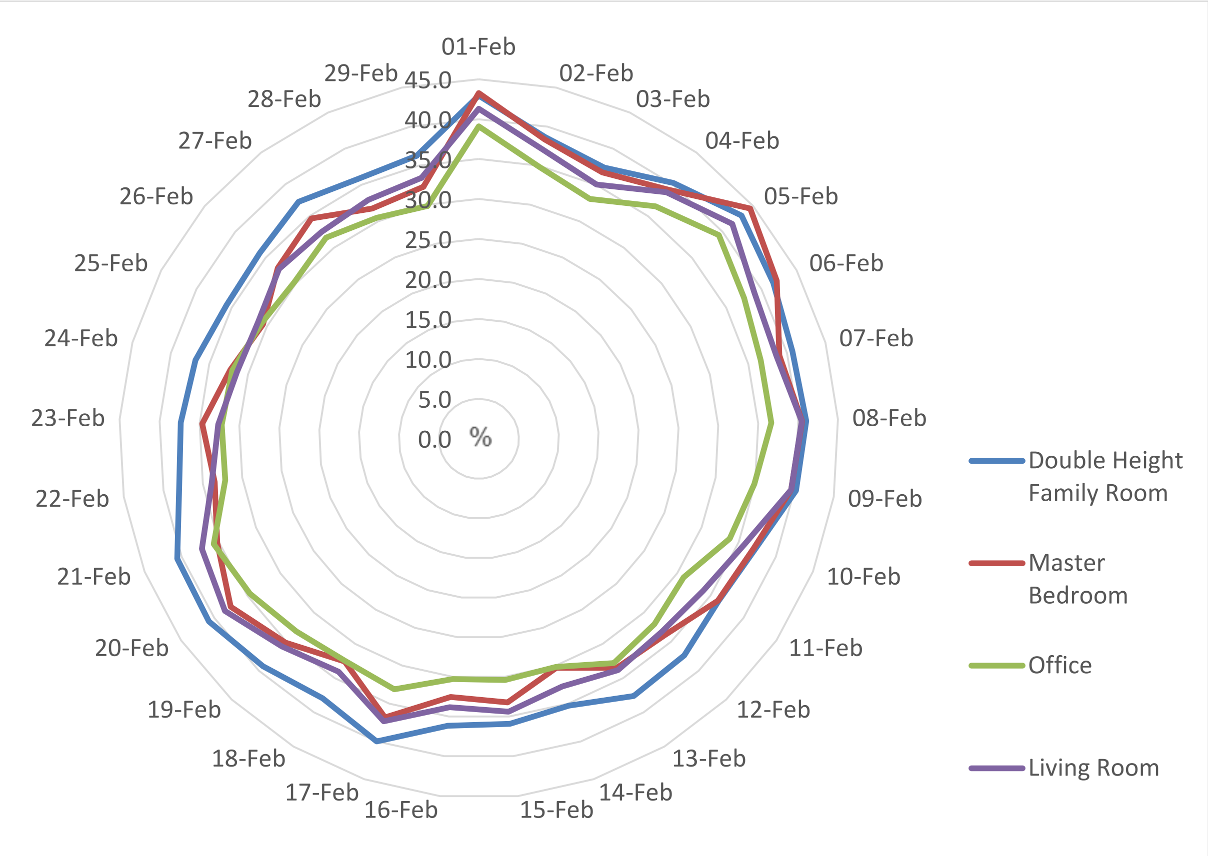


Figure 5.24 Monitored daily room relative humidity of the Passive House in February 2016.

Analogously, indoor relative humidity of February 2016 (a typical month in winter time) is shown in Figure 5.24 to display the monitored daily indoor room relative humidity. This month's house average relative humidity was only 35.8%. It can be seen from the figure that, the range of daily house relative humidity was between 30% and 45% in most of the time in that month. The relative humidity of upper level rooms was usually lower compared with ground level rooms. Also, the relative humidity of Master Bedroom was closed to the upper level's value. Because the residents mainly stayed in those rooms in winter time and the space heating demand of these rooms were higher compared to the Double Height Family Room and led to relatively higher room temperatures but opposite relative humidity. Although the Double Height Family Room's relative humidity in this month reached 38.4%, the highest monitored value in the property, all room's relative humidity were between 30% to 40% and they were comfortable enough for living space.

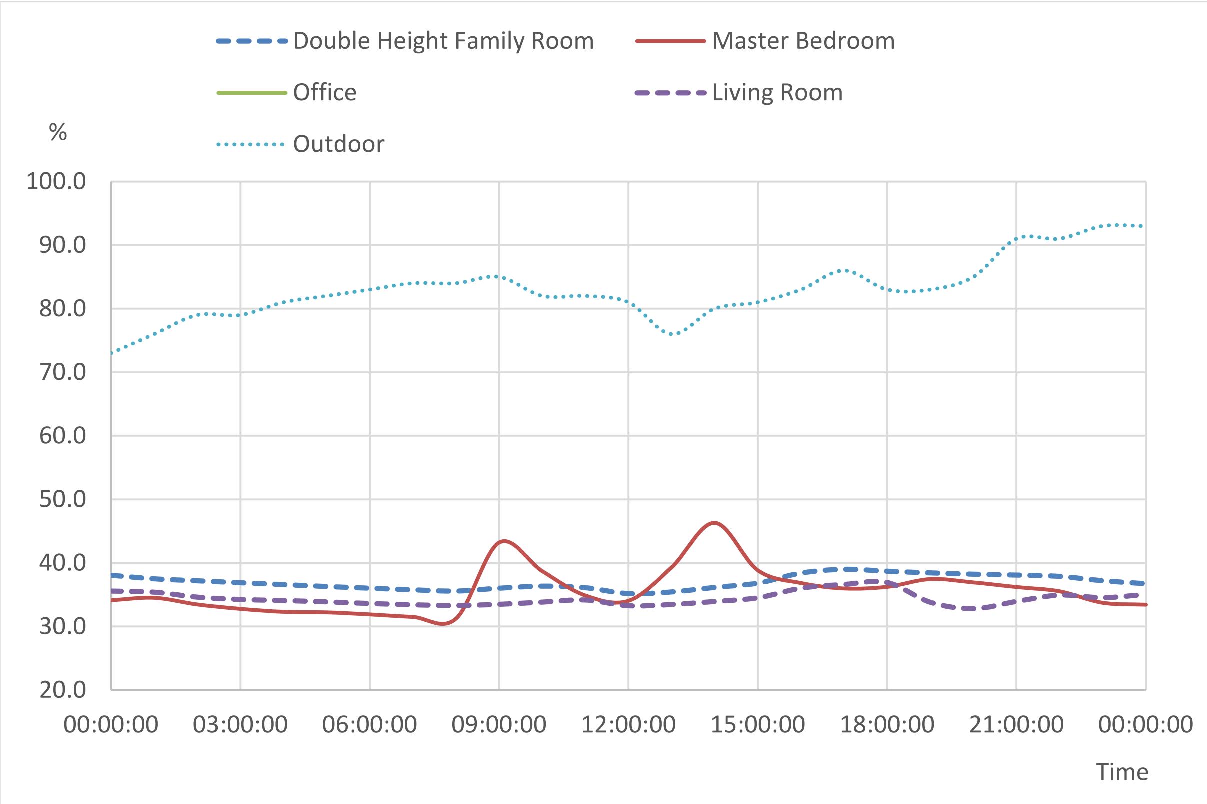


Figure 5.25 Monitored real time relative humidity of the Passive House on 16th January 2016.

On 16th January 2016, the coldest day in 2016, the house average indoor relative humidity was only 35.7%, which was a very comfortable level and less than half of the outdoor relative humidity. The battery of the Office's sensor died and didn't be changed in time so all other three rooms indoor environmental condition represented the whole house performance. It can be seen from the figure that the relative humidity for all the rooms were under 40% during the day. The highest daily room relative humidity was about 37.0% appeared in Double Height Family Room while the lowest relative humidity was about 34.4% of Living Room. Figure 5.25 shows the hourly relative humidity on 16th January, 2016. Despite the Master Bedroom, the trend of other rooms' relative humidity was very similar and stable. There were two unusual peak values appeared in the Master Bedroom on the day. Both relative humidity values increased more than 10% rapidly within one hour. This was due to the showers taken in the en-suite of the Master Bedroom by the two residents. The room's relative humidity rose up since the beginning of each shower and began to decrease when the residents finished their shower. Although the relative humidity of the Master Bedroom increased significantly along with the shower taken in the en-suite, the mechanical ventilation system helped to release the moisture efficiently and maintained the room relative humidity value to normal level quickly.

F. CO_2 Concentration

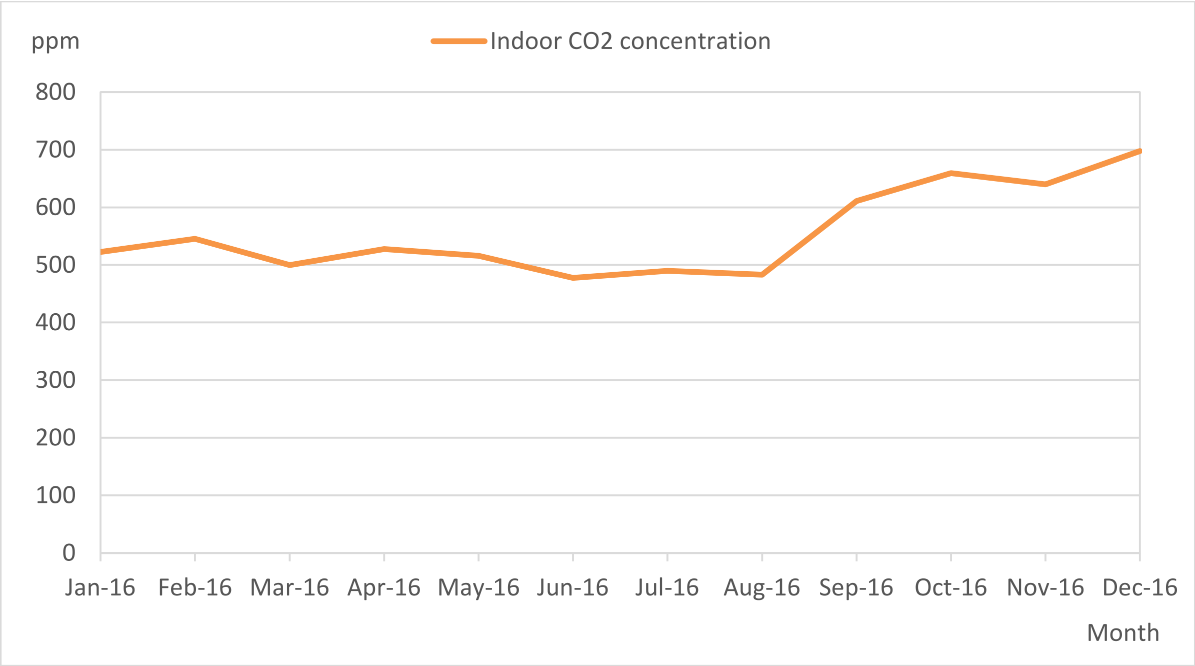


Figure 5.26 Monthly monitoring indoor CO_2 concentration for the Passive House.

Figure 5.26 shows the monthly measured indoor CO_2 concentration of the Passive House during the first monitoring year. There were 4 zones' indoor CO_2 concentration recoded by the sensors in the house including Double Height Family Room, Master Bedroom, Office Room and Living room. Thus, the indoor CO_2 concentration shown in the figure was the average relative humidity of the 4 zones in the property. From the data monitoring, it can be seen that the average indoor CO_2 concentration for the whole monitoring year was 529 ppm, which was a high level for domestic indoor air quality whereas the outdoor CO_2 levels are usually 350 - 450 ppm. The average monthly indoor CO_2 concentration during the traditional heating season (from January to April and November to December) didn't differ greatly from the non-heating season (from May to October)'s level. The big difference occurred due to the change of house residents and their occupancy since September. During the first eight monitoring month, the Passive House was only occupied by a couple, the average indoor CO_2 concentration in that period was only 508 ppm. From September 2016, the number of people lives in this property increased to 5, including a couple and their three kids. The house was fully occupied by the family and the average house CO_2 concentration rose about 150 ppm to 652 ppm compared to previous monitoring results. Although the average indoor CO_2 concentration in December 2016 nearly reached 700 ppm because of the rising heating demand and closed windows and doors in winter, the air quality of the Passive House was still remarkable as the indoor CO_2 concentration was within the maximum considered acceptable level of 1000 ppm.

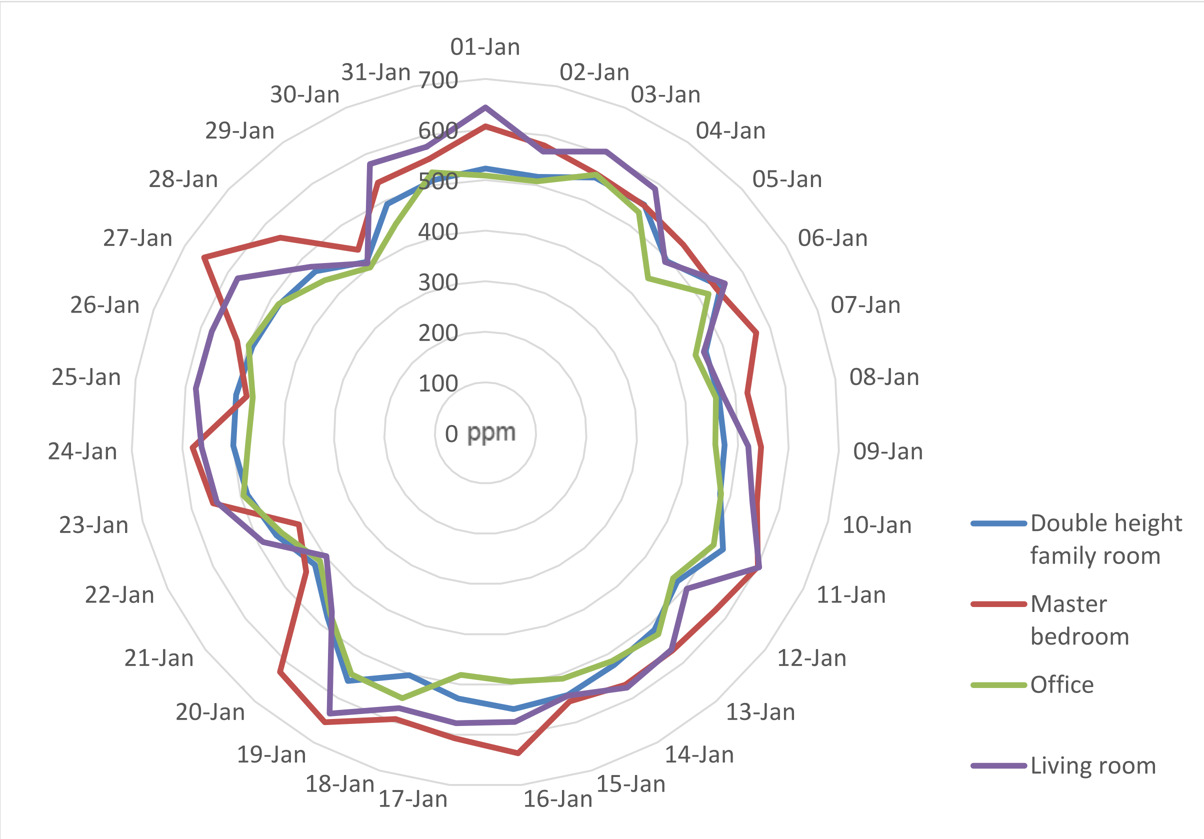


Figure 5.27 Monitored daily room CO_2 concentration of the Passive House in January 2016.

As the indoor CO_2 concentration would be affected by residents' occupancy, the house CO_2 concentration under the two different situations was discussed in this study. The indoor CO_2 concentration of January 2016 (a typical month under the first couple's occupancy) is shown in Figure 5.27 to display the monitored daily indoor CO_2 concentration. This month's house average CO_2 concentration was 545 ppm. The highest daily room CO_2 concentration was about 560 ppm appeared in Master Bedroom while the lowest CO_2 concentration was about 486 ppm of Office. It can be seen from the figure that, in most cases, the range of daily house

CO_2 concentration was between 400 ppm and 600 ppm. The indoor CO_2 concentration of Master Bedroom and Living Room were usually higher than Double Height Family Room and Office because the residents mainly stayed in these two rooms during winter time. In addition, the concentrated breathing during night time in the bedroom led to relatively high CO_2 concentration compared to other rooms in the property. However, the superb mechanical ventilation in the Passive House controlled all the room's air quality in high quality condition. In general, the indoor CO_2 concentration of this dwelling was maintained at an outstanding level which was only 100 ppm over the outdoor CO_2 concentration under this situation.

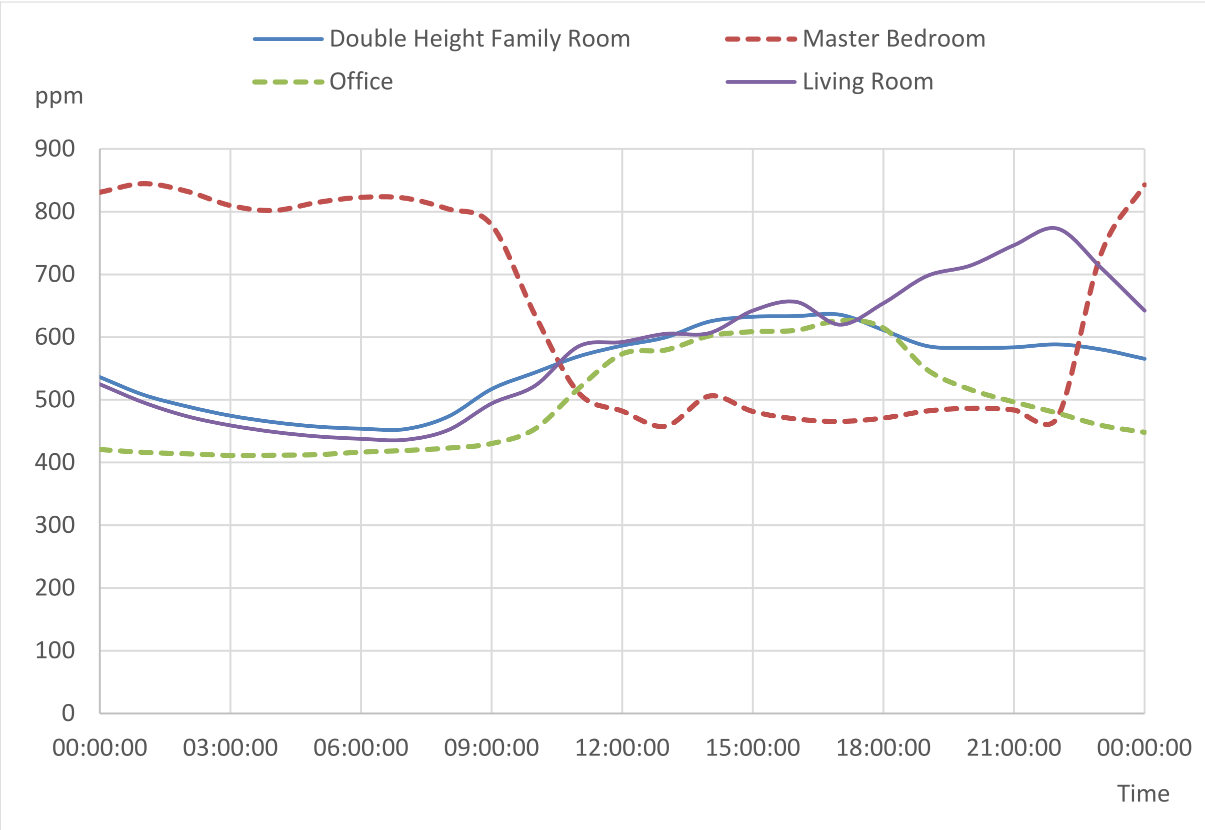


Figure 5.28 Monitored real time CO_2 concentration of the Passive House on 16^{th} January 2016.

The monitored real time indoor CO_2 concentration on 16^{th} January 2016 was selected to represent the typical performance under the first couple's occupancy. The house average indoor CO_2 concentration remained at 564 ppm on that day. The highest daily room CO_2 concentration was about 637 ppm appeared in Master Bedroom while the lowest CO_2 concentration was about 494 ppm of Office. Figure 5.28 shows the hourly CO_2 concentration on 16^{th} January 2016. It can be seen from the figure that the highest CO_2 concentration values generated in Master Bedroom during the night time sleeping hours. The CO_2 concentration increased significantly from around 480 ppm to 840 ppm within two hours (since 10 pm to 12 midnight). And the next 9 hours' CO_2 concentration before the residents woke up was all kept under 850 ppm. The overnight CO_2 concentration took about three hours to release to normal level from 9 am to 12 midday. As the bedroom was not occupied during day time, the CO_2 concentration was maintained at 478 ppm in the remaining 10 hours. Other three rooms' performances of CO2 concentration were opposite to the Master Bedroom as they were mainly occupied in the day time. The CO_2 concentration values for the rest rooms rose since 9 am and normally were kept at 600 ppm before evening. As Living Room was the main space that the residents stayed before sleeping, the CO_2 concentration increased and became the highest during that period.

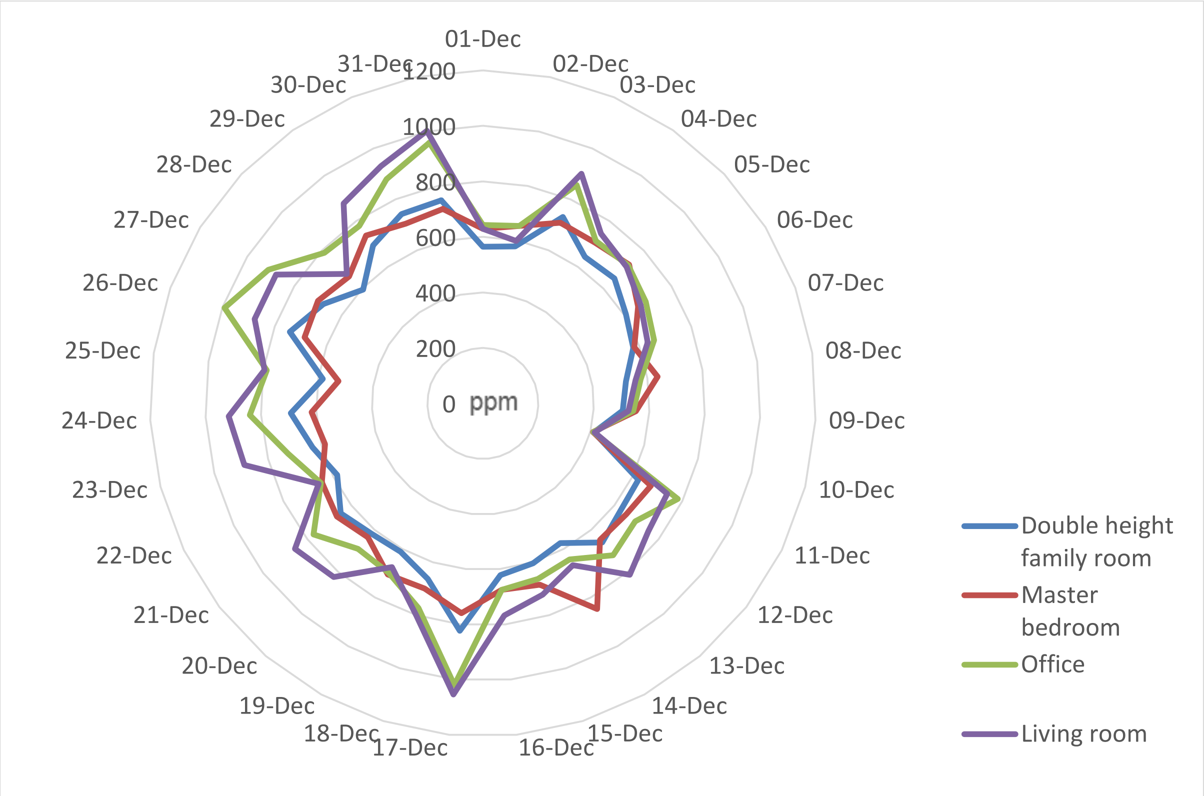


Figure 5.29 Monitored daily room CO_2 concentration of the Passive House in December 2016.

As the Passive House was fully occupied by the new family since September 2016, the indoor CO_2 concentration of December 2016 (a typical month under the new family's occupancy) is shown in Figure 5.29 to display the monitored daily indoor CO_2 concentration. This month's house average CO_2 concentration was 698 ppm, approximately 150 ppm higher compared with the previous couple's occupancy. The highest daily room CO_2 concentration was about 760 ppm appeared in Living Room while the lowest CO_2 concentration was about 631 ppm of Double Height Family Room. It can be seen from the figure that, in most cases, the range of daily house CO_2 concentration was between 600 ppm and 1000 ppm. The indoor CO_2 concentration of Living Room (760 ppm) and Office (739 ppm) were usually higher than

Double Height Family Room (631 ppm) and Master Bedroom (661 ppm). The Office was used as the third bedroom in this dwelling since September 2016 so the CO_2 concentration of this room was even higher than Master Bedroom. In addition, the residents mainly stayed in Living Room and the kid live in the third bedroom (previous Office), usually slept for one or two hours in the afternoon, these resulted in relatively high CO_2 concentration compared to the other two rooms in the property. However, the superb mechanical ventilation in the Passive House controlled all the room's air quality in high quality condition. In general, the indoor CO_2 concentration of this dwelling was still maintained at an outstanding level which was under 700 ppm under this situation.

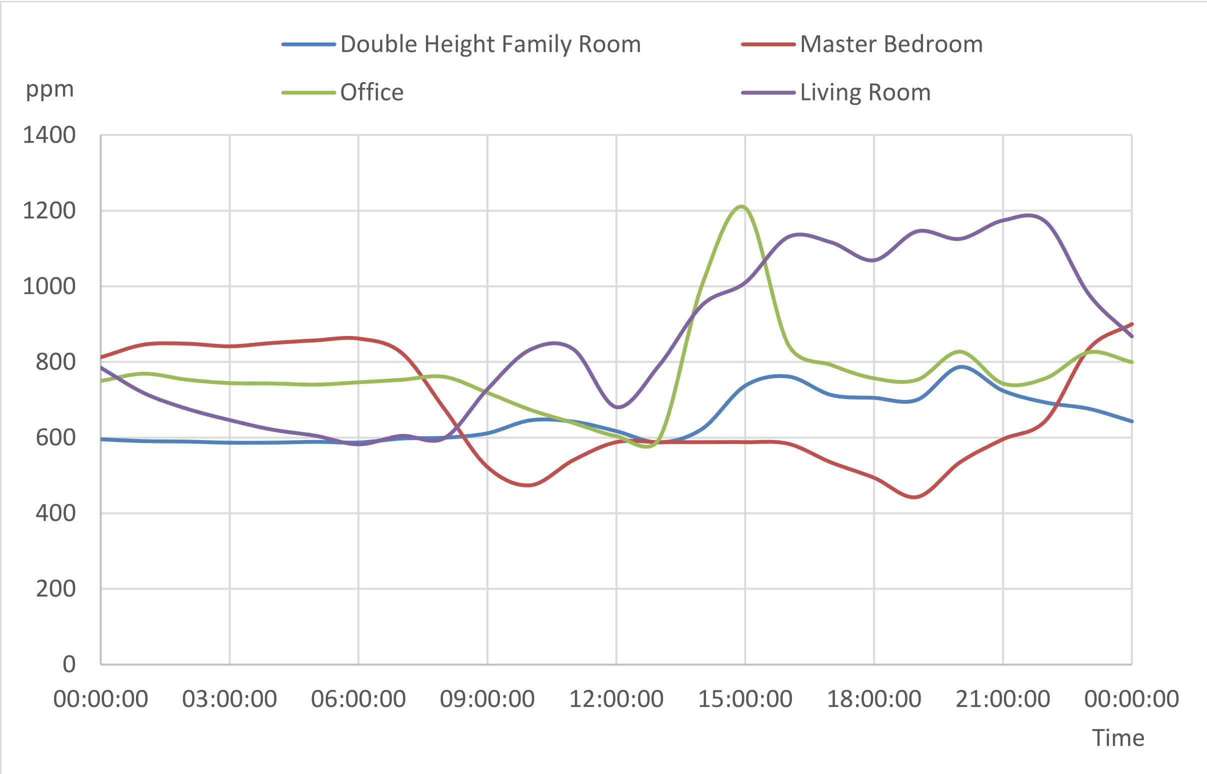


Figure 5.30 Monitored real time CO_2 concentration of the Passive House on 21st December 2016.

The monitored real time indoor CO_2 concentration on 21st December 2016 was selected to represent the typical performance under the new family's occupancy. The house average indoor CO_2 concentration remained at 735 ppm on that day. The highest daily room CO_2 concentration was about 857 ppm appeared in Living Room while the lowest CO_2 concentration was about 648 ppm of Double Height Family Room. Figure 5.30 shows the hourly CO_2 concentration on 21st December 2016. It can be seen from the figure that the highest CO_2 concentration values generated in Living Room during the day time and nearly reached 1200 ppm. Compare to the previous indoor CO_2 concentration performance occupied by the first couple, the room CO_2 concentration of Master Bedroom and Double Height Family Room were similar. As this is a big family, the time spent in Living Room increased obviously and this led to the rising of corresponding CO_2 concentration during daytime and evening. However, the superb mechanical ventilation in the Passive House controlled all the room's air quality in good and comfortable condition. In general, the indoor CO_2 concentration of this dwelling was still maintained at excellent level which was 735 ppm under the new family's fully occupancy.

5.4 Building modelling and simulation

5.4.1 *Model simulation and validation*

The simulation results generated by DesignBuilder indicate that the annual electricity and gas consumption of the Passive House were 7018.99 kWh and 11798.26 kWh, respectively. And the net conditioned building area of this Passive House estimated in the model was 221m^2. Hence, the total simulated energy consumption was 18817.25 kWh and the primary energy demand was 85.15 kWh/(m^{2}a). The actual treated floor area of the house is 219 m^2 based on the building information collected from the house owner.

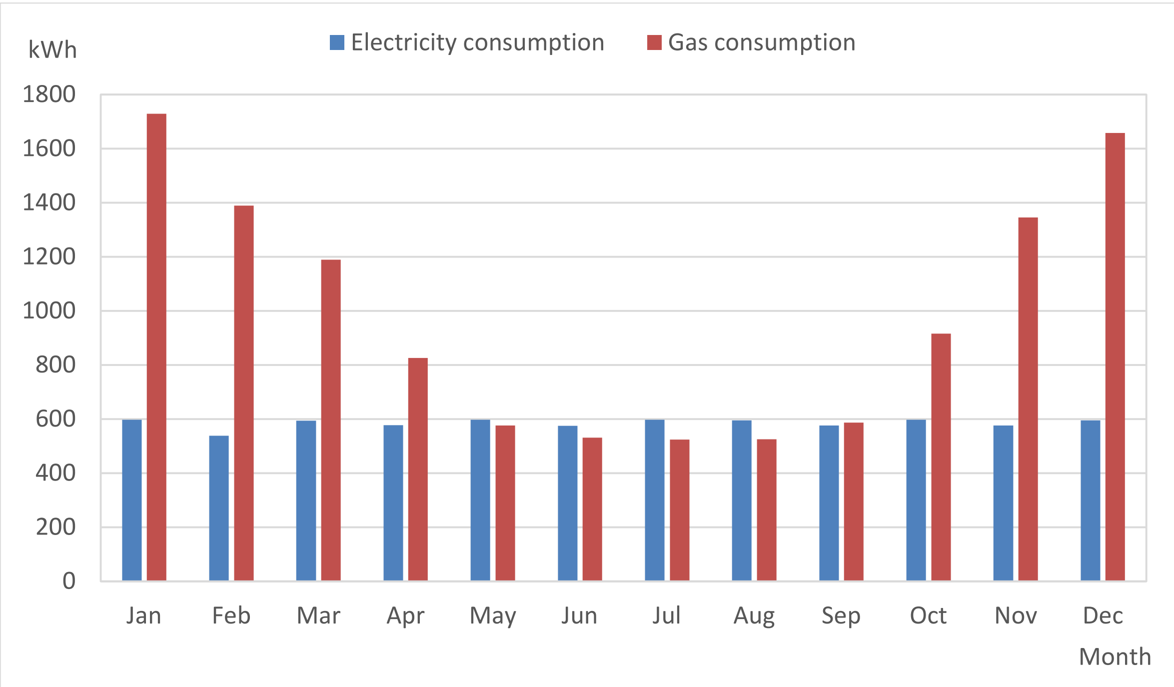
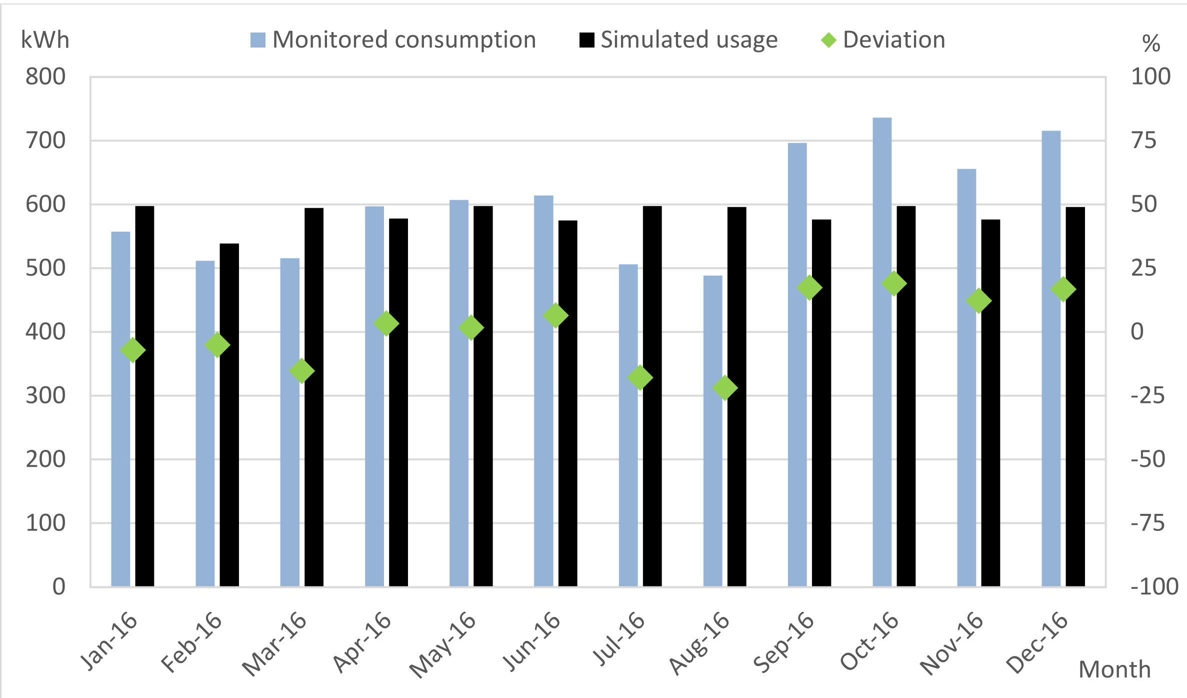


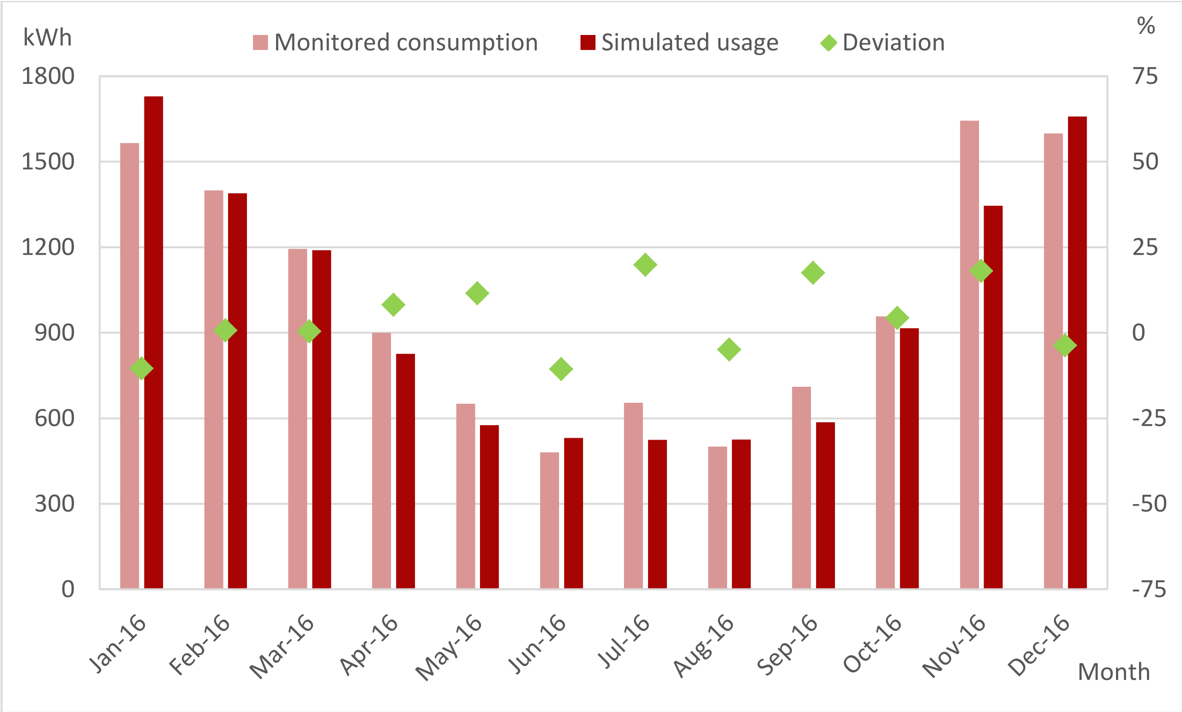
Figure 5.31 Simulated monthly electricity and gas consumption of the Passive House.

Figure 5.31 shows the simulated monthly electricity and gas consumption of the Passive House for a whole calendar year. It can be seen from the figure that electricity consumption for each month was relatively stable while gas consumption in summer were much lower than the energy consumption in winter due to the high energy demand for heating during the coldest months in a year. For electricity consumption, the highest and lowest monthly demands were 597.31 kWh in January and 538.41 kWh in February. For gas consumption, the usages during non-heating period maintained at the same level. The average monthly consumption of 610.06 kWh was supplied to domestic hot water only. Considering the heating energy, it can be known from the simulation results that the colder the weather was, the more heating energy it consumed. The biggest gas consumption appeared in January with 1728.96 kWh in order to keep the whole house warm in the winter. As weather was getting warm in April, the demand for space heating of the last heating month reduced and the monthly gas consumption dropped down to 826.15 kWh.

The actual annual electricity consumption and gas consumption for the Passive House were 7199.57 kWh and 12259.09 kWh and the actual total energy for a year was 19458.66 kWh. The total energy consumption error between actual measurement and simulation was 3.30% according to Equation (1) and (2), which was within the acceptable range. The CV(RMSE) was calculated as 10.08% (maximum value is 15%) and the MBE was +3.30% (within the ±5% requirement) according to Equation (3) and (4).



(a)



(b)

Figure 5.32 Comparison of the Passive House's monthly monitored energy consumption and simulated usage: (a) Electricity consumption, (b) Gas consumption.

The comparison of monthly monitored energy consumption and simulated usage and their percentage errors are shown in Figure 5.32. For electricity consumption, it is clear from the figure that, during the first six monitoring month, the deviations between monitored and simulated results were moderate and within the acceptable range. The reason for the abnormal values of the errors appeared since July to the rest of year was because the change of house occupancy. Firstly, all residents went away from home for holiday in July and August so the electricity demand must decrease than other normal month. This also happened in March and we can see the monitored electricity consumption was about 20% lower than expectation. Secondly, the house occupancy changed since September as more people moved in the house and this property was fully occupied. The actual monthly electricity demand increased for about 15% compared to the estimated results. However, the electricity consumption error between actual measurement and simulation of the whole year was 2.51% according to Equation (1) and (2), which was within the acceptable range. The CV(RMSE) was calculated as 14.01% (maximum value is 15%) and the MBE was +2.51% (within the ±5% requirement) according to Equation (3) and (4). For gas consumption, the CV(RMSE) and MBE were 11.57% and 3.76%, correspondingly. The biggest deviation between actual measured and simulated usage appeared in July of 19.85%. The reason was the same as the reduced occupants led to decreased house energy demand. In addition, the error in November was also bigger than usual level and over 15%. As it was a cold winter, the temperature of November was lower than regular years and its monthly average outdoor temperature was even lower than December in 2016. Thus, the space heating demand of the house grew up in this month and this led to the increasing of gas demand.

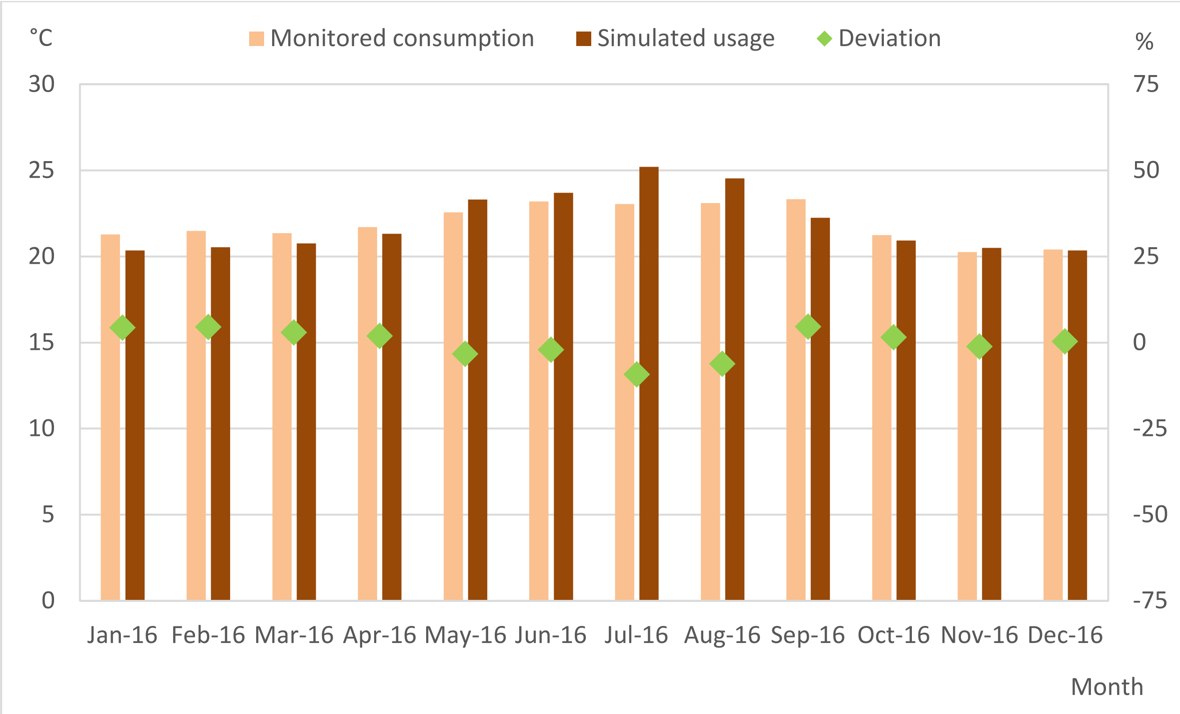


Figure 5.33 Comparison of Passive House's monthly monitored and simulated indoor temperature.

Figure 5.33 indicates the comparison of monthly monitored and simulated indoor temperature and their percentage errors. The annual monitored average indoor temperature was 21.9°C while the simulated indoor temperature in the model was 22.0°C. The CV(RMSE) and MBE were 4.39% and -0.30%, respectively. The relative large deviations occurred in July and August, the empty house period. The indoor temperature difference was near 2°C in those two month. There were two reasons for leading to this situation: firstly, no heat gains generated by residents' activities because no one was in the house; another consideration for this case should be the reduced heat gains generated by the household appliances and utilities due to relative lower energy demand. Hence, the monitored indoor temperature should be slightly under the simulated results as the result of the two reasons stated above.

In general, the comparison results above between actual and estimated energy consumption and indoor temperature of this Passive House show the high accurate of the DesignBuilder model. Considering the indoor temperature with the energy demand especially in the normal operation months, the thermal condition was still correct compared with the onsite measured data. The simulation model has been validated by the actual measured energy consumption and indoor temperature and it can be used for further analysis.

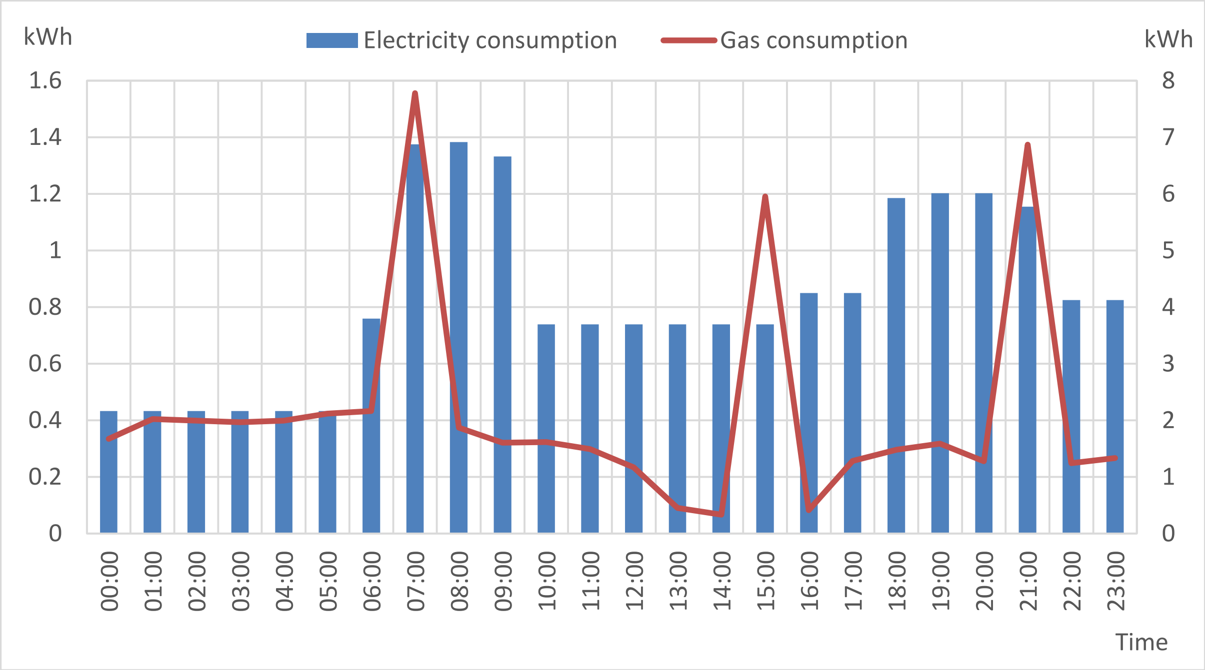


Figure 5.34 Simulated hourly energy consumption of the Passive House in heating season.

Estimated average hourly energy consumption in 24 hours in winter time (heating season) is shown in Figure 5.34. It demonstrated that there were two peaks of electricity demand in a day, between 7:00-9:00 and 18:00-21:00, and three peaks of gas demand appeared in the morning, afternoon and evening (6:00-8:00, 14:00-16:00 and 20:00-22:00), respectively. The energy trends matched with the actual situation well. The residents got up at around 6:30am and went to work before 9:30am and they came back home from work at around 6pm and went to bed at 10pm in the evening. The space heating was supplied by a gas boiler about 4 hours a day, one and a half hour in the early morning when they wake up and two and a half hour in the evening when they come back home. The peak value of gas consumption in the morning is lower than the other in the evening is due to the longer gas boiler operation time and the main cooking gas demand from the residents. The trend of electricity demand is similar to the heating. But the electricity demand in the evening is slightly higher because the increasing of residents occupancy after 6pm. When the residents were away from home to work and at sleeping period, the electricity consumption remained at a minimum standard. In general, the energy consumption during non-peak hours is below 20% of the energy demand of peak hours. Besides these high energy demand hours, the energy consumption for other time of a day remained at a relative low level.

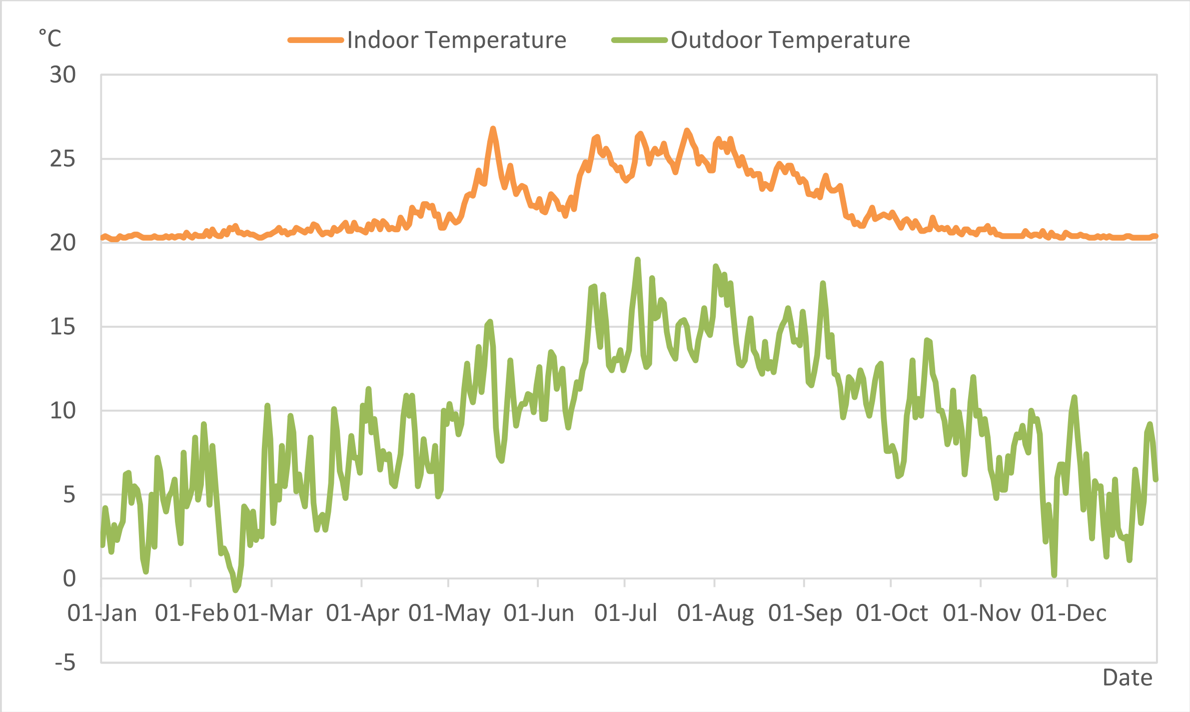


Figure 5.35 Comparison of Passive House's daily indoor and outdoor temperature.

The comparison of daily indoor and outdoor temperature estimated from the DesignBuilder model is shown in Figure 5.35. It can be seen from the simulation results that the indoor temperature during the whole heating season was 22.0°C, which is 0.1°C higher than the onsite monitored data. The temperature error between actual measurement and simulation was 0.46% according to Equation (1) and (2), which was within the acceptable range.

5.4.2 *Analysis of property performance*

For this selected Passive House, the realistic usage of electricity and gas consumption in the first monitoring year were 7199.57 kWh and 12259.09 kWh, respectively. The total energy consumption could be calculated as 19458.66 kWh and the primary energy demand for this house was 88.85 kWh/(m^2a). Compare the actual energy consumption with the Passive House standard, the primary energy demand was 25% lower than the 120 kWh/(m^2a) requirement. The average monthly gas consumption for domestic hot water was assumed and calculated as 523.25 kWh according to national statistics data, the annual total energy consumed in domestic hot water was 6279 kWh. Thus, we can know the annual total energy demand for space heating was 5980.09 kWh and the space heating demand of this dwelling was 27.31 kWh/(m^2a), 12.3 kWh/(m^2a) beyond the Passive House standard. Because the gas boiler connected with MVHR in the house is to help supply heating to desired indoor temperature.

Even in majority of the summer days, the boiler was not completely turned off and consumed more energy than expectation due to the demand and preference of the house residents.

The monitored indoor temperature, relative humidity and CO_2 concentration of four different zones (Double Height Family Room, Master Bedroom, Office and Living Room) in this house represented its great indoor environmental performance. The differences between highest and lowest values for monthly indoor temperature, relative humidity and CO_2 concentration were 2.5°C, 20.2% and 177 ppm, respectively. The annual average indoor temperature of the whole property was 21.9°C which was very comfortable and even 1.9°C beyond the Passive House standard. In terms of relative humidity, 45.5% represented the annual average level.

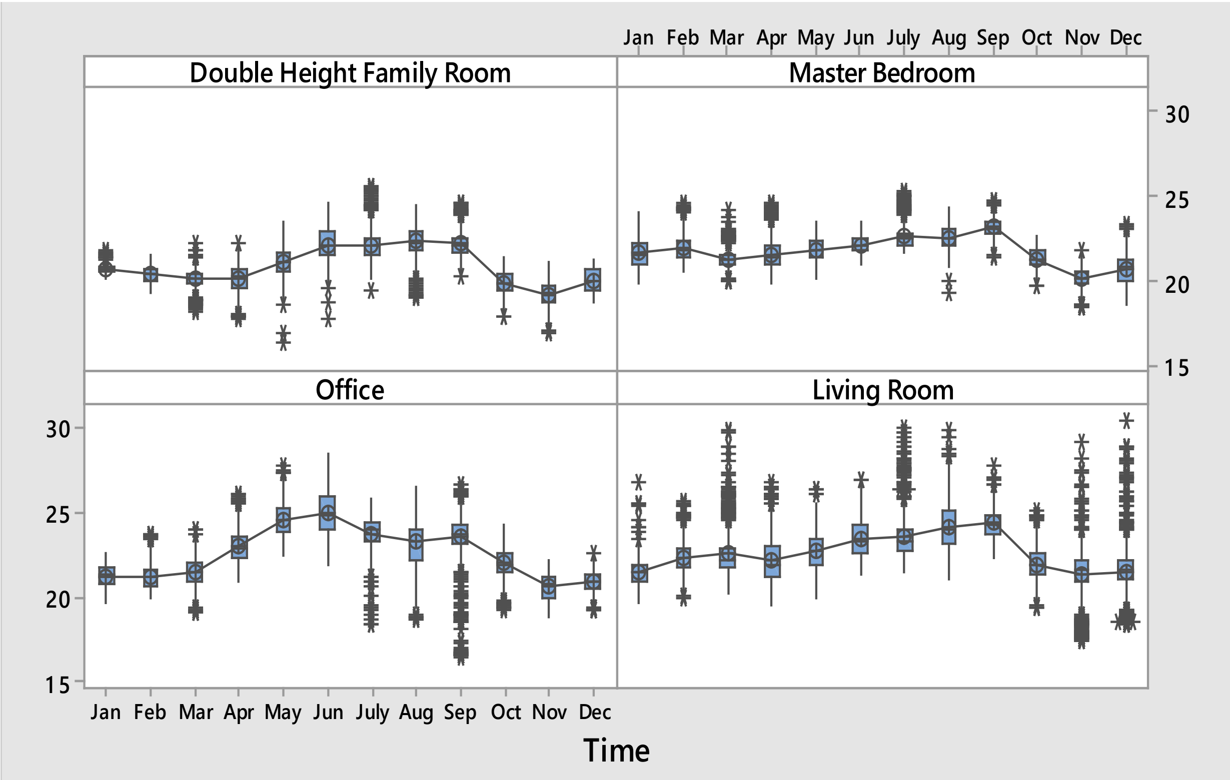


Figure 5.36 Boxplot of monthly indoor temperature of four different rooms in the Passive House.

Monthly indoor temperature trends of these four different rooms in the dwelling during the monitoring period are shown in Figure 5.36. In the boxplot figure, the tiny blue boxes represent the middle 50% of all the data. The upper and lower whiskers represent the upper and lower 25% of the distribution, respectively. The observations beyond the upper or lower whisker are the outliers. It can be seen from the figure that the temperature trend in lower floor was more stable and was about 2°C lower compared to the upper floor. During the winter heating season, the average indoor temperature for all zones were beyond 20°C, which was great performance with satisfied thermal comfort. But the indoor temperature in summer time was obviously around 3°C beyond the temperature in winter time, especially for the Office and Living Room in upper floor. This super-insulated dwelling may experience the summer overheating problem.

During the summer of the first monitoring year, we have noticed that the Office temperature has increased, especially in the evenings. The temperature has touched 28°C on one occasion. It was found that this was due to the large west facing window when the evening sun was out. There is no shading to that window as the house owner expected the proximity of high trees to prevent direct evening sunlight in the property design stage. Clearly, around the mid-summer equinox, this was not the case. Coupled with the fact the room is immediately above the plant room and the domestic hot water distribution then the office is prone to run at a slightly higher temperature than the rest if the house under normal conditions. So it was realised that not having an opening window in the office was a mistake. The result was that the office room temperature cannot be purged by opening a window and forcing air through, particularly at night.

Table 5.5 represents the assessment of indoor air quality in the Passive House. The monitored indoor temperature and relative humidity has been classified to several categories based on the CIBSE Guide A – Environmental design shown in the table to assess the thermal performance of the dwelling. The four different categories of the indoor CO_2 concentration (IDA) in the dwelling were classified according to the standard of EN 13779. And the average level of indoor CO_2 concentration for this dwelling was only 529 ppm. All the indoor environmental condition demonstrates the dwelling is under the best performance for more than 90% hours of monitoring.

	% hours	Double Height Family Room	Master Bedroom	Office	Living Room
Temperature	< 17°C	0.03	0	0.16	0
	17°C < T < 25°C	99.86	99.92	90.48	92.44
	> 25°C	0.11	0.08	9.36	7.56

	> 28°C	0	0	0.05	0.40
Relative humidity	< 30%	0.01	0.37	5.00	0.23
	30% < H < 70%	99.99	99.62	94.99	99.77
	> 70%	0	0.01	0.01	0
Carbon dioxide	< 800 ppm	99.44	91.81	95.77	95.09
	800ppm < CO_2 < 1000ppm	0.54	7.95	3.16	4.09
	1000ppm < CO_2 < 1400ppm	0.02	0.24	0.87	0.82
	> 1400 ppm	0	0	0.20	0

Table 5.5 Assessment of indoor air quality in the Passive House.

From the analysis above we know that the performance of this Passive House is fabulous. The super insulated dwelling keeps the energy consumption of this house under the requirement for one of the most rigorous building standard worldwide. Simultaneously, the indoor environmental condition including temperature, relative humidity and CO_2 concentrations of the dwelling are maintained at high quality level because of the advanced fabric construction, especially in winter time. However, the percentage hours for over 25°C in the Office and Living Room were closed to 10% and this indicated there would be a risk of overheating during summer time happened in the upper level of the property. An annual overheating analysis carried out by three criteria set out within CIBSE Technical Manual 52 was shown in Table 5.6. There were three criterions to evaluate if a zone existed overheating problem using the onsite monitored temperature data from May to September. The temperature percentage hour for over 25°C of Office and Living Room were closed to 10%, which is restricted by the Passive House standard. Overheating problem existed in May due to the super-fabric design.

Zone	Criterion	May	Jun	Jul	Aug	Sep
Office	C1 (% ΔT)	17.6	8.9	0	0	0
	C2 (Count of days when We>6)	9	3	0	0	0

	C3 (Instances when ΔT>4)	0	0	0	0	0
Master Bedroom	C1 (% ΔT)	0	0	0	0	0
	C2 (Count of days when We>6)	0	0	0	0	0
	C3 (ΔT>4)	0	0	0	0	0
Living Room	C1 (% ΔT)	0.3	0.3	6.3	1.3	0.3
	C2 (Count of days when We>6)	0	0	3	1	0
	C3 (ΔT>4)	0	0	0	0	0
Double Height Family Room	C1 (% ΔT)	0	0	0	0	0
	C2 (Count of days when We>6)	0	0	0	0	0
	C3 (ΔT>4)	0	0	0	0	0

Table 5.6 Overheating criterion analysis of the Passive House.

This Passive House is very energy efficient and its indoor environmental condition is also outstanding. However, the daily working combi gas boiler leads to relative higher energy consumption for space heating in winter and warmer indoor temperature in summer. Because both the space heating demand and indoor temperature of this dwelling were higher than the standard's requirement, the house energy demand could be further reduced by decreasing the space heating set-point temperature or previous scheduled heating hours. Thus, an investigation to further improve the property performance was conducted in the validated DesignBuilder model, which is shown in the following section.

5.5 Exploration to further improve property performance

5.5.1 *Adding cooling system*

Clearly, adding an opening window was not an option at that juncture to solve the office overheating problem for the house residents. So the options available to the house owners to choose from were as follows:

1. Add cooling to the MVHR supply ducting (The system needs to be redesigned);

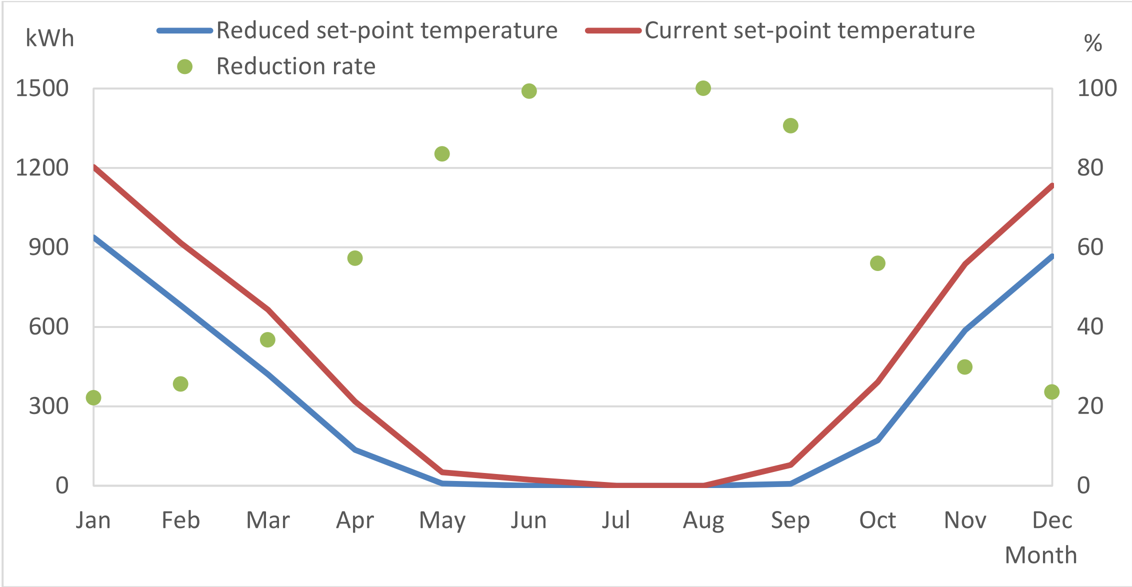
2. Put an extract fan in the Office to the outside (This option runs against the principals of Passive House - airtightness and thermal bridge and it would not necessarily reduce the temperature adequately or quickly).
3. Install portable air conditioning unit (This would need a large hole through the wall as no opening windows in the room. Similar issues to option 2 may happen. Above though this would definitely work but would occupy space on the floor. Overall, this is an inelegant, messy and noisy solution).
4. Use of an evaporative unit (The residents discounted this as it was totally unsuitable).
5. A small wall mounted split unit.

The house owner chose option 5 as being the easiest to achieve the desired objective with minimal compromise to the integrity of the airtightness and thermal efficiency. Only a small aperture was required to get the pipework and power cable through the thermal envelope and then this was resealed with tape and expanding foam. The small cooling unit was installed at the beginning of July 2016 and we can see that the room temperature in the Office can be easily reduced since then.

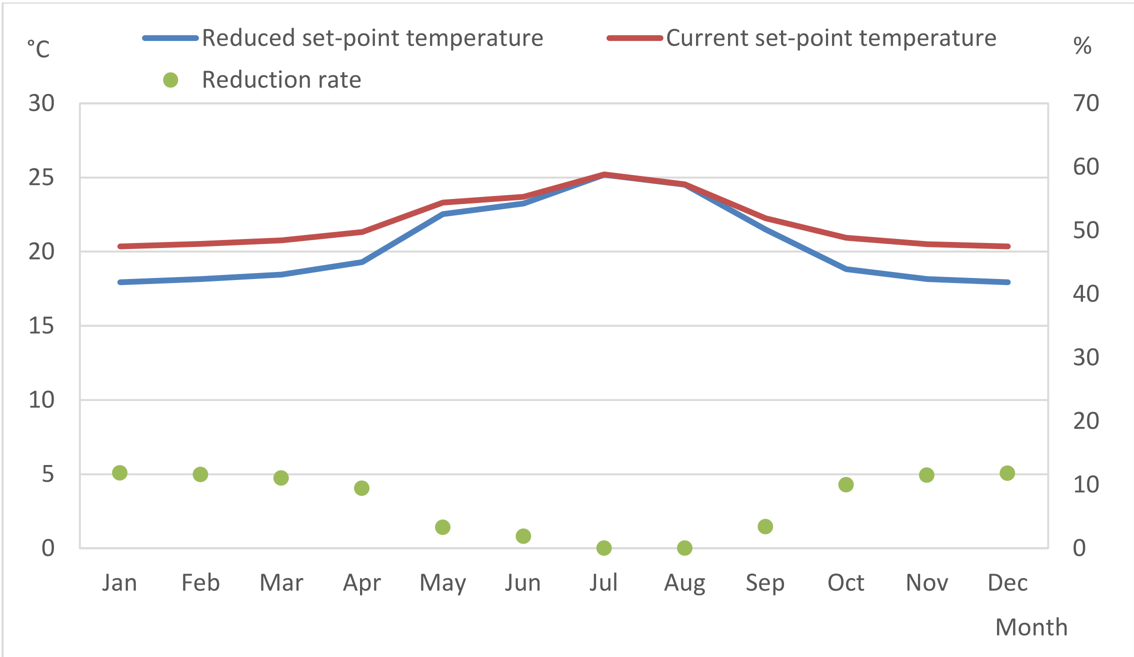
However, the room temperature does not remain down for long time if the air conditioning was turned off. This is a factor of having little thermal mass in the upstairs rooms. Never the less, the overheating problem has been temporary resolved and the Office can now be used as a comfortable room. Although the Office only overheats significantly when the sun is out which means plenty of generated solar PV electricity could power the cooling system to keep the room temperature down, but it also add the space cooling demand to the whole house. This solution is feasible for the actual situation of the Passive House, but the extra space cooling demand leads to higher primary energy demand and it needs to be considered in future research.

5.5.2 *Reduce the MVHR set-point temperature*

As the house residents preferred warmer indoor temperature condition, they set a higher MVHR set-point temperature and received 22°C as average household temperature all the year round and 20.6°C indoor temperature during the normal heating period (January to April and November to December). The 2°C indoor temperature beyond the Passive House standard caused more space heating energy demand of the property in winter time. That means, if the house temperature is reduced to the requirement in the standard (20°C), both the primary energy demand and space heating demand would drop down. According to the estimated results generated by the validated DesignBuilder models, if the annual indoor temperature maintains at 20.5°C, the total gas consumption in a year could be reduced about 15% from 11798.26 kWh to 9996.73 kWh. The decreased gas consumption was the direct saving of space heating demand, thus, the simulated space heating demand was only 17.43 kWh/(m^{2}a), which was very closed to the Passive House standard compared to the current demand.



(a)



(b)

Figure 5.37 The estimated changing trend for the Passive House performance: (a) gas consumption for space heating, (b) indoor temperature.

The comparison of the Passive House performance under different set-point temperature was shown in Figure 5.37. It can be seen from Figure 5.37 (a) that, once the indoor temperature was reduced from 22°C to 20.5°C, the monthly household gas consumption for space heating decreased along with the dropped indoor temperature. The heating gas consumption for each month reduced more than 20% according to the assumption generated by the validated DesignBuilder model. The winter reduction rates were lower than those in the summer. This is because during the traditional non-heating season, there is little space heating energy consumption under the reduced set-point temperature based on the simulation results. Thus, the reduction rates of gas consumption in summer time were very high and could even reach 100% occasionally.

From Figure 5.37 (b), it is clear that the changing of indoor temperature under different set-point temperature. In a year, the average indoor temperature dropped down around 1.5°C in each month compared to the current situation. The winter reduction rates were slightly higher than those in the summer. This is because during the traditional heating season, the indoor temperature for the whole house was controlled well by the MVHR system. The reduction rate during that period was stable and remained at about 11%. In summer time, the indoor temperature does not change too much based on the simulation results and the fluctuation were within 1°C.

Hence, this method could reduce the space heating demand significantly but seems not useful to overcome the summer overheating problem as the summer indoor temperature does not change a lot under the two different set-point temperature.

5.5.3 *Building fabric retrofit*

One of the main reason for the overheating happened in this Passive House is having little thermal mass especially in the upstairs rooms. Thermal mass is the ability of a material to absorb and store heat energy. In winter time, thermal mass could store the heat gains from the sun or thermal store and release it in the evening to keep the whole house warm. During summer time, it absorbs heat during the day and releases heat at night with cool breezes to keep the whole house in relative comfortable temperature. As a timber framed Passive House, the lightweight material has low thermal mass and this makes the indoor temperature fluctuate with outdoor temperature obviously. Because the winter house indoor temperature could be controlled by heating system in the property and maintain at comfortable level, there was no concerns for low winter indoor temperature. But in summer time, there was no cooling system in the house to reduce the overheated indoor temperature. Thus, low thermal mass was really a problem for the Passive House. Plus, unfixed all opening in the property, add shading to all openings could also help prevent the summer overheating problem.

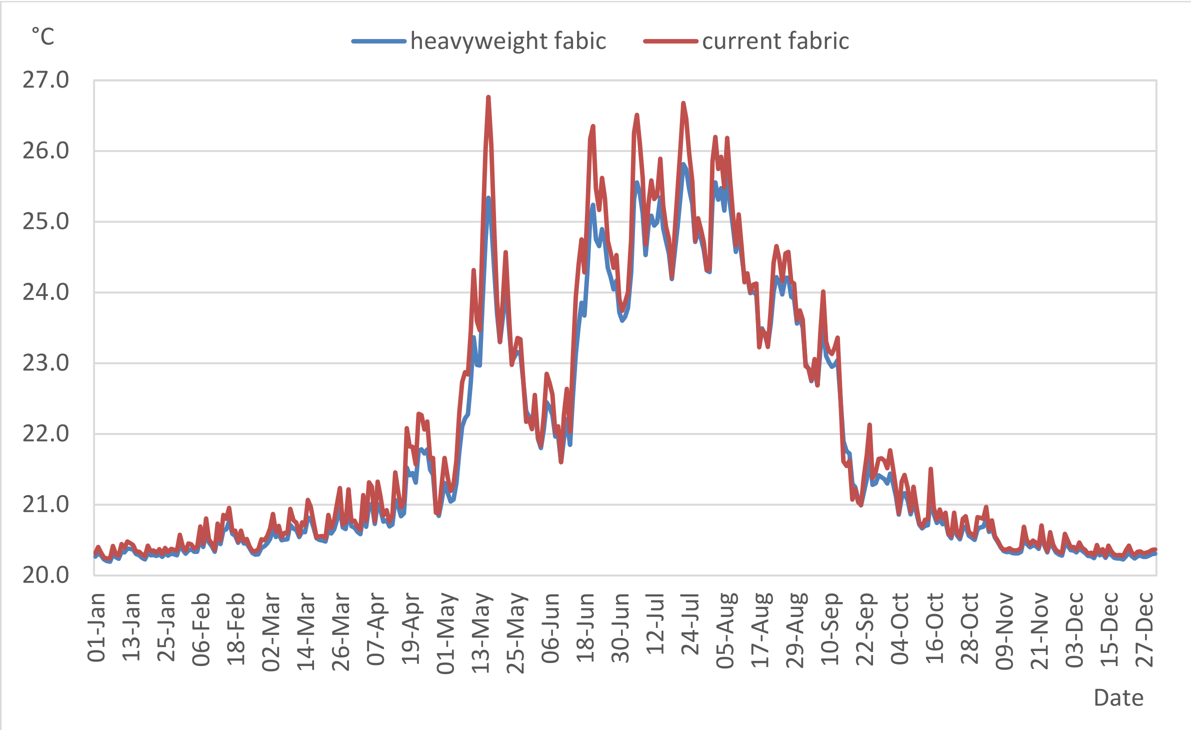


Figure 5.38 Impact of building fabric materials to the indoor temperature in the Passive House.

Figure 5.38 indicates the impact of building fabric materials to the indoor temperature estimated by the Passive House models. In the investigation, the original lightweight material of the dwelling (timber external wall) was replaced by a kind of heavyweight material (super insulated brick/block external wall). The red line shows the simulated average daily indoor temperature of the lightweight property. It is clear that there are several days in the summer that the house temperature is over 26°C. The blue line shows the daily indoor temperature performance of the heavyweight property in assumption. It can be seen from the figure that its annual average indoor temperature was 21.8°C, which is 0.2°C lower than the base building model. The difference between them appears in summer time as the indoor temperature of the heavyweight building model was 0.3°C lower than the other one. Moreover, during the hottest days in summer, the daily temperature of the heavyweight property is at least 1°C lower than the original timber frame Passive House. The highest indoor temperature of the heavyweight dwelling doesn’t exceed 26°C. Through the simulation results, we can know that in summer, the heavyweight building could relatively achieve more comfortable indoor temperature than lightweight building and it also can reduce the risk of overheating in those super insulated Passive House.

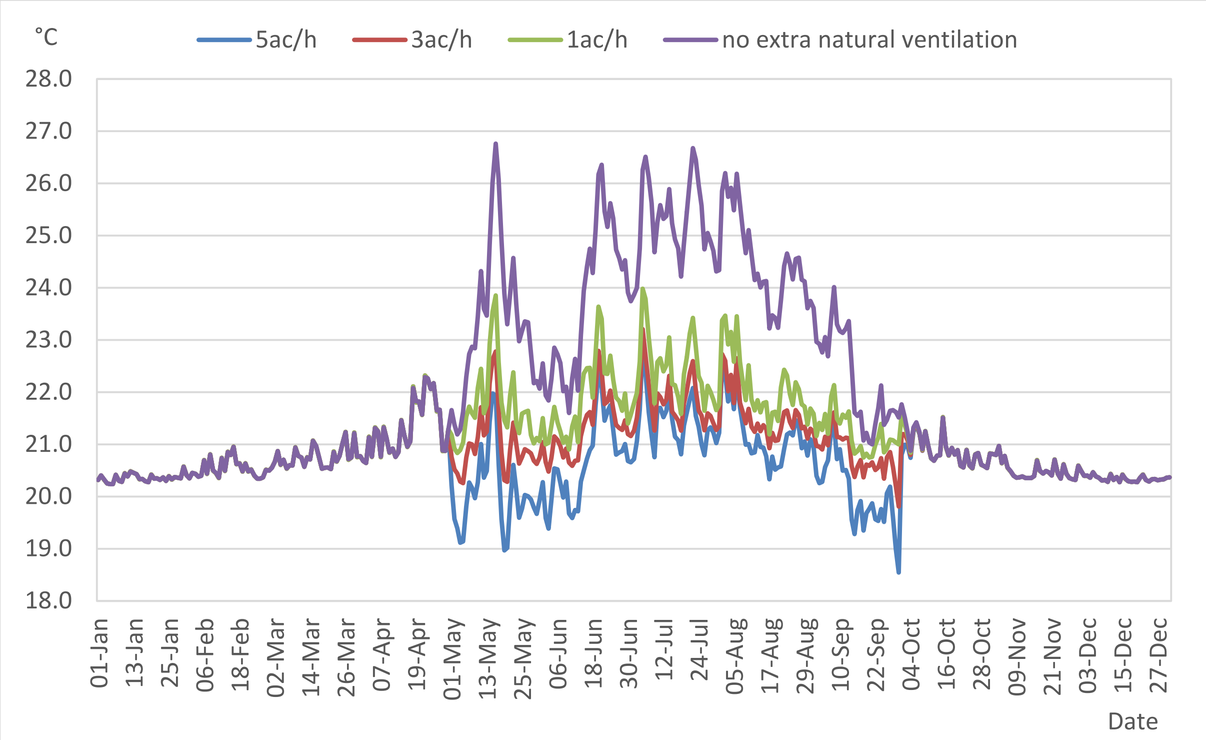


Figure 5.39 Impact of natural ventilation to the indoor temperature in the Passive House.

During the first monitoring year of the Passive House, we know that no extra natural ventilation applied to this low thermal mass property could lead to overheating problem in the summer time. Adding natural ventilation to the property is one of the methods to reduce the risk of the summer overheating issue. Figure 5.39 shows the impact of natural ventilation to the Passive House's indoor temperature simulated by the DesignBuilder model. In the assumption, the common area of lower level (corridor and double height family room) and the living room and office room in the upper level are applied extra natural ventilation from May to September. It can be seen from the figure that the natural ventilation in summer affects the house indoor temperature significantly during the specific period. The more natural ventilation is applied to the property, the lower house temperature is maintained according to the simulation results. The estimated average indoor temperature during the five months in summer under 5ar/h, 3ac/h, 1ac/h natural ventilation and original status are 20.7°C, 21.3°C, 21.9°C and 23.8°C, respectively. Thus, the effect of adding natural ventilation to this Passive House is obvious and it can reduce the summer indoor temperature.

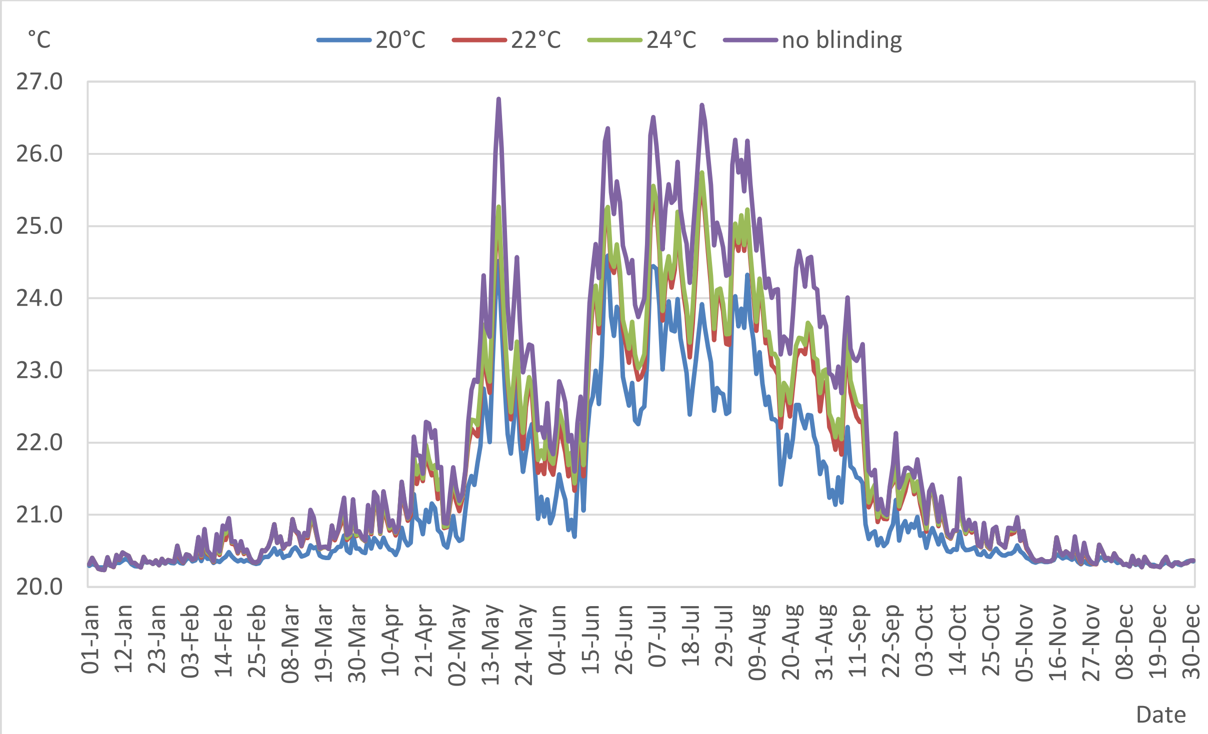


Figure 5.40 Impact of inner blinding to the indoor temperature in the Passive House.

There is no blinding installed in the Passive House to restrict the sunshine radiation during the summer time. Adding blinding to the openings in the property is one of the methods to reduce the risk of overheating. Figure 5.40 shows the impact of inner blinding to the Passive House's indoor temperature simulated by the DesignBuilder model. In the assumption, the blinding would be used when the indoor temperature reaches 20°C, 22°C or 24°C. It can be seen from the figure that the blinding affects the indoor temperature obviously, especially in the summer non-heating season. The difference of annual indoor temperature for those four cases was within 0.8°C. But during the traditional non-heating season, from May to October, the lower the blinding operation set-point is, the more comfortable indoor temperature achieves. From the simulation results, it can be known that the summer indoor temperature for the four cases (blinding operates at 20°C, 22°C, 24°C and no blinding) are 22.0°C, 22.6°C, 22.8°C and 23.3°C. When the blinding is used at 20°C indoor temperature, the average daily temperature in a year is all under 25°C.

Although the three methods mentioned above could effectively lower the Passive House indoor temperature, they may increase the total energy demand more or less. How to get the balance of achieving comfortable indoor temperature within required energy consumption is a key to solve the summer overheating problem. Also, there are many other factors could affect the changing of indoor temperature that we need to consider. Thus, an optimisation and analysis of building fabric retrofit was conducted in the validated DesignBuilder model to investigate the house performance to reduce the risk of house overheating.

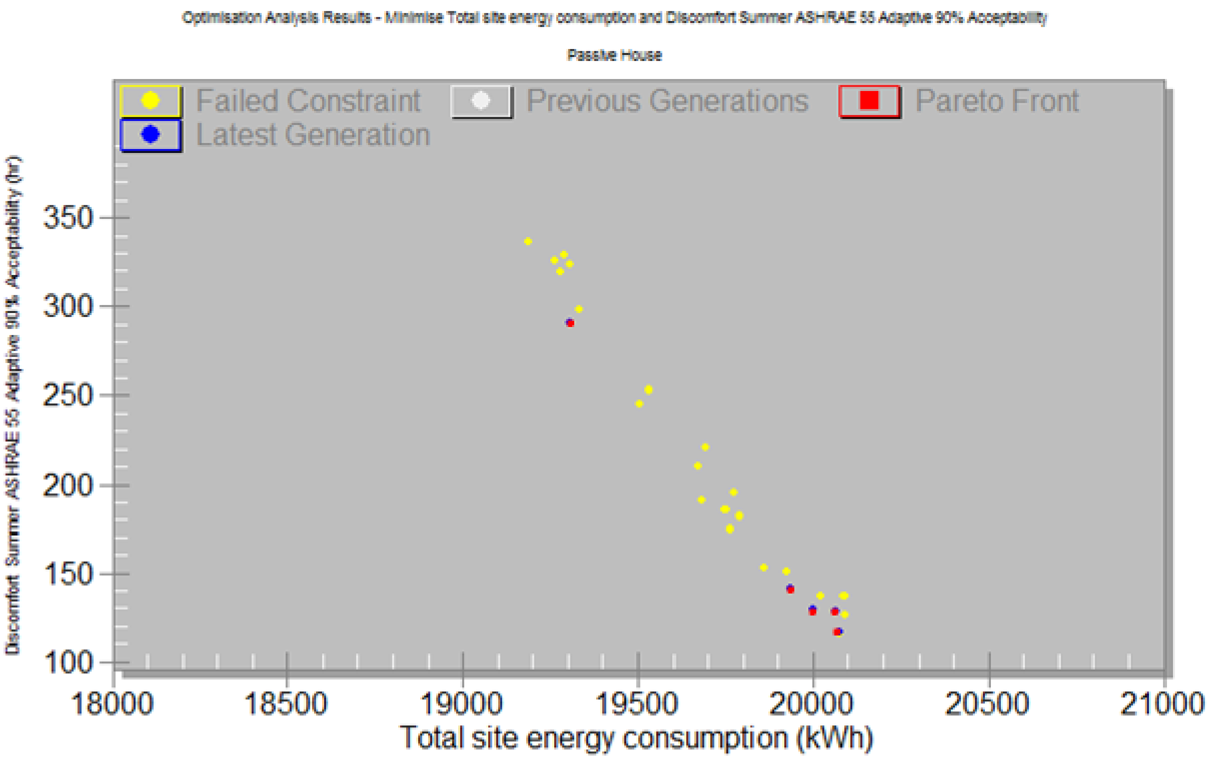


Figure 5.41 Optimisation results for the Passive House.

A feasibility study of optimisation to reduce the house heating demand and overheating risk was conducted by the DesignBuilder. The simulation model was set up to find the balance between annual energy consumption and summer discomfort hours of the dwelling by changing the parameters of design variables (e.g. building fabrics, window blind, thermal mass and mechanical ventilation set-point temperature). There were two objectives for the optimisation: to minimise total energy consumption and summer overheating hours, and the two constraints were defined according to the Passive House standard: primary energy demand should not exceed 120 kWh/(m^2a); maximum 10% of discomfort hours in a year was restricted in the optimisation simulations. The optimisation results are shown in Figure 5.41.

All the scatter points (4 different types of Generations dots) in the figure represent the estimated optimisation results. The Pareto Fronts (red dots) mean the best practical results calculated according to the model settings and satisfied with the limitations of total energy consumption and discomfort summer hours. Fail Constraints (yellow dots) indicate the results that fail to meet the assumed constrains stated above. The Latest Generations (blue dots) and Previous Generations (white dots) were all simulation results generated by the optimisation.

From the figure, it is found that the lightweight building consumes less energy but the summer discomfort hours were relatively high. The performance of heavyweight building is opposite. Its risk of summer overheating decreases but the energy consumption increases at the same time.

For the performance optimisation of this Passive House, as an existing property, no big change will take place on its advanced building fabrics from the view of cost saving. Thus, lower the MVHR set-point temperature from 20 °C to 18 °C and add window blinds are feasible to reduce both heating energy consumption and summer discomfort hours based on the simulation results. Taking into account the methods, it is predicted by the model that 18.9% space heating energy savings can be implemented. In addition, over 200 discomfort (overheating) hours could be eliminated and the carbon dioxide emissions saving would reach 13.4% under simulation. As the recommendations to prevent summer overheating problem for future new built property, except the methods listed above, other measures could be used according to the simulation results are: turn off gas boiler for space heating in summer months; increase thermal mass of the entire property; unfixed all openings; combine summer natural ventilation with the mechanical ventilation system to force air circulation through the house and adding cooling system.

5.6 Summary

The case study of a super-insulated Passive House was investigated in this chapter, by undertaking field audits, actual energy and indoor environment data measurements, collection, house performance analysis, building modelling and the optimisation of property performance to reduce overheating risk. The energy consumption and indoor environmental condition of this Passive House have been monitored for more than one year by a proprietary monitoring package, and the actual data was analysed in this study. The actual annual total energy consumption for this house was 19458.66 kWh and the primary energy demand was 88.85 kWh/(m^2a). The final electricity consumption of this Passive House was 7199.57 kWh while the gas usage was 12259.09 kWh. With 55.98 kWh/(m^2a) space heating demand the house indoor temperature remained at 21.9°C, which was a very comfortable indoor temperature for living. The 45.5% average indoor relative humidity and the 529 ppm average indoor CO_2 concentration for the whole monitoring year presented superb building performance of this property.

The DesignBuilder model was validated by actual energy consumption and onsite indoor environmental condition recorded by the monitoring kits. The validated model was used to evaluate the property performance from the view of low energy consuming and indoor thermal comfort. As summer overheating was observed in this Passive House, reduce the MVHR set-point temperature and add window blind are feasible to reduce both heating energy consumption and summer discomfort hours based on the simulation results. It is predicted by the model that 18.9% space heating energy savings can be implemented. In addition, over 200 discomfort (overheating) hours could be eliminated.

Overall, this case study indicates the energy performance and indoor environment condition of this Passive House is outstanding. With state-of-art building materials, it is feasible to exceed basic regulatory requirements of low energy buildings and provide comfortable living atmosphere. When the summer overheating problem is solved, this type of Passive House provides a future building development direction that balances the annual energy consumption and summer discomfort hours in the dwelling. Based on the analysis in this study, it shows the advantages of Passive House in achieving high thermal comfort, low energy consumed and low carbon emissions.

Chapter 6. Building performance comparison between the Conventional House and Passive House

6.1 Introduction

The building performance of the selected Conventional House and Passive House were summarised and analysed in Chapter 4 and Chapter 5. It is known from the two case studies that both energy and indoor environmental performance of the Conventional House were maintained at average national level, which was not very energy efficient and its indoor environmental conditions were relatively poor. For the Passive House, the primary energy demand and winter indoor environment conditions were outstanding. Due to the lightweight building design, it faced the summer overheating problem, but it is still shows the advantages in achieving high thermal comfort, low energy consumed and low carbon emissions overall. This study aims to find out the differences between these two types of residential properties and give further recommendations to improve their building performance.

6.2 Comparison of energy conformance

6.2.1 *Electricity performance*

The annual electricity consumption of the Conventional House was 2457.21 kWh based on the validated DesignBuilder model and its electricity demand was 27.30 kWh/(m^2a). The annual electricity consumption of the Passive House were 7018.99 kWh according to the estimated results so its electricity demand was 31.76 kWh/(m^2a). The electricity demand of the Passive House was 4.46 kWh/(m^2a) higher than the value of the Conventional House. There were three main reasons led to this result: firstly, the mechanical ventilation with heat recovery system in the property consumed 1.08 kWh electricity per day, and this constitutes 1.8 kWh/(m^2a) in the total electricity demand. Secondly, all cookers and hobs in the Passive House are electric but those in the Conventional House are gas consumers. Based on the statistical data and monitoring results in the Conventional House, the daily cooking energy consumption was around 1.5 kWh. This means 2.5 kWh/(m^2a) electricity demand was consumed by cooking. At last, the total electricity consumption of the Passive House includes the electricity consumed in their garden but the Conventional House did not affect by this issue. The two pond pumps (110W and 80W) in the garden of the Passive House running twenty four hours a day, seven days a week occupied about 7.6 kWh/(m^2a) of the house total electricity demand. Exclude these consumption, the electricity demand of the Passive House was 19.86 kWh/(m^2a), which was 27.3% lower than the Conventional House's electricity demand. Considering the basic electricity demand for a residential property, the data shows the Passive House is more electricity efficiency compared to the Conventional House.

6.2.2 *Gas/heating performance*

The annual gas consumption of the Conventional House was 10348.53 kWh based on the validated DesignBuilder model and its gas demand was 114.98 kWh/(m^2a). The annual gas consumption of the Passive House were 11798.26 kWh according to the estimated results so its gas demand was 53.38 kWh/(m^2a). The gas demand of the Passive House was less than half of the value of the Conventional House. This represents the advantage of Passive House that consumes very low energy with relative low carbon dioxide emission at the same time. Based on the simulation results, the gas consumption of heating and domestic hot water for the Conventional House were 3641.85 kWh and 6141.52 kWh. Hench, its gas demand of heating and domestic hot water were 40.47 kWh/(m^2a) and 68.24 kWh/(m^2a), respectively. For the Passive House, the gas consumption of heating and domestic hot water were 5618.86 kWh and 6179.40 kWh. Thus, its gas demand of heating and domestic hot water were 25.42 kWh/(m^2a) and 27.96 kWh/(m^2a), separately.

It can be known from the data that both gas demand of heating and domestic hot water of the Conventional House were much higher than the Passive House. This reflected an issue that the high gas consuming Conventional House was not only faced the problem of relatively low level of building fabric and insulation that led to weak air tightness. Such high gas demand for domestic hot water indicated the bad performance of the boiler used in the property. As I have mentioned in Chapter 4, the energy efficiency of the old style boiler has reduced to half value compared to those new condensing boilers on the market.

6.2.3 *Renewable energy application*

For the Passive House, solar PV was used to supply electricity and even heating when the generation was excess. According to the monitoring data, the annual solar PV generation was 4325.06 kWh. In reality, 85% of the solar PV electricity generated onsite was used in the property. Among them, 45% was consumed as electricity and 40% was converted to thermal store for heating purpose. This made the household net electricity and gas consumption in a year reduce to 5100.61 kWh and 10061.19 kWh, and the corresponding net electricity and gas demand were 23.08 kWh/(m^2a) and 45.53 kWh/(m^2a). There was no renewable energy utilised in the Conventional House. This also represents a possibility to reduce the net energy consumption for the property in the future investigation. The energy performance of this two different types of properties has been summarised in Table 6.1 below. All the data used in this comparison were the simulation results generated by the validated DesignBuilder models. The reason is the realistic space heating and domestic hot water consumption for these two properties were not monitored by the sensors in detail. However, each of the DesignBuilder model for both houses was validated and calibrated by actual building performance and national or regional statistic data. Thus, the estimated energy demand could represent the energy performance of these two houses.

<table>
<tr><td colspan="2" rowspan="2"></td><td>Conventional House</td><td>Passive House</td></tr>
<tr><td>kWh/(m²a)</td><td>kWh/(m²a)</td></tr>
<tr><td colspan="2">Primary energy demand</td><td>142.28</td><td>85.15</td></tr>
<tr><td colspan="2">Electricity demand</td><td>27.30</td><td>31.77</td></tr>
<tr><td rowspan="4">Gas demand</td><td>In total</td><td>114.98</td><td>53.38</td></tr>
<tr><td>Space heating demand</td><td>40.47</td><td>25.42</td></tr>
<tr><td>Domestic hot water demand</td><td>68.24</td><td>27.96</td></tr>
<tr><td>Cooking demand</td><td>6.27</td><td>-</td></tr>
<tr><td colspan="2">Renewable energy utilization</td><td>-</td><td>16.53</td></tr>
<tr><td colspan="2">Net primary energy demand</td><td>-</td><td>68.62</td></tr>
<tr><td colspan="2">Net electricity demand</td><td>-</td><td>23.09</td></tr>
<tr><td rowspan="3">Net gas demand</td><td>In total</td><td>-</td><td>45.53</td></tr>
<tr><td>Net space heating demand</td><td>-</td><td>21.68</td></tr>
<tr><td>Net domestic hot water demand</td><td>-</td><td>23.85</td></tr>
</table>

Table 6.1 Energy performance comparison between the Conventional House and the Passive House.

6.3 Comparison of indoor environmental performance

6.3.1 *Temperature*

The World Health Organisation (WHO) recommends temperatures of 21°C for the main living area and 18°C for the rest of the home [251]. The 1996 English House Condition Survey (EHCS), using spot temperatures, found that 6.9 million homes (28%) had living rooms at or below 16°C, and 10.9 million (44%) had cold hallways (see Figure 6.1) [249].

Indoor temperature (°C)	*Assumptions of physiological effect*	*Living rooms at these temperatures (million)*	*Halls/stairs at these temperatures (million)*
24+	Risk of strokes and heart attacks	0.4	0.3
21-24	Increasing discomfort	3.5	2.1
18-21	Comfortable temperatures	8.8	6.3
16-18	Discomfort, small health risk	4.1	4.6
12-16	Risk of respiratory diseases	2.5	4.7
9-12	Risk of strokes, heart attacks	0.2	0.9
< 9	Risk of hypothermia	0.1	0.7
Unhealthily cold (<12°C)		2.8	6.3
Total cold homes (<16°C)		6.9	10.9

Source: Richard Moore, pers. comm. Note: Outside temperature 5°C or below

Figure 6.1 Temperatures in homes and health effects in England, 1996.

The annual average indoor temperature of the Conventional House was 17.7°C based on the monitoring data. During the traditional heating season (January to April and November to December in a year), the average indoor temperature of the period was only 16.1°C. And the average indoor temperature during non-heating season for the Conventional House was 19.7°C summarised from the monitoring data. The lowest monthly indoor temperature dropped down to 15°C appeared in February and the hottest monthly indoor temperature reached 22.1°C in August. It can be seem from the recorded data that the indoor temperature of the Conventional House fluctuated along with the outdoor weather condition. The indoor temperature difference between the hottest and coldest month reached 7.1°C. In general, the winter indoor temperature of the property was at the bottom line of acceptable winter heating indoor temperature range (16°C to 24°C). However, it didn't meet the requirement of 18°C, which is the minimum temperature for comfort in the UK standard. The indoor temperature performance of this Conventional House was poor.

For the Passive House, the annual average indoor temperature was 21.9°C according to the recorded data. The average indoor temperature during the traditional heating season was 21.1°C summarised from the monitoring data while the average indoor temperature of this Passive House during the non-heating season maintained at 22.7°C. The lowest monthly indoor temperature was 20.3°C appeared in November due to a lower winter heating set-point temperature was set by those new residents. Although the hottest monthly indoor temperature reached 23.3°C appeared in September, the summer indoor temperature (from June to September) of this Passive House were almost the same that maintained at around 23°C. It can be seen from the monitoring data that the difference of indoor temperature for this Passive House during a year was very small. The maximum indoor temperature between the highest and lowest month did not exceed 3°C. The winter indoor temperature of the property met the Passive House standard and it was also within the comfortable temperature range (18°C to 21°C) in the UK standard. From the view of energy saving, the new house residents reduced the MVHR's heating set-point temperature from 22°C to 20°C cut down the space heating demand of the Passive House in winter but still received very comfortable indoor temperature. The indoor temperature performance of this Passive House was outstanding.

6.3.2 *Relative humidity*

The annual average indoor relative humidity of this Conventional House was 64.2% based on the monitoring data. During the traditional heating season (January to April and November to December in a year), the average indoor relative humidity of the period reached 66.0%. And the average indoor relative humidity during non-heating season for the Conventional House was 62.5% summarised from the monitoring data. The lowest monthly indoor relative humidity dropped down to 57.4% in August and the highest monthly indoor relative humidity increased to 73.5% in November. It can be seem from the recorded data that the indoor relative humidity of the Conventional House also fluctuated along with the outdoor weather condition. The biggest difference for monthly indoor relative humidity was 16.1%. However, the indoor relative humidity of the property was out of the comfortable indoor humidity range (30% to 60%) [250,252]. High humidity in the house can cause damage to the structure, for instance, condensation on windows, wet stains on ceilings and walls and mouldy bathroom. And these phenomenon are what actually happened in the Conventional House. Overall, the indoor relative humidity performance of this Conventional House was very poor.

For the Passive House, the annual average indoor relative humidity was 45.5% according to the recorded data. The average indoor relative humidity during the traditional heating season was 40.3% summarised from the monitoring data while the average indoor relative humidity of this Passive House during the non-heating season maintained at 50.8%. The lowest monthly indoor relative humidity was 35.9% appeared in February while the highest monthly indoor relative humidity reached 56.1% in September. The relative high summer indoor relative humidity was due to long windows opened time to increase natural ventilation for this property. It can be seem from the monitoring data that the difference of indoor maximum and minimum relative humidity for this Passive House during a year was 20.2%. Even though this value was not low due to the impact of different seasons, the house indoor relative humidity was within the comfortable range in the UK standard, especially in the coldest winter heating period. Thus, the indoor relative humidity performance of this Passive House was fabulous.

6.3.3 *CO_2 concentration*

The indoor CO_2 concentration recording work of the Conventional House was only conducted in one of the four bedrooms for nearly two months due to the lack of sensors during the period of monitoring. The average indoor CO_2 concentration of the Bedroom 3 in the winter heating season reached as high as 1798 ppm summarised from the monitoring data. This is an extremely high value as the maximum comfort and safe level of indoor CO_2 concentration required in the standard was 1000-1200 ppm [253,254]. Indoor CO_2 concentration over 1000 ppm is not recommended because it may cause health and safety issues. Hence, for this Conventional House, its indoor CO_2 concentration performance was unqualified.

Compared to the Conventional House, the indoor CO_2 concentration of the Master Bedroom in the Passive House was superb. The 588 ppm represented the room's average indoor CO_2 concentration during the whole winter heating season. For the entire property, according to the recorded data, the annual average indoor CO_2 concentration was only 556 ppm, which was a high level for domestic indoor air quality. The average indoor CO_2 concentration during the traditional heating season (572 ppm) didn't differ greatly from the non-heating season's level (539 ppm). The lowest monthly indoor CO_2 concentration was 478 ppm appeared in June while the highest monthly indoor CO_2 concentration reached 698 ppm in December. The relative high December indoor CO_2 concentration was due to the increased numbers of family members during the Christmas holiday period. In spite of the highest monthly indoor CO_2 concentration was close to 700 ppm, the house indoor CO_2 concentration performance was still excellent because they were all within the best indoor air quality level of 800 ppm. As the outdoor CO_2 levels are usually 350 - 450 ppm, the 556 ppm indoor CO_2 concentration of this Passive House shows its possibility to get good indoor air quality.

	Comfort level	Conventional House	Passive House
Temperature	-	17.7°C	21.9°C
	16°C - 24°C (winter heating season)	16.1°C	21.1°C
Humidity	30% - 50%	64.2%	45.5%
CO_2 concentration	<1000 ppm	1798 ppm (Bedroom 3)	556 ppm

Table 6.2 Indoor environmental condition performance comparison between the Conventional House and the Passive House.

The indoor environmental performance of this two different types of properties has been summarised in Table 6.2. All the data used in this comparison were the realistic recoded data collected during the monitoring periods.

6.4 Conventional House retrofitting methods

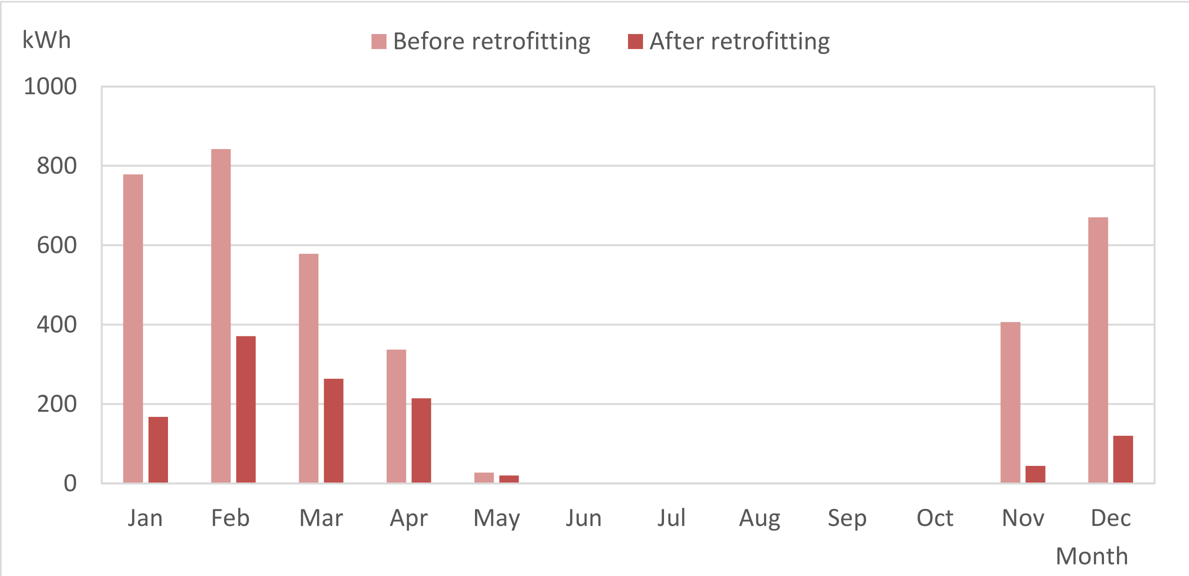
6.4.1 *Building fabrics*

Super insulated building envelope could prevent internal heat loss from the property, especially during the coldest winter heating season. It helps reduce the primary energy demand and space heating demand of the whole property and receive very comfortable indoor environmental condition at the same time. In order to improve the building performance of those traditional residential households, one of the methodologies is to conduct building fabrics retrofitting by using advanced construction materials. Through the investigation and studies conducted before, it can be known that Passive House is a good example to achieve both goals. Applying the advanced building materials and components of the Passive House to the Conventional House shows the superiority in reducing energy consumption and the improvement of indoor environmental condition.

Figure 6.2 Building façade of the Conventional House applied the Passive House building materials.

Figure 6.2 indicates the new external façade of the Conventional House simulated by the DesignBuilder software. Original double glazing windows were replaced by high quality triple glazing windows. Advanced insulation was added to the walls, roofs and slabs. The materials used for the retrofitting works were referred from the Passive House. After the entire building fabrics retrofitting, the simulation results generated by DesignBuilder indicate that the annual electricity and gas consumption of the Conventional House were 2457.21 kWh and 7909.23 kWh, respectively. Hence, the total simulated energy consumption was 10366.44 kWh and the primary energy demand of the dwelling was reduced to 115.18 kWh/(m^2a). In addition, the annual indoor temperature increases to 19.4°C based on the estimated results. Because all the settings of lighting, heating, domestic hot water and ventilation of the property were remained the same as before, the change of building fabrics only affected its performance of keeping the whole house warm. This reflected in the gas consumption for space heating dropped down to 1202.56 kWh and the indoor temperature during the traditional winter heating season rose up to 18.5°C according to the simulation.

The comparison of monthly gas consumption for heating and indoor temperature before and after the building fabrics retrofitting were shown in Figure 6.3. It can be seen from the results that the annual gas consumption for heating after the building fabrics retrofitting could be reduced 67% compared to its current status. And the average indoor temperature in winter increased to 18.5°C, which is enhanced nearly 3°C and is more comfortable than the 15.6°C before retrofitting.



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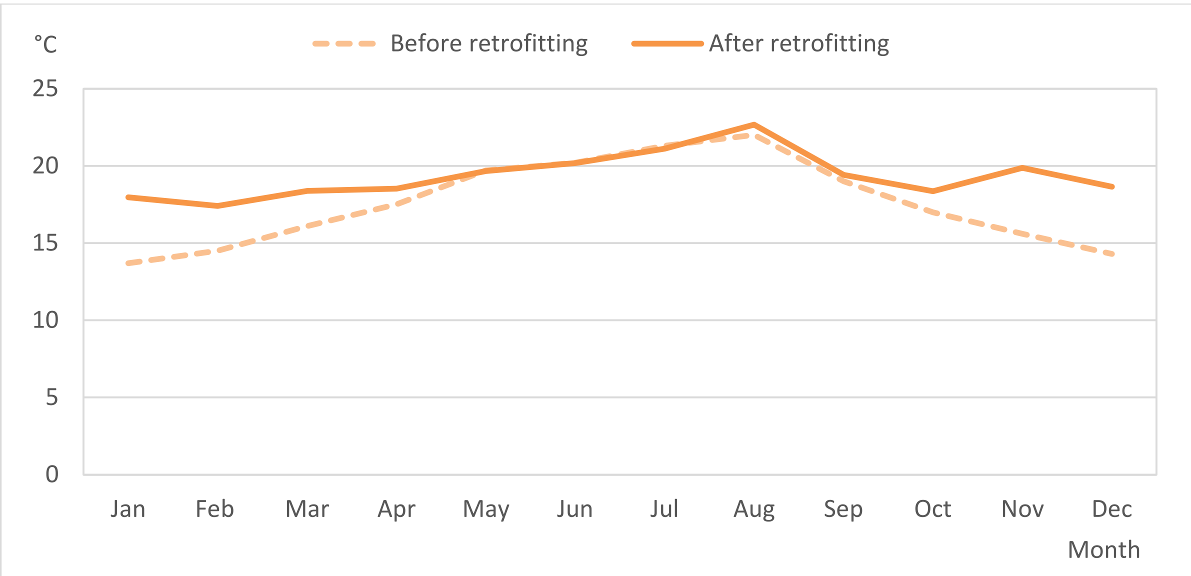


(b)

Figure 6.3 The comparison of Conventional House performance before and after the building fabrics retrofitting: (a) monthly gas consumption for heating, (b) monthly indoor temperature.

In order to keep the indoor temperature of the Conventional House during winter heating season at around 20°C to meet the Passive House standard, the estimated annual gas consumption would be 11442.1 kWh. The gas consumption increases about 10.6% compares to the actual usage but the winter indoor temperature of the Conventional House reaches

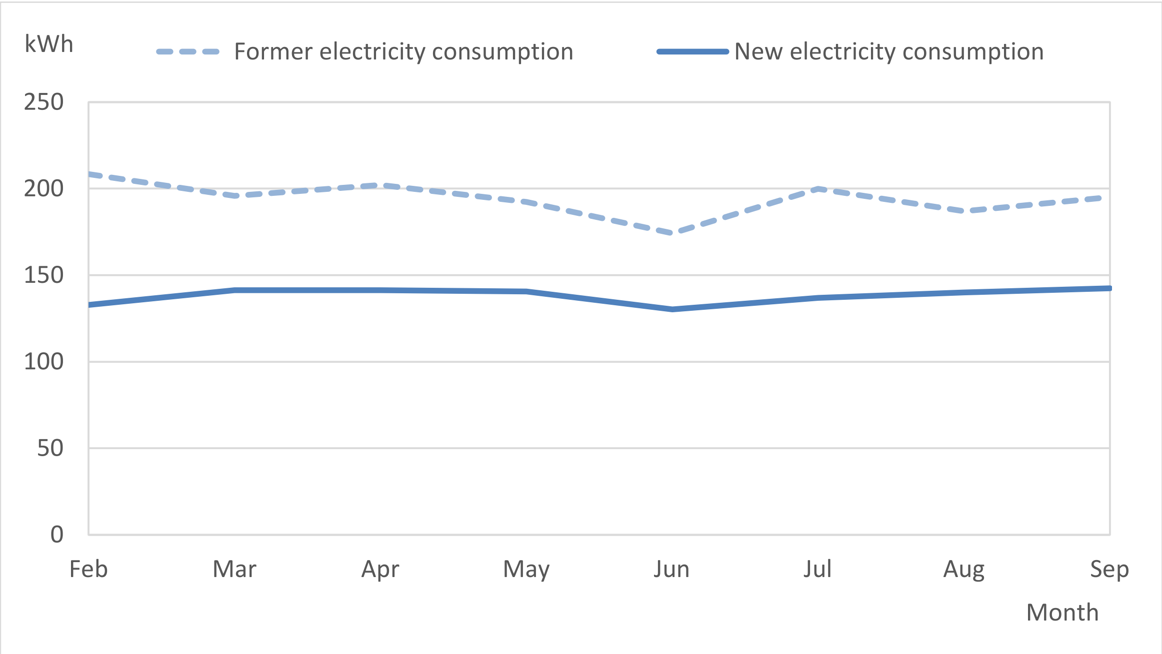
20.1°C based on the simulation results. The 4°C increased indoor temperature significantly improved the thermal comfort of the Conventional House. For the heating gas consumption, 4735.42 kWh is consumed to remain at the Passive House standard indoor temperature and the space heating demand is 52.62 kWh/(m^2a). The building fabrics retrofitting indicates the possibility to increase indoor thermal comfort of the Conventional House. However, the energy efficiency of the old boiler and the ventilation style need to be improved at the same time to maximum the advantages of traditional Conventional House retrofitting using different passive methods.

6.4.2 *Energy efficiency improvement*

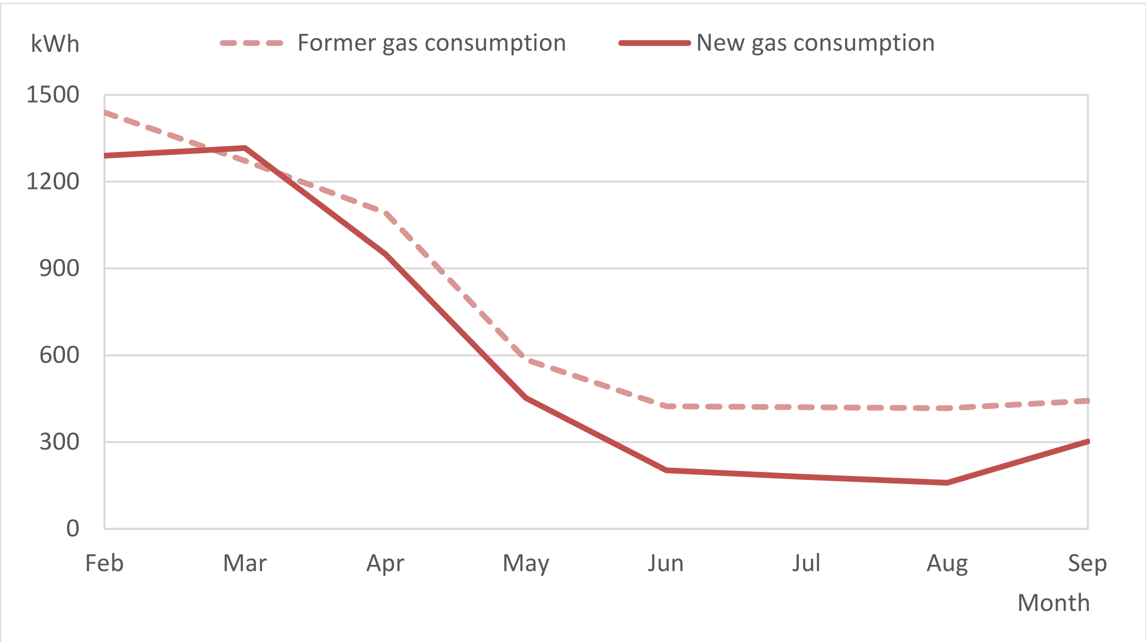
The old style gas boiler in the Conventional House was replaced at the end of 2016 by a new condensing combi gas boiler with 89.6% energy efficiency in order to reduce the whole house energy consumption (shown in Figure 6.4). After the replacement of the old gas boiler, the building performance (including electricity and gas consumption and indoor temperature) of the Conventional House has been improved obviously according to the monitored data.

Figure 6.4 The new condensing gas boiler installed in the Conventional House.

The measured energy consumption used in this study started from February to September 2017, the monthly average electricity consumption during this period decreased to 138.20 kWh compared to previous 194.33 kWh usage. Those eight month's gas consumption was only 4850.58 kWh, which was approximately 21.1% lower than the 6149.50 kWh former gas consumption during the same months. The indoor temperature data from January to June of this year is complete and available to use in this study as some data lost since July due to technical problem. The first six months average indoor temperature after the gas boiler replacement enhanced to 18.3°C, which was 1.3°C increased compared to the former house indoor temperature. The monthly electricity consumption, gas consumption and indoor temperature comparison of this Conventional House before and after the boiler replacement are shown in Figure 6.5.



(a)



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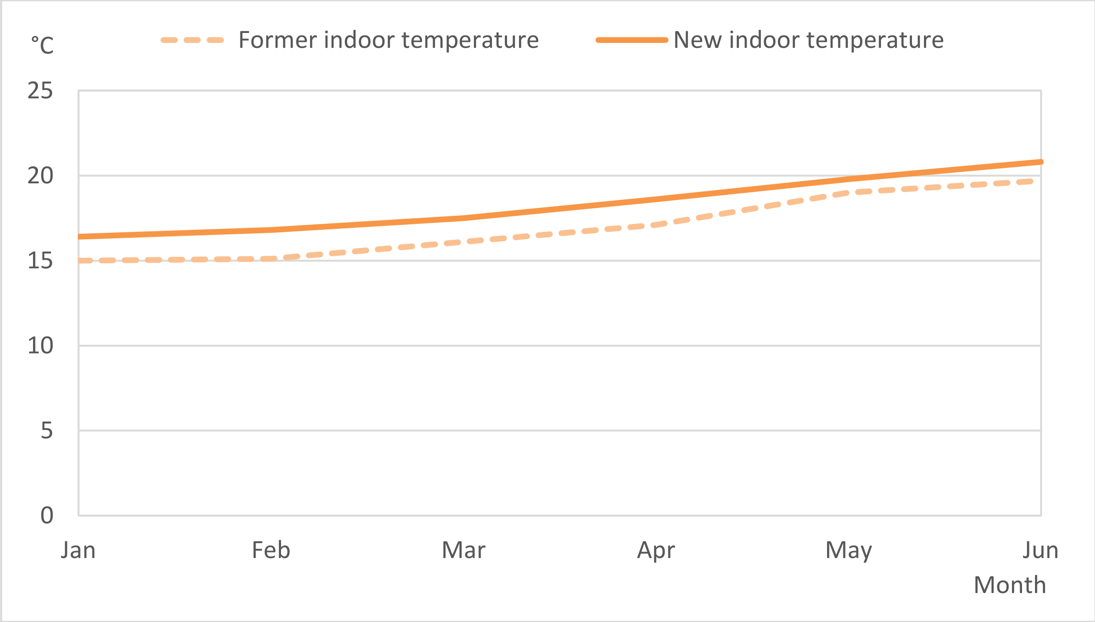


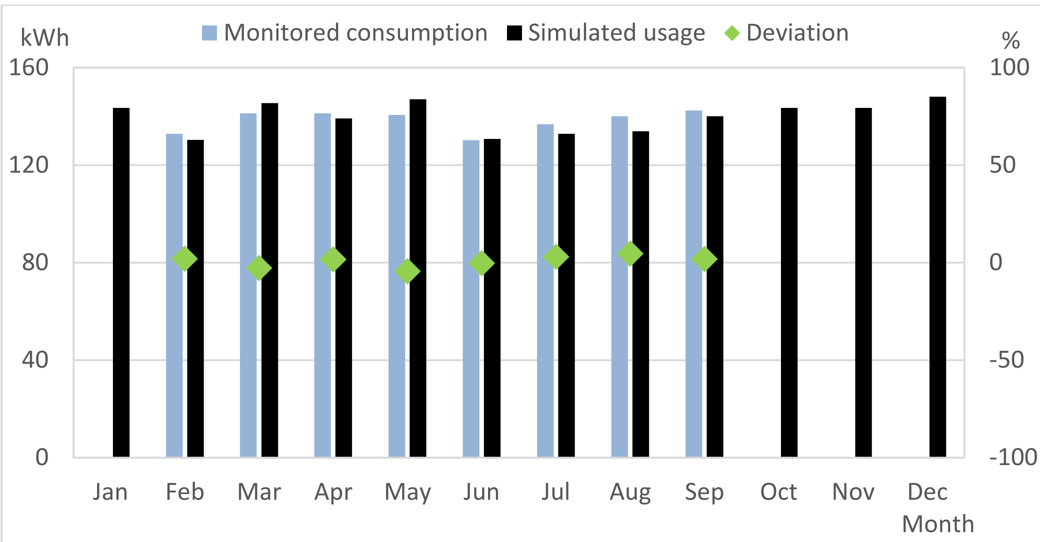
(c)

Figure 6.5 Monthly house performance comparison before and after the boiler replacement: (a) electricity consumption, (b) gas consumption, (c) indoor temperature.

It can be seen from Figure 6.5 that the house performance has been improved as the indoor temperature of this Conventional House increased to a relative comfortable level with lower energy demand during the monitoring period. The new energy efficiency boiler not only saves the gas consumption but also electricity consumption. This is because the gas boiler is driven by electricity when it works. Thus, in this monitoring period, the Conventional House consumed less electricity and gas and received relative higher indoor temperature as the result of the boiler replacement.

According to the situation of boiler replacement, a new DesignBuilder model was set up to predict the building performance of this Conventional House. The estimated results shows the annual electricity and gas consumption of the Conventional House are 1678.08 kWh and 9090.69 kWh, respectively. Hence, the total simulated energy consumption is 10768.77 kWh and the primary energy demand is 119.65 kWh/(m^2a). Among them, the gas consumption for space heating and domestic hot water are decreased to 5431.81 kWh and 3093.72 kWh, respectively. Thus, the space heating demand has been cut down to 60.35 kWh/(m^2a), which is much closer to the regulation. Moreover, the average annual indoor temperature could achieve 18.9°C in prediction, and the average monthly indoor temperature during the heating season is 17.3°C, which are both 1.2°C improvement compared to the realistic status.

The comparison of monthly monitored house performance and simulated results and their percentage errors are shown in Figure 6.6. The total energy consumption error between actual measurement and simulation was 1.50% according to Equation (1) and (2), which was within the acceptable range. The CV(RMSE) was calculated as 4.19% (maximum value is 15%) and the MBE was -1.50% (within the ±5% requirement) according to Equation (3) and (4). For electricity consumption, it is clear from the figure that the deviations between monitored and simulated results were very small and within the acceptable range. The CV(RMSE) was calculated as 2.91% and the MBE was 0.54%. The biggest deviation between actual measured and simulated usage appeared in May of -4.55% while the smallest error was only -0.50% of June. For gas consumption, the CV(RMSE) and MBE were 5.52% and -1.97%, respectively. The biggest deviation between realistic monitored and estimated consumption appeared in August of -20.28%.



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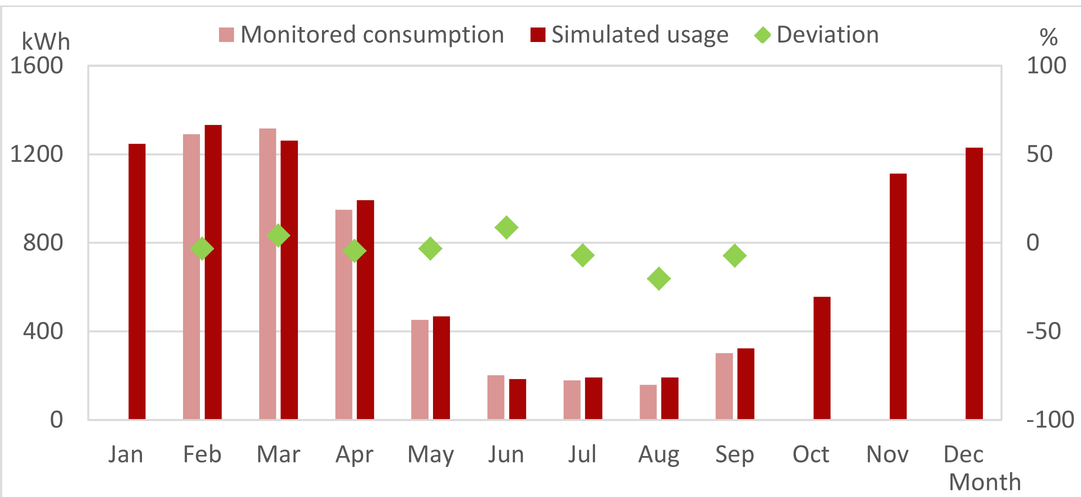

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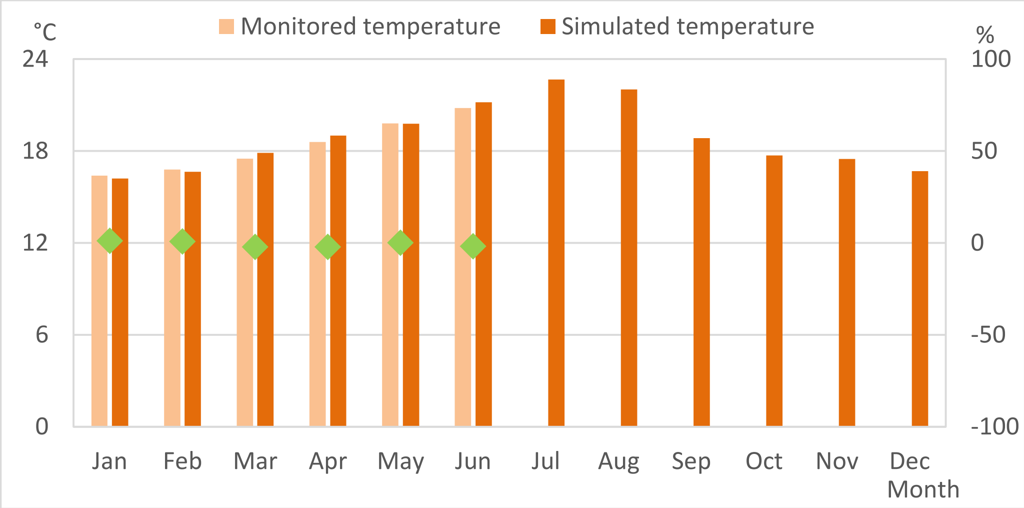


(c)

Figure 6.6 Comparison of monthly monitored house performance and simulated results: (a) electricity consumption, (b) gas consumption, (c) indoor temperature.

The reason for the abnormal values of the error was because the change of house occupancy. Relative hot summer led to reduced domestic hot water and cooking demand during the month. The smallest errors appeared in February and May of -3.30%. Under normal house operation, the simulated gas consumption was almost the same compared to the actual measured usage no matter in the heating season or non-heating season. From the view of this point, the model was still very accurate. The indoor temperature error between actual measurement and simulation only 0.73% according to those equations. The CV(RMSE) was calculated as 1.60% and the MBE was -0.73%, which were within the acceptable range. The range of errors for the house indoor temperature was within ±3%.

In general, the comparison results above between actual and estimated house performance of this Conventional House after boiler replacement show the high accurate of the DesignBuilder model. Although the energy consumption used in the calibration was only eight months data in a year, and the indoor temperature data was for the first six months in 2017, the energy and thermal performance of this Conventional House still represented the house performance in a year. In general, this simulation model has been validated by using actual measured energy consumption and indoor temperature and it can be used for further analysis.

In order to maintain the house temperature at 20.0°C, to meet the indoor temperature requires in the Passive House standard, more gas is consumed in the Convention House as the winter space heating demand is increasing. The simulation results generated by DesignBuilder model indicate that the annual electricity and gas consumption of the property were 1678.08 kWh and 13039.22 kWh, respectively. Hence, the total annual simulated energy consumption was 14717.30 kWh and the primary energy demand was 163.53 kWh/(m^2a). The house indoor temperature during the heating season reaches 19.6°C with 9380.34 kWh gas consumption for heating. Thus, the space heating demand of this Conventional House is 104.23 kWh/(m^2a), which is still very high compared to the Passive House standard. The monthly house performance under this circumstance is shown in Figure 6.7.

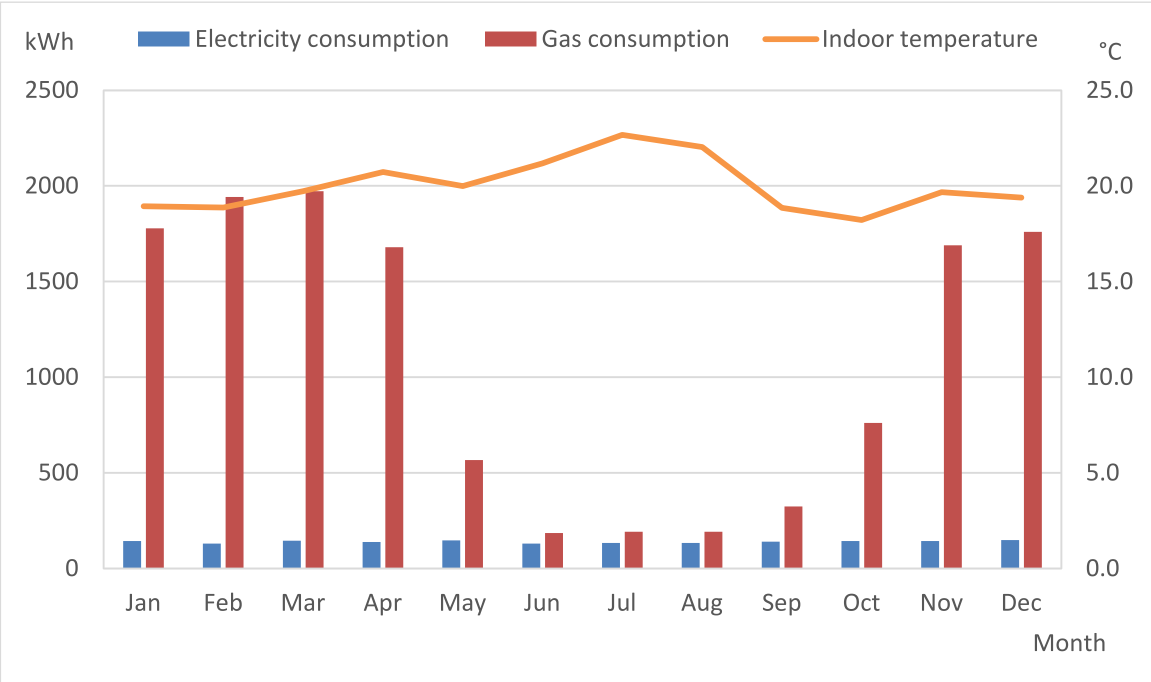
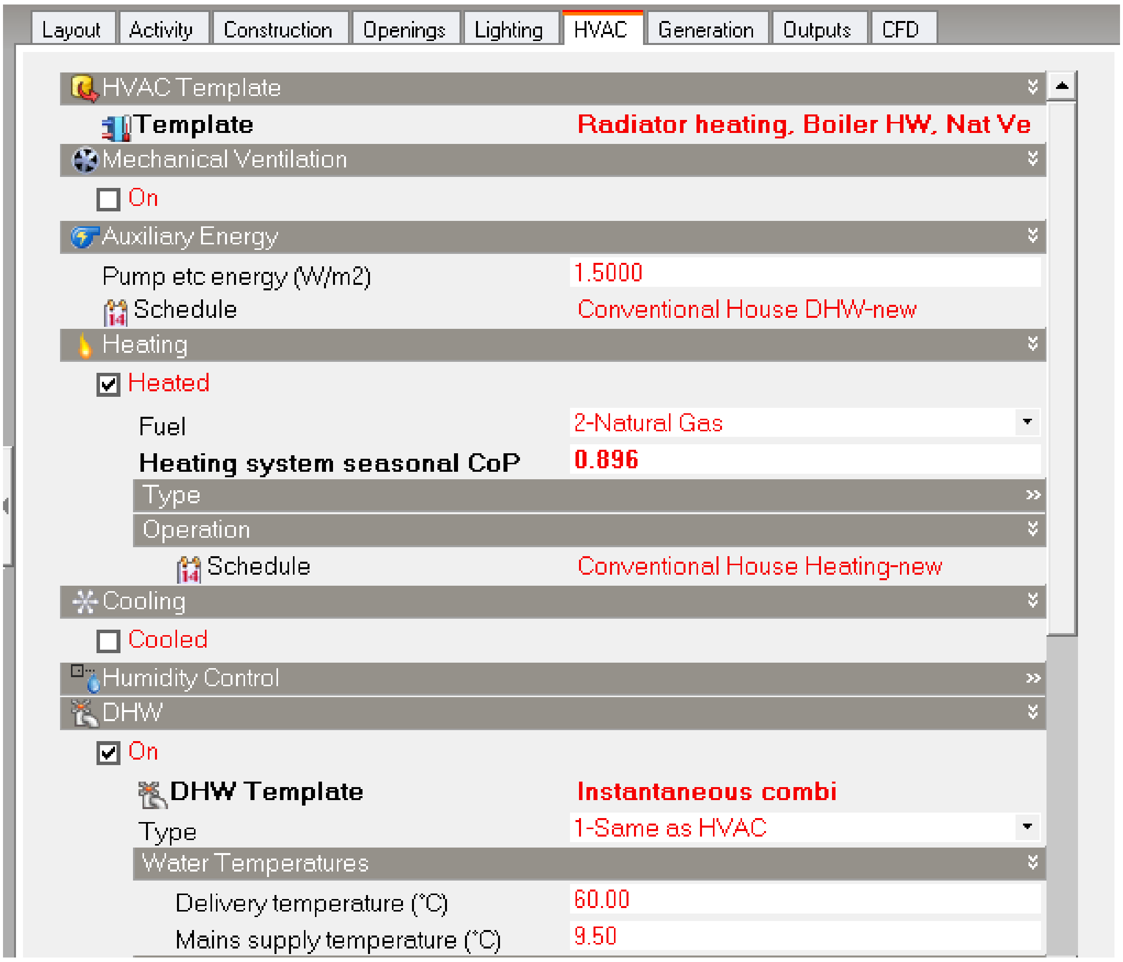


Figure 6.7 Simulated monthly house performance of the Conventional House with new boiler.

Because the low energy efficiency old gas boiler has been replaced by the new condensing boiler, although the primary energy demand and space heating demand are much higher than the Passive House standard. However, compared to previous house performance, the annual indoor temperature of the Conventional House is able to achieve 20°C under occupancy. It indicates the possibility to enhance Conventional House's performance by improving the energy efficiency of the heating system. Therefore, combine the building fabrics retrofitting and boiler replacement together is necessary to see the integrated effects of the Conventional House performance.

Figure 6.8 indicates the new settings in the DesignBuilder model for the Conventional House retrofitting combined the methods of building fabrics and boiler efficiency improvement. The simulation results generated by the software indicate that the annual electricity and gas consumption of the Conventional House were 2381.73 kWh and 6362.43 kWh, respectively. Hence, the total simulated energy consumption was 8744.16 kWh and the primary energy demand was only 97.16 kWh/(m^2a). In addition, the gas consumption for heating reduces to 2703.55 kWh according to the estimated results. The 30.04 kWh/(m^2a) space heating demand could provide the house with 20.5°C annual average indoor temperature, which is now approaching the Passive House standard. In this case, the primary energy demand and indoor temperature meet the requirements of Passive House standard after the integrated retrofitting. How to reduce the space heating demand further by other retrofitting methods is the key to convert the Conventional House to the low energy property.

(a)



(b)

Figure 6.8 Integrated DesignBuilder settings for the Conventional House retrofitting: (a) building fabrics, (b) boiler replacement.

6.4.3 *Ventilation system*

The difference between the Passive House and the integrated retrofitting Conventional House now is the type of ventilation. The Conventional House uses traditional natural ventilation for the entire property while the Mechanical Ventilation with Heat Recovery (MVHR) system is utilized in the advanced Passive House. Heat recovery is a process of preheating the cool incoming air by the relative warm exhaust air continuously. As the warm air is not directly exhausted to the outdoor atmosphere, a large portion of energy is saved to heat the cool incoming supply air. A MVHR system provides a solution to supply fresh air to all usable living space in a building with minimum heat lost. This Heat Recovery Ventilation helps retain approximately 90% heat and reduce the energy demand for a building. It also provides continuous fresh air and keeps the indoor environmental condition at a very comfortable level. In order to further reduce the space heating demand of the retrofitted Conventional House, the

Mechanical Ventilation with Heat Recovery system is considered to replace the typical natural ventilation utilised in the property.

The mechanical ventilation mode of the Passive House was applied to the retrofitted Conventional House DesignBuilder model. The simulation results generated by the software indicate that the annual electricity and gas consumption of the Conventional House were 4554.49 kWh and 4097.96 kWh, respectively. The reason for increased electricity consumption was due to the application of the mechanical ventilation. Hence, the total simulated energy consumption was 8652.45 kWh and the primary energy demand reduced to only 94.16 kWh/(m^2a). However, without natural ventilation, although the indoor temperature during winter heating season was very comfortable and could achieve 20.5°C average value, it faced a serious summer heating problem based on the estimated results.

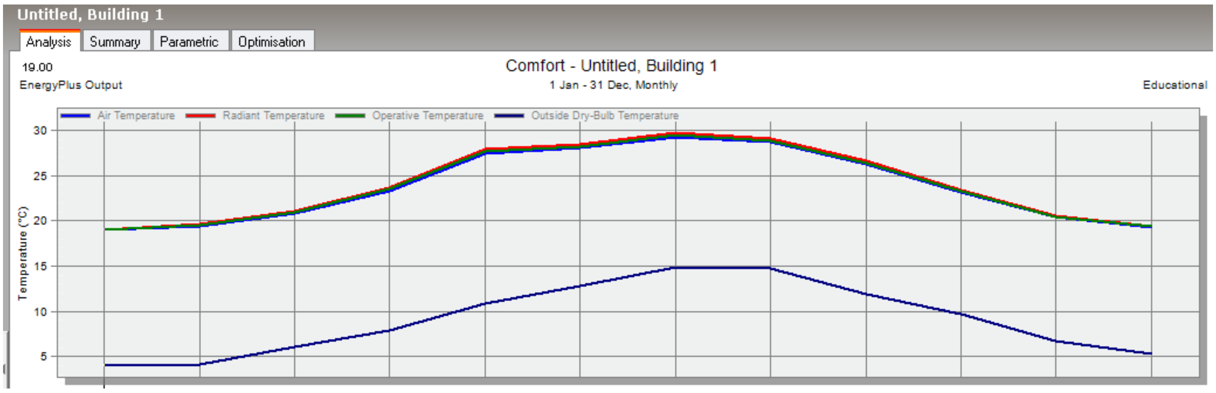


Figure 6.9 Indoor temperature prediction of the Conventional House model retrofitted with building fabrics, gas boiler and MVHR system.

Figure 6.9 indicates the indoor temperature prediction generated by the DesignBuilder model for the Conventional House retrofitting combined with the methods of building fabrics utilization, boiler efficiency improvement and MVHR system application. It can be seen from the figure that the highest indoor temperature under simulation could exceed 29°C in July. The high efficiency mechanical ventilation with heat recovery system stores too much heat and cannot exchange the relatively hot indoor air to outdoor in time. The property fully relies on the mechanical ventilation leads to the significant overheating occurs during summer time.

The DesignBuilder model shows the application of mechanical ventilation with heat recovery system help reduce the gas consumption of the retrofitted Conventional House. The key of the retrofitting is to lower the summer indoor temperature of the entire property. The easiest way to achieve this goal is to apply natural ventilation to the house during summer time. It assists the heat release from indoor to outdoor in those hottest months in a year and also maintains the excellent winter house performance.

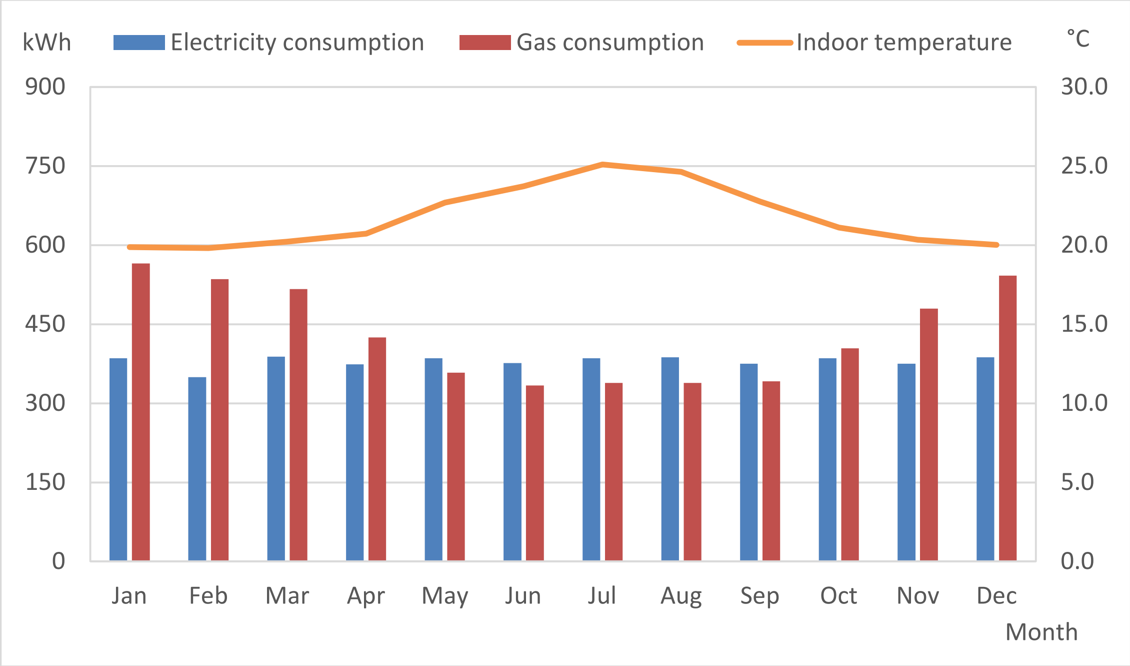


Figure 6.10 Simulated monthly house performance of the Conventional House with combined ventilation.

The simulation results generated by DesignBuilder model indicate that the annual electricity and gas consumption of the property were 4554.49 kWh and 5178.77 kWh, respectively. Hence, the total annual simulated energy consumption was 9733.26 kWh and the primary energy demand was 108.15 kWh/(m^2a). The house indoor temperature during the heating season reaches 20.2°C with only 1189.30 kWh heating gas consumption. Thus, the space heating demand of this Conventional House is just 13.21 kWh/(m^2a), which is within the range of Passive House standard. The monthly house performance under this circumstance is shown in Figure 6.10. The simulation results indicate the possibility to retrofit traditional Conventional House under the Passive House standard by different methods and it could achieve remarkable building performance.

6.4.4 *Solar PV utilisation*

As this Conventional House could be retrofitted to a low energy building that meets all the requirements restricted in the Passive House standard, the performance of its primary energy demand, space heating demand and indoor thermal comfort are exceptional in prediction. Thus, the solar PV utilisation is not mandatory to reduce the energy demand for this property.

However, the solar PV panel can be installed on this Conventional House to cut down its net electricity consumption, accordingly further reduce its net primary energy demand.

Based on the investigation study of the Passive House, same capacity but half amount of those installed solar PV panels is considered to this Conventional House. This is because the building area of the Passive House is more than double size of this Conventional House. Also, enough roof space is guaranteed for this amount of solar PV panel. In assumption, 2162.53 kWh solar PV electricity is generated and 85% of the total generation (1838.15 kWh) is used by the house according to the monitoring data gathered in the Passive House case study. In this study, all the 1838.15 kWh electricity is assumed to supply household appliances. Hence, the net electricity consumption decreases to 2716.34 kWh. It means the onsite solar PV generation could satisfy with most of the electricity demand of the mechanical ventilation with heat recovery system. Overall, the net primary energy demand can be cut down to 87.72 kWh/(m^2a), 19% lower than the previous 108.15 kWh/(m^2a) primary energy demand.

	Case 1	Case 2	Case 3	Case 4	Case 5
Primary energy demand (kWh/(m^2a))	142.28	154.44	97.16	108.15	87.72 (net)
Electricity demand (kWh/(m^2a))	27.30	27.30	26.46	50.61	30.18 (net)
Space heating demand (kWh/(m^2a))	40.47	52.62	30.04	13.21	13.21
Average indoor temperature (°C)	17.7	20.1	20.5	21.8	21.8

Table 6.3 Building performance comparison of the Conventional House under different retrofitting strategies.

The building energy and thermal performance of the Conventional House under different retrofitting strategies were compared with its original status in Table 6.3. Case 1 shows the original performance without any retrofitting methods; Case 2 shows the performance with building fabrics retrofitting; Case 3 shows the performance with building fabrics retrofitting and boiler energy efficiency improvement; Case 4 shows the performance combines building fabrics retrofitting, boiler energy efficiency improvement and mixed ventilation system; Case 5 shows the performance with all three listed methods and solar PV utilisation. All the data used in this comparison were the simulation results generated by the validated DesignBuilder models. From the simulation results, we can know that the Case 5 achieves the best house performance under different retrofitting strategies. As a typical size property in the UK, the retrofitting strategies of Case 4 satisfies with all demands restricted in the standard. After retrofitting, the Conventional House could also achieve comfortable indoor temperature with small energy demand in assumption. The need of solar PV utilisation is not mandatory in this study from the view of capital cost saving.

6.5 Demote Passive House to Conventional House level

To verify the Conventional House retrofitting methods from a reverse view, the building fabrics and operation schedules of the Passive House have been changed to the Conventional House level in the simulation. In the assumption, the energy consumption of the property should increase at least several times compared to its original low energy consuming performance. In addition, the average indoor temperature would decrease to an uncomfortable level.

Figure 6.11 Building façade of the Passive House applied the Conventional House building materials.

Figure 6.11 indicates the new external façades of the Passive House simulated using the DesignBuilder software. After the entire building fabrics retrofitting, the simulation results generated by DesignBuilder model indicate that the annual electricity and gas consumption of the Passive House are 6040.13 kWh and 25807.24 kWh, respectively. Hence, the total energy consumption is 31847.37 kWh and the primary energy demand of the dwelling grows to 144.11 kWh/(m^2a). In addition, the annual indoor temperature reduced to only 15.6°C based on the estimated results. Because all the settings of lighting, heating, domestic hot water and ventilation of the property are different from the original status of the Conventional House, both electricity and gas consumption and indoor thermal comfort level are effected by the changes.

	Conventional House	Demoted Passive House
Primary energy demand (kWh/(m^2a))	142.28	144.11
Electricity demand (kWh/(m^2a))	27.30	27.33
Gas demand (kWh/(m^2a))	114.98	116.78
Average indoor temperature (°C)	17.7	15.6

Table 6.4 Building performance comparison between the original Conventional House and the demoted Passive House.

The Building performance comparison between the original Conventional House and the demoted Passive House is shown in Table 6.4. The errors of energy demand between the two models are all within 1.5%, but the difference of average indoor temperature is 2.1°C. In this simulation, with similar energy consumption, the two properties receive different indoor environmental condition. The demoted Passive House is even colder than the non-retrofitted Conventional House. For indoor temperature, the acceptable deviation range is ±1°C for this two house. However, the average temperature of the demoted Passive House exceeds the error range and received a more uncomfortable indoor thermal condition according to the simulated results. There are two main reasons for this issues: firstly, this Passive House has 47 openings in total, once the advanced building materials are replaced by those traditional construction materials, its performance of heat preservation and airtightness is predicted to be worse than its original performance; secondly, the old gas boiler with extremely low energy efficiency is unable to provide effective heating demand and domestic hot water demand in this relative large residential property. Considering these two factors, the average indoor temperature of the demoted Passive House is relative lower and its building performance is not satisfied even compared with the non-retrofitted Conventional House.

However, this study still represents the possibility and accuracy of those retrofitting methods recommended in this research from the reverse view. No matter to retrofit the Conventional House to Passive House standard, or demote the Passive House to Conventional House level, the estimated basic building performance of energy and indoor environmental condition can be validated by the actual monitoring data. The building performance of these four different type of houses are summarised in Table 6.5.

	Primary energy demand ($kWh/(m^2a)$)	Average indoor temperature (°C)
Conventional House (CH)	142.28	17.7
Demoted Passive House (DPH)	144.11	15.6
Passive House (PH)	85.15	21.9
Retrofitted Conventional House (RCH)	108.15	21.8

Table 6.5 Building performance comparison of four different type of houses.

It can be seen from the table that, for the Conventional House and the Demoted Passive House, with similar primary energy demand, the Conventional House receives better indoor thermal comfort level. Building size, number of openings of the DPH lead to worse building airtightness. Thus, the difference of 2.1°C average indoor temperature is predicted between these two normal standard residential buildings in simulation. For the Passive House and the Retrofitted Conventional House, they achieve satisfied indoor temperature with relatively less primary energy demands compared to the other two types of houses. Moreover, the Passive House consumed only 80% energy of the RPH and its primary energy demand is also within the 120 $kWh/(m^2a)$ Passive House limitation. From the studies conducted before, it can be known that the gas demand of the RPH is lower than the Passive House, but its electricity demand is greater. Because the biggest electricity consumer in the RPH is MVHR system, and the electricity consumption for the two ventilation systems with similar settings are almost the same, the smaller Conventional House achieves larger electricity and primary energy demand as its building size is only 40% compared to the Passive House.

According to Table 6.5, the building performance comparison of the four different types of houses can also been shown in Figure 6.12. In this figure, the top left corner indicates the best building performance can be achieved with low energy consumption and warm indoor temperature. The bottom right corner represents the worst building performance with high energy consumption but cold indoor temperature. It is clear that if we use the Passive House standard as a benchmark, the performance of Passive House and Retrofitted Conventional House are outstanding while the performance of Conventional House and Demoted Passive House are disappointing. Based on this figure, the building performance of these four different types of houses sort from the best to the worst is: Passive House, Retrofitted Conventional House, Conventional House and Demoted Passive House. It also indicates the possibility to conduct retrofitting to improve the Conventional House performance.

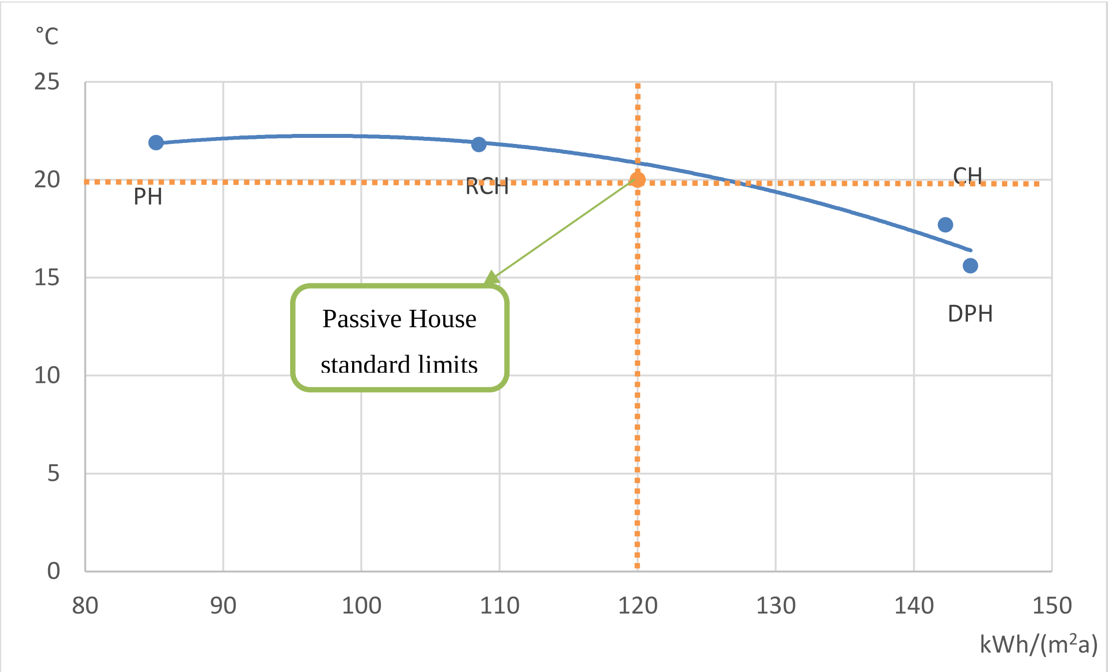


Figure 6.12 Building performance comparison of four different types of houses.

6.6 Net primary energy demand analysis

The reasonable utilisation of the onsite solar PV panels could reduce the net primary energy demand of the entire property. For the case of Passive House, from the monitoring data, it is known that the electricity of the 6 kW solar PV array was 4325.06 kWh in a year. The annual realistic usage of electricity and gas consumption were 7199.57 kWh and 12259.09 kWh, respectively. The total energy consumption could be calculated as 19458.66 kWh and the primary energy demand for this house was 88.85 kWh/(m^2a). According to national statistics data, the annual total energy consumed in domestic hot water was assumed as 6279 kWh and the space heating demand of this dwelling was 27.31 kWh/(m^2a).

In realistic, its utilisation rate was 85% and the rest 15% solar PV electricity generation was feeding back to the main grid because there is no energy storage system to store the extra electricity. Among them, about 45% of the annual solar PV electricity generation was supplied to the household appliances preferentially, and 40% of the total generated solar PV electricity was provided to the thermal store for the purpose of space heating and domestic hot water. This means, the annual electricity and gas consumption were saved 26.6% and 14.2% as the result of solar PV utilisation. Hence, the net primary energy demand, electricity demand and gas demand of the Passive House were 72.16 kWh/(m^2a), 24.12 kWh/(m^2a) and 48.05 kWh/(m^2a), respectively. In addition, according to national statistics data and actual measured data, the net space heating demand reduced to 23.44 kWh/(m^2a).

In assumption, energy storage system exists and all solar PV generation is fully utilised by the property. According to the actual energy consumption proportion, 53% of the generated solar PV electricity is used to supply the household appliances while the rest 47% generation is consumed by the thermal store as gas replacement. Thus, the net primary energy demand, electricity demand, gas demand and space heating demand of this Passive House were reduce to 69.10 kWh/(m^2a), 22.41 kWh/(m^2a), 46.70 kWh/(m^2a) and 22.78 kWh/(m^2a), respectively.

However, if all the solar PV generation is fully utilised as electricity or gas consumption, the net energy usage will be changed along with the schedules. Supposing the 4325.06 kWh solar PV generation is used as electricity purpose, 60% main grid electricity consumption is saved and the net electricity demand decreases to only 13.13 kWh/(m^2a). The net primary energy demand is also 69.10 kWh/(m^2a) and no net gas demand achieves under this situation. In case the 4325.06 kWh solar PV generation is used as gas purpose, 35% gas consumption is saved and the net gas demand reduces to only 36.23 kWh/(m^2a). In addition, space heating demand is calculated to 17.67 kWh/(m^2a). With same 69.10 kWh/(m^2a) net primary energy demand, no net electricity demand achieves under this situation.

From the analysis above, it is known that approximately 22% net primary energy demand of this Passive House can be saved by the fully utilisation of solar PV generation. If all solar PV generation is used as electricity purpose, 60% main grid electricity consumption is saved. If all solar PV generation is used as gas purpose, 35% gas consumption is saved. In order to become a net zero energy building, the capacity of current solar PV array has to be scaled up 4.5 times and generate 19462.77 kWh electricity to cover all energy demands of this Passive House. A 6 kW solar PV panel requires approximately 42 square meters of free roof space, for this Passive House, there is no enough roof space to install all the 189 m^2 solar PV panel because the total roof space of this property is about 145 m^2 according to the building floor plans. Thus, it is not possible to become a net zero energy building only rely on the solar PV utilisation.

But if the capacity of current solar PV array can be scaled up 2 times, all the generated energy (8650.12 kWh) is used as electricity purpose in priority, and then the rest generation is used as gas purpose, this Passive House could turn into a net zero electricity building and its net primary energy demand (this also means its net gas demand) is reduced to 49.35 kWh/(m^2a). Suppose the extra 1450.55 kWh solar PV generation is used for the space heating, the net space heating demand under this circumstance is 24.08 kWh/(m^2a). On the contrary, all the generated energy is used as space heating purpose in priority, the net gas demand (this also means its net domestic hot water demand) of this property reduces to only 16.48 kWh/(m^2a).

On the other hand, if the capacity of current solar PV array can be scaled up 3 times, all the generated energy (12975.18 kWh) is used as gas purpose in priority, and then the rest generation is used as electricity purpose, this Passive House could turn into a net zero gas building and its net primary energy demand (this also means its net electricity demand) is reduced to 29.60 kWh/(m^2a). On the contrary, all the generated energy is used as electricity and space heating purpose in priority, this Passive House could turn into a net zero electricity building and most of the space heating demand of this house can also be covered by the energy provided by the solar PV system. Under this circumstance, the 29.60 kWh/(m^2a) energy demand is for the domestic hot water demand.

6.7 Economics analysis

The retrofitting of the Conventional House presented in this analysis aim to reduce energy consumption and improve energy performance of the dwelling. The economic analysis associated with the above mentioned measures were assumed in terms of Simple Payback Time (SPBT) and Net Present Value (NPV) [295]:

$$\mathrm{SPBT} = \frac{\mathrm{I_0}}{\mathrm{S}} \tag{5}$$

$$\mathrm{NPV} = -\mathrm{I_0} + \sum_{\mathrm{n}=1}^{\mathrm{LS}} \frac{\mathrm{S_n} - \mathrm{C_n}}{(1+\mathrm{r})^{\mathrm{n}}} \tag{6}$$

$$S_n = S(1+i)^n \quad (7)$$

Where: I_0 is the initial investment cost of the project, S is the energy saving evaluated at year 0, S_n is the energy saving for year n, C_n is the maintenance cost for year n, n is the time period, LS is the lifespan, r is the discount rate of investment, i is the yearly increment of the cost of energy.

The operating costs were assumed according to the UK market and scenario by estimating the unit cost of electricity equal to 0.14 £/kWh and the unit cost of natural gas equal to 0.038 £/kWh[234-238]. The following information has been assumed in the analysis: cost for replacement windows: £6000, cost for installing insulation: £2000, cost for installing the heat recovery system: £7000. Thus, the total investment for retrofitting is £15000. The annual cost for energy saving is £650. Therefore, the SPBT for this Conventional House is 23 years.

NPV is calculated with consideration of an investment rate of 2% and different increments of the cost of energy (2%, 4% or 6%). In this economic analysis, we considered a lifespan of 30 years for windows and insulation, and of 15 years for the heat recovery system. In addition, the replacement of the heat recovery and other extraordinary maintenance works after 15 years is considered. In the evaluation of NPV, the maintenance cost of the heat recovery system (£500 per year, revaluated at 2% of inflation) was taken into account. On the contrary, no maintenance cost is assumed for window retrofitting. The NPVs under i=2%, i=4% and i=6% are £4475, £5150 and £5852, respectively.

This economic analysis shows the payback period for Conventional House retrofitting is not as long as the expectation. With £15000 investment at the very beginning could be get back in 23 years and the house thermal comfort during these years is fabulous compared to those traditional Conventional Houses. This is a valuable investment for both economics and high quality indoor environmental condition.

6.8 Summary

The comparison of the building performance between the Conventional House and the Passive House was conducted in this chapter. The Conventional House retrofitting methods has been validated through DesignBuilder models by using calibrated simulation results and measured data. Also, from the reverse view, demotes the Passive House standard to normal

Conventional House level, this study still represents the possibility and accuracy of those retrofitting methods recommended in this research. If we use the Passive House standard as a benchmark, the performance of Passive House and Retrofitted Conventional House are outstanding while the performance of Conventional House and Demoted Passive House are disappointing. Thus, the building performance of these four different types of houses sort from the best to the worst is: Passive House, Retrofitted Conventional House, Conventional House and Demoted Passive House. It also indicates the possibility to conduct retrofitting to improve the Conventional House performance.

Solar PV utilisation makes the net energy demand of the Passive House reduce to satisfied level. If all solar PV generation can be stored and used reasonably, with appropriate system size scale up, the Passive House could be a net zero electricity or gas building based on the calculation. If the capacity of current solar PV array can be scaled up 2 times, this Passive House could turn into a net zero electricity building and its net primary energy demand is reduced to 49.35 kWh/(m^2a). If the capacity of current solar PV array can be scaled up 3 times, this Passive House could turn into a net zero gas building and its net primary energy demand is reduced to 29.60 kWh/(m^2a). With appropriate renewable energy utilisation, the property could become a net zero energy building. A further specify analysis of renewable energy utilisation to make a building to be energy automatic will be conducted in the future.

Overall, this comparison study indicates the energy performance and indoor environment condition of the Passive House and retrofitted Conventional House are outstanding. The building performance of the Conventional House has been proved to improve significantly with building fabrics retrofitting, utilities energy efficiency improvement and ventilation optimisation in this study. Based on the analysis in this study, it shows the feasibility for traditional Conventional House to achieve better indoor environmental condition with relative low energy consumption using passive energy retrofitting methods.

Chapter 7. Conclusion and future work

This thesis presents a comprehensive study on the improvements of household energy performance and indoor environmental condition in a heating dominated country using retrofitting and passive energy saving methods. It aims to find out possible and feasible solutions for Conventional House retrofitting, overcome the summer overheating problem for Passive House, and then provide recommendations for feasible building performance improvement methods. The computational models were validated by actual monitored data and then they were used to conduct further study on retrofitting.

This study aimed to answer the following five main questions to achieve the goal:

- What are the energy and thermal patterns of a traditional detached Conventional House in the UK?
- What are the energy and thermal patterns of a super-insulated detached Passive House in the UK?
- What are the suitable solutions for buildings in cold countries or regions to reduce the heating demand?
- What is the possible and feasible retrofitting method to achieve Passive House standard for the UK Conventional Houses?
- What is the possible and feasible solution to reduce overheating risk for UK Passive Houses?

All the answers to the questions stated above have been discovered in this thesis. The findings are concluded in Section 7.1 and the recommendations for future work are summarised in Section 7.2.

7.1 Conclusions

The case study of a Conventional House was investigated in Chapter 4, by undertaking field audits, measurement of house structure, measurements and data collection of actual energy consumption and indoor environment, analysis of house performance, building modelling and validation, and simulation of building performance after retrofitting. The realistic annual energy consumption for this Conventional House was 13142.64 kWh and the primary energy demand was 146.03 kWh/(m^2a). With 40.47 kWh/(m^2a) space heating demand in winter, the house indoor temperature could be remained at only 16.1°C. In addition, the average indoor temperature of this house was also lower than the requirement, the house performance was unsatisfied and it also represented a typical residential property of UK existing dwelling built in 1970s.

The building fabrics of this Conventional House was improved to Passive House standard in the modelling simulation. The results of simulation work indicated the space heating demand could be reduced by 77.7% to 9.03 kWh/(m^2a) to keep the house at the same indoor temperature during the heating season. As the recommended indoor temperature of 20°C during the heating season was set in the compound retrofitting model, the estimated results indicated the primary energy demand and the space heating demand of the house were 93.04 kWh/(m^2a) and 25.34 kWh/(m^2a), respectively. From the simulation results, it is known that the energy performance and indoor environmental condition of this Conventional House can be improved to a high energy-saving dwelling by using the passive retrofitting methods. The results from this case study indicates the advantages and benefits of building retrofitting by using passive energy methods in achieving lower energy consumption, which resulted in low carbon dioxide emissions and good thermal comfort. It can provide a better quality environment for living in this type of Conventional House.

The case study of a Passive House was investigated in Chapter 5, by undertaking field audits, measurements and data collection of the actual energy consumption and indoor environment of the house, analysis of the house performance, building modelling and validation, and finding solutions to reduce summer overheating problem of the property. The actual annual energy consumption for this Passive House was 19458.66 kWh and the primary energy demand was 88.85 kWh/(m^2a). With 55.98 kWh/(m^2a) space heating demand in winter, the house indoor temperature could be remained at 21.9°C. The 45.5% average indoor relative humidity and the 529 ppm average indoor CO_2 concentration during the whole monitoring year presented excellent building performance of this dwelling. It is also found that the relative higher indoor temperature set by the house occupants led to more space heating demand and heat gains and increased the risk of summer overheating.

Detail analysis and modelling for this Passive House to solve its overheating problem was conducted in the model simulation. The results of simulation work indicated that by reducing MVHR set-point temperature and adding window blinds, 18.9% energy savings for space heating can be implemented and over 200 discomfort (overheating) hours in summer could be eliminated. The results from this case study indicates the advantages of Passive House in achieving high thermal comfort, low energy consumption and low carbon emissions. When the summer overheating problem is solved, this type of super-insulated Passive House can provide us a future building development direction that balances the annual energy consumption (space heating demand) and summer discomfort hours in the dwelling.

A comparison of the building performance between Conventional House and Passive House was conducted in Chapter 6. Based on the findings, retrofitting method to achieve low energy building was developed. In countries or regions with cold climate, particularly in the Europe, the Passive House standard is widely used to build super high energy efficiency building. The key of the Passive House concept is to minimise the energy demand of HVAC and heat loss through its super-insulated building fabrics. Using the principle of Passive House, it is found that the most insulated building envelops applied in the UK can reduce the reliance to the space heating system. A passive retrofitting method was investigated to reduce energy demand for the UK Conventional House. On the other hand, Passive House with super insulation and advanced building materials and components may cause overheating problem in the summer as the internal heat gains can't be removed from the dwelling in time and results in uncomfortable indoor temperature. But in the winter, it still needs to warm the whole dwelling efficiently and reduce heat loss. This usually requires a high energy efficiency heating system and a mechanical ventilation system to achieve the target.

The passive retrofitting methods to improve the performance of the Conventional House has been validated through DesignBuilder models by using calibrated simulation results and measured data. Also, from the reverse view, if the building envelop and materials of the Passive House are demoted to normal Conventional House level, its performance is reduced significantly to a very poor level in the prediction of validated DesignBuilder models. The building performance of these four different types of houses sort from the best to the worst is: Passive House, Retrofitted Conventional House, Conventional House and Demoted Passive House. According to the simulation results generated by DesignBuilder, the annual energy consumption for this Conventional House can be reduced to 9733.26 kWh and the primary energy demand was 108.15 kWh/(m^{2}a). With only 13.21 kWh/(m^{2}a) space heating demand in winter, the house indoor temperature could be remained at 20.2°C.

Solar PV utilisation provides a portion of energy to the Passive House and it makes the net energy demand of the dwelling from the national grid supplies (electricity and natural gas) reduce to satisfied level. If all generated power by solar PV can be stored in a storage unit and used reasonably, with appropriate system size being scaled up, the Passive House could be a net zero electricity or gas building. If the capacity of current solar PV array can be scaled up 2 times, this Passive House could turn into a net zero electricity building and its net primary energy demand is reduced to 49.35 kWh/(m^2a). If the capacity of current solar PV array can be scaled up 3 times, this Passive House could turn into a net zero gas building and its net primary energy demand is reduced to 29.60 kWh/(m^2a). With appropriate renewable energy utilisation, the property could become a net zero energy building.

7.2 Recommendations for future work

In this study, some limitations exist and the recommendations for future work can be summarised as follows:

- Firstly, the selection of sensors utilised in the research need to be improved. Due to the reason of research budget, several different types of monitoring sensors were used during the whole study. This cause an aditional and necessary sensor calibration steps before the whole minitoring work. The data collection of those sensors supplied by main power interrupted by house network or electricity switch-off problem and lost data until the problem fixed. Whereas most of the batteries-supplied sensors faced the problem of batteries dead and they stopped working before changing baterries in time. These impacts increased the risk of data lost and using unreliable data in the whole process of the study. Based on the actual performance of different types of sensors, Tinytag Plus 2 TGP-4500 waterproof temperature and relative humidity data logger are recommended for future monitoring work because of its advantages of high accuracy, long batteries life, and low cost.

- Secondly, the actual energy consumed in space heating were unknown for both case studies houses. Due to complex technical problems, the gas consumption can’t be differentiated to detailed usages for heating and domestic hot water. Moreover, the real time gas consumption for the Conventional House was not able to monitored because the gas meter was an old design and not suitable for gas flow measuring and recording. For future work, smart meters are highly suggested to instal in target buildings to collect dynamic energy conusumption. It helps understand accurate electricity and gas usages and provides detailed information of heating demand of the dwelling. Thus, more precise prediction, particularly for heating demamd can be made in the future studies.

- Thirdly, there is a need to conduct further investigation on building fabrics, thermal mass, insulation, ventilation pattern and shading for existing building retrofitting and to harmonise the outcomes of these explorations and find out the best building energy and indoor environmental performance. This is very important from the views of increasing the standards of building fabrics and insulation to minimise winter heating demand and the primary energy demand, and improving the levels of thermal mass and shading to reduce summer indoor overheating risk.

- Fourthly, an exploration on how residents occupy the dwelling can be carried out in the future. Better understanding of occupants' behavious and internal heat gains helps develop the methods to mitigate summer indoor discomfort hours for those properties with overheating trend.

- Finally, this study focus on the building performance and corresponding retrofitting methods of domestic dwellings in a heating dominated country, with relative cold climate. In future work, both domestic buildings and non-domestic buildings need to be considered to use the methodologies to improve their performance. Moreover, renewable energy technologies, batteries for electricity storage, low heat-loss thermal storage, air conditioning and control system can be further investigated to make the method adapt to all buildings even in cooling dominated countries with hot climate.

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Appendix

Appendix A: Selected hourly monitored room temperature in the Conventional House.

Time	BR 1	BR 3	LR	K	DR	BR 2	BR 4	C	$T_{outdoor}$
01/02/2016 00:00:00	15.82	15.84	16.56	16.88	15.1	17.2	15.6	16.6	9.2
01/02/2016 01:00:00	15.57	15.6	16.02	16.52	14.8	16.9	15.3	16.3	10.8
01/02/2016 02:00:00	15.42	15.4	15.6	16.17	14.5	16.7	15.2	16.0	11.5
01/02/2016 03:00:00	15.25	15.23	15.26	15.84	14.3	16.6	15.0	15.7	11.5
01/02/2016 04:00:00	15.21	15.11	14.99	15.57	14.2	16.4	14.9	15.5	11.0
01/02/2016 05:00:00	15.35	15.03	14.73	15.32	14.0	16.3	14.7	15.3	10.6
01/02/2016 06:00:00	15.46	15.18	15.08	15.18	14.4	16.5	14.9	15.1	11.1
01/02/2016 07:00:00	17.19	16.54	17.5	15.84	17.1	18.2	16.9	15.9	10.3
01/02/2016 08:00:00	17.33	16.89	17.76	16.63	17.0	18.2	17.1	16.8	10.3
01/02/2016 09:00:00	16.9	16.77	17.13	16.77	16.1	18.0	17.4	16.9	11.3
01/02/2016 10:00:00	16.62	16.49	16.38	16.76	15.7	17.8	17.3	17.0	12.0
01/02/2016 11:00:00	16.29	16.21	15.88	16.6	15.4	17.3	17.0	16.8	11.7
01/02/2016 12:00:00	16.01	15.95	15.53	16.52	15.2	16.9	16.6	16.5	10.3
01/02/2016 13:00:00	15.82	15.74	15.32	16.25	15.0	16.7	16.2	16.3	10.5
01/02/2016 14:00:00	15.83	15.75	15.29	15.89	14.8	16.4	16.0	16.1	10.3
01/02/2016 15:00:00	15.82	15.72	15.21	15.62	14.6	16.1	15.8	16.0	9.3
01/02/2016 16:00:00	15.48	15.45	14.89	15.4	14.4	15.9	15.5	15.7	7.9
01/02/2016 17:00:00	15.18	15.16	14.72	15.57	14.3	15.6	15.6	15.5	8.2
01/02/2016 18:00:00	15.53	15.4	15.3	16.42	15.4	16.2	15.9	15.6	8.1
01/02/2016 19:00:00	17.23	16.77	17.45	17.33	17.5	17.8	17.4	16.7	7.3
01/02/2016 20:00:00	18.23	17.54	18.85	17.83	18.4	18.7	18.3	17.6	5.9
01/02/2016 21:00:00	17.73	17.22	17.92	17.89	17.4	18.6	17.7	17.5	6.4
01/02/2016 22:00:00	16.98	16.91	17	17.65	16.5	18.5	17.1	17.2	5.9
01/02/2016 23:00:00	16.44	16.67	16.29	17.23	15.9	18.2	16.7	16.8	6.3
02/02/2016 00:00:00	16.03	16.31	15.76	16.75	15.4	17.8	16.3	16.4	6.4
02/02/2016 01:00:00	15.69	15.94	15.31	16.25	15.1	17.4	16.0	16.0	6.2
02/02/2016 02:00:00	15.39	15.66	14.94	15.79	14.8	17.1	15.6	15.5	6.3
02/02/2016 03:00:00	15.32	15.4	14.6	15.38	14.5	16.7	15.3	15.2	6.4
02/02/2016 04:00:00	15.02	15.14	14.32	15	14.3	16.5	15.0	14.9	6.1
02/02/2016 05:00:00	14.68	14.9	14.07	14.68	14.1	16.3	14.7	14.5	6.0
02/02/2016 06:00:00	14.76	14.73	14.38	14.42	14.2	16.3	14.7	14.3	6.1
02/02/2016 07:00:00	16.44	15.19	16.82	14.99	16.3	17.7	16.4	14.9	5.4
02/02/2016 08:00:00	16.41	15.4	16.7	15.89	16.5	17.8	16.6	15.6	5.2
02/02/2016 09:00:00	15.71	15.34	15.63	16.03	15.6	17.6	16.1	15.5	5.6
02/02/2016 10:00:00	15.3	15.02	14.93	16.53	15.3	17.2	15.7	15.7	5.9
02/02/2016 11:00:00	14.98	14.75	14.4	16.88	15.4	16.8	15.5	15.5	6.6
02/02/2016 12:00:00	14.78	14.55	14.07	16.69	15.4	16.4	15.4	15.4	6.6
02/02/2016 13:00:00	14.58	14.39	13.9	16.01	14.9	16.1	15.1	15.2	7.0
02/02/2016 14:00:00	14.59	14.37	14.06	15.46	14.4	15.7	14.9	15.0	7.7
02/02/2016 15:00:00	14.59	14.38	14.02	15.02	14.1	15.4	14.7	14.8	7.2
02/02/2016 16:00:00	14.31	14.15	13.79	14.68	13.8	15.0	14.5	14.6	6.0
02/02/2016 17:00:00	13.93	13.87	13.51	14.57	13.6	14.7	14.2	14.3	5.1
02/02/2016 18:00:00	14.32	13.81	14.5	15.42	14.6	15.0	14.6	14.3	4.5
02/02/2016 19:00:00	16.07	14.67	17.32	16.65	16.8	16.5	16.2	15.3	3.6

02/02/2016 20:00:00	17.12	15.43	18.14	17.41	17.9	17.7	17.1	16.2	2.9
02/02/2016 21:00:00	16.51	15.32	16.92	17.27	16.8	17.7	16.7	16.0	2.5
02/02/2016 22:00:00	15.73	14.98	15.92	16.9	15.7	17.4	15.9	15.7	2.6
02/02/2016 23:00:00	15.15	14.74	15.09	16.46	15.0	16.8	15.4	15.4	2.5
03/02/2016 00:00:00	14.69	14.57	14.56	15.92	14.5	16.4	15.0	15.2	2.9
03/02/2016 01:00:00	14.32	14.27	14.16	15.39	14.1	16.0	14.7	14.8	2.6
03/02/2016 02:00:00	14.1	13.98	13.82	14.91	13.8	15.7	14.4	14.4	2.4
03/02/2016 03:00:00	13.99	13.72	13.52	14.49	13.6	15.4	14.0	14.0	2.7
03/02/2016 04:00:00	13.56	13.48	13.24	14.13	13.3	15.2	13.7	13.7	2.9
03/02/2016 05:00:00	13.26	13.23	13.01	13.82	13.1	14.9	13.5	13.4	2.4
03/02/2016 06:00:00	13.38	13.26	13.31	13.63	13.3	15.0	13.5	13.2	2.2
03/02/2016 07:00:00	15.25	14.63	15.82	14.29	15.8	16.6	15.1	14.1	1.9
03/02/2016 08:00:00	15.3	14.88	16.22	15.07	15.8	16.6	15.4	14.8	2.1
03/02/2016 09:00:00	14.63	14.65	15.58	15.05	14.7	16.6	15.1	14.8	2.7
03/02/2016 10:00:00	14.23	14.27	15.12	15.05	14.3	16.8	14.9	14.8	3.9
03/02/2016 11:00:00	14.13	14.01	14.77	15.08	14.0	16.5	14.7	15.0	5.3
03/02/2016 12:00:00	13.98	13.84	14.25	14.93	13.8	16.0	14.5	14.9	6.0
03/02/2016 13:00:00	13.86	13.72	13.92	14.77	13.6	15.6	14.3	14.7	6.2
03/02/2016 14:00:00	13.84	13.72	13.88	14.41	13.3	15.2	14.2	14.5	6.1
03/02/2016 15:00:00	13.82	13.67	13.83	14.08	13.0	14.8	14.1	14.3	5.5
03/02/2016 16:00:00	13.55	13.47	13.54	13.76	12.8	14.5	13.8	14.1	4.4
03/02/2016 17:00:00	13.27	13.23	13.32	13.57	12.6	14.2	13.7	13.8	4.1
03/02/2016 18:00:00	13.82	13.61	14.4	14.68	13.7	14.7	14.2	14.1	3.8
03/02/2016 19:00:00	15.74	15.15	17.2	15.98	16.3	16.5	15.9	15.2	3.3
03/02/2016 20:00:00	16.8	16.06	18.38	16.77	17.3	17.8	16.8	16.2	2.4
03/02/2016 21:00:00	16.27	15.82	17.22	16.5	16.0	17.7	16.2	16.2	2.2
03/02/2016 22:00:00	15.59	15.34	16	16.13	14.9	17.4	15.6	15.8	3.8
03/02/2016 23:00:00	15.04	14.98	15.17	15.8	14.3	17.1	15.2	15.5	4.4
04/02/2016 00:00:00	14.69	14.85	14.59	15.41	13.9	16.6	14.9	15.4	4.7
04/02/2016 01:00:00	14.68	14.65	14.17	14.96	13.5	16.2	14.6	15.1	4.3
04/02/2016 02:00:00	14.43	14.43	13.84	14.57	13.2	15.9	14.4	14.8	4.0
04/02/2016 03:00:00	14.17	14.23	13.58	14.23	13.0	15.7	14.2	14.5	3.8
04/02/2016 04:00:00	13.89	14.06	13.34	13.85	12.8	15.4	13.9	14.2	3.9
04/02/2016 05:00:00	13.73	13.9	13.14	13.62	12.6	15.2	13.7	14.0	4.2
04/02/2016 06:00:00	14	14.03	13.53	13.41	13.0	15.3	13.8	13.8	5.3
04/02/2016 07:00:00	15.88	15.38	16.23	14.07	15.8	17.0	15.6	14.7	5.9
04/02/2016 08:00:00	16.02	15.71	16.38	15.33	15.8	17.1	15.9	15.6	5.8
04/02/2016 09:00:00	15.48	15.51	15.38	15.72	14.7	16.7	15.5	15.5	6.4
04/02/2016 10:00:00	15.13	15.31	14.67	15.7	14.4	16.6	15.3	15.7	7.9
04/02/2016 11:00:00	14.97	15.02	14.26	15.86	14.2	16.5	15.1	15.7	8.8
04/02/2016 12:00:00	14.82	14.85	14.03	19.1	16.4	16.3	14.9	15.6	9.5
04/02/2016 13:00:00	14.72	14.7	13.89	17.91	15.4	16.0	14.9	15.4	9.6
04/02/2016 14:00:00	14.54	14.56	13.74	16.67	14.6	15.7	14.9	15.2	9.3
04/02/2016 15:00:00	14.35	14.38	13.53	15.92	14.1	15.4	14.7	15.0	8.6
04/02/2016 16:00:00	14.17	14.23	13.38	15.83	14.0	15.1	14.5	14.8	8.3
04/02/2016 17:00:00	14.01	14.04	13.47	16.27	14.3	14.9	14.4	14.6	8.2
04/02/2016 18:00:00	14.68	14.51	14.64	16.85	14.9	15.4	15.0	14.8	8.3
04/02/2016 19:00:00	16.67	16.18	17.6	18.28	17.4	17.1	16.9	16.1	8.7
04/02/2016 20:00:00	17.74	17.22	18.84	18.74	18.2	18.4	17.9	17.2	9.0
04/02/2016 21:00:00	17.22	16.93	17.72	18.94	17.3	18.5	17.5	17.1	8.8
04/02/2016 22:00:00	16.77	16.68	16.7	18.85	16.6	18.2	17.0	17.0	8.9

04/02/2016 23:00:00	16.39	16.69	15.99	18.27	15.8	17.9	16.7	16.9	8.8
05/02/2016 00:00:00	16.13	16.52	15.5	17.68	15.4	17.6	16.4	16.9	8.5
05/02/2016 01:00:00	15.92	16.28	15.07	17.18	15.0	17.3	16.2	16.6	8.4
05/02/2016 02:00:00	15.74	16.07	14.78	16.75	14.7	17.1	16.0	16.3	9.1
05/02/2016 03:00:00	15.54	15.86	14.55	16.38	14.5	17.0	15.8	16.1	9.1
05/02/2016 04:00:00	15.42	15.73	14.32	16.04	14.3	16.8	15.7	15.8	8.8
05/02/2016 05:00:00	15.54	15.62	14.15	15.76	14.2	16.6	15.5	15.6	9.0
05/02/2016 06:00:00	15.74	15.72	14.56	15.58	14.5	16.7	15.6	15.5	8.9
05/02/2016 07:00:00	17.46	17.13	17.11	16.05	16.8	18.4	17.3	16.2	8.8
05/02/2016 08:00:00	17.49	17.42	17.21	17.05	17.0	18.5	17.6	17.1	8.8
05/02/2016 09:00:00	16.99	17.23	16.29	17.28	16.2	17.9	17.1	17.1	9.0
05/02/2016 10:00:00	16.58	16.79	15.66	16.89	15.6	17.4	16.7	16.9	9.1
05/02/2016 11:00:00	16.23	16.42	15.23	16.09	14.9	17.0	16.5	16.6	9.7
05/02/2016 12:00:00	15.89	16.1	14.87	15.6	14.5	16.7	16.2	16.3	10.3
05/02/2016 13:00:00	15.68	15.83	14.63	15.08	14.1	16.4	16.0	16.1	10.7
05/02/2016 14:00:00	15.51	15.65	14.46	15.11	14.1	16.2	15.8	15.9	10.6
05/02/2016 15:00:00	15.38	15.49	14.36	15.03	14.1	16.0	15.6	15.7	10.2
05/02/2016 16:00:00	15.19	15.29	14.18	14.83	14.0	15.7	15.5	15.5	9.9
05/02/2016 17:00:00	14.95	15.07	14.02	15.13	14.0	15.5	15.3	15.3	9.1
05/02/2016 18:00:00	15.48	15.41	15.1	15.85	15.2	16.0	15.7	15.4	8.9
05/02/2016 19:00:00	17.36	16.86	17.63	16.76	17.5	17.5	17.4	16.6	9.1
05/02/2016 20:00:00	18.39	17.7	18.67	17.73	18.6	18.5	18.4	17.6	7.6
05/02/2016 21:00:00	17.95	17.47	17.65	17.9	17.4	18.4	18.1	17.7	5.7
05/02/2016 22:00:00	17.33	17.12	16.75	17.81	16.5	18.1	17.5	17.4	4.9
05/02/2016 23:00:00	16.83	16.92	16.17	17.38	15.9	17.7	17.0	17.2	4.7
06/02/2016 00:00:00	16.43	16.97	15.63	16.88	15.4	17.5	16.7	17.3	3.7
06/02/2016 01:00:00	16.11	16.65	15.23	16.4	15.0	17.2	16.4	16.9	3.0
06/02/2016 02:00:00	15.82	16.32	14.88	15.96	14.6	16.9	16.1	16.5	3.0
06/02/2016 03:00:00	15.58	16.03	14.61	15.57	14.3	16.7	15.8	16.1	2.8
06/02/2016 04:00:00	15.52	15.79	14.37	15.23	14.1	16.4	15.5	15.7	2.7
06/02/2016 05:00:00	15.24	15.57	14.11	14.91	13.9	16.2	15.1	15.3	3.2
06/02/2016 06:00:00	15.26	15.57	14.47	14.64	14.0	16.2	15.0	15.1	3.3
06/02/2016 07:00:00	16.97	16.77	16.93	14.91	16.2	17.9	16.5	15.7	3.5
06/02/2016 08:00:00	16.99	17	17.09	15.5	16.5	17.9	16.7	16.5	3.5
06/02/2016 09:00:00	16.35	16.63	16.28	15.78	15.6	17.2	16.3	16.4	3.8
06/02/2016 10:00:00	15.93	16.26	15.79	15.67	14.9	16.8	16.0	16.2	4.2
06/02/2016 11:00:00	15.54	16.03	15.57	15.38	14.4	16.5	15.6	16.0	4.8
06/02/2016 12:00:00	16.13	16.36	16.72	15.41	15.3	16.9	16.0	16.1	5.2
06/02/2016 13:00:00	16.98	17.04	17.88	16.18	16.8	17.7	16.9	16.8	5.6
06/02/2016 14:00:00	16.61	16.73	17.02	16.23	16.0	17.4	16.4	16.7	6.4
06/02/2016 15:00:00	16.15	16.32	16.28	16.04	15.3	17.0	16.0	16.5	6.6
06/02/2016 16:00:00	15.76	15.97	15.73	15.77	14.7	16.7	15.7	16.2	6.7
06/02/2016 17:00:00	15.44	15.67	15.45	15.84	14.5	16.4	15.5	15.9	6.5
06/02/2016 18:00:00	15.94	15.94	16.31	16.04	15.4	16.8	15.9	16.0	6.9
06/02/2016 19:00:00	17.73	17.33	18.53	16.78	17.6	18.2	17.5	17.0	7.2
06/02/2016 20:00:00	18.56	18.2	19.48	17.38	18.5	19.2	18.3	18.0	7.3
06/02/2016 21:00:00	18.09	17.87	18.57	17.6	17.3	19.0	17.8	18.0	7.1
06/02/2016 22:00:00	17.49	17.45	17.83	18.29	16.3	18.6	17.2	17.6	6.9
06/02/2016 23:00:00	17	17.07	17.22	18.83	15.7	18.2	16.8	17.3	6.6
07/02/2016 00:00:00	16.64	16.87	16.57	18.48	15.3	17.9	16.5	17.1	6.0
07/02/2016 01:00:00	16.37	16.67	16.08	18.04	15.0	17.6	16.1	16.9	5.5

07/02/2016 02:00:00	16.09	16.38	15.68	17.35	14.8	17.3	15.9	16.5	4.6
07/02/2016 03:00:00	15.98	16.12	15.32	16.72	14.5	17.0	15.6	16.1	3.9
07/02/2016 04:00:00	15.77	15.89	15.02	16.17	14.3	16.8	15.4	15.7	3.5
07/02/2016 05:00:00	15.45	15.68	14.75	15.7	14.1	16.5	15.1	15.4	3.2
07/02/2016 06:00:00	15.45	15.66	14.97	15.32	14.3	16.5	15.1	15.1	2.8
07/02/2016 07:00:00	17.11	16.84	17.02	15.47	16.5	17.9	16.6	15.5	2.7
07/02/2016 08:00:00	17.24	16.98	17.15	15.99	16.6	18.2	16.8	16.2	3.1
07/02/2016 09:00:00	16.57	16.6	16.68	16.52	15.9	17.7	16.5	16.4	4.6
07/02/2016 10:00:00	16.09	16.17	16.43	17.08	15.6	17.4	16.2	16.4	6.0
07/02/2016 11:00:00	15.98	15.46	16.08	17.38	15.5	17.3	16.4	16.4	7.4
07/02/2016 12:00:00	15.68	14.9	15.83	17.42	15.6	17.0	16.1	16.0	8.5
07/02/2016 13:00:00	15.48	14.92	15.8	18.02	16.0	16.6	15.8	15.8	8.7
07/02/2016 14:00:00	15.37	14.92	15.77	18.58	16.0	16.2	15.5	15.6	7.2
07/02/2016 15:00:00	15.46	15.1	16.03	18.68	15.9	16.2	15.6	15.5	7.0
07/02/2016 16:00:00	16.55	16.08	17.57	19.42	17.8	17.1	16.5	16.2	6.5
07/02/2016 17:00:00	16.28	15.88	17.23	20.16	17.4	16.7	16.3	16.2	5.5
07/02/2016 18:00:00	16.54	16.19	17.64	19.73	18.3	17.0	16.5	16.2	4.6
07/02/2016 19:00:00	17.99	17.48	19.68	20.05	19.8	18.5	17.8	17.3	4.8
07/02/2016 20:00:00	18.77	18.23	20.36	20.31	20.2	19.5	18.6	18.2	4.3
07/02/2016 21:00:00	18.18	17.8	19.25	20	18.7	19.4	18.3	18.2	3.9
07/02/2016 22:00:00	17.39	17.24	18.11	19.35	17.4	19.1	17.8	17.7	4.5
07/02/2016 23:00:00	16.77	16.77	17.27	18.7	16.7	18.7	17.7	17.2	5.0
08/02/2016 00:00:00	16.41	16.63	16.64	18.13	16.1	18.3	17.7	17.0	5.5
08/02/2016 01:00:00	16.17	16.38	16.16	17.58	15.7	17.9	17.4	16.7	5.6
08/02/2016 02:00:00	15.96	16.13	15.75	17.08	15.3	17.6	17.1	16.3	4.8
08/02/2016 03:00:00	15.91	15.88	15.38	16.62	15.0	17.4	16.8	16.0	4.3
08/02/2016 04:00:00	15.57	15.7	15.07	16.21	14.7	17.1	16.5	15.7	4.1
08/02/2016 05:00:00	15.31	15.48	14.78	15.83	14.5	16.8	16.2	15.3	4.4
08/02/2016 06:00:00	15.38	15.55	15.03	15.58	14.7	16.9	16.1	15.1	4.7
08/02/2016 07:00:00	17.06	16.81	17.42	16.17	17.2	18.5	17.5	15.9	5.0
08/02/2016 08:00:00	17.08	17.07	17.73	16.72	17.1	18.6	17.8	16.6	5.8
08/02/2016 09:00:00	16.61	16.78	16.82	17.27	16.1	18.0	17.4	16.8	6.3
08/02/2016 10:00:00	16.14	16.36	15.74	16.67	15.3	17.5	16.7	16.5	6.7
08/02/2016 11:00:00	15.85	15.97	15.16	16.24	14.8	17.2	16.4	16.4	7.1
08/02/2016 12:00:00	15.63	15.72	14.83	15.88	14.6	17.1	16.2	16.2	8.3
08/02/2016 13:00:00	15.43	15.51	14.66	16.11	14.6	16.8	16.0	16.0	8.0
08/02/2016 14:00:00	15.27	15.32	14.51	15.9	14.4	16.6	15.8	15.8	8.2
08/02/2016 15:00:00	15.1	15.16	14.34	15.58	14.2	16.2	15.5	15.6	8.0
08/02/2016 16:00:00	14.88	14.98	14.18	15.27	14.0	15.9	15.3	15.4	6.9
08/02/2016 17:00:00	14.69	14.76	14.07	15.17	13.9	15.8	15.1	15.2	6.3
08/02/2016 18:00:00	15.21	15.19	15.19	16.14	15.3	16.3	15.6	15.4	5.6
08/02/2016 19:00:00	16.97	16.68	17.97	17.21	17.8	17.9	17.2	16.5	5.4
08/02/2016 20:00:00	17.95	17.54	19.18	17.78	18.7	19.0	18.0	17.4	6.4
08/02/2016 21:00:00	17.42	17.15	18.14	18.02	17.4	18.9	17.3	17.3	6.2
08/02/2016 22:00:00	16.75	16.76	17	17.68	16.4	18.7	16.7	17.0	6.1
08/02/2016 23:00:00	16.22	16.41	16.28	17.15	15.7	18.2	16.3	16.6	5.9
09/02/2016 00:00:00	15.86	16.17	15.68	16.6	15.2	17.8	16.0	16.3	5.2
09/02/2016 01:00:00	15.53	15.88	15.22	16.1	14.8	17.4	15.7	16.0	4.4
09/02/2016 02:00:00	15.27	15.62	14.82	15.66	14.5	17.1	15.4	15.6	4.4
09/02/2016 03:00:00	15.03	15.4	14.5	15.27	14.2	16.8	15.1	15.3	4.5
09/02/2016 04:00:00	14.83	15.18	14.23	14.93	14.0	16.5	14.8	15.0	4.9

09/02/2016 05:00:00	14.69	14.96	13.98	14.63	13.8	16.2	14.6	14.7	4.4
09/02/2016 06:00:00	14.98	15.04	14.32	14.36	14.1	16.3	14.6	14.5	4.0
09/02/2016 07:00:00	16.52	16.36	16.83	14.96	16.6	17.9	16.1	15.3	4.1
09/02/2016 08:00:00	16.44	16.56	16.89	15.83	16.5	17.8	16.3	16.1	4.0
09/02/2016 09:00:00	15.77	16.15	15.9	15.81	15.3	17.5	15.8	15.8	4.6
09/02/2016 10:00:00	15.3	15.85	15.18	15.57	14.7	17.3	15.4	15.6	5.5
09/02/2016 11:00:00	15.02	15.46	14.71	15.25	14.3	16.9	15.2	15.6	6.1
09/02/2016 12:00:00	14.79	15.07	14.38	15.38	14.1	16.5	15.0	15.5	6.8
09/02/2016 13:00:00	14.67	14.79	14.16	15.48	14.1	16.2	14.8	15.3	6.9
09/02/2016 14:00:00	14.47	14.57	13.99	15.02	13.8	15.9	14.6	15.1	6.2
09/02/2016 15:00:00	14.25	14.3	13.76	14.6	13.5	15.5	14.5	14.8	5.7
09/02/2016 16:00:00	13.99	14.04	13.55	14.26	13.3	15.1	14.2	14.5	5.3
09/02/2016 17:00:00	13.83	13.78	13.45	14.23	13.2	14.9	14.2	14.4	4.4
09/02/2016 18:00:00	14.27	14.07	14.48	15.21	14.4	15.1	14.5	14.4	4.0
09/02/2016 19:00:00	16.02	15.45	17.27	16.11	16.9	17.0	16.1	15.4	3.5
09/02/2016 20:00:00	16.97	16.36	18.31	16.46	17.9	18.4	16.9	16.3	2.6
09/02/2016 21:00:00	16.5	16.05	17.19	16.43	16.6	18.2	16.5	16.4	2.0
09/02/2016 22:00:00	15.88	15.59	16.16	16.11	15.5	17.6	15.8	16.1	2.1
09/02/2016 23:00:00	15.31	15.3	15.4	15.78	14.8	17.0	15.4	15.8	2.1
10/02/2016 00:00:00	14.94	15.3	14.82	15.35	14.3	16.6	15.2	15.9	3.1
10/02/2016 01:00:00	14.7	15.03	14.4	14.9	13.9	16.3	14.9	15.5	3.7
10/02/2016 02:00:00	14.74	14.75	14.05	14.67	13.7	16.0	14.6	15.1	3.9
10/02/2016 03:00:00	14.43	14.51	13.78	14.43	13.4	15.8	14.3	14.8	3.7
10/02/2016 04:00:00	14.1	14.29	13.53	14.13	13.3	15.5	14.1	14.5	3.1
10/02/2016 05:00:00	13.84	14.06	13.32	13.81	13.1	15.2	13.8	14.2	2.5
10/02/2016 06:00:00	13.97	14.11	13.63	13.54	13.3	15.3	13.8	13.9	1.7
10/02/2016 07:00:00	15.68	15.48	16.1	14.04	15.9	17.0	15.3	14.7	1.4
10/02/2016 08:00:00	15.65	15.69	16.11	14.88	15.7	17.0	15.6	15.5	1.6
10/02/2016 09:00:00	15.1	15.27	15.14	14.91	14.5	17.1	15.5	15.5	2.5
10/02/2016 10:00:00	14.73	15.02	14.42	15.15	14.2	17.2	15.2	15.5	3.7
10/02/2016 11:00:00	14.44	14.61	13.95	15.5	14.2	17.2	15.0	15.5	5.1
10/02/2016 12:00:00	14.27	14.33	13.64	15.12	13.9	16.5	14.9	15.3	6.0
10/02/2016 13:00:00	14.18	14.2	13.54	14.62	13.5	15.9	14.8	15.0	6.8
10/02/2016 14:00:00	14.22	14.2	13.76	14.11	13.0	15.5	14.6	14.8	6.4
10/02/2016 15:00:00	14.31	14.23	13.74	13.77	12.8	15.2	14.5	14.8	6.8
10/02/2016 16:00:00	14.32	14.16	13.57	13.54	12.7	14.9	14.3	14.6	5.5
10/02/2016 17:00:00	13.95	13.9	13.26	13.43	12.6	14.7	14.2	14.4	3.5
10/02/2016 18:00:00	14.33	14.14	14.07	14.61	13.8	15.0	14.5	14.5	2.8
10/02/2016 19:00:00	16.03	15.36	16.81	15.77	16.4	16.5	16.2	15.5	1.7
10/02/2016 20:00:00	16.94	16.18	17.91	16.16	17.4	17.9	16.9	16.3	2.1
10/02/2016 21:00:00	16.42	15.88	16.83	16.32	16.1	17.9	16.5	16.3	2.0
10/02/2016 22:00:00	15.68	15.43	15.8	16.23	15.0	17.5	16.0	15.9	1.9
10/02/2016 23:00:00	15.07	15.05	15.01	15.73	14.3	17.0	15.5	15.5	1.7
11/02/2016 00:00:00	14.6	14.88	14.4	15.23	13.8	16.5	15.1	15.2	1.3
11/02/2016 01:00:00	14.27	14.59	13.92	14.71	13.4	16.1	14.8	14.9	1.2
11/02/2016 02:00:00	13.95	14.31	13.53	14.27	13.1	15.7	14.4	14.5	0.9
11/02/2016 03:00:00	13.66	14.02	13.23	13.82	12.9	15.4	14.1	14.2	0.2
11/02/2016 04:00:00	13.43	13.79	12.96	13.44	12.6	15.1	13.8	13.8	0.5
11/02/2016 05:00:00	13.38	13.56	12.71	13.09	12.3	14.8	13.5	13.6	-0.3
11/02/2016 06:00:00	13.51	13.59	13.04	12.79	12.6	14.8	13.4	13.3	0.1
11/02/2016 07:00:00	15.11	14.88	15.53	13.33	15.3	16.3	15.1	14.1	0.3

11/02/2016 08:00:00	15.03	15.14	15.46	14.41	15.1	16.4	15.3	14.8	-0.1
11/02/2016 09:00:00	14.45	14.82	14.4	14.6	14.2	16.8	15.2	14.8	1.6
11/02/2016 10:00:00	14.28	14.57	13.73	14.86	14.0	17.0	15.2	15.3	3.4
11/02/2016 11:00:00	14.13	14.28	13.34	15.03	13.7	16.5	15.0	15.4	4.8
11/02/2016 12:00:00	13.9	14.01	13.02	14.62	13.2	15.9	14.7	15.0	5.8
11/02/2016 13:00:00	13.8	13.82	12.88	14.26	13.0	15.4	14.5	14.8	6.2
11/02/2016 14:00:00	13.94	13.96	13.24	13.92	12.7	15.1	14.3	14.6	6.0
11/02/2016 15:00:00	14.23	14.1	13.33	13.78	12.6	14.7	14.2	14.7	5.7
11/02/2016 16:00:00	14.25	14.01	13.12	13.65	12.5	14.4	14.1	14.5	4.7
11/02/2016 17:00:00	13.79	13.73	12.84	13.6	12.4	14.3	13.9	14.2	3.1
11/02/2016 18:00:00	14.15	14.05	13.87	14.98	13.9	14.9	14.3	14.3	2.5
11/02/2016 19:00:00	15.93	15.54	16.43	15.88	16.3	16.7	16.1	15.4	3.0
11/02/2016 20:00:00	16.93	16.47	17.84	16.19	17.3	17.8	17.0	16.5	2.7
11/02/2016 21:00:00	16.37	16.14	16.75	16.19	15.9	17.6	16.4	16.4	2.0
11/02/2016 22:00:00	15.65	15.68	15.69	15.77	14.7	17.2	15.8	16.2	0.6
11/02/2016 23:00:00	15.05	15.28	14.94	16.13	13.9	16.7	15.3	15.8	0.8
12/02/2016 00:00:00	14.58	15.06	14.32	15.49	13.4	16.2	15.0	15.6	0.0
12/02/2016 01:00:00	14.25	14.77	13.83	14.77	13.0	15.8	14.7	15.2	-0.8
12/02/2016 02:00:00	13.94	14.49	13.44	14.17	12.7	15.4	14.3	14.8	-1.5
12/02/2016 03:00:00	13.88	14.18	13.11	13.63	12.4	15.1	14.0	14.4	-1.8
12/02/2016 04:00:00	13.52	13.92	12.82	13.18	12.1	14.7	13.6	14.0	-1.7
12/02/2016 05:00:00	13.14	13.64	12.57	12.79	11.9	14.4	13.3	13.6	-1.9
12/02/2016 06:00:00	13.21	13.58	12.92	12.46	12.1	14.5	13.2	13.3	-2.2
12/02/2016 07:00:00	14.85	14.77	15.38	12.98	14.8	16.2	14.7	14.1	-1.9
12/02/2016 08:00:00	14.82	15.02	15.34	13.93	14.7	16.2	14.9	14.7	-1.2
12/02/2016 09:00:00	14.17	14.69	14.35	14.04	13.7	16.2	14.6	14.5	0.9
12/02/2016 10:00:00	13.84	14.35	13.65	14.08	13.3	16.4	14.4	14.5	2.1
12/02/2016 11:00:00	13.61	13.95	13.19	14.03	12.9	16.0	14.1	14.5	5.0
12/02/2016 12:00:00	13.51	13.68	12.92	13.84	12.7	15.6	13.9	14.5	7.5
12/02/2016 13:00:00	13.51	13.57	12.87	13.61	12.5	15.3	13.8	14.4	7.8
12/02/2016 14:00:00	13.5	13.49	12.87	13.28	12.3	15.0	13.7	14.3	6.8
12/02/2016 15:00:00	13.32	13.38	12.69	13.02	12.1	14.6	13.7	14.0	4.8
12/02/2016 16:00:00	13.12	13.21	12.43	12.82	11.9	14.2	13.5	13.8	4.6
12/02/2016 17:00:00	12.84	13.01	11.93	12.55	11.6	13.8	13.2	13.5	3.8
12/02/2016 18:00:00	13.36	13.44	13.08	13.84	13.0	14.3	13.6	13.6	2.6
12/02/2016 19:00:00	15.29	15.13	16.17	14.89	15.7	16.1	15.5	14.9	1.4
12/02/2016 20:00:00	16.38	16.04	17.4	15.52	16.6	17.3	16.5	15.9	1.0
12/02/2016 21:00:00	15.88	15.57	16.31	16.08	15.3	17.0	16.0	15.9	1.7
12/02/2016 22:00:00	15.21	15.09	15.25	15.45	14.1	16.6	15.3	15.5	1.4
12/02/2016 23:00:00	14.64	14.91	14.51	14.86	13.4	16.1	14.9	15.2	1.4
13/02/2016 00:00:00	14.2	14.63	13.9	14.37	12.9	15.7	14.5	14.9	1.0
13/02/2016 01:00:00	13.82	14.3	13.43	13.88	12.5	15.3	14.1	14.5	0.7
13/02/2016 02:00:00	13.58	14.02	13.07	13.47	12.3	15.0	13.8	14.2	1.3
13/02/2016 03:00:00	13.31	13.75	12.77	13.09	12.0	14.7	13.5	13.8	1.8
13/02/2016 04:00:00	13.18	13.55	12.52	12.95	11.8	14.5	13.2	13.5	1.7
13/02/2016 05:00:00	13.27	13.32	12.3	12.72	11.7	14.2	13.0	13.3	1.6
13/02/2016 06:00:00	13.37	13.44	12.71	12.49	12.0	14.3	13.0	13.1	1.6
13/02/2016 07:00:00	15.13	14.88	15.33	12.81	14.8	16.2	14.8	13.8	1.8
13/02/2016 08:00:00	15.32	15.2	15.52	13.44	14.8	16.2	14.9	14.7	2.2
13/02/2016 09:00:00	15.59	15.65	16.1	14.76	15.2	16.3	15.3	15.2	2.7
13/02/2016 10:00:00	16.98	16.88	17.72	16	17.0	17.7	16.7	16.5	3.3

13/02/2016 11:00:00	16.8	17.06	17.21	16.73	16.2	17.5	16.5	16.8	3.5
13/02/2016 12:00:00	16.17	16.97	16.32	17.74	15.4	16.7	15.8	16.6	3.5
13/02/2016 13:00:00	15.66	17.11	15.67	16.89	14.6	16.1	15.3	16.3	1.9
13/02/2016 14:00:00	15.29	16.79	14.98	15.93	13.8	15.6	15.1	16.3	1.4
13/02/2016 15:00:00	14.93	16.23	14.43	15.13	13.3	15.1	14.8	16.0	2.4
13/02/2016 16:00:00	14.58	15.8	14.04	14.52	12.9	14.8	14.5	15.7	2.4
13/02/2016 17:00:00	14.23	15.43	13.67	14.04	12.6	14.4	14.2	15.3	1.9
13/02/2016 18:00:00	14.67	15.57	14.52	13.71	13.5	14.8	14.4	15.4	1.9
13/02/2016 19:00:00	16.35	16.7	17.13	14.13	16.2	16.5	15.8	16.4	1.9
13/02/2016 20:00:00	17.23	17.43	18.17	14.81	17.1	17.3	16.6	17.2	2.2
13/02/2016 21:00:00	16.63	17.18	16.92	15.17	15.6	16.7	16.1	17.1	2.2
13/02/2016 22:00:00	16.06	16.83	15.86	16.1	15.1	16.1	15.7	16.8	1.9
13/02/2016 23:00:00	15.58	16.6	15.42	15.74	14.2	15.6	15.4	16.5	1.4
14/02/2016 00:00:00	15.25	16.59	15.02	15.06	13.5	15.3	15.3	16.5	1.4
14/02/2016 01:00:00	14.89	16.64	14.46	14.43	13.1	15.0	14.8	16.3	1.2
14/02/2016 02:00:00	14.52	16.7	13.99	13.88	12.7	14.6	14.3	15.8	0.8
14/02/2016 03:00:00	14.16	16.36	13.61	13.37	12.4	14.2	13.9	15.4	0.4
14/02/2016 04:00:00	13.77	15.95	13.28	12.95	12.1	13.8	13.4	15.0	-0.6
14/02/2016 05:00:00	13.4	15.64	12.99	12.57	11.8	13.5	13.1	14.6	-0.9
14/02/2016 06:00:00	13.4	15.66	13.29	12.23	12.1	13.5	13.0	14.3	-2.0
14/02/2016 07:00:00	14.86	16.73	15.83	12.48	14.7	15.0	14.6	15.1	-1.4
14/02/2016 08:00:00	15.02	16.96	15.8	12.94	14.5	15.1	14.7	15.5	0.2
14/02/2016 09:00:00	14.59	16.67	14.74	13.13	13.6	14.9	14.3	15.4	1.1
14/02/2016 10:00:00	14.27	16.35	14	13.51	13.3	14.7	14.1	15.3	1.8
14/02/2016 11:00:00	13.93	16.12	13.52	13.32	12.9	14.3	13.7	15.0	1.8
14/02/2016 12:00:00	13.75	15.73	13.21	13.07	12.5	14.0	13.8	15.0	3.0
14/02/2016 13:00:00	13.63	15.19	13.25	12.96	12.3	13.8	13.8	14.9	3.5
14/02/2016 14:00:00	13.5	14.7	13.47	12.73	12.0	13.6	13.7	14.6	3.3
14/02/2016 15:00:00	13.44	14.4	13.32	12.43	11.7	13.4	13.6	14.4	3.3
14/02/2016 16:00:00	13.16	14.04	12.93	12.23	11.5	13.2	13.3	14.1	1.9
14/02/2016 17:00:00	12.84	13.68	12.52	12.18	11.3	12.9	13.0	13.8	1.3
14/02/2016 18:00:00	13.34	13.93	13.47	12.28	12.2	13.5	13.3	13.8	0.3
14/02/2016 19:00:00	15.18	15.07	16.22	13.26	14.5	15.3	14.8	14.9	0.3
14/02/2016 20:00:00	16.03	15.88	17.22	14.46	15.2	16.2	15.6	15.8	0.3
14/02/2016 21:00:00	15.42	15.62	15.88	14.57	14.0	15.6	15.1	15.7	0.9
14/02/2016 22:00:00	14.73	15.15	14.67	14.22	13.0	14.9	14.5	15.3	1.0
14/02/2016 23:00:00	14.18	14.75	13.84	13.77	12.4	14.4	14.1	14.9	1.0
15/02/2016 00:00:00	13.77	14.56	13.29	13.48	12.1	14.0	13.9	14.7	0.5
15/02/2016 01:00:00	13.38	14.81	12.88	13.17	11.8	13.7	13.5	14.5	0.4
15/02/2016 02:00:00	13.08	15.26	12.56	12.75	11.5	13.3	13.0	14.3	0.2
15/02/2016 03:00:00	12.78	15.48	12.25	12.38	11.2	13.0	12.7	14.1	0.0
15/02/2016 04:00:00	12.57	14.98	12.1	12.07	11.0	12.7	12.4	14.0	-0.2
15/02/2016 05:00:00	12.23	14.23	12.1	11.81	10.8	12.4	12.1	13.4	0.1
15/02/2016 06:00:00	12.22	13.88	12.56	11.68	11.1	12.4	12.0	13.0	-0.4
15/02/2016 07:00:00	13.91	14.93	14.87	12.48	13.5	14.1	13.6	13.9	-0.2
15/02/2016 08:00:00	14.19	14.94	14.88	13.25	13.3	14.4	14.0	14.3	0.5
15/02/2016 09:00:00	13.65	14.48	13.75	13.27	12.3	13.9	13.5	14.1	1.1
15/02/2016 10:00:00	13.17	13.85	13.02	13.07	11.8	13.4	13.0	13.8	2.0
15/02/2016 11:00:00	12.73	13.33	12.63	13.04	11.6	13.1	12.7	13.6	3.1
15/02/2016 12:00:00	12.39	12.96	12.45	12.77	11.5	12.9	12.5	13.3	3.8
15/02/2016 13:00:00	12.23	12.73	12.41	12.48	11.2	12.7	12.4	13.0	4.1

15/02/2016 14:00:00	12.31	12.7	12.62	12.17	11.0	12.5	12.3	12.9	4.3
15/02/2016 15:00:00	12.42	12.67	12.52	11.86	10.8	12.3	12.3	12.9	3.9
15/02/2016 16:00:00	12.27	12.48	12.18	11.62	10.6	12.1	12.1	12.7	2.6
15/02/2016 17:00:00	11.88	12.21	11.73	11.43	10.5	11.9	11.9	12.5	1.4
15/02/2016 18:00:00	12.4	12.59	12.61	11.72	11.4	12.5	12.3	12.5	-0.1
15/02/2016 19:00:00	14.38	14.13	15.41	14.02	14.7	14.7	14.2	13.8	-0.4
15/02/2016 20:00:00	15.34	15.11	16.77	15.58	15.9	15.9	15.3	14.9	-0.5
15/02/2016 21:00:00	14.82	14.81	15.77	15.33	14.5	15.6	14.7	14.9	-1.5
15/02/2016 22:00:00	14.14	14.49	14.84	14.66	13.1	15.2	13.9	14.6	-2.0
15/02/2016 23:00:00	13.54	14.12	14.02	13.93	12.3	14.6	13.4	14.2	-2.1
16/02/2016 00:00:00	13.09	13.83	13.32	13.29	11.8	14.1	13.3	14.0	-1.8
16/02/2016 01:00:00	12.74	13.47	12.8	12.76	11.4	13.7	12.8	13.6	-2.0
16/02/2016 02:00:00	12.43	13.1	12.41	12.3	11.1	13.4	12.3	13.2	-2.4
16/02/2016 03:00:00	12.17	12.75	12.07	11.87	10.8	13.0	11.9	12.8	-2.4
16/02/2016 04:00:00	12.13	12.47	11.78	11.52	10.6	12.7	11.6	12.4	-2.5
16/02/2016 05:00:00	11.73	12.2	11.51	11.19	10.3	12.4	11.3	12.0	-2.5
16/02/2016 06:00:00	11.77	12.16	11.87	11.14	10.7	12.5	11.2	11.7	-2.2
16/02/2016 07:00:00	13.63	13.5	14.68	11.72	13.6	14.3	12.7	12.8	-2.1
16/02/2016 08:00:00	13.8	13.81	14.74	12.88	13.8	14.5	13.4	13.5	0.1
16/02/2016 09:00:00	13.19	13.43	13.66	13.34	12.8	14.2	13.1	13.5	1.9
16/02/2016 10:00:00	12.8	13.19	12.95	13.56	12.5	14.0	12.8	13.4	3.5
16/02/2016 11:00:00	12.52	12.82	12.55	13.35	12.1	13.7	12.6	13.3	4.6
16/02/2016 12:00:00	12.48	12.63	12.57	13.23	12.1	13.6	12.5	13.1	4.6
16/02/2016 13:00:00	14.27	13.93	14.67	13.98	14.6	15.2	13.8	13.9	4.9
16/02/2016 14:00:00	15.15	14.73	15.34	14.96	15.3	16.0	14.7	14.9	5.5
16/02/2016 15:00:00	14.57	14.28	14.21	14.97	14.0	15.4	14.2	14.7	5.5
16/02/2016 16:00:00	13.92	13.81	13.29	14.57	13.0	14.7	13.6	14.3	5.3
16/02/2016 17:00:00	13.38	13.38	12.74	14.47	12.6	14.1	13.3	13.9	5.2
16/02/2016 18:00:00	13.83	13.67	13.8	15.62	13.5	14.4	13.5	13.9	5.1
16/02/2016 19:00:00	15.54	15.02	16.72	16.38	16.2	16.1	15.0	15.0	5.2
16/02/2016 20:00:00	16.38	15.83	17.88	16.78	17.1	17.1	15.8	15.9	5.2
16/02/2016 21:00:00	15.81	15.47	16.45	16.88	15.7	16.9	15.3	15.8	5.1
16/02/2016 22:00:00	15.11	14.99	15.64	16.98	14.5	16.6	14.8	15.4	5.0
16/02/2016 23:00:00	14.64	14.55	14.8	16.48	13.9	16.2	14.4	15.0	4.9
17/02/2016 00:00:00	14.24	14.37	14.14	15.76	13.5	15.8	14.2	14.7	5.1
17/02/2016 01:00:00	13.98	14.17	13.7	15.11	13.1	15.5	13.9	14.4	5.1
17/02/2016 02:00:00	13.76	13.96	13.32	14.59	12.8	15.2	13.7	14.1	4.7
17/02/2016 03:00:00	13.56	13.76	13.02	14.13	12.5	14.9	13.4	13.7	4.3
17/02/2016 04:00:00	13.36	13.63	12.75	13.76	12.3	14.7	13.2	13.4	4.2
17/02/2016 05:00:00	13.45	13.48	12.53	13.42	12.1	14.4	12.9	13.1	4.0
17/02/2016 06:00:00	13.72	13.63	12.95	13.17	12.5	14.6	12.9	13.0	3.9
17/02/2016 07:00:00	15.43	15.02	15.68	13.57	15.2	16.5	14.5	13.4	3.9
17/02/2016 08:00:00	15.48	15.36	15.64	14.2	15.2	16.7	14.7	14.4	4.0
17/02/2016 09:00:00	14.75	14.93	14.67	14.33	14.3	16.1	14.2	14.5	4.4
17/02/2016 10:00:00	14.27	14.69	14.05	14.27	13.5	15.4	13.9	14.4	4.9
17/02/2016 11:00:00	13.94	14.3	13.69	14.07	13.1	15.2	13.6	14.3	5.0
17/02/2016 12:00:00	13.75	13.98	13.45	14.15	12.8	14.9	13.4	14.3	5.4
17/02/2016 13:00:00	13.51	13.7	13.27	14.06	12.8	14.6	13.3	14.0	5.2
17/02/2016 14:00:00	13.31	13.44	13.13	13.66	12.5	14.4	13.1	13.9	4.7
17/02/2016 15:00:00	13.98	13.89	14.18	13.5	13.5	14.9	13.8	14.1	4.5
17/02/2016 16:00:00	15.73	15.32	16.56	14.01	16.0	16.2	15.6	15.2	4.2

17/02/2016 17:00:00	15.61	15.32	16.18	14.51	15.4	16.4	15.4	15.5	3.7
17/02/2016 18:00:00	15.88	15.54	16.23	16.11	15.7	16.7	15.6	15.6	3.4
17/02/2016 19:00:00	17.26	16.74	18.13	17.24	17.7	18.1	17.1	16.6	3.1
17/02/2016 20:00:00	17.97	17.43	18.98	17.55	18.3	18.9	17.8	17.4	2.7
17/02/2016 21:00:00	17.27	16.95	17.8	17.25	16.8	18.4	17.1	17.2	2.4
17/02/2016 22:00:00	16.56	16.42	16.61	16.77	15.5	18.0	16.4	16.9	2.0
17/02/2016 23:00:00	15.98	15.96	15.79	16.06	14.7	17.6	15.9	16.5	1.5
18/02/2016 00:00:00	15.53	15.73	15.09	15.49	14.1	17.2	15.4	16.2	1.4
18/02/2016 01:00:00	15.14	15.48	14.6	14.99	13.7	16.7	15.0	15.8	1.3
18/02/2016 02:00:00	14.79	15.14	14.18	14.48	13.3	16.3	14.7	15.4	1.0
18/02/2016 03:00:00	14.53	14.82	13.84	14.01	13.1	16.0	14.3	15.0	0.4
18/02/2016 04:00:00	14.27	14.54	13.52	13.57	12.8	15.7	14.0	14.6	0.0
18/02/2016 05:00:00	13.98	14.27	13.23	13.2	12.5	15.3	13.7	14.2	-0.2
18/02/2016 06:00:00	14.18	14.18	13.43	12.89	12.8	15.3	13.6	13.9	-1.0
18/02/2016 07:00:00	15.58	15.23	15.63	13.26	15.2	17.1	15.2	14.7	-1.6
18/02/2016 08:00:00	15.55	15.48	15.72	14	15.2	17.3	15.5	15.4	-0.8
18/02/2016 09:00:00	15.12	15.16	14.89	14.51	14.5	17.0	15.6	15.6	0.8
18/02/2016 10:00:00	14.77	14.8	14.36	15.05	14.3	16.9	15.6	15.8	3.1
18/02/2016 11:00:00	14.47	14.52	14.02	15.18	14.0	16.5	15.2	15.7	4.7
18/02/2016 12:00:00	14.13	14.23	13.81	14.96	13.7	15.8	14.7	15.1	5.8
18/02/2016 13:00:00	13.86	13.98	13.62	14.55	13.4	15.3	14.4	14.7	5.7
18/02/2016 14:00:00	13.98	13.98	13.68	14.17	13.2	14.9	14.2	14.6	5.9
18/02/2016 15:00:00	14.17	14.11	13.66	13.88	13.0	14.6	14.2	14.6	5.6
18/02/2016 16:00:00	14.28	14.18	13.48	13.64	12.8	14.4	14.1	14.5	4.8
18/02/2016 17:00:00	13.94	13.93	13.13	13.48	12.6	14.2	13.9	14.3	3.5
18/02/2016 18:00:00	14.31	14.14	13.85	14.4	13.6	14.7	14.3	14.3	2.1
18/02/2016 19:00:00	16.01	15.51	16.32	15.46	16.3	16.6	16.1	15.4	1.7
18/02/2016 20:00:00	16.96	16.37	17.47	16.39	17.3	17.8	17.0	16.4	1.8
18/02/2016 21:00:00	16.35	16	16.61	16.73	15.9	17.4	16.3	16.3	0.8
18/02/2016 22:00:00	15.67	15.5	15.6	16.36	14.7	17.1	15.7	15.9	0.7
18/02/2016 23:00:00	15.07	15.08	14.89	16.52	14.1	16.6	15.3	15.5	0.9
19/02/2016 00:00:00	14.63	15.11	14.32	15.79	13.6	16.1	15.0	15.5	0.5
19/02/2016 01:00:00	14.3	14.9	13.84	15.05	13.1	15.8	14.7	15.3	1.0
19/02/2016 02:00:00	14	14.56	13.46	14.44	12.8	15.4	14.4	14.8	1.2
19/02/2016 03:00:00	13.73	14.25	13.15	13.98	12.5	15.1	14.1	14.4	0.5
19/02/2016 04:00:00	13.48	13.99	12.85	13.54	12.2	14.8	13.8	14.1	0.0
19/02/2016 05:00:00	13.48	13.74	12.57	13.14	12.0	14.6	13.5	13.7	-0.7
19/02/2016 06:00:00	13.52	13.7	12.82	12.82	12.2	14.6	13.3	13.5	-0.6
19/02/2016 07:00:00	15.08	14.96	15.06	13.42	15.0	16.4	14.7	14.1	-0.3
19/02/2016 08:00:00	15.1	15.21	15.42	14.26	15.1	16.9	15.2	14.9	0.2
19/02/2016 09:00:00	14.55	14.85	14.61	14.65	14.4	16.7	15.1	14.9	2.3
19/02/2016 10:00:00	14.23	14.68	14.1	15.03	14.1	16.7	14.9	15.1	4.8
19/02/2016 11:00:00	14.07	14.42	13.79	15.47	13.9	16.1	14.5	15.0	6.3
19/02/2016 12:00:00	13.82	14.12	13.64	15.57	13.6	15.5	14.2	14.7	6.7
19/02/2016 13:00:00	13.63	13.84	13.45	15.65	13.3	15.1	14.0	14.4	6.6
19/02/2016 14:00:00	13.41	13.59	13.28	15.17	13.3	14.8	13.8	14.2	6.8
19/02/2016 15:00:00	13.24	13.37	13.04	14.59	13.0	14.6	13.7	14.0	7.4
19/02/2016 16:00:00	13.05	13.19	12.94	14.13	12.7	14.5	13.5	13.7	7.4
19/02/2016 17:00:00	12.88	12.97	12.77	13.81	12.4	14.5	13.4	13.5	7.2
19/02/2016 18:00:00	13.53	13.4	13.51	14.31	13.5	14.8	13.8	13.7	7.8
19/02/2016 19:00:00	15.49	15.01	15.93	15.45	16.3	16.3	15.5	14.9	8.1

19/02/2016 20:00:00	16.54	15.96	17.24	16.51	17.3	17.3	16.6	16.0	8.9
19/02/2016 21:00:00	16.19	15.77	16.64	16.63	16.1	17.1	16.3	16.1	8.4
19/02/2016 22:00:00	15.63	15.44	15.73	16.75	15.2	17.1	15.7	15.9	7.8
19/02/2016 23:00:00	15.14	15.14	15.13	17.99	14.7	16.8	15.4	15.7	7.4
20/02/2016 00:00:00	14.73	14.82	14.57	18.82	14.5	16.5	15.1	15.4	7.0
20/02/2016 01:00:00	14.46	14.62	14.13	18.28	14.3	16.2	14.9	15.1	6.2
20/02/2016 02:00:00	14.22	14.41	13.75	17.32	14.1	16.0	14.7	14.8	6.0
20/02/2016 03:00:00	13.98	14.19	13.46	16.43	13.8	15.7	14.5	14.4	5.9
20/02/2016 04:00:00	13.77	13.99	13.22	15.74	13.5	15.5	14.2	14.1	6.2
20/02/2016 05:00:00	13.59	13.83	12.98	15.16	13.3	15.4	14.0	13.9	5.9
20/02/2016 06:00:00	13.96	13.92	13.22	14.77	13.6	15.5	14.1	13.7	6.1
20/02/2016 07:00:00	15.51	15.36	15.56	15.11	16.2	17.3	15.8	14.7	6.0
20/02/2016 08:00:00	15.54	15.72	16.03	15.57	16.2	17.7	16.1	15.2	5.9
20/02/2016 09:00:00	15.2	15.43	15.3	15.88	15.2	17.0	15.6	15.3	6.7
20/02/2016 10:00:00	14.82	15.12	14.89	16.07	14.8	16.4	15.2	15.2	7.1
20/02/2016 11:00:00	14.49	14.84	14.82	15.91	14.4	16.2	14.9	15.0	7.7
20/02/2016 12:00:00	14.31	14.64	14.79	16.31	14.5	15.9	14.7	14.9	8.1
20/02/2016 13:00:00	14.2	14.5	14.63	16.44	14.6	15.7	14.6	14.8	8.4
20/02/2016 14:00:00	14.17	14.38	14.56	16.56	14.5	15.8	14.5	14.6	8.4
20/02/2016 15:00:00	15.2	15.07	15.79	16.23	15.7	17.0	15.5	15.2	8.4
20/02/2016 16:00:00	15.52	15.18	15.85	16.15	15.7	17.0	15.6	15.7	7.7
20/02/2016 17:00:00	15.17	14.95	15.4	16.41	15.1	16.6	15.3	15.6	7.1
20/02/2016 18:00:00	15.6	15.23	16.15	17.42	15.9	16.8	15.8	15.6	6.3
20/02/2016 19:00:00	17.17	16.49	18.58	17.78	18.4	18.2	17.5	16.6	5.9
20/02/2016 20:00:00	17.93	17.21	19.67	17.9	19.1	19.0	18.2	17.4	5.5
20/02/2016 21:00:00	17.53	16.93	18.38	18.03	17.7	18.7	17.7	17.4	5.5
20/02/2016 22:00:00	16.84	16.47	17.25	17.71	16.6	18.5	17.0	17.1	5.0
20/02/2016 23:00:00	16.31	16.3	16.41	17.31	15.9	18.2	16.5	16.7	5.1
21/02/2016 00:00:00	15.88	16.12	15.75	16.77	15.4	17.9	16.1	16.5	5.5
21/02/2016 01:00:00	15.56	15.83	15.23	16.25	14.9	17.6	15.8	16.2	5.3
21/02/2016 02:00:00	15.26	15.58	14.8	15.78	14.6	17.2	15.5	15.8	5.6
21/02/2016 03:00:00	15.19	15.36	14.45	15.37	14.3	16.9	15.2	15.5	5.5
21/02/2016 04:00:00	15.03	15.18	14.14	15.03	14.1	16.7	15.0	15.2	6.3
21/02/2016 05:00:00	14.73	15.01	13.89	14.71	13.9	16.4	14.7	14.9	6.3
21/02/2016 06:00:00	14.88	15.07	14.27	14.5	14.2	16.5	14.8	14.7	6.4
21/02/2016 07:00:00	16.77	16.37	16.78	14.82	16.7	18.2	16.5	15.2	6.6
21/02/2016 08:00:00	17.09	16.65	16.83	15.39	16.6	18.5	16.8	15.9	7.0
21/02/2016 09:00:00	16.5	16.34	16.13	15.75	15.6	17.8	16.4	16.3	7.7
21/02/2016 10:00:00	16.02	16.04	15.74	15.91	15.0	17.3	16.0	16.1	8.3
21/02/2016 11:00:00	15.73	15.86	15.63	15.73	14.7	17.1	15.6	16.0	8.9
21/02/2016 12:00:00	15.67	15.83	15.5	15.66	14.6	17.0	15.4	16.0	9.3
21/02/2016 13:00:00	15.8	15.65	15.25	15.62	14.6	17.0	16.0	16.3	9.8
21/02/2016 14:00:00	15.56	15.49	15.01	15.42	14.4	16.6	15.7	15.9	9.5
21/02/2016 15:00:00	15.45	15.41	15.02	15.27	14.3	16.3	15.5	15.7	9.4
21/02/2016 16:00:00	16.51	16.23	16.73	15.49	15.9	17.4	16.6	16.3	8.5
21/02/2016 17:00:00	16.85	16.45	17.07	16.05	16.2	17.7	17.0	16.8	7.7
21/02/2016 18:00:00	17.13	16.81	17.63	16.72	16.6	18.0	17.2	16.9	7.0
21/02/2016 19:00:00	18.5	18.12	19.71	18.05	18.7	19.3	18.6	17.9	7.0
21/02/2016 20:00:00	19.25	18.82	20.31	18.57	19.5	20.1	19.1	18.7	6.4
21/02/2016 21:00:00	18.75	18.38	18.98	18.57	18.2	19.9	18.5	18.6	5.6
21/02/2016 22:00:00	18.02	17.9	17.95	18.21	17.1	19.5	17.9	18.3	4.4

21/02/2016 23:00:00	17.43	17.61	17.19	17.73	16.4	19.0	17.4	18.0	4.2
22/02/2016 00:00:00	16.98	17.6	16.51	17.18	15.8	18.6	17.1	17.9	3.5
22/02/2016 01:00:00	16.66	17.21	15.93	16.63	15.4	18.2	16.7	17.4	3.0
22/02/2016 02:00:00	16.3	16.77	15.46	16.13	15.0	17.9	16.3	16.9	2.4
22/02/2016 03:00:00	15.93	16.39	15.06	15.68	14.7	17.5	15.9	16.4	2.1
22/02/2016 04:00:00	15.59	16.04	14.71	15.25	14.5	17.1	15.6	15.9	2.2
22/02/2016 05:00:00	15.47	15.7	14.37	14.86	14.2	16.8	15.2	15.4	2.4
22/02/2016 06:00:00	15.43	15.62	14.57	14.54	14.4	16.8	15.1	15.1	2.3
22/02/2016 07:00:00	16.81	16.62	16.9	15.11	16.8	18.3	16.6	15.7	2.5
22/02/2016 08:00:00	16.85	16.77	16.85	15.76	16.6	18.4	17.1	16.6	3.2
22/02/2016 09:00:00	16.36	16.41	15.88	15.7	15.8	18.3	17.2	16.8	4.4
22/02/2016 10:00:00	15.9	16.16	15.16	15.98	15.7	18.4	16.8	16.8	5.5
22/02/2016 11:00:00	15.66	15.79	14.69	15.98	15.1	17.9	16.5	16.9	6.9
22/02/2016 12:00:00	15.48	15.53	14.43	15.85	14.7	17.5	16.2	16.5	6.9
22/02/2016 13:00:00	15.34	15.34	14.39	16.27	14.8	17.0	16.0	16.2	7.6
22/02/2016 14:00:00	15.57	15.45	14.65	16.06	14.7	16.8	15.9	16.2	7.5
22/02/2016 15:00:00	15.86	15.63	14.79	15.67	14.4	16.5	15.9	16.2	7.0
22/02/2016 16:00:00	15.88	15.73	14.68	15.48	14.2	16.3	15.8	16.1	6.6
22/02/2016 17:00:00	15.53	15.47	14.43	16.44	14.0	16.0	15.6	15.8	5.8
22/02/2016 18:00:00	15.81	15.75	15.45	17.28	15.7	16.4	16.0	15.8	5.5
22/02/2016 19:00:00	17.36	17.17	18.37	18.63	19.1	18.0	17.8	16.9	5.2
22/02/2016 20:00:00	18.18	18.08	19.5	19.38	19.8	18.8	18.7	17.8	4.8
22/02/2016 21:00:00	17.88	17.83	18.38	18.93	18.3	18.7	18.1	17.8	4.6
22/02/2016 22:00:00	17.3	17.48	17.6	18.25	17.0	18.5	17.5	17.5	3.3
22/02/2016 23:00:00	16.71	17.15	16.96	17.48	16.1	18.3	17.0	17.1	2.2
23/02/2016 00:00:00	16.41	16.87	16.21	16.79	15.4	17.8	16.6	16.8	1.7
23/02/2016 01:00:00	16.21	16.58	15.61	16.17	15.0	17.4	16.2	16.5	1.1
23/02/2016 02:00:00	15.77	16.29	15.13	15.65	14.6	17.1	15.9	16.1	1.0
23/02/2016 03:00:00	15.43	16.01	14.73	15.16	14.2	16.7	15.5	15.8	-0.2
23/02/2016 04:00:00	15.15	15.77	14.38	14.69	13.9	16.4	15.2	15.4	-0.1
23/02/2016 05:00:00	14.82	15.47	14.06	14.28	13.6	16.1	14.9	15.0	-0.4
23/02/2016 06:00:00	14.84	15.42	14.22	13.93	13.7	16.1	14.7	14.8	-0.7
23/02/2016 07:00:00	16.23	16.57	16.55	14.54	16.2	17.6	16.1	15.6	-0.7
23/02/2016 08:00:00	16.2	16.67	16.88	15.27	16.2	17.9	16.7	16.2	0.2
23/02/2016 09:00:00	15.65	16.27	16.03	15.54	15.8	18.5	16.7	16.1	2.0
23/02/2016 10:00:00	15.32	15.86	15.26	16.13	15.8	18.8	16.6	16.3	4.0
23/02/2016 11:00:00	15.04	15.41	14.72	16.52	15.4	18.5	16.1	16.4	5.7
23/02/2016 12:00:00	14.82	15.1	14.37	15.66	14.7	17.4	15.7	16.1	6.0
23/02/2016 13:00:00	14.54	14.77	14.11	15.07	14.0	16.5	15.3	15.5	6.5
23/02/2016 14:00:00	14.43	14.52	13.93	14.58	13.6	16.1	15.1	15.3	5.8
23/02/2016 15:00:00	14.32	14.36	13.75	14.24	13.4	15.7	15.0	15.0	5.9
23/02/2016 16:00:00	14.16	14.21	13.57	13.91	13.2	15.3	14.8	14.8	5.4
23/02/2016 17:00:00	13.88	13.99	13.18	13.41	12.8	15.0	14.6	14.5	4.3
23/02/2016 18:00:00	14.39	14.34	14.13	14.1	13.6	15.6	14.9	14.8	2.5
23/02/2016 19:00:00	16.13	15.78	16.93	14.98	16.2	17.3	16.6	15.9	1.6
23/02/2016 20:00:00	17.18	16.71	18.1	15.84	17.3	18.3	17.5	16.9	0.9
23/02/2016 21:00:00	16.68	16.32	16.87	15.88	16.0	18.1	17.0	16.8	0.2
23/02/2016 22:00:00	15.93	15.78	15.81	15.58	14.8	17.7	16.3	16.4	-0.9
23/02/2016 23:00:00	15.32	15.52	15	15.62	14.1	17.1	15.8	16.0	-0.9
24/02/2016 00:00:00	14.81	15.29	14.4	15.21	13.6	16.6	15.4	15.8	-1.1
24/02/2016 01:00:00	14.44	14.93	13.93	14.6	13.2	16.2	15.1	15.3	-1.6

24/02/2016 02:00:00	14.1	14.55	13.55	14.07	12.9	15.7	14.7	14.9	-1.7
24/02/2016 03:00:00	13.76	14.24	13.22	13.58	12.6	15.4	14.3	14.4	-2.5
24/02/2016 04:00:00	13.47	13.93	12.9	13.14	12.3	15.0	14.0	14.0	-2.1
24/02/2016 05:00:00	13.41	13.63	12.62	12.77	12.0	14.7	13.6	13.7	-1.6
24/02/2016 06:00:00	13.46	13.66	12.96	12.51	12.3	14.7	13.5	13.4	-1.6
24/02/2016 07:00:00	15.02	14.79	15.5	13.22	14.9	16.4	15.2	14.1	-1.8
24/02/2016 08:00:00	15.05	14.98	15.47	14.23	15.0	16.5	15.6	15.0	-0.8
24/02/2016 09:00:00	14.6	14.67	14.46	14.53	14.4	16.3	15.4	15.1	1.1
24/02/2016 10:00:00	14.16	14.47	13.73	14.77	14.0	16.1	15.1	15.0	2.5
24/02/2016 11:00:00	14.02	14.1	13.22	15.07	13.8	15.8	15.0	15.3	3.7
24/02/2016 12:00:00	13.54	13.8	12.61	13.6	12.9	15.2	14.5	14.9	4.6
24/02/2016 13:00:00	13.06	13.48	12.16	13.07	12.1	14.6	13.9	14.3	5.1
24/02/2016 14:00:00	13.29	13.54	12.39	12.72	11.9	14.4	13.8	14.2	5.4
24/02/2016 15:00:00	13.87	13.92	12.89	12.65	12.1	14.1	13.9	14.4	6.1
24/02/2016 16:00:00	13.82	13.93	12.81	12.59	12.1	13.9	13.8	14.3	4.9
24/02/2016 17:00:00	13.33	13.57	12.25	12.38	11.8	13.6	13.5	13.9	3.6
24/02/2016 18:00:00	13.64	13.88	13.18	13.83	13.0	14.1	14.0	13.9	2.7
24/02/2016 19:00:00	15.48	15.47	16.28	14.88	16.0	15.9	15.8	15.0	1.6
24/02/2016 20:00:00	16.36	16.37	17.46	15.54	16.9	17.2	16.5	16.0	0.4
24/02/2016 21:00:00	15.8	15.86	16.2	15.63	15.4	16.9	15.9	15.8	-0.4
24/02/2016 22:00:00	15.07	15.32	15.18	15.38	14.2	16.5	15.3	15.4	0.3
24/02/2016 23:00:00	14.46	14.98	14.43	14.85	13.4	16.0	14.8	15.1	0.1
25/02/2016 00:00:00	13.98	14.68	13.8	14.31	12.9	15.5	14.4	14.7	-0.3
25/02/2016 01:00:00	13.63	14.33	13.29	13.8	12.5	15.1	14.1	14.4	-1.1
25/02/2016 02:00:00	13.32	13.98	12.87	13.32	12.2	14.8	13.7	14.0	-1.8
25/02/2016 03:00:00	13.04	13.68	12.53	12.9	11.9	14.4	13.4	13.6	-2.1
25/02/2016 04:00:00	12.98	13.39	12.23	12.5	11.6	14.1	13.1	13.3	-2.5
25/02/2016 05:00:00	12.57	13.11	11.93	12.14	11.4	13.8	12.7	12.9	-2.5
25/02/2016 06:00:00	12.57	13.12	12.3	11.84	11.6	13.8	12.7	12.6	-1.7
25/02/2016 07:00:00	14.31	14.38	14.96	12.68	14.3	15.6	14.2	13.5	-1.1
25/02/2016 08:00:00	14.23	14.6	14.91	13.63	14.3	15.6	14.4	14.1	-0.1
25/02/2016 09:00:00	13.58	14.22	13.87	13.57	13.1	15.4	13.8	13.8	1.1
25/02/2016 10:00:00	13.15	13.88	13.14	13.35	12.4	15.3	13.5	13.7	2.2
25/02/2016 11:00:00	13	13.6	12.77	13.55	12.4	15.3	13.3	14.0	3.8
25/02/2016 12:00:00	12.86	13.19	12.39	13.51	12.2	14.8	13.2	13.9	5.0
25/02/2016 13:00:00	12.76	12.97	12.23	13.4	12.0	14.5	13.1	13.7	5.5
25/02/2016 14:00:00	12.62	12.77	12.03	12.97	11.8	14.2	13.0	13.5	4.9
25/02/2016 15:00:00	12.38	12.59	11.78	12.57	11.6	13.7	12.9	13.2	4.6
25/02/2016 16:00:00	12.18	12.36	11.59	12.31	11.4	13.4	12.7	12.9	3.8
25/02/2016 17:00:00	11.99	12.14	11.52	12.25	11.3	13.2	12.5	12.8	3.1
25/02/2016 18:00:00	12.58	12.57	12.75	13.67	12.5	13.8	13.0	12.9	2.7
25/02/2016 19:00:00	14.53	14.23	15.73	15.01	15.6	15.6	14.8	14.1	2.6
25/02/2016 20:00:00	15.67	15.17	16.84	15.18	16.4	16.8	16.0	15.2	2.4
25/02/2016 21:00:00	15.08	14.77	15.68	15.08	15.0	16.7	15.4	15.3	2.2
25/02/2016 22:00:00	14.32	14.28	14.73	14.73	13.8	16.3	14.8	15.0	2.0
25/02/2016 23:00:00	13.78	14.06	14.02	14.29	13.1	15.8	14.3	14.7	1.9
26/02/2016 00:00:00	13.45	14.22	13.43	13.84	12.6	15.4	14.2	14.9	1.7
26/02/2016 01:00:00	13.18	14.05	12.96	13.44	12.2	15.0	13.9	14.6	1.4
26/02/2016 02:00:00	12.95	13.68	12.61	13.03	12.0	14.7	13.5	14.2	1.3
26/02/2016 03:00:00	12.75	13.33	12.3	12.68	11.7	14.4	13.2	13.7	1.2
26/02/2016 04:00:00	12.56	13.07	12.06	12.38	11.5	14.2	12.9	13.4	1.1

26/02/2016 05:00:00	12.37	12.83	11.81	12.07	11.3	13.9	12.7	13.0	1.0
26/02/2016 06:00:00	12.73	12.88	12.22	11.81	11.6	14.0	12.7	12.8	0.9
26/02/2016 07:00:00	14.49	14.3	14.91	12.84	14.4	15.8	14.4	13.8	1.0
26/02/2016 08:00:00	14.53	14.57	14.96	13.87	14.3	15.8	14.7	14.4	1.6
26/02/2016 09:00:00	13.93	14.32	13.93	13.78	13.2	15.6	14.1	14.2	3.2
26/02/2016 10:00:00	13.49	13.93	13.19	13.48	12.5	15.2	13.6	14.0	4.5
26/02/2016 11:00:00	13.11	13.47	12.76	12.99	12.1	14.7	13.2	13.6	5.7
26/02/2016 12:00:00	12.79	13.08	12.48	12.74	11.7	14.5	13.0	13.4	6.7
26/02/2016 13:00:00	12.7	12.83	12.31	12.76	11.7	14.4	12.9	13.4	7.1
26/02/2016 14:00:00	12.62	12.7	12.13	12.57	11.6	14.2	12.8	13.3	6.8
26/02/2016 15:00:00	12.48	12.55	11.9	12.37	11.5	13.7	12.7	13.1	6.1
26/02/2016 16:00:00	12.57	12.63	12.15	12.3	11.7	13.6	12.6	12.9	5.6
26/02/2016 17:00:00	14.07	13.77	14.54	13.47	13.9	15.1	14.1	13.8	4.6
26/02/2016 18:00:00	14.93	14.56	15.69	15.23	15.0	15.8	14.8	14.5	3.8
26/02/2016 19:00:00	16.32	15.91	17.79	16.59	17.2	17.1	16.1	15.6	2.3
26/02/2016 20:00:00	17.09	16.61	18.34	16.9	17.6	17.9	16.8	16.5	0.9
26/02/2016 21:00:00	16.49	16.23	16.98	16.59	16.0	17.5	16.3	16.5	0.3
26/02/2016 22:00:00	15.77	15.88	15.86	16.04	14.7	17.2	15.6	16.1	0.8
26/02/2016 23:00:00	15.12	15.44	15.1	15.38	13.9	16.7	15.1	15.6	1.1
27/02/2016 00:00:00	14.63	15.26	14.41	14.87	13.3	16.2	14.6	15.3	0.7
27/02/2016 01:00:00	14.23	14.9	13.83	14.41	12.9	15.8	14.2	15.0	-0.3
27/02/2016 02:00:00	13.91	14.52	13.43	13.91	12.6	15.4	13.8	14.5	-0.9
27/02/2016 03:00:00	13.57	14.15	13.05	13.43	12.3	15.1	13.5	14.1	-1.3
27/02/2016 04:00:00	13.3	13.82	12.73	12.96	12.0	14.7	13.2	13.7	-1.3
27/02/2016 05:00:00	12.98	13.52	12.47	12.55	11.7	14.4	12.9	13.4	-0.8
27/02/2016 06:00:00	13.19	13.51	12.78	12.26	12.0	14.4	12.8	13.1	-0.7
27/02/2016 07:00:00	15.11	14.83	15.32	12.59	14.6	16.1	14.6	13.6	-0.3
27/02/2016 08:00:00	15.2	15.02	15.34	13.19	14.5	16.3	14.9	14.3	0.6
27/02/2016 09:00:00	14.45	14.6	14.58	13.71	13.6	15.6	14.3	14.5	1.2
27/02/2016 10:00:00	13.96	14.17	14.15	14.32	13.1	15.2	13.9	14.3	2.1
27/02/2016 11:00:00	13.71	13.82	13.96	14.22	12.9	15.0	13.7	14.3	4.6
27/02/2016 12:00:00	13.51	13.61	13.86	13.88	12.8	14.8	13.5	14.2	6.1
27/02/2016 13:00:00	14.1	13.97	14.97	14.03	14.0	15.4	14.0	14.3	4.3
27/02/2016 14:00:00	14.65	14.31	15.45	14.16	14.7	16.2	14.7	14.6	4.6
27/02/2016 15:00:00	14.37	14.09	14.79	14.06	13.9	16.0	14.2	14.5	5.2
27/02/2016 16:00:00	14.01	13.85	14.3	13.88	13.3	15.8	13.9	14.5	5.1
27/02/2016 17:00:00	13.77	13.68	13.98	13.93	12.8	15.3	13.6	14.4	3.6
27/02/2016 18:00:00	14.28	14.04	14.91	15.07	13.8	15.6	14.2	14.5	2.5
27/02/2016 19:00:00	15.93	15.43	17.3	16.37	16.7	16.9	16.1	15.5	2.8
27/02/2016 20:00:00	16.87	16.35	18.12	17.13	17.5	17.8	17.0	16.4	2.8
27/02/2016 21:00:00	16.45	16.08	16.93	16.76	16.1	17.8	16.6	16.5	2.5
27/02/2016 22:00:00	15.74	15.6	15.93	16.11	14.8	17.4	15.9	16.2	1.8
27/02/2016 23:00:00	15.16	15.17	15.15	15.45	14.0	17.0	15.4	15.8	0.8
28/02/2016 00:00:00	14.69	14.92	14.51	14.83	13.5	16.5	14.9	15.4	0.8
28/02/2016 01:00:00	14.37	14.63	13.98	14.32	13.1	16.1	14.5	15.0	0.9
28/02/2016 02:00:00	14.31	14.37	13.59	13.8	12.7	15.7	14.1	14.6	0.8
28/02/2016 03:00:00	13.96	14.17	13.27	13.38	12.5	15.4	13.8	14.3	-0.3
28/02/2016 04:00:00	13.64	13.94	12.95	12.97	12.2	15.1	13.5	13.9	-0.9
28/02/2016 05:00:00	13.34	13.72	12.65	12.6	11.9	14.7	13.2	13.6	-1.3
28/02/2016 06:00:00	13.42	13.72	12.99	12.35	12.2	14.8	13.1	13.4	-1.2
28/02/2016 07:00:00	14.94	15.08	15.58	12.82	14.7	16.7	14.7	14.1	-0.5

28/02/2016 08:00:00	15.01	15.27	15.77	13.63	14.9	16.9	15.2	14.9	-0.2
28/02/2016 09:00:00	14.72	14.82	14.91	14.74	15.0	16.8	15.4	15.2	2.7
28/02/2016 10:00:00	14.34	14.5	14.45	15.3	14.5	16.5	15.0	15.0	4.4
28/02/2016 11:00:00	14.1	14.37	14.23	15.15	13.9	16.1	14.4	14.9	5.7
28/02/2016 12:00:00	14.1	14.68	14.19	15.26	13.9	15.7	14.4	15.1	6.4
28/02/2016 13:00:00	15.05	15.4	15.76	15.76	15.2	16.8	15.2	15.4	6.8
28/02/2016 14:00:00	15.94	15.93	16.76	15.83	16.0	17.7	16.1	16.1	6.2
28/02/2016 15:00:00	16.39	15.9	16.4	15.74	15.2	17.3	16.3	16.7	6.1
28/02/2016 16:00:00	15.93	15.68	15.79	15.58	14.7	17.1	16.0	16.5	4.2
28/02/2016 17:00:00	16.32	16.05	16.63	15.74	15.5	17.5	16.5	16.6	2.9
28/02/2016 18:00:00	17.02	16.73	17.83	16.83	16.6	18.0	17.0	16.9	1.4
28/02/2016 19:00:00	18.23	17.91	19.66	17.46	18.4	19.0	18.1	17.7	0.5
28/02/2016 20:00:00	18.76	18.42	20.2	17.58	18.7	19.6	18.7	18.4	-0.4
28/02/2016 21:00:00	18.03	17.88	18.69	17.68	17.2	19.2	18.0	18.1	-1.0
28/02/2016 22:00:00	17.17	17.38	17.58	17.48	15.9	18.7	17.3	17.6	-1.6
28/02/2016 23:00:00	16.44	16.95	16.66	16.61	15.0	18.1	16.7	17.1	-1.9
29/02/2016 00:00:00	15.92	16.48	15.88	15.77	14.4	17.5	16.1	16.6	-1.5
29/02/2016 01:00:00	15.44	16.06	15.26	15.09	13.9	17.0	15.6	16.1	-1.2
29/02/2016 02:00:00	15.05	15.68	14.77	14.53	13.5	16.6	15.2	15.6	-1.4
29/02/2016 03:00:00	14.7	15.33	14.32	14.06	13.2	16.2	14.8	15.2	-0.7
29/02/2016 04:00:00	14.4	15	13.97	13.64	12.9	15.9	14.5	14.8	-0.7
29/02/2016 05:00:00	14.29	14.69	13.64	13.23	12.6	15.5	14.1	14.4	-1.3
29/02/2016 06:00:00	14.31	14.61	13.99	12.92	12.8	15.5	14.0	14.1	-1.7
29/02/2016 07:00:00	15.82	15.78	16.59	13.43	15.3	17.2	15.7	14.8	-1.3
29/02/2016 08:00:00	15.87	15.99	16.36	14.44	15.4	16.9	16.0	15.6	0.0
29/02/2016 09:00:00	15.27	15.65	15.13	14.95	14.5	16.5	15.4	15.5	2.5
29/02/2016 10:00:00	14.81	15.14	14.38	15.68	14.0	16.1	15.1	15.3	4.6
29/02/2016 11:00:00	14.54	14.75	14.07	15.88	14.2	16.0	15.0	15.3	6.4
29/02/2016 12:00:00	14.32	14.48	13.82	15.81	14.0	15.7	14.8	15.1	7.0
29/02/2016 13:00:00	14.12	14.27	13.68	15.38	13.6	15.4	14.5	14.8	7.2
29/02/2016 14:00:00	13.92	14.08	13.44	14.75	13.2	15.0	14.3	14.6	6.9
29/02/2016 15:00:00	13.68	13.86	13.2	14.24	12.8	14.6	14.0	14.3	6.4
29/02/2016 16:00:00	13.55	13.73	13.17	13.9	12.7	14.4	13.8	14.0	5.8
29/02/2016 17:00:00	14.58	14.45	14.74	14.84	14.5	15.5	14.8	14.5	4.6
29/02/2016 18:00:00	15.38	15.08	15.92	15.83	15.6	16.1	15.4	15.1	3.9
29/02/2016 19:00:00	16.79	16.36	18.23	17.01	17.7	17.6	16.8	16.1	4.1
29/02/2016 20:00:00	17.5	17.02	19.17	17.42	18.4	18.4	17.4	16.9	4.1
29/02/2016 21:00:00	16.88	16.61	17.84	18.1	17.0	18.1	16.7	16.8	4.3
29/02/2016 22:00:00	16.17	16.11	16.58	18.02	15.7	17.8	16.1	16.4	4.0
29/02/2016 23:00:00	15.63	15.77	15.65	17.14	14.9	17.3	15.6	15.9	3.5

Appendix B: Selected hourly monitored room temperature in the Passive House.

Time	$T_{outdoor1}$	$T_{outdoor2}$	DHFR	MB	OR	LR
01-Feb						
00	8.2	8.0	21.0	21.5	21.5	22.1
01	9.2	9.1	20.9	21.4	21.5	21.8
02	9.7	9.7	20.8	21.3	21.4	21.6
03	10.2	10.2	20.7	21.3	21.3	21.4
04	10.2	10.2	20.6	21.2	21.3	21.3
05	10.1	10.1	20.5	21.1	21.2	21.1
06	10.1	10.1	20.4	21.0	21.1	21.0
07	9.9	9.9	20.5	21.1	21.1	21.1
08	10.0	10.0	20.9	21.3	21.2	21.4
09	10.7	10.6	20.9	21.9	21.3	21.4
10	11.3	11.3	21.0	21.8	21.5	21.5
11	10.9	11.0	21.0	21.6	21.8	21.7
12	11.0	11.0	21.1	21.5	22.2	22.2
13	10.9	10.9	21.2	21.4	22.5	23.2
14	10.1	10.2	21.5	21.4	22.6	23.6
15	9.6	9.6	21.5	21.4	22.7	23.8
16	8.8	8.8	21.3	21.3	22.4	23.3
17	7.9	7.9	20.9	21.3	22.3	22.8
18	7.4	7.4	20.7	21.2	22.4	22.5
19	7.5	7.4	20.5	21.1	22.3	22.3
20	6.6	6.6	20.5	21.0	22.0	22.3
21	5.8	5.7	20.4	20.9	22.0	22.2
22	5.8	5.7	20.5	20.9	21.8	22.4
23	5.9	5.7	20.7	21.4	21.7	22.6
02-Feb						
00	5.9	5.8	20.7	21.4	21.7	22.3
01	5.8	5.7	20.5	21.2	21.5	22.0
02	5.8	5.7	20.6	21.1	21.4	21.9
03	5.8	5.7	20.7	21.5	21.4	22.0
04	5.6	5.5	20.7	21.5	21.4	21.9
05	5.5	5.4	20.6	21.3	21.3	21.7
06	5.4	5.2	20.6	21.4	21.2	21.6
07	5.3	5.2	20.8	21.6	21.2	21.8
08	5.1	4.9	20.9	22.0	21.3	21.9
09	5.4	5.2	21.0	22.3	21.4	21.9
10	6.1	5.9	21.1	22.7	21.5	22.0
11	6.6	6.4	21.0	22.3	21.7	22.0
12	6.6	6.4	21.0	22.0	21.8	22.1
13	6.6	6.5	21.0	21.8	21.9	22.9
14	6.7	6.6	21.0	21.6	22.1	23.3
15	6.5	6.4	21.0	21.5	22.6	23.2
16	6.0	5.9	20.8	21.3	22.5	22.7
17	5.5	5.4	20.6	21.2	22.1	22.5
18	4.9	4.8	20.5	21.1	22.1	22.5
19	4.6	4.5	20.8	21.4	21.9	22.7
20	4.2	4.0	20.9	21.4	21.8	22.7
21	3.9	3.8	20.8	21.2	21.6	22.6

22	3.8	3.6	20.7	21.1	21.7	22.5
23	3.8	3.6	20.7	21.2	21.7	22.6
03-Feb						
00	3.7	3.5	20.9	21.3	21.4	22.5
01	3.6	3.4	20.8	21.3	21.2	22.3
02	3.3	3.2	20.8	21.2	21.0	22.1
03	3.1	2.8	20.9	21.5	20.9	22.1
04	3.3	3.1	20.8	21.4	20.8	22.0
05	3.6	3.4	20.8	21.4	20.7	22.0
06	3.6	3.4	20.9	21.6	20.7	22.0
07	3.7	3.5	20.9	21.8	20.6	21.8
08	3.5	3.3	20.7	21.7	20.6	21.5
09	3.7	3.4	20.8	22.1	20.6	21.7
10	4.2	4.0	20.9	22.2	21.0	22.0
11	4.9	4.6	20.9	22.0	21.3	22.2
12	5.5	5.2	21.0	21.8	21.4	22.5
13	5.9	5.7	21.1	21.6	21.7	23.6
14	6.2	6.0	21.1	21.5	21.9	24.0
15	6.1	6.0	21.1	21.3	22.1	23.7
16	5.6	5.5	21.0	21.2	22.0	23.2
17	5.1	5.0	20.7	21.1	21.9	22.7
18	4.7	4.6	20.6	21.0	22.0	22.3
19	4.3	4.2	20.7	21.1	22.1	22.4
20	3.8	3.8	21.0	21.3	22.0	22.7
21	3.8	3.7	21.0	21.5	21.9	22.9
22	4.2	4.0	21.1	21.6	21.8	23.0
23	4.6	4.4	21.0	21.8	21.7	22.8
04-Feb						
00	4.8	4.6	20.8	21.7	21.5	22.4
01	4.9	4.7	20.6	21.6	21.4	22.1
02	4.7	4.5	20.7	21.8	21.4	22.0
03	4.5	4.3	20.8	21.9	21.4	22.0
04	4.6	4.4	20.7	21.8	21.3	21.8
05	5.2	5.0	20.6	21.7	21.2	21.6
06	6.0	5.9	20.8	21.9	21.3	21.6
07	6.4	6.3	20.9	21.9	21.3	21.6
08	6.6	6.5	21.0	22.4	21.3	21.6
09	6.8	6.7	20.9	22.0	21.4	21.5
10	7.2	7.1	20.8	21.7	21.7	21.6
11	7.8	7.7	20.9	21.6	22.1	21.9
12	8.2	8.1	20.9	21.5	22.2	22.2
13	8.3	8.2	20.8	21.4	22.4	22.6
14	8.2	8.2	20.8	21.3	22.5	22.4
15	8.0	8.0	20.6	21.2	22.5	22.1
16	7.7	7.7	20.5	21.2	23.4	21.8
17	7.5	7.4	20.5	21.1	23.4	21.6
18	7.6	7.5	20.6	21.0	23.6	21.5
19	8.0	7.9	20.5	20.9	23.6	21.7
20	8.2	8.1	20.4	20.9	22.4	21.8
21	8.2	8.2	20.4	20.8	21.6	22.1
22	8.2	8.2	20.8	21.0	21.6	22.4

23	8.5	8.4	21.0	21.1	21.7	22.6
05-Feb						
00	8.8	8.7	21.1	21.2	21.7	22.4
01	8.7	8.6	21.0	21.1	21.6	22.1
02	8.7	8.6	20.8	21.1	21.5	21.8
03	8.9	8.8	20.6	21.0	21.4	21.6
04	8.9	8.9	20.5	21.0	21.3	21.5
05	8.8	8.8	20.4	21.0	21.2	21.3
06	8.7	8.6	20.5	21.0	21.2	21.5
07	8.7	8.7	20.9	21.3	21.3	21.7
08	8.6	8.6	21.0	22.1	21.5	21.7
09	8.7	8.6	20.9	22.0	21.5	21.7
10	8.6	8.6	20.7	21.7	21.9	21.5
11	8.8	8.7	20.7	21.5	21.9	21.5
12	9.2	9.1	20.7	21.3	22.2	21.6
13	9.6	9.5	20.7	21.2	22.3	21.9
14	9.7	9.7	20.7	21.2	22.5	22.1
15	9.5	9.5	20.7	21.1	22.6	22.1
16	9.1	9.1	20.6	21.0	22.6	21.9
17	9.1	9.0	20.5	20.9	22.5	21.7
18	8.8	8.8	20.5	20.9	22.6	21.7
19	8.7	8.7	20.4	20.8	22.6	21.7
20	8.6	8.7	20.4	20.7	22.3	21.8
21	7.3	7.4	20.4	20.7	22.0	22.0
22	6.2	6.2	20.4	20.6	21.8	22.2
23	5.8	5.8	20.7	20.8	22.1	22.6
06-Feb						
00	5.2	5.2	20.9	21.0	22.3	22.6
01	4.7	4.7	20.7	21.0	22.0	22.2
02	4.4	4.3	20.5	20.8	21.8	21.9
03	4.3	4.2	20.5	20.8	21.7	21.8
04	4.0	3.8	20.7	21.0	21.6	21.9
05	4.2	3.9	20.7	21.2	21.6	21.9
06	3.8	3.5	20.7	21.4	21.5	21.9
07	3.7	3.4	20.8	22.1	21.5	22.0
08	3.7	3.4	20.8	22.6	21.5	21.9
09	4.3	4.0	20.9	22.6	21.7	22.0
10	4.6	4.4	21.0	22.4	21.7	21.9
11	4.7	4.5	20.9	22.0	21.7	21.8
12	5.1	4.8	20.8	21.7	21.6	21.7
13	5.6	5.4	20.8	21.5	21.7	21.6
14	6.5	6.3	20.7	21.3	21.7	21.5
15	7.2	7.1	20.7	21.1	21.8	21.4
16	7.6	7.5	20.7	21.0	21.7	21.4
17	7.7	7.6	20.7	21.0	21.9	21.3
18	7.8	7.8	20.6	21.3	22.1	21.3
19	7.8	7.8	20.5	21.1	21.9	21.2
20	7.8	7.8	20.4	20.9	21.7	21.1
21	7.5	7.5	20.6	21.0	21.6	24.9
22	7.1	7.1	20.8	21.0	21.5	24.9
23	6.8	6.7	20.9	21.0	21.4	24.1

07-Feb						
00	6.2	6.1	21.0	20.9	21.4	23.3
01	6.0	5.9	20.8	20.9	21.3	22.7
02	5.5	5.4	20.6	20.8	21.2	22.2
03	5.2	5.1	20.3	20.8	21.1	21.9
04	5.1	4.9	20.4	20.8	21.0	21.9
05	4.8	4.7	20.6	21.0	20.9	21.9
06	4.7	4.5	20.8	21.2	20.9	21.9
07	4.3	4.2	20.8	21.6	20.8	21.9
08	4.1	4.0	20.9	22.0	20.8	21.9
09	4.4	4.2	20.9	22.2	20.9	22.1
10	5.0	4.8	21.0	22.5	21.0	22.5
11	5.4	5.2	21.0	22.6	21.6	22.8
12	6.4	6.2	21.0	22.4	21.9	22.9
13	7.2	7.0	21.0	22.1	21.9	23.3
14	6.9	6.8	20.9	21.9	21.9	23.5
15	6.5	6.4	20.8	21.7	22.0	23.2
16	6.4	6.3	20.9	21.6	21.8	22.9
17	6.0	5.9	20.8	21.4	21.7	22.6
18	5.4	5.3	20.8	21.3	21.6	22.6
19	4.7	4.6	20.7	21.1	21.5	22.7
20	4.0	3.9	20.5	21.0	21.5	22.9
21	4.6	4.3	20.5	21.1	21.5	23.0
22	5.1	4.9	20.9	21.3	21.6	23.1
23	5.4	5.3	20.8	21.7	21.5	22.8
08-Feb						
00	5.8	5.6	20.6	21.4	21.4	22.4
01	5.6	5.5	20.6	21.3	21.3	22.2
02	5.3	5.2	20.7	21.4	21.3	22.2
03	4.9	4.8	20.8	21.5	21.3	22.2
04	5.0	4.8	20.9	21.7	21.3	22.2
05	5.0	4.8	20.9	21.8	21.3	22.2
06	5.1	4.9	20.9	21.9	21.3	22.0
07	5.2	5.0	20.9	21.9	21.3	21.9
08	5.3	5.1	21.0	22.6	21.4	21.9
09	5.5	5.3	20.9	22.3	21.5	21.9
10	5.8	5.6	20.8	21.8	21.7	22.2
11	6.4	6.2	20.7	21.6	22.0	22.4
12	7.1	6.9	20.7	21.5	22.1	22.5
13	7.5	7.3	20.7	21.4	22.3	22.8
14	7.4	7.3	20.7	21.3	22.3	22.7
15	7.4	7.3	20.7	21.3	22.5	22.7
16	6.9	6.9	20.6	21.2	22.5	22.3
17	6.6	6.5	20.5	21.1	22.1	22.1
18	6.3	6.2	20.4	21.0	22.8	22.1
19	6.1	6.0	20.6	21.1	23.6	22.5
20	6.3	6.1	21.0	21.5	23.7	22.6
21	6.5	6.3	21.0	21.6	23.8	22.8
22	6.2	6.1	20.9	21.4	23.7	22.9
23	5.7	5.6	20.8	21.6	22.6	22.6
09-Feb						

00	5.5	5.3	20.7	21.4	21.8	22.3
01	5.4	5.3	20.5	21.3	21.6	22.1
02	5.3	5.1	20.6	21.3	21.4	22.0
03	5.2	5.0	20.8	21.5	21.3	22.0
04	5.1	4.9	20.9	21.6	21.2	22.1
05	5.0	4.8	20.9	21.8	21.2	22.1
06	4.8	4.6	20.9	21.9	21.1	22.0
07	4.6	4.4	20.9	21.9	21.1	21.8
08	4.5	4.3	20.9	21.7	21.0	21.7
09	4.4	4.3	21.0	21.8	21.0	21.9
10	4.7	4.5	21.1	22.0	21.4	22.0
11	5.1	4.9	21.2	21.8	21.5	22.1
12	5.5	5.3	21.1	21.7	21.7	22.2
13	5.7	5.5	21.2	21.5	21.6	22.1
14	5.6	5.4	21.1	21.3	21.5	22.0
15	5.4	5.3	21.0	21.2	21.5	21.9
16	5.2	5.1	20.8	21.1	21.6	21.7
17	5.1	4.9	20.7	21.3	21.6	21.5
18	5.0	4.8	20.6	21.0	21.5	21.5
19	4.8	4.7	20.5	20.8	21.5	21.7
20	4.7	4.6	20.4	20.7	21.4	21.8
21	4.3	4.3	20.3	20.6	21.3	21.9
22	3.6	3.7	20.5	20.7	21.3	22.1
23	3.0	3.1	20.6	21.4	21.4	22.3
10-Feb						
00	2.8	2.7	20.6	22.1	21.3	22.2
01	3.9	3.6	20.7	22.1	21.3	22.1
02	4.3	4.1	20.7	22.3	21.3	22.0
03	4.4	4.2	20.7	22.4	21.2	21.9
04	4.3	4.2	20.7	22.5	21.2	21.9
05	3.9	3.8	20.8	22.6	21.2	21.8
06	3.6	3.4	20.8	22.5	21.2	21.8
07	2.9	2.9	20.8	22.5	21.2	21.8
08	2.2	2.1	20.8	22.5	21.1	21.8
09	3.1	2.7	20.8	22.8	21.2	21.8
10	4.2	3.9	20.8	23.2	21.4	22.3
11	4.9	4.6	21.1	23.5	21.9	22.8
12	5.5	5.3	21.3	23.6	22.0	23.4
13	6.0	5.8	21.4	23.4	22.2	24.9
14	5.8	5.6	21.4	22.9	22.4	25.5
15	5.5	5.3	21.3	22.6	22.6	24.7
16	5.2	5.1	21.1	22.3	22.4	24.1
17	4.6	4.5	20.9	22.2	22.0	23.5
18	3.9	3.9	21.0	22.2	22.2	23.3
19	3.5	3.3	21.2	22.2	22.9	23.6
20	3.3	3.2	21.3	22.3	23.0	23.6
21	3.4	3.2	21.2	22.3	23.1	23.6
22	3.3	3.1	21.3	22.2	23.1	23.6
23	2.8	2.8	21.3	22.9	23.0	23.5
11-Feb						
00	2.7	2.5	21.0	22.6	23.0	23.0

01	2.8	2.6	20.8	22.2	22.9	22.6
02	2.8	2.6	20.9	22.2	22.9	22.5
03	2.7	2.5	21.0	22.4	22.9	22.5
04	2.5	2.3	21.0	22.5	22.9	22.5
05	2.0	1.9	21.0	22.7	22.9	22.4
06	2.1	2.0	21.0	22.8	22.9	22.3
07	1.6	1.6	21.0	23.0	22.9	22.2
08	1.9	1.6	21.0	23.4	22.9	22.2
09	2.6	2.3	21.0	23.4	23.0	22.3
10	3.8	3.4	21.1	23.3	22.8	22.5
11	4.6	4.3	21.1	23.4	22.7	23.0
12	5.4	5.2	21.2	23.1	22.5	23.3
13	5.9	5.7	21.3	22.8	22.6	24.7
14	6.2	6.0	21.4	22.5	22.9	25.7
15	6.1	6.0	21.4	22.3	23.1	25.5
16	5.4	5.4	20.7	22.1	22.9	24.8
17	4.1	4.2	20.4	21.9	22.6	24.1
18	2.8	2.9	20.2	21.8	22.4	23.7
19	1.9	1.9	20.5	21.9	22.3	23.9
20	1.2	1.1	20.6	22.1	22.0	23.9
21	0.4	0.3	20.7	22.2	21.7	23.9
22	-0.2	-0.4	20.6	22.7	21.5	24.0
23	-0.7	-1.0	20.5	23.2	21.4	23.9
12-Feb						
00	-0.8	-1.1	20.3	23.4	21.2	23.7
01	-1.1	-1.4	20.2	23.5	21.1	23.4
02	-1.2	-1.6	20.1	23.6	20.9	23.2
03	-0.9	-1.3	20.0	23.7	20.8	23.1
04	-0.9	-1.2	20.0	23.7	20.6	23.0
05	-0.3	-0.7	19.9	23.7	20.5	22.9
06	-0.4	-0.6	19.9	23.7	20.4	22.8
07	-0.9	-1.2	19.9	23.7	20.4	22.7
08	-0.9	-1.3	19.9	23.8	20.3	22.6
09	0.3	-0.2	20.0	24.4	20.8	22.7
10	1.4	0.9	20.1	24.0	21.2	22.9
11	2.9	2.4	20.2	23.8	21.5	23.4
12	3.7	3.4	20.4	23.6	21.8	23.7
13	4.2	3.9	20.8	23.5	22.1	23.9
14	4.7	4.4	20.8	23.4	22.4	24.3
15	4.7	4.5	20.8	23.0	22.4	24.2
16	4.6	4.4	20.5	22.7	22.2	23.7
17	4.1	4.0	20.2	22.5	21.8	23.3
18	3.4	3.3	20.4	22.6	21.8	23.5
19	2.9	2.7	20.6	22.8	21.8	23.6
20	2.7	2.5	20.7	22.9	21.8	23.6
21	2.8	2.6	20.7	23.0	21.9	23.7
22	2.3	2.2	20.6	22.7	21.8	23.6
23	1.2	1.0	20.3	22.6	21.7	23.1
13-Feb						
00	0.7	0.4	20.0	22.3	21.5	22.7
01	1.0	0.7	20.2	22.5	21.5	22.9

02	1.5	1.2	20.2	22.7	21.5	23.0
03	1.9	1.6	20.1	23.0	21.4	22.7
04	2.1	1.8	20.2	23.3	21.5	22.8
05	2.0	1.9	20.2	23.0	21.4	22.5
06	2.2	1.9	20.1	22.8	21.3	22.3
07	2.0	1.9	20.2	23.4	21.4	22.5
08	2.2	1.9	20.2	23.0	21.4	22.3
09	2.7	2.4	20.5	22.8	21.2	22.5
10	3.1	2.8	20.6	22.7	21.3	22.4
11	3.7	3.5	20.4	22.4	21.3	22.2
12	3.9	3.6	20.3	22.2	21.2	22.0
13	4.4	4.1	20.1	22.0	21.3	21.9
14	4.0	3.8	20.0	21.8	21.2	21.8
15	4.2	3.9	19.9	21.7	21.2	21.8
16	4.3	4.0	19.9	21.6	21.1	21.6
17	3.8	3.6	20.2	21.8	21.0	21.9
18	3.3	3.1	20.3	21.8	20.8	21.7
19	3.3	3.1	20.1	21.7	20.8	21.4
20	3.3	3.1	20.0	21.6	20.7	21.2
21	3.2	3.0	20.4	21.8	20.6	21.6
22	3.1	2.9	20.5	22.0	20.6	21.7
23	2.8	2.7	20.4	21.9	20.6	21.5
14-Feb						
00	2.6	2.4	20.2	21.7	20.5	21.2
01	2.7	2.5	20.0	21.5	20.4	20.9
02	2.5	2.4	20.3	21.7	20.3	21.3
03	2.4	2.3	20.4	21.8	20.3	21.4
04	2.4	2.2	20.2	21.7	20.3	21.1
05	2.3	2.1	20.1	21.5	20.2	20.8
06	2.2	2.0	20.3	21.7	20.1	21.2
07	2.3	2.1	20.4	21.9	20.1	21.3
08	2.0	1.8	20.3	21.8	20.1	21.0
09	1.9	1.6	20.1	21.5	20.2	20.7
10	2.0	1.7	19.9	21.4	20.4	20.9
11	2.8	2.5	19.8	21.3	20.5	21.2
12	2.8	2.5	19.7	21.2	20.5	21.2
13	3.0	2.7	19.9	21.3	20.5	21.8
14	3.1	2.9	20.3	21.4	20.6	22.3
15	3.4	3.1	20.4	21.3	20.9	22.6
16	3.1	3.0	20.2	21.2	20.9	22.4
17	2.3	2.1	20.2	21.2	20.6	22.0
18	2.1	1.8	20.4	21.5	20.5	22.2
19	1.7	1.5	20.5	21.7	20.4	22.2
20	1.7	1.4	20.6	22.0	20.4	22.2
21	1.8	1.5	20.6	22.2	20.4	22.2
22	1.8	1.5	20.6	22.3	20.4	22.1
23	1.8	1.5	20.4	22.2	20.4	22.0
15-Feb						
00	1.9	1.6	20.5	22.4	20.4	22.1
01	1.8	1.5	20.6	22.5	20.3	21.6
02	1.5	1.3	20.6	22.6	20.3	21.2

03	1.3	1.1	20.4	22.4	20.2	20.9
04	1.2	0.9	20.2	22.1	20.1	20.6
05	1.1	0.8	20.4	22.2	20.0	20.3
06	1.0	0.7	20.5	22.6	20.0	20.1
07	0.8	0.4	20.3	22.6	20.0	19.9
08	0.9	0.6	20.2	23.2	19.9	20.3
09	1.0	0.6	20.5	23.2	20.1	21.0
10	1.1	0.7	20.4	22.8	20.4	21.5
11	1.5	1.1	20.2	22.5	20.7	21.6
12	2.5	2.2	20.0	22.2	20.8	22.0
13	3.2	2.9	20.0	22.0	20.7	23.1
14	3.4	3.2	20.1	21.8	20.8	23.9
15	3.5	3.3	20.1	21.7	21.2	24.0
16	3.3	3.1	19.9	21.6	21.0	23.6
17	2.8	2.7	20.0	21.6	20.7	23.4
18	2.1	2.0	20.4	22.1	20.5	23.5
19	1.2	1.3	20.5	22.5	20.4	23.5
20	0.8	0.7	20.5	22.6	20.3	23.5
21	0.1	0.0	20.4	22.5	20.8	23.2
22	-0.3	-0.5	20.5	22.7	21.1	23.5
23	-0.2	-0.4	20.5	22.9	21.0	23.6
16-Feb						
00	-0.3	-0.5	20.4	23.1	21.0	23.5
01	-0.3	-0.5	20.4	23.2	21.0	23.3
02	0.1	-0.2	20.3	23.5	20.9	23.2
03	0.0	-0.3	20.3	23.7	20.9	23.1
04	0.1	-0.3	20.3	23.8	20.9	23.0
05	0.2	-0.2	20.2	23.8	20.9	23.0
06	0.0	-0.3	20.2	23.8	20.8	22.9
07	0.0	-0.3	20.2	24.2	20.8	22.9
08	0.4	0.0	20.4	24.6	21.0	22.9
09	1.2	0.8	20.4	24.3	21.2	23.0
10	1.9	1.5	20.3	23.8	21.2	22.9
11	2.8	2.4	20.2	23.5	21.2	23.3
12	3.6	3.3	20.6	23.5	21.2	23.7
13	4.5	4.2	20.7	23.3	21.2	24.2
14	4.7	4.5	20.7	23.0	21.2	24.5
15	4.8	4.5	20.6	22.7	21.1	23.8
16	4.7	4.5	20.4	22.5	20.9	23.2
17	4.4	4.2	20.1	22.3	20.7	22.8
18	4.3	4.1	20.0	22.3	20.6	22.8
19	4.3	4.1	20.4	22.7	20.5	23.1
20	4.4	4.2	20.6	22.8	20.8	23.2
21	4.4	4.2	20.4	22.5	20.8	23.2
22	4.3	4.1	20.2	22.4	20.5	23.1
23	4.4	4.1	20.3	22.4	20.5	23.3
17-Feb						
00	4.3	4.1	20.4	22.3	20.4	23.0
01	4.2	4.0	20.2	22.1	20.4	22.7
02	4.0	3.7	19.9	22.0	20.3	22.4
03	3.8	3.6	20.0	22.1	20.3	22.4

04	3.7	3.4	20.2	22.4	20.3	22.5
05	3.6	3.4	20.1	22.2	20.2	22.2
06	3.5	3.3	20.0	22.0	20.2	21.9
07	3.5	3.2	20.1	22.1	20.2	22.1
08	3.6	3.4	20.3	22.7	20.2	22.2
09	3.8	3.5	20.2	22.7	20.3	22.1
10	3.9	3.6	20.2	22.3	20.3	22.0
11	4.0	3.8	20.1	22.0	20.4	21.9
12	4.3	4.0	20.0	21.8	20.7	22.0
13	4.4	4.1	19.9	21.7	20.7	22.0
14	4.3	4.1	20.3	21.8	20.7	22.3
15	4.1	4.0	20.4	21.8	20.6	22.3
16	4.0	3.8	20.2	21.8	20.6	22.2
17	3.9	3.7	20.0	21.7	20.5	22.1
18	3.7	3.6	20.2	21.8	20.4	22.5
19	3.5	3.4	20.4	22.3	20.4	22.6
20	3.4	3.2	20.3	22.1	20.3	22.6
21	3.1	3.0	20.1	21.9	20.3	22.6
22	3.1	2.9	20.2	22.0	20.2	22.9
23	3.0	2.8	20.4	22.2	20.2	23.0
18-Feb						
00	2.7	2.6	20.4	22.1	20.2	22.6
01	2.4	2.3	20.1	21.9	20.1	22.2
02	2.3	2.1	20.0	21.8	20.1	22.0
03	1.9	1.8	20.2	22.1	20.0	22.2
04	1.4	1.3	20.3	22.5	20.0	22.3
05	0.8	0.8	20.3	22.8	19.9	22.4
06	0.4	0.3	20.4	23.1	19.9	22.4
07	0.1	0.0	20.4	23.3	19.9	22.4
08	0.7	0.3	20.5	23.8	19.9	22.5
09	1.6	1.2	20.6	24.1	20.0	22.7
10	2.7	2.4	20.5	24.3	20.3	22.8
11	4.0	3.6	20.7	24.2	20.8	23.4
12	4.9	4.6	20.7	24.1	21.4	23.3
13	5.4	5.1	20.7	23.5	21.3	24.2
14	5.8	5.7	20.8	23.1	21.2	25.4
15	5.8	5.6	20.8	22.8	21.3	24.9
16	5.8	5.6	20.8	22.5	21.3	24.9
17	4.9	4.8	20.5	22.3	21.3	24.2
18	4.2	4.1	20.3	22.2	21.2	23.6
19	3.6	3.5	20.1	22.0	21.1	23.1
20	3.2	3.1	20.4	22.4	21.1	23.6
21	2.8	2.7	20.6	23.2	21.2	24.0
22	2.7	2.5	20.7	23.5	21.2	24.1
23	2.3	2.2	20.6	23.1	21.1	23.7
19-Feb						
00	2.0	1.8	20.3	22.8	20.9	23.1
01	1.9	1.7	20.5	22.8	20.7	23.1
02	1.9	1.7	20.5	22.9	20.6	23.0
03	1.9	1.6	20.3	22.6	20.5	22.6
04	2.0	1.7	20.3	22.5	20.4	22.5

05	2.0	1.7	20.5	22.7	20.4	22.6
06	1.9	1.6	20.3	22.6	20.3	22.3
07	1.8	1.5	20.3	22.5	20.2	22.1
08	2.2	1.7	20.6	22.8	20.3	22.4
09	2.7	2.4	20.5	23.1	20.4	22.4
10	3.5	3.1	20.3	22.6	20.5	22.5
11	4.3	4.0	20.2	22.4	20.7	22.8
12	5.1	4.8	20.1	22.2	20.7	22.9
13	5.5	5.3	20.0	22.0	20.7	23.1
14	5.5	5.3	19.9	21.9	20.7	23.0
15	5.9	5.7	19.8	21.9	20.6	22.7
16	6.3	6.1	19.9	21.8	20.6	22.6
17	6.3	6.2	20.3	21.9	20.5	23.0
18	6.0	5.9	20.4	21.9	20.5	23.0
19	6.2	6.0	20.4	22.0	20.5	22.8
20	7.0	6.8	20.3	22.0	20.5	22.6
21	7.7	7.5	20.2	21.9	20.5	22.4
22	7.6	7.5	20.1	21.8	20.5	22.4
23	7.2	7.2	20.1	21.9	20.4	22.3
20-Feb						
00	7.0	7.0	20.4	22.0	20.3	22.4
01	6.2	6.3	20.3	21.9	20.2	22.2
02	5.7	5.7	20.1	21.8	20.2	22.0
03	5.7	5.6	20.0	21.7	20.1	21.9
04	5.9	5.8	20.3	21.9	20.1	22.2
05	5.7	5.7	20.3	21.9	20.1	22.0
06	5.7	5.7	20.2	21.8	20.0	21.8
07	5.8	5.7	20.2	21.8	20.0	21.9
08	6.1	5.9	20.5	22.2	20.0	22.2
09	6.3	6.2	20.5	22.5	20.4	22.2
10	6.5	6.4	20.4	22.5	20.5	22.2
11	6.7	6.6	20.3	22.2	20.5	22.1
12	7.2	7.1	20.2	22.0	20.7	22.1
13	7.7	7.5	20.2	21.8	20.7	22.1
14	7.9	7.8	20.2	21.7	20.8	22.4
15	7.6	7.6	20.3	21.7	20.8	22.3
16	7.5	7.5	20.1	21.6	20.7	22.2
17	7.3	7.3	20.4	21.9	20.6	23.0
18	7.4	7.3	20.5	22.2	20.6	22.9
19	6.8	6.9	20.4	22.0	20.5	22.5
20	6.3	6.3	20.2	21.8	20.5	22.3
21	6.2	6.1	20.1	21.7	20.4	22.0
22	6.1	6.1	19.9	21.6	20.3	21.8
23	6.2	6.1	20.1	22.0	20.3	22.1
21-Feb						
00	5.9	5.9	20.3	22.2	20.3	22.3
01	5.9	5.9	20.2	21.8	20.2	22.0
02	6.1	6.0	20.0	21.6	20.2	21.7
03	6.3	6.2	19.8	21.4	20.1	21.5
04	6.4	6.3	20.0	21.8	20.1	21.9
05	6.3	6.3	20.2	22.0	20.1	22.0

06	5.8	5.9	20.2	21.7	20.1	21.7
07	5.8	5.7	20.1	21.6	20.1	21.6
08	6.7	6.4	20.2	21.6	20.1	21.6
09	7.4	7.2	20.1	21.4	20.2	21.4
10	7.6	7.5	20.0	21.3	20.3	21.3
11	8.0	7.9	20.0	21.2	20.4	21.2
12	8.6	8.5	19.9	21.1	20.5	21.2
13	8.9	8.8	19.8	21.1	20.5	21.1
14	9.4	9.3	19.8	21.0	20.5	21.0
15	9.9	9.8	19.9	21.2	20.6	21.3
16	9.2	9.4	20.4	21.8	20.6	21.8
17	8.5	8.6	20.5	21.7	20.6	21.7
18	8.0	8.1	20.3	21.5	20.6	21.6
19	7.3	7.5	20.2	21.3	20.5	21.4
20	6.7	6.8	20.0	21.2	20.5	21.2
21	6.0	6.1	20.2	21.7	20.4	21.6
22	5.4	5.5	20.3	22.0	20.4	21.8
23	4.8	4.9	20.3	21.8	20.4	21.7
22-Feb						
00	4.6	4.6	20.3	21.6	20.3	21.7
01	4.2	4.2	20.0	21.3	20.2	21.4
02	3.6	3.6	20.1	21.7	20.2	21.6
03	3.4	3.3	20.2	22.3	20.1	21.9
04	3.2	3.1	20.2	22.3	20.1	21.9
05	3.2	3.1	20.2	22.5	20.1	21.9
06	3.3	3.1	20.3	22.5	20.1	21.9
07	3.3	3.1	20.2	22.2	20.0	21.8
08	3.7	3.4	20.4	22.5	20.1	21.9
09	4.6	4.3	20.5	22.3	20.2	22.0
10	5.4	5.1	20.4	22.0	20.4	22.0
11	6.3	6.0	20.3	21.9	20.5	22.3
12	6.9	6.6	20.3	21.8	20.6	22.6
13	7.2	7.0	20.3	21.7	20.7	23.2
14	7.7	7.4	20.4	21.6	20.9	24.0
15	7.6	7.6	20.5	21.5	21.2	24.1
16	7.0	7.1	20.5	21.4	21.1	24.2
17	6.6	6.7	20.4	21.3	21.0	23.7
18	5.5	6.0	20.2	21.3	20.8	23.1
19	5.0	5.3	20.1	21.2	20.7	22.7
20	4.7	4.9	20.0	21.9	20.6	22.7
21	4.4	4.6	20.4	22.2	20.5	23.1
22	3.7	4.0	20.5	22.0	20.5	23.3
23	3.9	3.8	20.4	21.8	20.4	23.1
23-Feb						
00	3.5	3.7	20.4	21.7	20.3	22.8
01	2.8	3.1	20.2	21.5	20.3	22.4
02	2.4	2.6	19.9	21.4	20.1	22.1
03	1.8	2.1	20.1	21.8	20.1	22.4
04	1.5	1.6	20.2	22.3	20.0	22.6
05	1.4	1.4	20.2	22.2	20.0	22.4
06	1.3	1.3	20.3	22.5	19.9	22.5

07	1.2	1.1	20.3	22.7	19.9	22.3
08	1.4	1.2	20.2	22.6	20.4	22.0
09	2.2	1.7	20.2	22.6	20.9	22.3
10	3.4	2.8	20.3	22.7	21.3	22.5
11	4.4	3.8	20.3	22.5	21.4	22.8
12	5.3	4.8	20.3	22.3	21.5	23.0
13	5.8	5.4	20.3	22.1	21.6	23.4
14	5.5	5.4	20.3	21.9	21.6	23.3
15	5.3	5.2	20.2	21.7	21.5	22.9
16	5.2	5.1	20.2	21.6	21.3	22.8
17	4.6	4.7	20.1	21.5	21.4	22.5
18	3.2	3.6	19.8	21.3	21.6	22.3
19	1.8	2.3	19.6	21.2	21.7	22.2
20	1.1	1.4	19.6	21.3	21.4	22.6
21	1.3	1.3	19.9	21.8	21.5	23.2
22	0.8	1.0	20.1	22.2	21.5	23.4
23	-0.1	0.1	20.1	22.6	21.5	23.5
24-Feb						
00	-0.7	-0.6	20.0	22.4	21.4	23.1
01	-1.3	-1.2	19.7	22.0	21.2	22.6
02	-1.6	-1.6	19.7	22.2	21.2	22.6
03	-2.2	-2.2	19.8	22.5	21.2	22.6
04	-2.6	-2.7	19.7	22.7	21.1	22.6
05	-3.0	-3.1	19.7	23.0	21.0	22.5
06	-2.9	-3.2	19.6	23.6	20.9	22.5
07	-3.1	-3.3	19.6	23.8	20.9	22.4
08	-2.7	-3.1	19.7	24.4	21.0	22.4
09	-0.9	-1.7	19.9	24.3	21.3	22.6
10	1.1	0.1	20.1	24.1	21.5	22.7
11	2.8	1.9	20.1	23.6	21.7	22.8
12	3.8	3.2	20.1	23.2	21.8	23.2
13	4.1	3.6	20.2	22.9	21.9	23.6
14	3.9	3.6	20.2	22.6	21.9	23.9
15	4.7	4.1	20.4	22.3	22.3	24.4
16	4.2	4.1	20.4	22.1	22.1	24.0
17	3.5	3.5	20.3	21.9	21.9	23.4
18	3.3	3.3	20.0	21.7	21.9	22.9
19	2.9	2.9	19.7	21.5	21.8	22.6
20	2.2	2.3	19.5	21.4	21.4	22.2
21	1.8	1.9	19.5	21.5	21.2	22.3
22	1.1	1.3	19.8	22.0	21.3	23.0
23	0.9	1.0	19.9	22.3	21.3	23.1
25-Feb						
00	0.5	0.6	19.9	22.0	21.2	22.7
01	-0.3	-0.1	19.5	21.7	21.0	22.2
02	-0.9	-0.8	19.6	22.0	21.0	22.3
03	-1.4	-1.4	19.7	22.5	21.1	22.5
04	-1.5	-1.6	19.7	22.9	21.0	22.5
05	-1.5	-1.6	19.7	23.3	20.9	22.5
06	-1.6	-1.7	19.7	23.5	20.9	22.4
07	-1.2	-1.5	19.7	23.6	20.9	22.4

08	-0.5	-0.9	19.8	23.9	21.0	22.4
09	0.6	-0.1	19.9	23.8	21.3	22.3
10	1.9	1.2	19.9	23.0	21.4	22.2
11	3.1	2.3	19.8	22.5	21.5	22.3
12	4.3	3.6	19.8	22.2	21.6	22.6
13	4.9	4.5	19.9	22.0	21.7	22.7
14	5.1	4.9	19.9	21.8	21.8	22.8
15	4.6	4.5	20.4	21.8	22.0	22.9
16	4.1	4.1	20.4	21.6	21.9	22.6
17	3.6	3.6	20.2	21.4	21.8	22.3
18	3.2	3.2	19.9	21.4	21.8	22.1
19	2.9	2.9	19.7	21.3	21.7	22.2
20	2.6	2.6	20.1	21.7	21.7	22.7
21	2.4	2.4	20.2	22.1	21.7	23.0
22	2.2	2.2	20.1	22.0	21.6	22.9
23	2.2	2.1	20.2	22.0	21.7	22.9
26-Feb						
00	2.1	2.0	20.2	22.0	21.6	22.6
01	2.2	2.0	19.9	21.7	21.4	22.2
02	2.2	2.0	19.6	21.5	21.3	21.8
03	2.0	1.8	19.4	21.4	21.1	21.5
04	1.9	1.8	19.5	21.4	21.1	21.8
05	1.9	1.8	19.7	21.8	21.1	22.0
06	1.9	1.7	19.7	21.9	21.1	21.7
07	2.0	1.7	19.6	21.9	21.0	21.5
08	2.2	1.8	19.6	22.4	21.0	21.4
09	2.4	2.1	19.5	22.5	21.1	21.3
10	3.1	2.7	19.7	22.3	21.0	21.8
11	3.8	3.5	20.0	22.1	21.2	22.0
12	4.5	4.2	20.0	21.7	21.7	21.9
13	4.5	4.3	19.9	21.5	21.9	21.7
14	4.7	4.5	19.7	21.2	21.8	21.7
15	4.7	4.6	19.6	21.1	21.6	21.6
16	4.4	4.3	19.4	20.9	21.4	21.4
17	3.8	3.8	19.3	20.8	21.3	21.2
18	3.3	3.3	19.4	20.7	21.2	21.1
19	2.7	2.8	19.8	21.2	21.1	21.6
20	2.1	2.2	19.9	21.4	21.0	21.7
21	1.8	1.8	19.7	21.1	20.9	21.5
22	2.0	1.9	19.4	20.9	20.7	21.4
23	1.6	1.6	19.3	21.1	20.6	21.5
27-Feb						
00	1.3	1.2	19.6	21.7	20.6	21.8
01	1.4	1.3	19.7	22.1	20.5	21.9
02	1.5	1.3	19.7	22.3	20.5	21.8
03	1.4	1.3	19.5	21.9	20.5	21.4
04	1.4	1.2	19.3	21.6	20.4	21.2
05	1.4	1.2	19.5	22.0	20.3	21.5
06	1.4	1.2	19.7	22.4	20.3	21.6
07	1.4	1.2	19.7	22.9	20.3	21.8
08	1.6	1.4	19.8	23.9	20.4	21.8

09	2.1	1.8	19.8	23.6	20.7	21.8
10	2.9	2.4	19.7	22.8	21.1	21.7
11	4.2	3.6	19.7	22.4	21.3	21.9
12	5.6	5.1	19.6	22.1	21.4	22.2
13	6.3	6.1	19.7	21.8	21.5	22.4
14	6.0	6.0	19.6	21.6	21.5	22.2
15	5.5	5.5	19.5	21.4	21.4	21.9
16	5.2	5.1	19.5	21.3	21.2	21.6
17	4.8	4.8	19.4	21.1	21.1	21.4
18	4.2	4.3	19.5	21.1	21.0	21.4
19	3.6	3.8	19.9	21.5	21.2	21.9
20	3.5	3.5	20.0	21.4	21.1	21.8
21	3.4	3.4	19.8	21.2	21.1	21.6
22	3.0	3.1	19.7	21.0	21.0	21.5
23	2.6	2.7	19.5	21.0	21.0	21.4
28-Feb						
00	2.2	2.2	19.8	21.3	21.1	21.7
01	1.8	1.8	19.7	21.4	21.1	21.5
02	1.9	1.8	19.5	21.3	20.9	21.1
03	1.6	1.6	19.4	21.3	20.9	21.1
04	1.3	1.3	19.6	21.9	21.0	21.4
05	1.2	1.1	19.8	22.4	21.1	21.6
06	1.1	1.1	19.8	22.6	21.1	21.6
07	1.1	1.0	19.8	22.4	21.1	21.3
08	1.5	1.3	19.7	22.2	21.1	21.0
09	2.0	1.7	19.5	21.9	21.1	21.1
10	3.0	2.4	19.5	21.7	21.2	21.3
11	4.5	3.9	19.4	21.6	21.3	21.5
12	5.8	5.3	19.4	21.4	21.3	21.6
13	6.4	6.1	19.5	21.3	21.4	22.0
14	6.9	6.6	19.7	21.3	21.6	23.1
15	6.6	6.5	19.9	21.1	21.8	23.4
16	5.9	5.9	19.9	21.1	21.7	23.3
17	4.2	4.7	19.8	21.2	21.5	22.8
18	2.5	2.9	20.1	21.9	21.3	23.0
19	1.2	1.4	20.2	22.4	21.1	23.3
20	0.4	0.6	20.2	22.8	21.0	23.5
21	-0.3	-0.3	20.3	23.1	20.9	23.7
22	-0.8	-0.8	20.3	23.3	20.8	23.7
23	-1.4	-1.4	20.2	23.0	20.7	23.6
29-Feb						
00	-1.6	-1.7	19.9	22.6	20.6	23.0
01	-1.7	-1.9	19.5	22.2	20.5	22.5
02	-1.4	-1.7	19.4	22.0	20.3	22.4
03	-0.9	-1.3	19.6	22.5	20.2	22.7
04	-0.8	-1.1	19.7	22.9	20.2	22.5
05	-0.8	-1.0	19.5	22.5	20.1	22.1
06	-0.6	-1.0	19.5	22.5	20.0	22.2
07	0.3	-0.2	19.7	22.8	20.0	22.4
08	1.1	0.6	19.7	22.6	20.1	22.0
09	2.0	1.5	19.6	22.7	20.2	21.8

10	3.0	2.5	19.5	22.5	20.4	21.7
11	3.9	3.4	19.5	22.2	21.0	22.0
12	4.7	4.3	19.3	21.9	21.1	21.9
13	4.7	4.5	19.2	21.7	21.0	21.8
14	4.9	4.7	19.0	21.5	20.9	21.6
15	5.1	4.8	18.9	21.3	20.8	21.5
16	5.1	4.9	18.8	21.1	20.7	21.4
17	4.7	4.6	19.1	21.4	20.6	21.6
18	4.2	4.1	19.5	22.2	20.8	22.1
19	4.2	4.0	19.8	22.7	20.7	22.9
20	4.2	3.9	20.0	22.7	20.6	23.4
21	4.1	3.9	19.9	22.3	20.5	23.4
22	3.5	3.3	19.7	21.9	20.4	23.2
23	2.8	2.7	19.6	21.7	20.4	23.1