Assessment of the technical potential for multifunction building zero-carbon renovation with EnergyPlus

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Abstract

Energy consumed in the building field accounts for 30–40% of social energy consumption in the entire world. The energy used in office-educational buildings, especially in developed countries, takes up a large proportion, because of the high occupant density, long running time and high brightness and comfort requirement. This research aims at predicting the renovation potential for office-educational building in the energy-saving aspect. One typical existing educational building in the UK has been chosen as the research object; EnergyPlus computer model, which accurately reflects the building style, material, structures and Heating, Ventilation and Air Conditioning system is established. After the simulation of energy performance and carbon emission of the original building, some insulation measures and renewable technologies (photovoltaics, solar thermal etc.) have been added as the renovation method. Then, theoretical calculation and computer simulation about the effect of the renovations above have been conducted to reflect the improvement. Carbon-saving effects of renovation methods were compared and analyzed. Only 2.2% of carbon emissions can be reduced by improving the air-tightness of the building and the *U*-value of windows, but great carbon saving achieved by adding renewable devices. About 40.8% of the carbon emissions reduced due to the application of all the renovation methods. The result of this study will provide some critical references for the choosing and prediction of renovation methods in the energy-saving field in the UK.

Keywords: zero-carbon; building renovation; EnergyPlus; solar; PV

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1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

If a variety of sustainable technologies can effectively reduce the fossil fuel consumption in buildings, relative technologies must be readily adaptable to existing buildings as well as new buildings. The importance of renovation in existing building has been frequently mentioned in recent years due to the huge proportion of energy used in building fields and the great gap of energy efficiency between traditional buildings and newly designed green buildings. A test for an example office building provided by Knissel [1] can prove this phenomenon as well: by improving the energy efficiency, the example office building can reduce the primary energy need from 235 to 67 kWh/m^2 a.

This study aimed at predicting the potential of energy-saving renovation for a typical office–educational building. EnergyPlus is chosen as the main simulation tool in this research. A building named Sustainable Research Building (SRB), which is located in the UK, has been selected as a basic example. The function of this building can well satisfy the requirement, but the thermal performance still needs to be improved. There are three primary objectives: the first one is to calculate the energy consumption of the initial building by EnergyPlus in original conditions. The second objective includes improving the thermal performance of this building

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by passive strategies and testing their energy-saving effects. After this, active sustainable building technologies are added to this building and the data of energy consumption will be compared with the former ones.

At the end of this article, the conclusion of total energy-saving effect of renovation is given. The results of this research can reflect the ability of zero-carbon renovations in office–educational buildings in the UK for a certain extent.

1.2 Literature review

For the purpose of reducing carbon equivalent emissions and enhancing energy efficiency, the UK has its own standard: the BRE Environmental Assessment Method (BREEAM). It has been widely implemented in public building design in order to improve energy efficiency and sustainability. Building Regulations Part L2A (Part L2A) [2], which came into operation in 2006, mentions that the *U*-value of the roof, wall, floor and window should be limited under 0.25, 0.350, 0.25 and 2.2 W/m^2 K, respectively, in the energy and fuel saving of the construction sector. This standard is stricter than this kind of standard in developing countries [3].

For the passive building energy-saving technologies, previous research has had some achievements on general nature ventilation systems in the systematic method, such as the research of using double facade to improve ventilation by Gratia and De Herde [4]. Meanwhile, shading devices have also been densely studied for the purpose of the building saving energy. Kuhn *et al.* [5] point out that the type and control method of the shading device must be well considered because it will affect the heating and cooling need obviously. van Moesek *et al.* [6] also simulated the control factor of shading. In his research, mixed control parameters that involve indoor temperature and solar radiation can cause the utmost influence of the balance between internal comfort and building energy consumption. Solar collectors are widely used in the design of green building to provide the energy of the hot water system, space heating and cooling. Aringhoff [7] mentioned that up to 100–120 GWh energy can be produced from 1 km^2 area solar radiation every year in many positions of the Earth, which means that 50 MW energy from a coal or gas plant can be saved. The main function of a solar collector is hot water preheating and space heating; the space cooling function is only studied in recent years [8]. The photovoltaic (PV) system normally has less efficiency than a solar thermal collector, but electricity generated by the PV can be directly used to electric equipments. Recent researches of PVs have paid more attention to the conveniences of the designer and final user [9] and small-sized PV cell which makes it very easy to compose PV panels in different measurements [10, 11]. The install position is distinct in different countries; more than four-fifths of used PV is set on the roof in Germany in 2010 [12]. But in the UK, this proportion is lower.

Figure 1. *Appearance of the SRB.*

2 RESEARCH METHODOLOGY

In order to describe the research method, the details of different kinds of definitions and the calculation principles are stated in this section.

2.1 Study object definition and parameter

2.1.1 *Basic model definition*

In this study, the SRB, which is located in the main campus of the University of Nottingham and faces 45° north by east, was selected as a model to stand for the typical office–educational building. SRB is mainly used by postgraduate students for the purpose of education and research.

As can be seen in Figure 1, it is a rectangle designed, three floor, light-weight building. SRB consists of two lecture rooms, two PhD rooms, a laboratory, four small staff offices and a few accessory rooms.

In order to simulate the thermal performance and study renewable energy, the model of SRB is divided into various zones in EnergyPlus. Figure 2 presents the dipartition and position of each zone.

SRB has a steel load carrying structure and lightweight exterior protected construction. Under the existing constructions, the main external wall, floor, roof and window and door have the *U*-value of 0.36, 0.52, 0.2, 2.7 and 0.51 W/m^2 K, respectively.

2.1.2 *Building operation and occupancy parameters*

The definition of this part will strictly base on the UK building regulation and actual situation of SRB. The detailed equipment operation and occupancy parameters can be listed in Table 1.

According to CIBSE Guide A [13], education and office space should keep 19–21°C and 21–23°C in winter. The

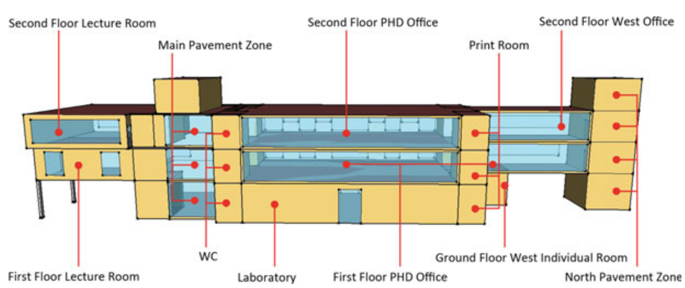

Figure 2. *Zone dipartition of the SRB.*

Table 1. *Building operation and occupancy parameters.*

Zone name	Area (m^2)	Occupancy/person	Lighting/W	Equipment/W
First floor lecture room	55	Date: 7/1–30/3, 4/5–31/5, 14/9–4/12		
		Time: 9.00–12.30: 48	9.00–16.30: 132	9.00–16.30: 275
		12.30–16.30: 80	16.30–24.00: 33	
Second floor lecture room	136	Date: 7/1–30/3, 4/5–31/5, 14/9–4/12		
		Time: 9.00–12.30: 18	9.00–16.30: 326	9.00–16.30: 680
		12.30–16.30: 30	16.30–24.00: 82	
First floor PHD office zone	312	Date: 2/1–23/4, 29/4–21/12		
		Time: 9.00–12.30: 27	9.00–12.30: 624	9.00–12.30: 4860
		12.30–17.00: 38	12.30–19.00: 936	12.30–17.00: 6840
		17.00–19.00: 5	19.00–24.00: 312	17.00–19.00: 900
Second floor PHD office	260	Date: 2/1–23/4, 29/4–21/12		
		Time: 9.00–12.30: 24	9.00–12.30: 520	9.00–12.30: 4320
		12.30–17.00: 29	12.30–19.00: 780	12.30–17.00: 5220
		17.00–19.00: 4	19.00–24.00: 260	17.00–19.00: 720
Laboratory	230	Date: 2/1–23/4, 29/4–21/12		
		Time: 9.00–17.00: 8	9.00–12.30: 552	9.00–17.00: 11 500
		17.00–19.00: 3	12.30–19.00: 828	
			19.00–24.00: 276	
Second floor west office	56	Date: 2/1–23/4, 29/4–21/12		
		Time: 9.00–17.00: 4	12.30–17.00: 168	9.00–17.00: 800
		17.00–19.00: 1	17.00–19.00: 280	17.00–19.00: 200
			19.00–24.00: 56	
All pavement zones	304	Date: 2/1–23/4, 29/4–21/12		
		Time: All DAY NONE	12.30–17.00: 912	Time: All DAY NONE
			17.00–19.00: 3040	
			19.00–24.00: 608	
Other small accessory rooms	108	Date: 2/1–23/4, 29/4–21/12		
		Time: All DAY NONE	12.30–17.00: 540	Time: All DAY NONE
			17.00–19.00: 216	

Table 2. *HVAC operation and set point parameter.*

	Lecture room zones	PhD and lab zones	Professor office
Heating operation date	7/1–30/3, 4/5–31/5, 14/9–4/12	2/1–23/4, 29/4–21/12	2/1–23/4, 29/4–21/12
Heating operation time	9.00–16.30	9.00–19.00	9.00–19.00
Heating temperature set point	19°C	19°C	21°C

Table 3. *Hot water system design parameter.*

	Lecture room zones	PhD and lab zones	Professor office
Hot water supply date	7/1–30/3, 4/5–31/5, 14/9–4/12	1/2–4/23, 4/29–12/21	1/2–4/23, 4/29–12/21
Hot water demand	15 l/day	22 l/day	22 l/day
Hot water peak demand	9 l/hour	9 l/hour	9 l/hour

setting of the space heating operation period is based on the building usage schedule. Detailed definition is listed in Table 2.

Hot water temperature in the tap is defined as 50°C; 60°C is the set-point temperature in the hot water tank in EnergyPlus. The capacity of the hot water tank is 500 l. The parameters of the hot water system in EnergyPlus are listed in Table 3.

The air infiltration parameter is 0.5 ACH in EnergyPlus. Once the indoor temperature is higher than 23°C and meanwhile the outdoor temperature is lower than 23°C, windows will be opened to keep the indoor temperature comfortable.

2.1.3 *Weather condition*

This research does not focus on the study of SRB in its real climatic condition but studies the standard office–educational building under a typical UK climate. So, Birmingham's weather condition has been chosen due to its location and typicality climates characteristic. Birmingham has a temperate maritime climate, which means mild summer and cold winter. Figure 3 shows the relationship between average temperature and comfort zone as well as solar radiation.

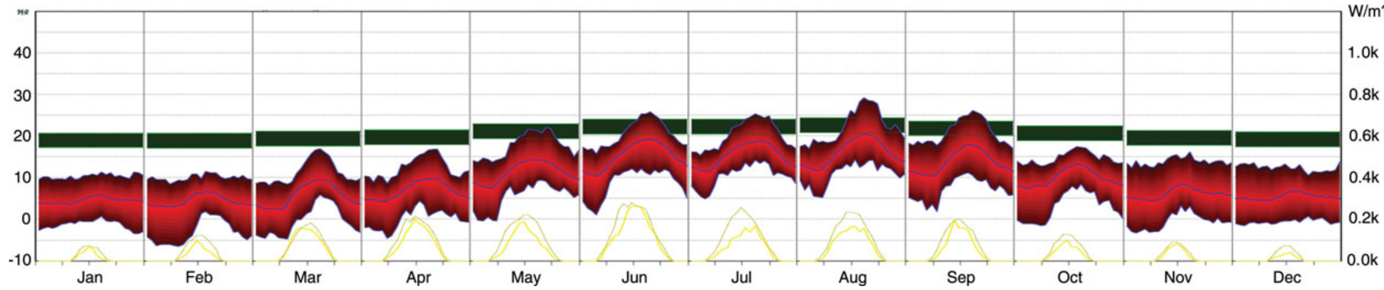

Figure 3. *Temperature comfort zone and solar radiation.*

Table 4. *Wind and rainfall data in Birmingham.*

Month	Jan	Feb	Apr	Mar	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Average wind speed (m/s)	10	9	10	9	10	9	10	10	9	9	9	8	9
Wind probability %	36	31	42	33	39	25	36	36	29	25	35	23	32
Precipitation (mm)	56	48	52	48	55	57	47	67	54	53	59	66	662

Monthly average wind speed and precipitations are comparatively well proportioned all year. The detailed wind and rainfall data are listed in Table 4.

2.2 Principle of EnergyPlus and carbon emission calculation method in this research

The thermal simulation of EnergyPlus is mainly based on the heat balance calculation like BLAST [14]. A predictor–corrector method is used in EnergyPlus to calculate the energy balance for inter-zonal air and deal with the result of difference balances. The heat balance calculation is needed as the prerequisites.

The amount of carbon equivalent emissions can be converted from energy consumption. For the convenience of calculation and comparison, the energy source for all kind of demand is assumed as grid electric.

- For the saving results of carbon dioxide emission by a solar thermal hot water system:

$$C_s = (Q_{abs} - Q_{los}) \times Cf_{de}$$

where Q_{abs} is the solar collector absorbed energy, Q_{los} the energy loss from the total solar thermal system and Cf_{de} the carbon dioxide factor for used electric, $Cf_{de} = 0.422$ kgCO_2/kWh.

- For the saving results of carbon dioxide emission by the PV system:

$$C_s = (Q_{gen} - Q_{los}) \times Cf_{de}$$

where Q_{gen} is the energy generated from the PV arrays, Q_{los} the energy loss from the PV system and Cf_{de} the carbon dioxide factor for grid-displaced electric, $Cf_{de} =$ 0.568 kgCO_2/kWh.

- For the conversion between carbon dioxide emission and carbon equivalents emission

The conversion between CO_2 emission and carbon equivalents emission depends on the ratio of the atomic mass of a carbon dioxide molecule to the atomic mass of a carbon atom (44:12). So one unit of CO_2 equivalent = 0.2727 unit of carbon equivalent [15].

3 RENOVATION PROCEDURE AND RESULT DISCUSSION

This section describes the simulation results of original SRB, innovated SRB by passive strategies and innovated SRB by active strategies (renewable energy technologies).

3.1 Simulation results and analysis of original SRB

The simulation results and analysis of original SRB will be given in this section. Indoor comfort situation, heat gain and loss methods, conditions of energy consumption and carbon emissions will be the emphasis of analysis. A full understanding of original SRB can be found in this section.

3.1.1 *Analysis of indoor temperature and comfort situation*

According to the simulation of EnergyPlus, accurate hourly temperature data of original SRB can be obtained. They are processed and analyzed below. Data listed here also will be used in Section 3.2.1 as the correlation data.

Temperature in winter and summer design days. To research the temperature in winter and summer design days, the ultimate indoor environment under the worst weather conditions can be observed. Figure 4 shows the temperature curve in the coldest day, which was 15 February. The light blue range represents the comfort zone (winter: 19–23°C, summer: 21–24°C);

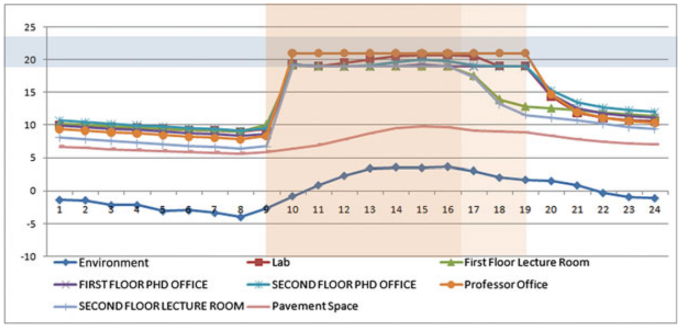

Figure 4. *Temperature curve in the coldest day.*

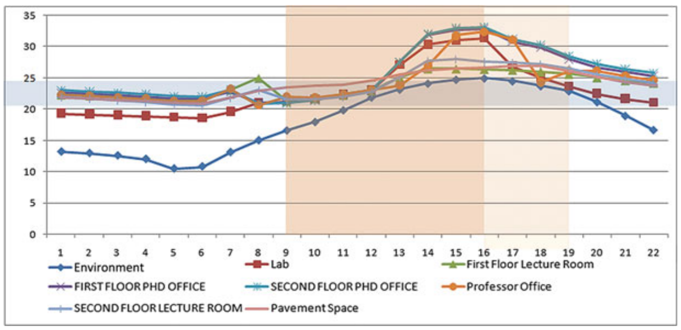

Figure 5. *Temperature curve in the hottest day.*

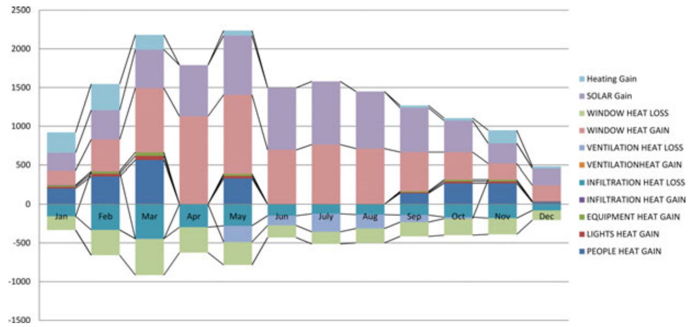

Figure 6. *Heat gain and loss in the lecture room (KWh).*

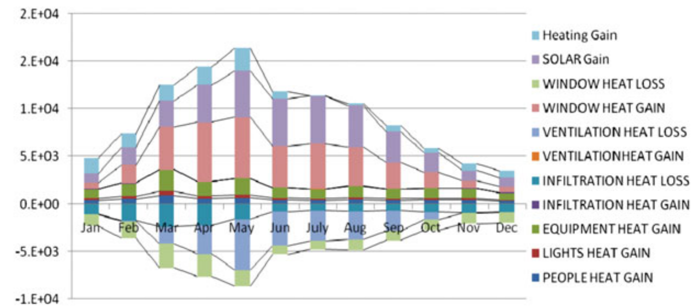

Figure 7. *Heat gain and loss in the PhD room (KWh).*

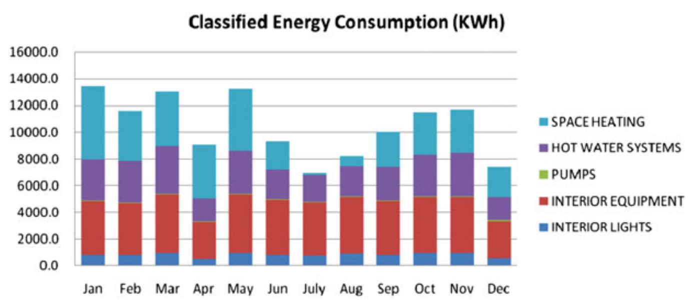

Figure 8. *Monthly energy consumption classification.*

light red range means all zones are occupied and very light red means only PhD room and professor office are used. All important zone are heated in occupied times, internal air temperature will increase from 9°C to 19–21°C in 1 h due to the work of the heating system. In contrast, pavement space (no heating system) only keeps at 6–10°C in day time. The importance of heating can be found in the comparison.

For the hottest day (16 August), the internal temperature has a 5°C decrease due to the opening of windows are before SRB start occupied. Temperatures in all rooms keep in the comfort zone before 13:00, and then increase to 26–33°C at 16:00, respectively, because of huge internal gains. It can be easily found that temperature cannot be controlled in the comfort zone without a cooling system in this specific climate where the outdoor temperature can reach to 25°C (Figure 5).

3.1.2 *Analysis of heat gain and loss path*

In this section, monthly data of heat gain and loss in different ways will be given to provide a deep understanding of thermal performance. Analysis results here will provide the direct evidence of passive renovation in Section 3.2.

Lecture room. Heat gain from windows reach its peak value in May because the indoor and outdoor temperature difference got the peak at that time. Solar gains keep relatively steady from May to August but reach its peak in July. In winter, heat mainly losses from windows and infiltration, while from windows and ventilation in summer. The chart of heat gain and loss of lecture room can be seen in Figure 6.

PhD room. From Figure 7, heat gain from windows became bigger because of the huge window area. Internal heat gain is comparatively more important due to large quantity of computers. Indoor and outdoor temperature difference lead to the peak heat gain and loss appears in May as well. For the whole year, windows, solar and infiltration in these two rooms above should be vitally concerned in the followed renovation.

3.1.3 *Energy consumption and carbon emission*

Monthly energy consumption of SRB. As can be seen from Figure 8, in January, March and May, SRB needs the most energy due to the high occupation coefficient and low outdoor

Table 5. *Monthly carbon emission and proportion.*

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Total energy consumption (kWh)	13 422	11 568	13 085	9091	13 260	9346	6986	8227	10 014	11 472	11 693	7400	12 5564
Total carbon equivalent (kg)	1996	1720	1945	1352	1971	1390	1039	1223	1489	1706	1739	1100	18 669
Heating energy consumption (kWh)	8531	6863	7688	5710	7864	4374	2238	3033	5159	6280	6508	3998	68 244
Heating carbon equivalent (kg)	1268	1020	1143	849	1169	650	333	451	767	934	968	594	10 147
Heating proportion	64%	59%	59%	63%	59%	47%	32%	37%	52%	55%	56%	54%	54%

temperature. Energy need for lighting and internal equipment remains stable all year and generally takes half of the total energy. Another half of the energy is used in heating aspect, which includes space heating and hot water heating system. For the structure itself, the energy need of January's space heating and hot water can be a reference of heating need in renovation design.

Monthly carbon equivalent emission. Carbon equivalent emission from the total energy consumption of SRB and from the heating system will be discussed separately. The annual carbon equivalent emission of SRB is 18 669 kg, while 10 147 kg carbon equivalent is produced in the heating system which takes 54.4% of the total emission.

The proportion of the heating system carbon emission is always fluctuant. Because of the fixed lighting and equipment carbon emission in the occupied time, this ratio is affected by outdoor temperature and building heat loss. The monthly energy consumption and carbon equivalent emission is listed in Table 5.

The energy consumption, carbon emission and it's proportion analyze here will be the basic benchmarks to evaluate the effects of renovation below.

3.2 Application of passive strategies and simulation results

Based on the analysis of original SRB, the parameters of passive improving methods and the effects of these improvements will be assumed in this section.

3.2.1 *Description of passive strategies*

The details of passive improvement methods are listed below.

- Automatic shading devices are installed above the main windows. They have the same width as windows, the distance of overhanging of them are 1.2 m. The position of shading broad can be seen in Figure 9.

The shading broad will only unfold in the hottest months which are July, August and September. Shading broad unfold from 12:00 to 17:00 in July, from 9:30 to 17:00 in August and September.

- The windows open time is controlled automatically by a temperature sensor. For lecture rooms, PhD offices and laboratory, windows will be opened when indoor temperature exceeds 23°C and meanwhile higher than the outdoor temperature. For professor's office, the outdoor temperature set point is 24°C. The control system will run 1 h before the occupied time in morning and all windows will be closed at 24:00.
- All the external windows of SRB are renovated; argon gas is filled in the 12 mm space between two layers of 6 mm low-e glass. The U-value of windows reduces from 2.71 to 2.11 W/m^2 K.

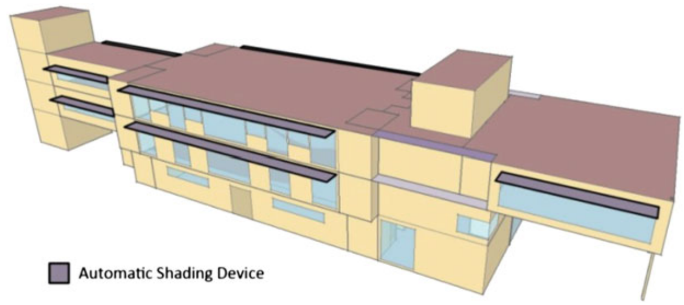

Figure 9. *Position of shading broad.*

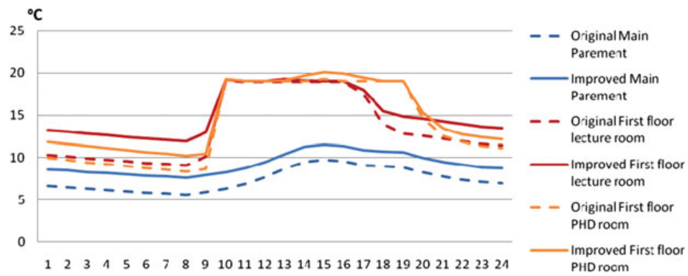

Figure 10. *Temperature of typical zones in the coldest day.*

3.2.2 *Improvement in internal temperature aspect*

Improvement in winter. Indoor temperature on the coldest day can represent the worst situation in winter; three typical zones are selected to show the common internal temperature. Figure 10 shows the temperature change in the coldest day. Temperature in the first floor PhD room has a slight increase in the working time than original situation. In the zones of both PhD room and lecture room, temperatures have a visible increase in the improved SRB in morning and night when the heating system is not working. There is a 3–4°C temperature difference between improved and original SRB.

Temperature in the main pavement space (with no heating system) increases 2–3°C all day.

The common raise in the indoor temperature in typical zones at the coldest day clearly reflects the effect of improvement.

Improvement in summer. As mentioned above, the main problem in summer is these overheated hours. Lecture rooms are not used in summer, so the test is only based on typical PhD room (first floor PhD room).

Figure 11 shows the reduction in overheated hours which is divided into different temperature ranges. Generally speaking, total overheated hours in summer reduce from 67.7 to 27.75 h, the uncomfortable hours' proportion in the total occupied time drops from 9.7 to 4.2% in the first floor PhD room.

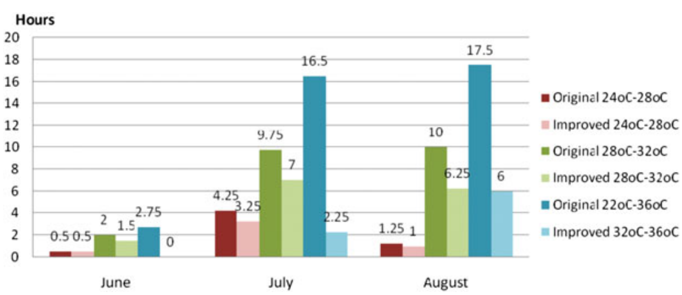

Figure 11. *Divided not comfort hours in summer months.*

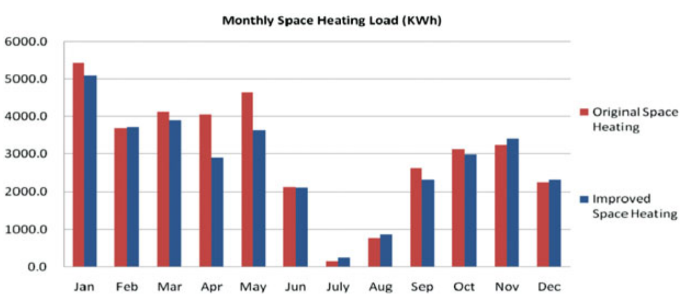

Figure 12. *Change of monthly space heating load.*

3.2.3 *Improvement in energy consumption and carbon emission*

The passive strategies will not affect lighting, internal equipment and water heating system because the shading devices only work in lightful hours and the tinny energy needed for windows control can be ignored, the analysis of energy consumption change will only focus on the space heating aspect.

Improvement in space heating load of SRB. The effect of passive renovation can be reflected in Figure 12. Space heating energy consumption reduces in most of the months, except February, July, November and December. Great effect can be seen in April and May which have 25–30% energy demand reduction. But in February, July, November and December, the heating demand keeps in original level or even a slight increasing. In summary, 7.5% of heating demand reduces by the effectiveness of passive strategies.

Reduction in carbon equivalent emission. Due to the drop in the space load of SRB by passive strategies, the carbon equivalent emission declines as well. Detailed carbon equivalent emission values are listed in Table 6.

As can be read from Table 6, the annual carbon emission of whole SRB is reduced from 18 669 to 18 262 kg which means 2.2% cutting down. The carbon emission from the heating system has an annual reduction of 4.0% due to the effect of passive strategies.

3.3 Theoretical calculation and simulation result analysis of active strategies

After the description of passive improvement, the renovation by active strategies will be stated in this section. The theoretical calculation will be given first to define the area and angle of the PV and solar collectors, followed by EnergyPlus simulation which used the parameters obtained in theoretical calculation.

3.3.1 *Theoretical calculation and parameters definition of renewable energy*

The theoretical calculation of renewable energy will be given in this part to make a basic guidance for the settings in EnergyPlus. The theoretical area needed for the solar thermal collector will be given first because of it's higher efficiency, the remaining area will be utilized by the PV system.

Table 6. *Monthly reduction of carbon emission.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Total carbon emission (kg)	1996	1720	1945	1352	1971	1390	1039	1223	1489	1706	1739	1100	18 669
Original	1946	1723	1913	1181	1822	1386	1053	1237	1444	1684	1763	1110	18 262
Improved	2.5%	−0.2%	1.6%	12.6%	7.6%	0.3%	−1.3%	−1.1%	3.0%	1.3%	−1.4%	−0.9%	2.2%
Improvement													
Heating carbon emission (kg)	1268	1020	1143	849	1169	650	333	451	767	934	968	594	10 147
Original													
Improved	1218	1023	1111	679	1020	647	347	465	722	912	992	604	9740
Improvement	3.9%	−0.3%	2.8%	20.0%	12.7%	0.5%	−4.2%	−3.1%	5.9%	2.4%	−2.5%	−1.7%	4.0%

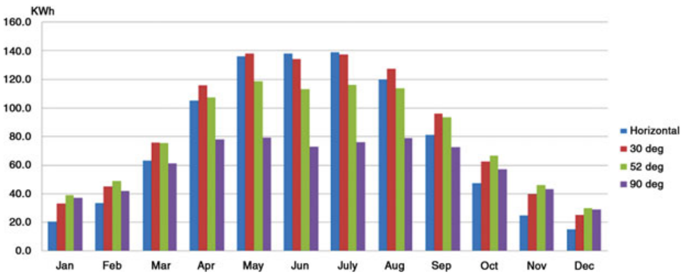

Figure 13. *Monthly solar radiation of 1 m^2 surface in different tilts.*

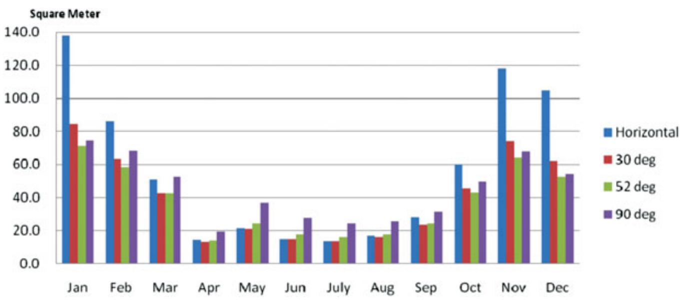

Figure 14. *Monthly needed area with difference tilt surface.*

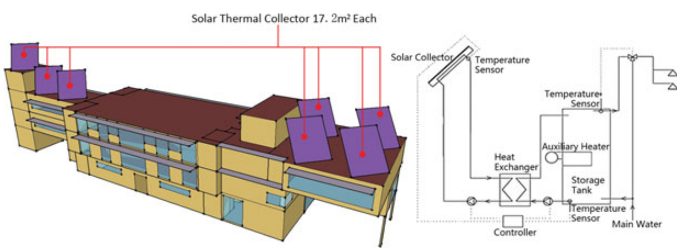

Figure 15. *Description of a solar thermal collector.*

Theoretical calculation of a solar thermal collector. The area of the solar thermal collector is based on its performance and hot water load of SRB. Collectors are defined face to south which is the best orientation. The ratio between hot water energy need (from 3.1.3) and collector absorption per square meter (Figure 13) with different title can become the evidences for the calculation of collector's area.

Figure 14 shows the result of calculation above, a collector with 52° tilted needs the smallest area (71.2 m^2) in the worst month (January). To satisfy the hot water need in the worst month, solar thermal collectors are defined at this angle.

SunEarth Inc SSC-40 was selected as the typical model of solar collectors; the initial efficiency of this production is 70.2%, and the total system heat loss is assumed at 15%. Consequently, the designed area of the solar collector with 52° tilted is 71.2 m^2/0.702/(1−15%) = 119.3 m^2.

As shown in Figure 15: seven collector arrays (17.2 m^2 each) are set on the southeast and northwest ends of the SRB roof, 120.4 m^2 areas is provided which is enough for the theoretical area.

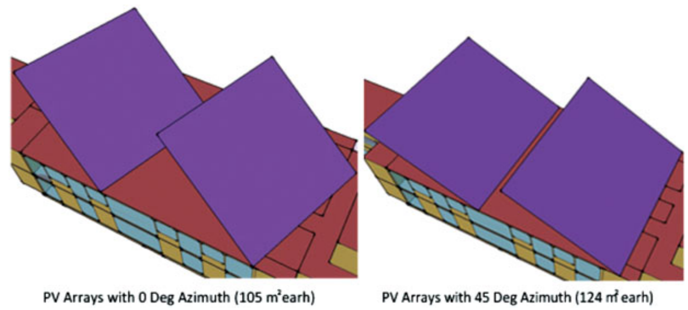

Figure 16. *PV position and area with different azimuth angles.*

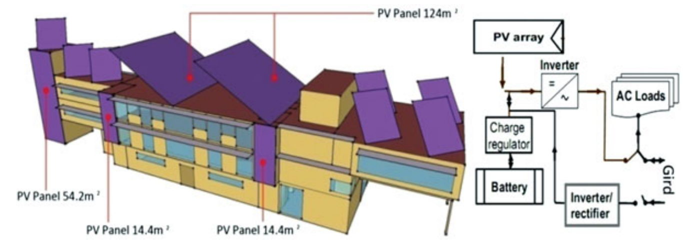

Figure 17. *Definition of the PV system.*

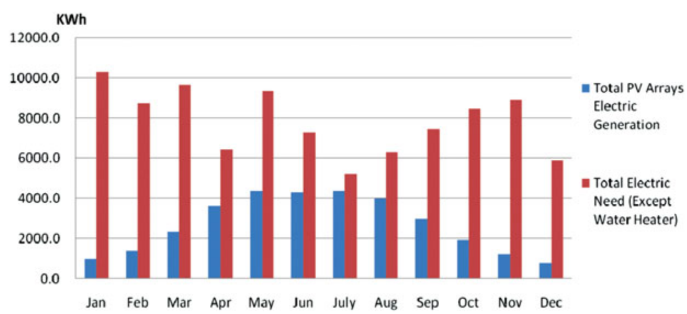

Figure 18. *Monthly electric need and production.*

Theoretical calculation of the PV system. As can be seen in Figure 16, two kinds of direction on the roof can be chosen for PV installation—face to south or face to north by east which follows the SRB direction. Considering the roof area and avoiding light obscuration, 210 m^2 PV array can be installed with 0° azimuth, it can extend to 248 m^2 with 45° azimuth. In the calculation, the average efficiency is set at 13% and the energy loss from wires and invertors is not considered. The total annual electric production of PV arrays at 45° azimuth (31 851.2 kWh) is 13.4% higher than it at 0° azimuth (28 096.6 kWh).

As shown in Figure 17, PV arrays on the roof are defined at 45° azimuth and 30° tilted, 248 m^2. Besides the available area on the roof of SRB, PV panels can be installed on the southwest façade of SRB, 80.4 m^2 PV panels can be installed there at 90° tilt and −45° azimuth.

In this grid-connected system, both the efficiency of an inverter and electric absorbance by the grid are defined at 90%; the active area in PV arrays is 92% in theoretical calculation.

Table 7. *Carbon equivalent emission reduction by passive and active strategies.*

Unit: kg	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Original carbon equivalent	1996	1720	1945	1352	1971	1390	1039	1223	1489	1706	1739	1100	18 669
Passive strategies improved	1946	1723	1913	1181	1822	1386	1053	1237	1444	1684	1763	1110	18 262
Active strategies improved	1382	1092	1085	415	739	450	124	337	660	975	1144	763	9166
Improvement between passive and active	29.0%	36.6%	43.3%	64.9%	59.5%	67.5%	88.2%	72.7%	54.3%	42.1%	35.1%	31.3%	49.8%
Total improvement	30.8%	36.5%	44.2%	69.3%	62.5%	67.6%	88.1%	72.4%	55.7%	42.8%	34.2%	30.7%	50.9%

Table 8. *Main parameters of the renewable energy system.*

Solar Collector	Fluid type	Water
	Test flow rate	0.000317
PV panel	Active Area	92%
	Transmittance absorptance product	0.95
	Short-circuit current	6.5 A
	Short-circuit voltage	21.6 V
	Reference temperature	25°
	Reference insolation	1000 W/m^2
	Module heat loss coefficient	30 W/m^{2}K
	Temperature coefficiency of short-circuit current	−0.079
	Temperature coefficiency of short voltage	0.02
Water tank	Tank volume	500 l
	Heat loss coefficient	5 W/K
	Max water temperature	82°
PV inverter	Radiative fraction	0.25
	Rated maximum continuous output power	25 kW
	Night tare loss power	200 W
	Nominal voltage input	368 V
	Efficiency at 20% power	0.839
	Efficiency at 40% power	0.897
	Efficiency at 60% power	0.916
	Efficiency at 90% power	0.934
	Efficiency at 100% power	0.93

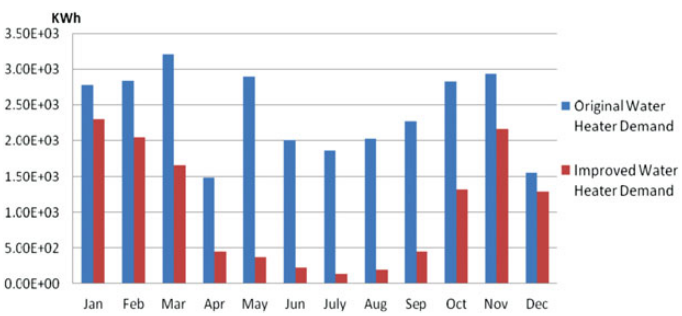

Figure 19. *Monthly energy demand of original and improved water heater.*

The relationship between PV electric generation and electric need of SRB is shown in Figure 18. The total electric need does not include energy consumption from a water heater because it can be covered by a solar thermal collector in the calculation above. By applying the PV system, the annual electric need of SRB reduces from 94 094.8 to 61 648.5 KWh, account for 34.5% of the annual electric need.

Theoretical reduction of carbon equivalent emission. As shown in Table 7, the carbon emission reduces by 49.8% between the value after passive strategies' improvement and the value after all strategies' improvement. For the total carbon emission decrease, comparing the value with original SRB, 50.9% annual reduction occurs.

3.3.2 *Simulation in EnergyPlus and results analysis*

The area and parameters of the solar thermal collector and PV have been obtained in Section 3.3.1 by theoretical calculation. The definition of a renewable energy system in EnergyPlus is strictly based on the set mentioned above. The definitions of key parameters of these systems are listed in Table 8.

Energy generation analysis of a renewable energy system. Solar thermal collector: The heat generated from the solar thermal collector can be respected by the reduction of water heating energy demand, which takes great majority energy in the hot water system. The heat from the collector can cover all the hot water need in the theoretical calculation, but according to Figure 19, it only has 56% decline by a solar collector due to the mismatch between generation and heat demand and losses.

PV system: The energy generation of the PV system can be reflected by inverter data. As can be seen in Table 9, the annual energy produced by the PV system to SRB electric load is 33 133.9 kWh which is more than the theoretical calculation (32 446 kWh).

Generally speaking, the inverter output is higher than the theoretical value in strong solar radiation months and lower than it in weak solar radiation months. The change of inverter

Table 9. *Monthly inverter data.*

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Inverter DC energy input (kWh)	939.1	1533.3	2856.2	3959.0	4952.6	5230.7	5374.8	4632.6	3263.6	2097.1	1101.5	844.1	36 784.7
Inverter AC energy output (kWh)	814.7	1351.5	2560.4	3579.8	4497.4	4756.4	4886.7	4203.6	2937.1	1859.8	954.2	732.3	33 133.9
Inverter DC to AC efficiency	84.9%	85.8%	87.0%	87.8%	88.0%	88.1%	88.2%	88.1%	87.5%	86.3%	85.0%	84.9%	87.1%

efficiency is an important reason for this. The monthly comparison of rthe eal output and theoretical value can be seen in Figure 20.

Change of energy consumption and carbon emissions. The original and improved energy consumption is listed in Table 10. By the help of all improvement of SRB, the total energy need reduces from 125 563.5 to 74 378.5 kWh, falling by 40.8%. The maximum decline appears in July, from 6985.9 to 439.4 kWh; 93.7% energy is saved by renovation. In winter months, there was only a reduction in energy of 22.2 and 9.7%, in January and December, respectively.

The carbon emission is another important index for the assessment of improvement methods. As can be read from Table 11, 7610.3 kg carbon equivalent emissions can be saved by the final renovation, falling by 40.8%. In the most conspicuous month, carbon equivalent emissions can be reduced from 1039 to 65.3 kg.

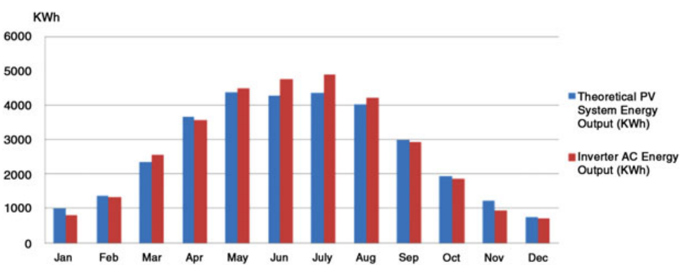

Figure 20. *Monthly PV theoretical and real output.*

4 CONCLUSION AND RECOMMENDATION

According to the study above, the zero-carbon target is hard to achieve by the passive and active improvement strategies above. However, the result of improved SRB provides a preferable energy performance according to the EnergyPlus simulation. To summarize the result of the renovation of SRB, although the energy consumption from the internal equipment limits the total result, great improvement is still achieved. The carbon emission after renovation is 7.4 kg/m^2, which is far below the requirement of the suggested value of good practice which is 21.3 kg/m^2 [16].

If only the energy consumption from the heating system (space heating and hot water) is considered, the carbon emission reduces from 6.8 to 1.38 kg/m^2; 79.4% energy can be saved by renovation. The detailed effect of the renovation strategies can be read from Table 12.

Table 10. *Monthly energy need of original and improved SRB.*

Unit: kWh	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Original energy consumption	13 422.2	11 567.6	13 084.9	9090.9	13 259.7	9345.5	6985.9	8227.4	10 013.9	11 471.9	11 693.2	7400.4	125 563.5
Improved energy consumption	11 783.1	96 41.8	90 68.7	3680.4	50 57.2	2970.8	439.4	2497.2	4928.0	7716.5	9911.5	6684.0	74 378.5
Energy saving proportion	12.2%	16.6%	30.7%	59.5%	61.9%	68.2%	93.7%	69.6%	50.8%	32.7%	15.2%	9.7%	40.8%

Table 11. *Reduction of carbon emission by renovation.*

Unit: kg	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Original carbon equivalent	1996	1720	1945	1352	1971	1390	1039	1223	1489	1706	1739	1100	18 669
After passive strategies	1946	1723	1913	1181	1822	1386	1053	1237	1444	1684	1763	1110	18 262
Improvement of passive strategies	2.5%	−0.2%	1.6%	12.6%	7.6%	0.3%	−1.3%	−1.1%	3.0%	1.3%	−1.4%	−0.9%	2.2%
After active strategies	1751.9	1433.6	1348.4	547.2	751.9	441.7	65.3	371.3	732.7	1147.3	1473.7	993.8	11 058.7
Total improvement	12.2%	16.7%	30.7%	59.5%	61.9%	68.2%	93.7%	69.6%	50.8%	32.7%	15.3%	9.7%	40.8%

Table 12. *Effect of the renovation strategies.*

	Total space		HVAC space	
	Energy demand (kWh/m^2)	Carbon emission (kg/m^2)	Energy demand (kWh/m^2)	Carbon emission (kg/m^2)
Total demand	83.9	12.5	123.4	18.3
Original SRB				
Improved SRB	49.7	7.4	73.0	10.9
Heating demand				
Original SRB	45.6	6.8	67.0	9.9
Improved SRB	9.3	1.4	13.7	1.9

Some recommendations can be provided according to this research.

- For office–educational buildings with a huge area ratio of the window to wall under the UK climate, contribution of passive method modification is far from enough for the requirement of zero carbon building. But if we consider to add renewable energy technologies, which are available on the market, the 50% reduction in total energy saving can be reached in a similar building condition.
- The gap between the theoretical calculation and real situation of energy generation from a solar thermal collector cannot be ignored. Due to the shade between collectors, energy load mismatch and the increase in pump energy need, only 54% energy of the theoretical value can be absorbed.
- The inverter in the PV system should be selected cautiously. The probability of the peak power is always very low which leads to the low efficiency of the inverter most times. The peak power in the theoretical value cannot be the only evidence in the selection of the inverter.

It should be mentioned that this study does not consider the effect of economic factors and equipment accident factors; the result may be modified if these factors are added in for consideration.

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