Analysing the life cycle carbon performance of a Passivhaus-standard retrofitted suburban dwelling in Hunan, China

CHENFEI LIU [1] STEVE SHARPLES[2] HANIYEH MOHAMMADPOURKARBASI[2]

[1] Cardiff University, Cardiff, UK
[2] University of Liverpool, Liverpool, UK

ABSTRACT: Against the background of climate change and resource exhaustion, sustainable retrofitting of existing residential buildings has been widely accepted as a vital way to lower global energy consumption and greenhouse gas emissions in the building sector. The Passivhaus EnerPHit retrofit is considered to have the potential to achieve a large percentage of energy saving compared to most existing buildings. However, research that focused on the environmental impact of the Passivhaus is still considered a small amount. This study aimed to carry out a deep life cycle carbon assessment based on a case building under the hot summer and cold winter climate region in China. The embodied carbon and transport carbon of each retrofitting measure was gathered using the carbon source from the One Click LCA database. The operational carbon of both the pre-retrofit case and retrofitted case for 30 years lifespan was simulated by DesignBuilder with current and future weather files. For the result, the life cycle carbon footprint of pre-retrofit and retrofitted cases showed a significant difference in the changing trend over the lifespan, and at the end, a carbon reduction of 83.4% was achieved in the retrofitted case which equalled to 4 tonnes of carbon saving per square meter of the floor area.
KEYWORDS: Life cycle carbon footprint, Embodied cardon, climate change, Passivhaus

1. INTRODUCTION

Energy retrofitting of existing housing has been recognised as a method with great potential for sustainable intervention in the building sector, in order to respond to climate change and resource depletion. China is expected to take a reasonable responsibility for this intervention because there is a great housing stock in China and the majority of its stock has a poor energy performance. How to efficiently reduce the energy consumption while keeping a good indoor thermal comfort in the existing housing is an important topic. Passive houses can lead to 80-90% energy saving compared with traditional buildings, so are considered to be one of the most effective ways to reduce building energy consumption [1].

Among the existing residential buildings in China, those in the hot summer cold winter zone have the dual demand of space heating and cooling, and so are undoubtedly significant energy consumers. Thus, this paper discusses the efficiency in terms of both energy saving and carbon emission of retrofitting existing dwellings achieving the Passivhaus EnerPHit standard, through a life cycle study of case building located in suburban area of Hunan province, which belong to the hot summer cold winter climate area.

2. LITERATURE REVIEW

The performance of Passivhaus has been widely proven, especially in Europe and cold climate regions [2]. In Europe, over 100 Passivhaus buildings were investigated as part of the CEPHEUS project, and they achieved a space heating demand which was 15-20% of that for standard new buildings [3]. In China, however, the Passivhaus standard is a relatively new concept. The first certified Passivhaus was the Hamburg House at the 2010 World Expo in Shanghai. Since then, over 100 Chinese Passivhaus projects have been completed or are under construction, mainly in the cooler northern regions of the country [4]. According to Yang's study about four Passivhaus projects built in northern China, the simulated results show that the Passivhaus only requires 46% of the total heating and cooling energy if the buildings were built in accordance with the local energy saving standard- which already required a 65% energy saving compared with the conventional building [5]. The first residential Passivhaus built in southern China achieved a 95% energy saving standard compared to conventional dwellings [6].

However, for achieving the strict energy criteria of Passivhaus standard, extra material inputs to the entire envelope fabric, airtightness and mechanical systems of the building are involved [7]. The manufacture of those

extra materials can consume a large amount carbon emissions, which are expected to be factored into the construction process of Passivhaus buildings [8]. Moreover, the deep retrofitted building is supposed to operate for many more years so the time period is actually a significant factor for the performance evaluation. As such, a considerable uncertainty could appear to the initial evaluated results, as many important factors, such as energy consumption and carbon emissions, could accumulate over the lifetime of the building [9].

Life cycle analysis (LCA) is an advanced technique which assesses the entire investments and paybacks over a considered time period [10]. The benefit of life cycle analysis is that it allows many factors to be involved in its evaluation boundary, and it assesses the retrofitted results according to the relative effectiveness and robustness of the retrofitting measures over different time scales rather than a stabilised performance [11]. Overall, life cycle assessment involves all activities, such as the manufacturing process of building materials and products, transportation, distribution, use, maintenance, disposal and recycling that occur in a building's entire lifetime [12].

Although the projects in China suggest that substantial operational energy use in buildings could be reduced by achieving the Passivhaus standard, examples of benefits analysed through life cycle studies are very limited. Therefore, this study is trying to fill this gap through a case study which was previously retrofitted to the Passivhaus EnerPHit standard.

3. SCOPE AND METHODOLOGY

3.1 Case study

The case building (Figure 1) in this paper was a semi-detached 4-storey occupied residential building with a reinforced-concrete structure and no insulation. This building is in the southwest of Hunan province in China and is situated in the hot summer – cold winter climate region. A previous analysis of the case building [13] suggested the annual heating and cooling demand could be decreased from 150.6 kWh/m2a and 42 kWh/m2a under the pre-retrofit status, to 14.9 kWh/m2a and 11.5 kWh/m2a for heating and cooling respectively after a Passivhaus standard retrofitting process. This study aimed to evaluate the performance of the Passivhaus standard retrofitting through a 30 years life cycle assessment, the energy saving and carbon payback time will be analysed.

Figure 1:
The case building of the study.

Figure 2:
The location of the case building on the China's climate map.

3.2 Life cycle analysis

Table 1 demonstrates the building's whole life cycle stages based on sustainability of construction works framework in standard BS EN 15978 and the stages were included in this study.

The embodied carbon data of all the materials and products involved in the retrofit, and the transportation carbon were collected and calculated through software One Click LCA. For the in-use stage, software DesignBuilder was used for simulated the operational energy consumption during the 30 years lifespan with future weather condition considered. The current weather and future weather files for the case region for year 2030, 2040 and 2050 used in DesignBuilder simulations were generated by the Meteonorm weather generator using the IPCC AVR4 A1B scenario. For the operational carbon emission during the

assumed 30 years lifetime, a carbon conversion factor of 0.87 kgCO2e/kWh for electricity, which represents the current carbon emission for the electricity generated in China based on the One Click LCA database, was used to convert the yearly energy consumption of the pre and post retrofit cases to yearly operational carbon emissions. For the whole life cycle carbon emission, Eq. (1) demonstrates how it was calculated.

Table 1:
The whole life cycle carbon stages and the scope of this analysis

Stages	Include?	Scopes
A1-A3: Product stage	√	Embodied carbon of retrofitting related materials and products
A4: Transport	√	Transport carbon for delivering materials to building cite
A5: Construction	×	Out of scope due to no reliable data source
B: In use	√	Heating and cooling carbon emission over the assumed lifespan, retrofitting products replacement
C: End of life	×	Out of scope due to no reliable data source
D: benefits to future life cycle	×	Out of scope due to no reliable data source

$$LCCF = \sum_{i=0}^{i}(EC^i m^i + TC^i m^i d^i + RC^i) + \sum_{y=0}^{y} OC^y \quad (1)$$

where LCCF - life cycle carbon footprint ($kgCO_2e/m^2$);
EC - embodied carbon value of material i ($kgCO_2e/m^2$);
i - item of material;
m - mass of material I, (kg or m^2);
TC - transport carbon value of material i ($kgCO_2e/m^2$);
d - distance of transport for material i, (km);
y – year;
OC - operational carbon in year y ($kgCO_2e/m^2$);
RC - replacement carbon of material i, ($kgCO_2e$).

4. Results

4.1 Embodied carbon

Table 2 illustrates the embodied carbon data of the materials and products required for retrofitting and building operation, and as mentioned earlier, those data were sourced from the China database of the software One Click LCA. However, there are several products for which the software has no data for Chinese manufacture, thus generic data were used. In addition, produces replacement due to technical life ends during the 30 years lifespan was also considered, - the MVHR system and Air conditioning system required in the retrofitted case and pre-retrofit case respectively both have a technical life of 15 years and one replacement of them is needed during the considered lifespan. Table 2 listed the embodied carbon of those two systems, however, their carbon emission was included in the operational carbon emission rather than the embodied carbon emission in this study.

Table 2:
Embodied carbon data of the retrofitting related materials sourced from software One Click LCA.

Materials list	Embodied carbon
Insulation Rockwool	1.31 $kgCO_2e/kg$
MVHR system	1420 $kgCO_2e/unit$
Air conditioning system	814 $kgCO_2e/unit$
Electricity	0.87 $kgCO_2e/kWh$
Window-triple glazed	80.4 $kgCO_2e/m^2$
Window blinds	23.64 $kgCO_2e/m^2$

Table 3 demonstrates the breakdown of embodied carbon value for each building component and their total embodied carbon. The total carbon emission of the retrofitting was converted to a function unit of $kgCO_2e/m^2$, which was divided by floor area ($297m^2$) of the retrofitted space. Rockwool insulation for exterior wall took the biggest share in the retrofitting, and if the insulation for roof and floors are also taken in account, the insulation material accounts for 73% of the total embodied carbon of the retrofitting, which was 99.33 $kgCO_2e/m^2$.

Table 3:
Breakdown of retrofitting embodied carbon (EC) of each building component.

	Mass	EC
Ex wall insulation	7563 kg	9907 $kgCO_2e$
Roof insulation	2238 kg	2931 $kgCO_2e$
Floor insulation	2238 kg	2931 $kgCO_2e$
Int floor insulation	4475 kg	5862 $kgCO_2e$
Windows	62 m^2	4985 $kgCO_2e$
Blinds	62 m^2	1456 $kgCO_2e$
MVHR system	-	1420 $kgCO_2e$
Sum		99.33 $kgCO_2e/m^2$

It is therefore meaningful to highlight that selecting an insulation material with a low embodied carbon value would be a potential way of decreasing the environmental impact. One efficient way is to use organic insulation materials, such as cellulose insulation which is made mainly from recycled paper fibres. It has an embodied carbon value around 0.22 $kgCO_2e/kg$, and it is nearly six times lower than that of Rockwool. In this study, however, Rockwool was originally selected in the retrofitting analysis because it is one of the most used insulation materials in Chinese market. The

environmental impact of Rockwool is relatively low compared with other traditional insulation materials; thus, it was decided not to replace Rockwool with an organic insulation material in this case study, in order to reflect carbon influence in the general situation.

4.2 Transport carbon

The amount of carbon emissions from transporting the retrofitting related materials from the factories gate to construction site in this life cycle analysis was calculated based on the One Click LCA database, which has a regional typical value for the transport distance and transport method for each product type. The actual distances of the materials that were applied in this case study were unfortunately not managed to record during the site investigation. However, the regional typical values could be more representative of the general situation of the transport released carbon emission in the case region.

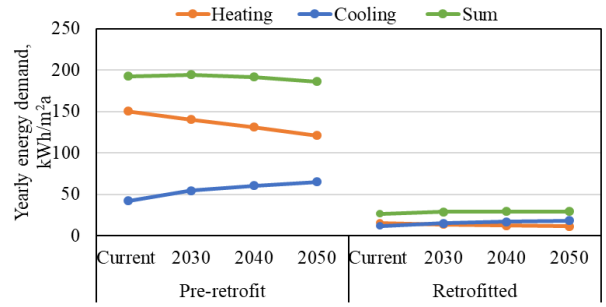
For insulation materials, One Click LCA considered they were transported by trailers that has 40 tons of capacity and the distance was fixed to 60 km. For windows and the related items, they were considered with the same transport type with insulation materials, but the distance was 380 km. For the MVHR system, it was delivered by trucks with 9 tons of capacity and the delivery distance was 320 km. As a result, a total transport carbon for the retrofitting plan was 90.9 $kgCO_2e$, and after converted to a function unit in this study, the value was 0.31 $kgCO_2e.m^2$, which could almost be ignorable when compared with the embodied carbon.

4.3 Operational carbon

According to the discussed analysis scope, the heating and cooling energy consumption values were required for calculation of the operational carbon emission during the 30 years lifespan.

Figure 3 demonstrates the DesignBuilder simulated yearly energy consumptions of both the pre-retrofit case and the retrofitted case under current, 2030, 2040 and 2050 weather condition. The simulated results indicated a big energy consumption difference between the pre and after retrofit condition, which the energy consumption of the retrofitted case was much lower no matter the different weather condition. Moreover, the heating and cooling energy demand had an opposite trend over the time, which were rise and fall respectively for both the pre and after retrofit cases.

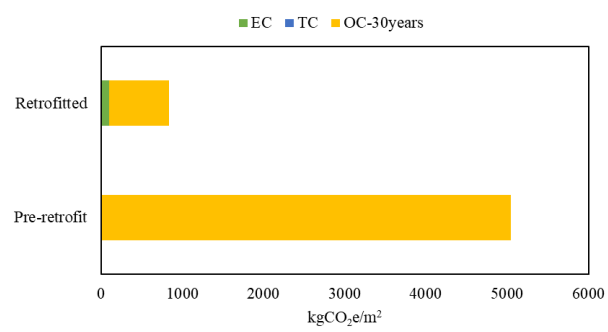
Figure 3:
Energy demand of the case building under pre-retrofit and retrofitted cases and different weather conditions.



4. 4 Life cycle carbon footprint

Once the carbon emission in each of the life cycle stages had been calculated, a comparison between the total embodied, transportation and 30 years operational carbon under the pre and post retrofit cases was made. As the result is shown in Figure 4, for the retrofitted case, the percentage of the embodied carbon took about 11.9% in the total emission, and the rest of carbon emission was basically from the operational stage, as the transport carbon could essentially be ignored. For the pre-retrofit case, its operational carbon was about six times more than that in retrofitted case, which was expected, as its energy consumption was higher than the retrofitted cases by large proportions, especially under the current weather condition.

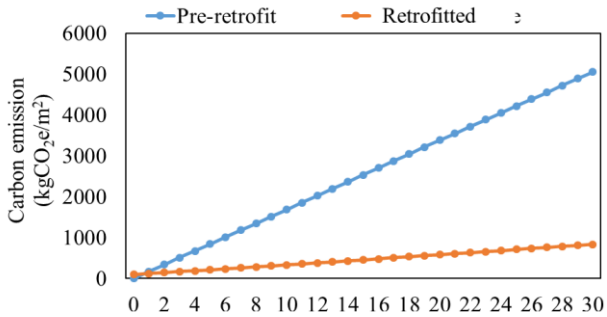
Figure 4:
Comparison between Embodied (EC), transport (TC) and operational (OC) carbon in the retrofitted and pre-retrofit case.



Then, the life cycle carbon footprints of both pre and post retrofit cases were determined and are presented in Figure 5. From this figure, a much obvious upward trend in the footprint of the pre-retrofitted case than the Passivhaus standard retrofitted case could be view. Due to the yearly operational carbon of the pre-retrofit case (165.8 $kgCO_2e/m2$ in current weather condition) was much higher than the retrofit caused carbon emissions (99.3 $kgCO_2e/m2$), the carbon

payback time of the retrofitting plans was only one year, and a carbon saving of 85.3% could be achieved in the retrofitted case at the end of 30 years lifetime.

Figure 5:
Life cycle carbon footprint of the pre and post retrofitted cases over a 30 year lifespan.

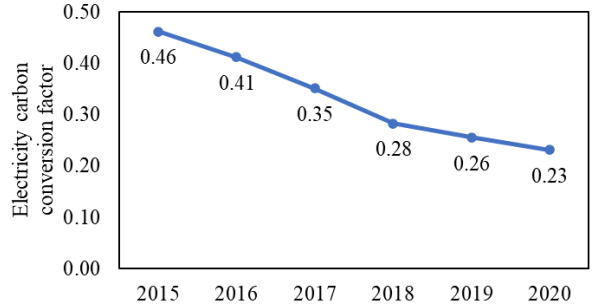


4.5 The uncertainty of carbon emission for energy generation

Furthermore, an issue that should be highlighted is the carbon emission of the secondary energy generation, which could heavily affect the LCCF analysis result, and therefore it is significant uncertainty for life cycle analysis. Operational carbon usually accounts for the largest share of the life cycle carbon, whilst the carbon emissions of the energy production source could change markedly over a building's lifetime. For example, Figure 6 illustrates the carbon conversion factor for the electricity which has been produced in the UK in recent years, where the value was dropped from 0.46 $kgCO_2e/kWh$ in 2015 to 0.23 $kgCO_2e/kWh$ in 2020 because of a decrease in coal use and increase in gas and renewable sources involved in electricity generation [14].

Including this factor into the LCCF calculation in this study, the final life cycle carbon result when was greatly changed. When the UK 2020 carbon emission factor for electricity generation was adopted, the life cycle carbon results for the pre-retrofit case and the retrofitted case was doped from 5048 $kgCO_2e/m^2$ and 837 $kgCO_2e/m^2$ to 1354 $kgCO_2e/m^2$ and 299 $kgCO_2e/m^2$ respectively, which were around 3.7 times lower than the results calculated with China's electricity carbon conversion factor. Therefore, it is important to take the change of environmental impact from energy generation in the future into consideration, and the uncertainty from this issue could be lower if the carbon payback could be achieved in the early years after retrofitting is completed.

Figure 6:
Carbon conversion factors for electricity produced in the UK in recent years.



5. Conclusion

The significant benefit in energy-saving of the Passivhaus buildings was widely proven with cases all over the world, while their environmental impact of carbon emission was overlooked by the Passivhaus standard. This study focused on the life cycle carbon analysis in order to assist a comprehensive analysis of the performance of EnerPHit retrofitting measures from perspectives other than energy efficiency, using a case building in China that experienced a hot summer - cold winter climate. The life cycle analysis was carried out for a lifespan of 30 years, and the energy consumption needed for life cycle analysis was simulated with future weather files.

Analysis of the carbon payback time suggested that the retrofitting plans had a very short payback time of just one year, because the retrofitting embodied carbon was less than the operational carbon emission of the pre-retrofit case in just one year. Throughout the life cycle, a carbon reduction of 83.4% relative to the carbon emission of the pre-retrofit case was expected from implementation of the retrofitting plan, equal to a reduction of around 4 tonnes of carbon emissions. However, it was found that the carbon result is highly dependent on the carbon factor of the energy source to operating the building. The above-mentioned results were calculated with the electricity source currently being produced in China. If UK electricity production sources had been used instead, then the carbon payback time would increase to 2 years, and the potential carbon savings in the lifespan would decrease to around 1 tonne. The carbon emissions from producing electricity are expected to be reducing in the future, therefore, the short payback of one year was positive news since the embodied carbon savings could be paid back quickly, and carbon savings in following operational time could be committed even if the carbon efficiency of producing electricity could be largely improved in the future.

In conclusion, the results from this study showed that a significant carbon reduction could be achieved by the Passivhaus EnerPHit retrofitting under China's hot summer and cold winter climate. However, the findings provided by this research were limited within the research scope, which only considered the main life cycle stages of a building.

Moreover, economic analysis should be another essential factor to consider for Passivhaus standard retrofitting because it is a major element for the building industry to select this method of retrofitting. Therefore, further analysis should cover a detailed life cycle cost assessment in the next step of this study.

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