**Evaluating the potential energy savings of retrofitting low-rise suburban dwellings towards the Passivhaus EnerPHit standard in a hot summer/cold winter region of China**

# Abstract

This paper considers the potential heating and cooling energy savings from retrofitting to the Passivhaus EnerPHit standard a low-rise suburban dwelling in the southern Chinese town of Huilong, which has a hot summer/cold winter climate. An existing residential building in Huilong was chosen as a case study and a baseline digital model was created with the dynamic thermal simulation software DesignBuilder. The model was validated using 12 months of air temperature and relative humidity measurements from the building. The virtual retrofitting process of the baseline model involved insulating the envelope, improving the airtightness and adopting a high efficiency mechanical ventilation heat recovery system. It was more difficult to reach the EnerPHit cooling energy demand criterion than the heating target, and so additional passive cooling from shading and natural ventilation were adopted to finally achieve the EnerPHit standard. The final simulation results suggest that the EnerPHit standard for energy was successfully achieved, with a 90% heating energy demand reduction (down to 14.9 kWh/m2a), and a 70% cooling energy demand (down to 12.6 kWh/m2a), compared to the dwelling’s baseline values.

# Key words:

Step-by-step retrofitting; Passivhaus EnerPHit standard; Energy saving; Suburban residential building.

# Introduction

China is the world’s biggest consumer of energy, with buildings being responsible for around 21% of the country’s total energy demand – a figure that is predicted to rise to 29% by 2040 [1]. Urban and rural housing account for 37% and 34% respectively of the building-related energy consumption [2]. Therefore, improving the energy efficiency performance of new and existing housing is a key area to address when considering how to achieve China’s carbon emission reduction targets. China’s National Energy Research Institute reports that the emission reduction potential in the building sector could be 74% by 2050, which is 1.5 times that of the industrial sector [3].

However, China’s current compulsory green building regulations are mainly aimed at new buildings. There has been much less regulatory interest in the energy retrofit of existing buildings, even though there is around 43 billion m2 floor area of existing buildings in China, with more than 90% of them having poor energy performance [4]. Therefore, upgrading those existing buildings through energy-efﬁcient renovation is a potentially significant means for energy saving and emission mitigation [5]. The Chinese government has been updating the building energy standards with the overall goal of energy saving in recent decades, and the aim of achieving a 50% energy saving in residential buildings is presented in the latest energy-saving standard for the hot summer/cold winter climate regions [6]. One possible long-term solution to achieving massive retrofit energy savings is the very rigorous retrofit standard known as EnerPHit, which was developed by the German Passivhaus Institute [7]. The Passivhaus standard is based on the principle of minimising heat losses from opaque and transparent building envelope components, eliminating thermal bridges and having very low air leakage. A mechanical ventilation system with heat recovery is used to further reduce the ventilation heat loss and recycle the exhaust heat from the building. As a result, the energy used to maintain a comfortable indoor environment is very low. The energy efficiency of Passivhaus has been widely proven throughout Europe, especially in cold climate regions [8][9]. Over 100 Passivhaus buildings were investigated as part of the CEPHEUS project in Europe, and they achieved a space heating demand which was 15-20% of that for standard new buildings [10]. A 55-83% reduction in energy consumption was claimed in the Passivhaus standard retrofitting of historic buildings [11]. Wang reviewed the energy performance of frequently used Passivhaus technologies and their interaction with indoor environment quality in Passivhaus buildings under different weather conditions [12]. Requirements and strategies towards the Passivhaus standard in residential building in different countries have been reviewed in [13]. More recently, Passivhaus buildings are being built in warmer climate regions, with some of these buildings reporting summer overheating or cooling demand being higher than the Passivhaus requirement [14][15].

In China, the Passivhaus standard is a relatively new concept, and the EnerPHit retrofit approach is even less familiar. 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 [16]. Based on certification information, all of the certificated 46 Passivhaus projects in China have achieved 15 kWh/m2a or less for space heating [17]. The first residential Passivhaus built in southern China achieved a 95% energy savings compared to conventional dwellings, maintained indoor air temperature between 20°C to 26°C and achieved 90% energy savings during operation [18]. Although such projects in China suggest that substantial operational energy use in buildings could be saved by achieving the Passivhaus standard, these projects are mostly new build high-rise buildings in urban areas. Examples of retrofitting buildings towards the corresponding Passivhaus standard are very limited, even though upgrading the energy performance of the numerous existing residential buildings is imperative to achieve energy-saving goals.

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. They are also considered as challenging when it comes to meeting strict energy retrofit criteria, such as the Passivhaus EnerPHit standard.

Therefore, to assess the nature and magnitude of this challenge, this study investigated an ordinary suburban residential building in Wugang, in the southern China province of Hunan, which experiences a hot summer/cold winter climate. The aim was to examine the energy performance of an existing dwelling when it was subject to the Passivhaus EnerPHit retrofit standard through a step by step energy efficiency retrofitting process. The EnerPHit criteria are slightly different according to the climate type, and for Wugang’s climate EnerPHit’s energy demand is limited to 20 kWh/m2a and 15 kWh/m2a for space heating and cooling respectively, and the airtightness of the building to a maximum value of one air change per hour (ac/h) [19]. The dwelling was modelled using the dynamic simulation tool DesignBuilder. Air temperature and relative humidity data were recorded continuously in the Huilong dwelling for a 12-month period and these data were used to test the validity of the DesignBuilder model. The retrofitting process followed the Passivhaus guidance and heating and cooling energy savings were reviewed following the retrofitting steps.

# The baseline case study dwelling

A typical semi-detached four-storey residential/commercial building in Huilong (Figure 1) was selected as the baseline case study building. Huilong is a small town in the southwest province of Hunan. There are many towns similar to Huilong in Hunan, which means that the findings from this study could be quite widely applied. In China, outside of cities and counties (which are one administrative level lower than cities), the administrative level is classed as ‘rural’, even though the governance includes towns as well as villages. Huilong is in a hot summer/cold winter climate zone, with temperatures peaking around 32°C in summer and dropping down to around 2°C in winter. In recent decades, a large proportion of Chinese dwellings in towns and villages have been replaced with low or mid-rise reinforced concrete buildings. The case building was constructed in 2006 without any insulation, and its main thermal parameters are summarised in Table 1. The ground floor of this building is for commercial use, like most town dwellings in Hunan, and the top three floors are three individual flats, which each have the same layout as shown in Figure 2. Only the residential areas were considered for the retrofitting in this study.



Figure 1. View of the Huilong case building and location of Huilong in Hunan province.

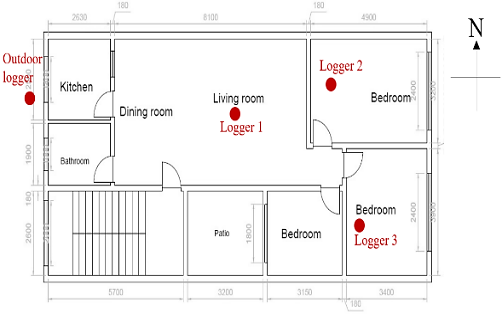


Figure 2. Floor plan and data logger locations (●).

Table 1. Building construction inputs for the baseline model

|  |  |  |
| --- | --- | --- |
|  | Construction detail | U-Value |
| Exterior wall | 5mm putty paint, 10mm cement mortar, 180mm clay brick, 10mm cement mortar, 10mm outside porcelain tiles | 2.32 W/m²K |
| Interior wall | 5mm putty paint, 10mm cement mortar, 180mm clay brick, 10mm cement mortar, 5mm putty paint | 2.30 W/m²K |
| Roof | 50mm cement, 100m reinforced concrete raft, 400mmair gap, 10mm wood board, 5mm putty paint | 1.90 W/m²K |
| Ground floor | 20mm Rammed earth, 10mm gravel, vapor membrane, 100m reinforced concrete, 50mm Terrazzo | 1.30 W/m²K |
| Internal floors | 10mm porcelain tiles, 10mm cement, 50mm cement mortar, 100m reinforced concrete raft, 5mm putty paint | 2.44 W/m²K |
| Windows | 4mm single glass, Aluminium window frame | 5.85 W/m²K |

Air temperature and relative humidity data were recorded from 1st July 2018 to 30th June 2019 under free running conditions. A Rotronic TL-1D device was used in both the living room and secondary bedroom, while a Rotronic CL 11 was used in the main bedroom. Outdoor data were recorded using an EasyLog EL-GFX-2. The measurement devices were new and being used for the first time, and so their factory calibrations were accepted. According to the manufacturers, the Rotronic loggers have a measurement accuracy of ±0.3°C for temperature and <2.5% for relative humidity, while the measurement accuracy of the EasyLog logger is ±0.35°C and <2.05% respectively. Figure 2 shows the location of each device - the indoor loggers were placed on a shelf away from any internal heat source, and the outdoor logger was placed in a naturally-ventilated box underneath a shelter and so was not exposed to direct solar gain. All data were logged at 15-mintute intervals. Monthly mean values from the monitoring are presented in Figure 3, which shows a large external temperature range over the 12-month period, with the outdoor temperatures changing from a peak of 31.1°C in July 2018 to a low of 6.2°C in January 2019. Indoor temperatures were about 1°C warmer than outdoors and were 32.3°C and 6.6°C in July and January respectively. Relative humidity levels were more stable but quite high throughout the 12 months, ranging for outdoor values from 70% to 90%, and for indoor values from 60% to 90%. Overall, the recorded data suggest there is an unsatisfactory indoor thermal comfort level in the uninsulated base case building due to the severe hot summer/cold winter climate.

Figure 3. The 12-month measured monthly mean indoor/outdoor temperatures (T) and relative humidities (RH).

# Research methodology

The main objective of this study was to assess the energy saving potential of retrofitting a typical suburban low-rise residential building towards the Passivhaus EnerPHit standard. To achieve this purpose, the energy usage patterns before and after a series of retrofitting measures of the case building were investigated through the dynamic building performance simulation software, DesignBuilder (version 6.1.3) [20]. A weather file used for simulation was generated by the climate database software Meteonorm using a source from the closest weather station to Huilong, located in Wugang [21].

## **3.1 General information of the model**

The baseline scenario was modelled with the features of the actual building. The window-to-wall ratio for the east and west façades were 0.35 and 0.31 respectively. The thermal information of the envelope is shown is Table 1, and only the residential areas (the three flats on the top three floors with a total floor area of 297m2), were planned to be retrofitted. The other spaces in this building were set as semi-exterior unconditioned space, while the wall or floor adjacent to the semi-exterior space were considered as exterior envelope during retrofitting and set as semi-exposed envelope in DesignBuilder simulations. Because the airtightness of the case building was not able to be measured, a study by Chen that used blower doors [22] was referenced. Chen’s work tested the airtightness performance of several flats in a building in China which had the same type of construction as the case building, and the measured values were between 1.6 ach to 6.4 ach [22]. Moreover, the calibration results in section 4.1 suggested that the DesignBuilder baseline model was closest to the actual measured data with an airtightness level of 3 ach, and so this value was selected for the baseline model simulation. The heating and cooling setpoint temperatures were set to the EnerPHit standard comfort temperature requirements of 20℃ and 25℃ respectively for all of the simulations. The occupancy activity schedule was defined according to the type of the indoor room location, with a metabolic rate of 90W/person in bedrooms, 110W/person in the living room, 160W/person in the kitchen and 120W/person in the bathroom [23]. A LED lighting pattern was modelled for all the rooms with a power density of 2.5 W/m2. Two weather files were developed for the testing of the DesignBuilder model - one using the locally measured weather data outside the dwellings while the other was a thirty year mean weather file generated from Meteonorm.

## **3.2 Calibration of the baseline model**

To check the accuracy of the DesignBuilder baseline model, an attempt to validate the model was made for the period 1st July and 31st December 2018 (i.e. both summer and winter conditions). A weather file was created using the weather data measured outside the dwellings. When the same DesignBuilder baseline model was run using the thirty year mean weather file data generated from Meteonorm, Figure 4 shows that agreement was also good for the autumn/winter months but was poorer for the summer months. This might be because the historical Meteonorm data are generating cooler summer temperatures than are actually being experienced currently. However, for the virtual analysis of the retrofitting measures over a year, it was decided to use the Meteonorm file as it gives a much longer-term view of the climate, potentially dampening the impact of any unusually cold or hot periods. Also, for the retrofitting study it was the relative changes in energy demand that were of interest whereas with the baseline validation it was the absolute values that were important.

## **3.3 Step-by-step retrofitting to meet the EnerPHit standard**

The first aim of this research was to explore whether the case building could manage to achieve the strict Passivhaus EnerPHit standard under the hot summer/cold winter climate. Following the standard, the concept of a ‘fabric first’ approach, which prioritises heat retention and reduced air leakage, followed by using an efficient heating and ventilation system, were applied to the retrofitting. After considering retrofitting strategies, internal (rather than external) fabric insulation was selected. It was decided to apply a 250mm thickness of Rockwool insulation for the whole envelope. The single glazed windows were replaced with triple glazed windows, which have a similar thermal performance to other Passivhaus buildings in China. Furthermore, the airtightness was modelled as 0.6 ac/h (lower than the EnerPHit criterion). A mechanical ventilation system with a sensible and enthalpy heat recovery function (MVHR) was modelled, considering Hunan’s humid and cold weather conditions. This system provided fresh air almost all year round and strongly assisted the heating supply in winter. The use of an air conditioning system is necessary to supply active cooling as the outdoor average summer temperature can be above 30℃. It is also used to supply heating during winter-time. Moreover, additional passive cooling from shading and ventilation cooling were adopted to finally achieve the EnerPHit standard for cooling energy demand.

# Results

## **4.1 Baseline model calibration**

The calibration of the DesignBuilder baseline model compared the differences between field measured indoor temperature values and the simulated values. The DesignBuilder baseline model included the original construction materials, lights and equipment. Figure 4 displays the average indoor temperature comparisons from DesignBuilder simulations and the measured values between 1st July and 31st December. Since it was not possible to measure the actual airtightness of the case building, DesignBuilder simulation assumed possible airtightness values from one to five ach, and the value displayed in the figure shows that when the case building had an assumed airtightness of three ach was when it was closest to the actual situation. The results show that the temperature gap between the simulated value when DesignBuilder ran with the Meteonorm weather data and the field recorded values was about 3℃ in summer months, which might be because the real outside measured temperature was a similar value higher than the Meteonorm weather data file. Thus, the field recorded outdoor temperature and relative humidity were edited to create the weather data, and the result showed that the simulated indoor temperature values and measured indoor temperature values were closely aligned, which gave confidence in the simulation of the Passivhaus retrofitting.

Figure 4. Monthly average indoor temperatures: measured and DesignBuilder (DB) simulated values.

## **4.2 Energy performance before retrofit**

For the field recorded energy consumption in one of the flats, the peak monthly electricity used in summer and winter were 368 kWh and 693 kWh respectively, while the average value of months which used no heating and cooling was 233 kWh. The reason that electricity consumption in summer and winter months was higher than other months could be because of the electric fans and plug-in heaters used to provide thermal comfort. However, the field recorded thermal data shows the monthly mean indoor temperature in the peak energy months were 30.5℃ and 7.9℃ for summer and winter respectively, which are unsatisfactory from a comfort point of view, especially compared with the Passivhaus standard comfort range of 20℃ to 25℃.

The DesignBuilder baseline model was used to evaluate the energy consumption when the space was assumed to heat and cool towards the target comfort temperature range of 20℃ to 25℃. Because the type of plug-in heaters typically used by the residents are not powerful enough to achieve the targeted comfort level, a radiator heating system and an air conditioning system were selected for the simulation in the baseline model so that the energy required to reach comfort in the baseline case could be assessed. The predicted DesignBuilder baseline model energy consumption was, unsurprisingly, much higher than the EnerPHit standard due to the very poor envelope insulation. The predicted annual heating demand of 150.6 kWh/m2a, was more than seven times the Passivhaus standard value, while the predicted annual cooling demand of 42 kWh/m2a, was about three times the required value. This illustrates that heating is the dominant energy consumer in this climate for these types of dwellings, and that the energy saving possibilities for heating are much higher than for cooling through a deep energy retrofitting. However, as will be discussed later, it was found that achieving cooling energy savings was more challenging than achieving heating energy savings by retrofit measures.

## **4.3 Retrofitting measures**

### **4.3.1 Retrofitting approach**

A series of numerical simulations were carried out in order to analyse the improvements arising from the retrofit process. The main purpose was to quantify how the required heating and cooling energy consumptions in the building changed following the retrofit steps to eventually meet the EnerPHit standard. The retrofitting process was mainly divided into five core phases: (i) improving the building envelope insulation performance; (ii) reducing airtightness of the retrofitted area to 0.6 ac/h; (iii) installing a mechanical ventilation system with heat recovery; (iv) the coefficient of performance of the air conditioning system for heating was slightly improved; and (v) passive cooling (shading and natural ventilation) were adopted. Those retrofitting measures follow the Passivhaus concept of a fabric first approach where, for each of the measures to work efficiently, is reliant on the successful application of the previous retrofitting step, and their cooperation largely improves the energy efficiency of the case building in reaching the EnerPHit standard.

### **4.3.2 Building envelope retrofitting**

The retrofitting steps for improving the insulation performance of the envelope involved incrementally applying Rockwool insulation to the outside wall, roof and floors, followed by the replacement of the exterior windows and doors. The details of the envelope thermal performance after applying these measures are shown in Table 2. The 'first floor' is the bottom of the retrofitting space because only the residential space on the top three floors of the building was considered for retrofitting. A comparison of heat losses from the main fabric elements of the building before and after the insulation retrofit is shown in Figure 5, in which the exterior wall and glazing lost the most heat in the building before retrofit and a total of 83% of the heat loss from the building fabric could be saved by adding sufficient insulation. Figure 6 shows how the heating and cooling demand in the building changed with the different stages of the retrofitting.

Table 2. Building fabric retrofit and resultant U-values

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Insulation material | Insulation thickness | U-value before  Retrofit (W/m2K) | U-value after  Retrofit (W/m2K) |
| Walls | Rockwool | 250mm | 2.30 | 0.125 |
| Roof | Rockwool | 250mm | 1.76 | 0.123 |
| First floors | Rockwool | 250mm | 2.85 | 0.126 |
| Interior floors | Rockwool | 250mm | 2.85 | 0.126 |
| Glazing | Triple glazing LoE |  | 5.85 | 0.78 |
| Doors |  |  | 2.82 | 0.833 |

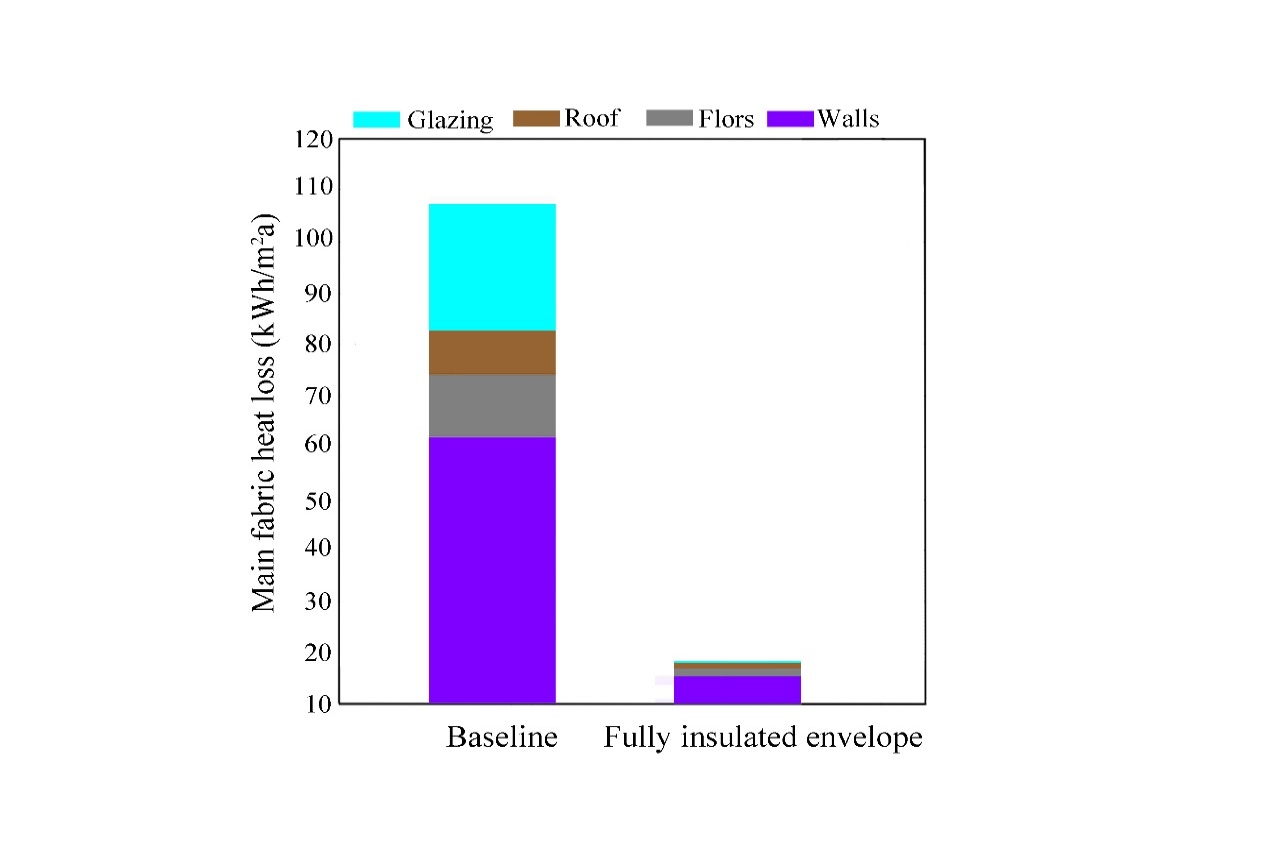


Figure 5. Fabric heat loss before and after envelope insulation retrofit.

Figure 6. Annual heating and cooling energy demand - incremental insulation retrofitting.

In terms of energy saved by retrofitting, on the heating side, 48% of energy is saved from the whole envelope insulation. More specifically, the wall insulation was the most efficient measure as it decreased the yearly demand to 118 kWh/m2a from the baseline value of 150.6 kWh/m2a. Both the roof insulation and first floor insulation each contributed around 10 kWh/m2a of energy saving, bringing the demand down to 94.5 kWh/m2a. Then, the insulation was applied on the interior floor as well, as interior floors are insulated in real Passivhaus buildings. This gave a further energy reduction of 4.5 kWh/m2a. Next, the single glazed windows were replaced with triple low emissivity (LoE) argon filled glazing, which lowered the demand to 78.4 kWh/m2a. On the cooling demand side, the energy demand showed a less significant decrease over the whole envelope insulation retrofit process, from 42 kWh/m2a to 29.4 kWh/m2a (a 30% reduction). The factor that contributed most to the cooling energy reduction is the high-performance windows, which lowered the value by about 6 kWh/m2a. The interior floor insulation increased the interior heat gain in summertime and the cooling demand was enhanced by 1 kWh/m2a. Furthermore, both the heating and cooling demand remained the same after fitting the three new flat entrance doors with a lower U-value of 0.833 W/m2K. This could be because they face the staircase, which is a semi-exposed space, rather than an outside environment. The overall results suggest that the heating energy consumption was very sensitive to the level of the whole envelope insulation, while the cooling energy demand was more sensitive to the transparent envelope.

### **4.3.3 Building airtightness retrofitting**

In this step of retrofitting, the airtightness of the three flats was lowered down to an excellent value of 0.6 ac/h instead of the EnerPHit standard of 1.0 ac/h, because the experience of real Passivhaus suggests a very low airtightness is necessary to achieve the EnerPHit standard. To attain 0.6 ac/h, exterior windows should be placed next to the wall insulation layer and an air leakage protection membrane should be applied on the interior side at the window-wall junctions to stop air leakage and thermal bridges. Figure 7 shows that the heating demand reduced dramatically to 17.3 kWh/m2a after the adoption of a low airtightness level, achieving a 78% energy saving from the last retrofitting phase. The cooling demand was 22.8 kWh/m2a, which was an energy saving of 22% from the last phase. The results show that lowering the airtightness level is an extremely efficient measure for energy saving, and that the heating demand had reached the EnerPHit standard. However, before and during this phase, the model was simulated with natural ventilation with the aim of supplying the minimum fresh air the occupants need. Windows were controlled by the schedules set for the function and activity of each room, which causes a serious risk of poor indoor air quality during the times when the windows are closed, like sleeping time. This risk led to the next retrofitting measure.

Figure 7. Comparison of energy demand between the phase 1 and phase 2 airtightness retrofitting

### **4.3.4 Mechanical Ventilation with Heat Recovery (MVHR) system**

During this phase of the retrofitting a mechanical ventilation system with heat recovery (MVHR) function was modelled to ensure a healthy indoor air quality and to recover the interior heat losses. Three outside air supply rates scenarios of the mechanical ventilation system and both sensible and enthalpy heat recovery methods for each scenario were simulated. The sensible method recovered the heat from the exhaust air was modelled with an efficiency of 85%. The enthalpy method involves both sensible and latent heat recovery, where the supply temperature and humidity ratio are both affected by the indoor exhaust air, and the effectiveness of the latent heat recovery was modelled as 80% efficient. The assumption of the heat recovery efficiencies refers to the most commonly used MVHR systems in China [24]. Figure 8 represents the simulated heating and cooling demands when the system operates with different scenarios. In scenario 1 the ventilation system supplied the fresh air depending on the indoor zone size and with a delivery rate equivalent to 3 ac/h. The heating and cooling demand were 22.0 kWh/m2a and 22.7 kWh/m2a respectively when the sensible heat recovery method is used, while when operating with the enthalpy method, the cooling demand went down to 17.3 kWh/m2a and the heating demand remained the same. In scenario 2 the group of results was defined by the zone size as well, but with the outside air delivery rate lowered to the equivalent of 1.25 ac/h. In this scenario, the heating demand was lowered to 19.5 kWh/m2a and the cooling demand was 17.8 kWh/m2a when using the enthalpy method, which was 3 kWh/m2a lower than when the sensible method value of 20.7kWh/m2a. Scenario 3 had the mechanical ventilation system suppling fresh air determined by the minimum fresh air needs of the occupants. The energy demand was now the lowest among the three scenarios - the heating demand was 17.9 kWh/m2afor both heat recovery methods, and the cooling demand was slightly lower when the enthalpy method was used, which is 17.2 kWh/m2a. In summary, the enthalpy heat recovery method was a more suitable retrofitting measure for the studied climate, with the field recorded weather data showing that the local average outdoor relative humidity was quite high, over 70%, all year round. Thus, the enthalpy heat recovery method neutralized the relatively wet outdoor supply air and dry indoor exhaust air, which contributed to a lower energy consumption for cooling. When the MVHR system with the enthalpy heat recovery method was used, the energy saving results of scenarios 2 and 3 were both quite good, so those two scenarios were both rolled into the next step of retrofitting.

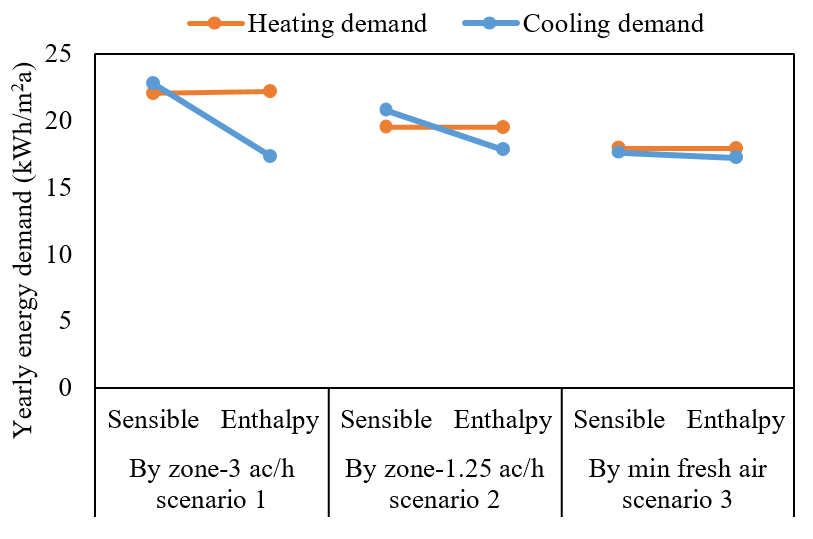


Figure 8. Comparison of energy demand for three mechanical ventilation system scenarios.

### **4.3.5 Heating system efficiency**

In this step, the coefficient of performance (CoP) of the air conditioning system for heating was increased from 1 to 1.2, to see the possibility for energy savings. Figure 9 represents the energy demand of the case building after the heating CoP higher was set to 1.2. The heating demand for scenarios 2 and 3 decreased to 16.2 kWh/m2 and 14.9 kWh/m2 respectively, which are both 16% saving from the last phase, and the cooling demands of the two scenarios remained the same as in last phase. In general, the retrofitting was successful, with significant amounts of energy saved to this stage. Because scenario 3 has a better energy efficiency, it was taken into next round of retrofitting to check the possibility of further cooling energy savings.

Figure 9. Energy demand for scenarios 2 and 3 when the heating CoP of the MVHR system is 1.2.

### **4.3.6 Passive cooling measures**

Passive methods of cooling, using shading and nature ventilation, were adopted in this phase of the retrofitting based on the building’s condition and the local climate context. In Passivhaus, solar shading systems are usually activated during summer months to prevent unwanted solar gain, while they are not activated outside of summer in order to permit solar gain to warm the indoor environment. It has been found that the shading of west and south facing windows is efficient and necessary to limit solar heat gains as well as maintaining comfortable indoor temperatures in hot continental climates [25]. So, the shading could heavily affect the cooling demand and the indoor comfort in the studied building because it is in a hot climate and all the exterior windows are mainly on the west and east façades. Window blinds shading was firstly considered for this case because it is easy to control and may be more economical compared with shading devices like overhangs, side fins and automatic self-shading device. Three types of window blinds, which had with three different slat solar reflectances of high (0.8), medium (0.5) and low (0.2) were simulated and they were placed on the inside and outside of the exterior windows respectively to check the most efficient cooling method. The window blinds were operated depending on the schedule shown in Table 3, and the results from the modelling are given in Figure 10.

Table 3. Schedule for window blinds shading operation

|  |  |  |
| --- | --- | --- |
| **From 1 June to 31 Aug** |  | **From 1 Sep to 31 May** |
| For: weekdays and weekends |  | For: weekdays and weekends |
| Until 07:00, 0% operation\*  Until 08:00, 25% operation  Until 09:00, 50% operation  Until 10:00, 75% operation  Until 18:00, 100% operation  Until 19:00, 50% operation |  | Until 24:00, 0% operation |
| \*Blinds operate with set slat angle 45º and are pulled down to cover a different % of the window area. | | |

Figure 10 suggests that the cooling demand was lower than in the last retrofitting phase no matter which type of window blinds was applied or placed on which side of the window. The heating demand remained the same as the shading was not active in wintertime. The solar gain from the exterior windows was always lower when the blinds were placed on the outside of the windows while it was lowest when the blinds had a low solar reflectance. The cooling demand was always lower when the blinds were outside of the windows, and when the blinds had a low solar reflectance, and the lowest value was 13.2 kWh/m2a, which is 4 kWh/m2a (23%) lower than it was in the last retrofitting phase. However, it is interesting to find that when the blinds were placed on the inside of the window, the cooling demand was lowest when the blinds had a high solar reflectance, while when it was placed on the outside, the cooling demand was lowest when the blinds had a low solar reflectance. This may be because when the blinds are inside the window, the high reflection helps to reflect the radiation back out of the window, while when the blinds are outside, the low reflection performance reduces the radiation reflects between the slats and less solar radiation eventually enter the window. In conclusion, the position of the window blinds could cause a big difference in the cooling demand, and the solar reflectance of the blinds also affects the energy demand. For this study, placing the blinds with low solar reflectance outside of the windows is adopted because the predicted cooling demand was the lowest.

Figure 10. Annual heating demand, cooling demand and exterior window solar gain when blinds with three different solar reflectance were adopted inside and outside of the windows.

Natural ventilation is also an important passive way to reduce energy consumption and maintain thermal comfort in Passivhaus. Night-time natural ventilation cooling can help to reduce the overheating problem in summertime [26]. In the hot summer/cold winter climate region, however, it is important to keep all the windows closed and only ventilate by the MVHR system in summer. This is because the outdoor temperature is usually much higher than the Passivhaus required upper comfort temperature of 25℃, even at night-time. However, during transitional seasons natural ventilation is still a good way to improve indoor air quality and reduce energy consumption [27]. Thus, the natural ventilation was activated by outdoor temperature control in the DesignBuilder simulation, which only operated when the outdoor temperature was between the Passivhaus comfort temperature range of 20℃ to 25℃. So, the natural ventilation method would not increase the heating demand and could assist with maintaining the indoor temperature passively when the outdoor temperature is suitable. Figure 11 shows the annual heating, cooling demand and heat gain through exterior ventilation after natural ventilation was applied. The results show that the heat gain from exterior ventilation from the last retrofitting step was none due to the natural ventilation being off. After it was turned on, there was a 4.1 kWh/m2a heat loss from the building, which led to a cooling demand decrease, from 13.2 kWh/m2a to 12.6 kWh/m2a. The cooling demand did not decrease significantly because the time when the outdoor temperature was between 20℃ to 25℃ was short in the year, which is not surprising based on the field recorded outdoor temperature, but a slight reduction in energy consumption was helpful.

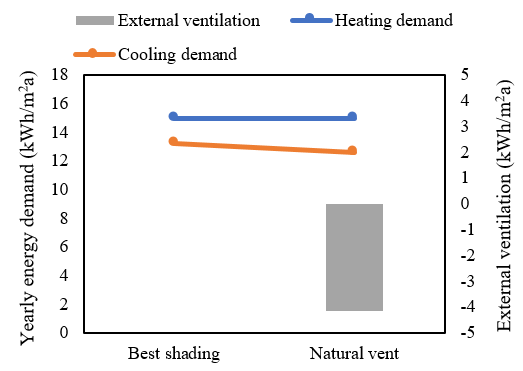


Figure 11. Annual heating demand, cooling demand and heat gain from exterior ventilation before and after natural ventilation was adopted.

### **4.3.7 Retrofitting summary**

In this study, the result from the field investigation of electricity demand and the simulation of the pre-retrofit building both suggested that the energy consumption for heating was far more than for cooling to keep a relatively comfortable indoor environment. From the retrofitting process, it has been found that all the measures gave a contribution to the achieved energy savings, but the function of sufficient insulation and a very low air leakage envelope were dominant for reducing the energy usage in heating, while low airtightness, the MVHR system, and passive cooling had a dominant effect on cooling demand reduction. The retrofitting strategies of thick insulation and low airtightness of the envelope were adopted mainly because of the very high heating energy demand of the pre-retrofit building. However, the insulation does not reduce the cooling demand efficiently, but the low airtightness could, based on the simulation results. Figure 12 summarises the energy demand reductions following the step-by-step retrofitting process. The case building saw a huge reduction heating and cooling demand, from 150.6 kWh/m2a and 42 kWh/m2a in the pre-retrofitted baseline situation to 14.9 kWh/m2a and 12.6 kWh/m2a after retrofitting, energy savings of 90.1% and 70% respectively. The EnerPHit standard requires an energy demand for heating and cooling in this climate area of 20 kWh/m2a and 15 kWh/m2a respectively, and so the achieved energy demand for the retrofitted dwelling was 5.1 and 2.4 kWh/m2a respectively lower than the criteria values. For comparison, the operational energy demand of a Passivhaus hotel building in this hot summer/cold winter climate area of China was measured, and it achieved 90% energy saving with the heating demand of 15 kWh/m2a, which is very similar with the simulated results in this study, while the hotel’s cooling demand (33 kWh/m2a) is much higher because higher cooling is needed in hotels and there is less efficient use of passive cooling measures [18].

Figure 12. The heating and cooling demand decreases following the step by step retrofitting process.

# Conclusions

This paper has considered the application of the Passivhaus EnerPHit retrofitting standard to suburban low-rise dwellings in a hot summer/cold winter climate region of China. An ordinary residential building in Huilong, Hunan province, was taken as a case study to evaluate the effectiveness of the Passivhaus retrofit standard. The step-by-step retrofitting measures, from insulating the exterior envelope to applying a high-performance mechanical ventilation system, were simulated to determine the suitable solutions for this case. It was concluded that it was possible to retrofit this building to the EnerPHit standard, giving greatly reduced energy demands for heating and cooling. Heating was the dominant energy demand of the pre-retrofitted building due to the heat losses through the uninsulated, leaky envelope. The heating demand was very sensitive to the opaque envelope insulating measures (40% energy saved) and airtightness level (40% energy saved), and together with the energy saved from high-performance windows (8%), the energy consumption was down to the required EnerPHit standard value. For cooling demand, the contribution from the high thermal insulation opaque envelope (12%) was smaller than from the low airtightness (16%) and high-performance windows (18%).

The use of a MVHR system was essential to supply fresh air to the indoor space under the studied climate because the outdoor thermal environment could not provide indoor comfort with natural ventilation for most of the year. This case study adopted a MVHR system with 85% sensible heat recovery efficiency and 80% latent heat recovery. The latent heat recovery function is fundamental for this climate because of the high humidity, and this function helps reduce the cooling demand by about 5 kWh/m2a. The simulation results also suggested that the different fresh air supply modes of the MVHR system affected the heating energy consumption. As a result of the retrofit measure, the heating demand achieved the EnerPHit standard, but the cooling demand did not meet the standard until passive cooling measures were adopted. Using blinds with a low solar reflectance (0.2) outside the window was the most efficient shading way which to reduce the cooling demand, while using natural ventilation when the outdoor temperature was under the Passivhaus comfort range of 20°C to 25°C slightly reduced the cooling demand. The heating and cooling demands that were finally achieved from all the retrofitting measures were actually about 25% and 16% below the EnerPHit criteria. Therefore, future work will undertake a parametric analysis to investigate the possibility of reducing the thermal performance of the envelope whilst still meeting the standard. The thermal and airtight performance of the envelope which will be required to balance the insulation need in winter with the heat dissipation requirement in summer, in the context of a hot summer/cold winter climate, will also be studied further. Cost is a key parameter in any retrofit project, and so life cycle cost analysis and the payback time of the retrofitting measures will be analysed in future research in order to determine the payoff between retrofitting costs and the energy savings.

# References

[1] BP Energy Outlook 2019. Available:

<https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html>.

[2] China Association of Building Energy Efficiency, China Building Energy Research Report of 2018, 2018. [Online]. <http://www.cabee.org/site/content/22960.html>

[3] China Association of Building Energy Efficiency, China Building Energy Research Report, 2016. <http://www.efchina.org/Attachments/Report/report-20170710-1/report-20170710-1>

[4] M. Li, J. Zhao, and N. Zhu, “Method of checking and certifying carbon trading volume of existing buildings retrofits in China,” *Energy Policy*, vol. 61, pp. 1178–1187, 2013.

[5] Z. Ma, P. Cooper, D. Daly, and L. Ledo, “Existing building retrofits: Methodology and state-of-the-art,” *Energy and Buildings*, vol. 55, pp. 889-902, 2012.

[6] D. Yan, T. Hong, C. Li, Q. Zhang, J. An, and S. Hu, “A thorough assessment of China’s standard for energy consumption of buildings,” *Energy and Buildings*, vol. 143, pp. 114–128, 2017.

[7] C. Hopfe, The Passivhaus Designer’s Manual: a technical guide to low and zero energy buildings, London: Routledge, Taylor & Francis Group, 2015

[8] P. Rohdin, A. Molin, and B. Moshfegh, “Experiences from nine passive houses in Sweden - Indoor thermal environment and energy use,” *Building and Environment*, vol. 71, pp. 176-185, 2014.

[9] M. Dowson, A. Poole, D. Harrison, and G. Susman, “Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal,” *Energy Policy*, vol. 50, pp. 294-305, 2012.

[10] J. Schnieders and A. Hermelink, “CEPHEUS results: Measurements and occupants’ satisfaction provide evidence for Passive Houses being an option for sustainable building,” Energy Policy, vol. 34, no. 2 SPEC. ISS., pp. 151–171, 2006.

[11] F. Moran, T. Blight, S. Natarajan, and A. Shea, “The use of Passive House Planning Package to reduce energy use and CO 2 emissions in historic dwellings,” Energy Build., 2014.

[12] Y. Wang, J. Kuckelkorn, F. Y. Zhao, H. Spliethoff, and W. Lang, “A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings,” Renew. Sustain. Energy Rev., vol. 72, no. November 2016, pp. 1303–1319, 2017.

[13] S. Guillén-Lambea, B. Rodríguez-Soria, and J. M. Marín, “Review of European ventilation strategies to meet the cooling and heating demands of nearly zero energy buildings (nZEB)/Passivhaus. Comparison with the USA,” Renew. Sustain. Energy Rev., vol. 62, pp. 561–574, 2016.

[14] V. Badescu, N. Laaser, and R. Crutescu, “Warm season cooling requirements for passive buildings in Southeastern Europe (Romania),” *Energy*, vol. 25, pp. 3284-3300, 2010.

[15] P. A. Fokaides, E. Christoforou, M. Ilic, and A. Papadopoulos, “Performance of a Passive House under subtropical climatic conditions,” *Energy and Buildings*, vol. 133, pp. 14-31, 2016.

[16] M. Lu, X. Xingzhao, “Practical experiments and implementation of the Passive house concept in China,” 22nd Passivhaus conference proceedings, 2018. https://passipedia.org/phi\_publications/international\_passive\_house\_conference\_contributions\_5?do=.

[17] Passive House Database. [online]. Available:

<https://passivehouse-database.org/index.php?lang=en#s_25e379cb2d7ebbf5028ba61920db8ce7>

[18] Jiangqiu Sui; Yangyang Meng, “Practice and Exploration of German Passive House in China Real Estate Project, Jiuzhang mansion by Poly group in Taizhou,Zhejiang,” *Low Carbon World*, vol. 7, pp. 163–164, 2019.

[19] “Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard,” 2016. [Online]. <https://passiv.de/downloads/03_building_criteria_en.pdf>

[20] V. Garg, J. Mathur, S. Tetali, and A. Bhatia, *Building energy simulation: A workbook using designbuilder*. London: CRC Press, Taylor & Francis Group, 2017.

[21] Meteonorm website. [Online]. https://meteonorm.com/en/.

[22] S. Chen, M. D. Levine, H. Li, P. Yowargana, and L. Xie, “Measured air tightness performance of residential buildings in North China and its influence on district space heating energy use,” Energy Build., vol. 51, pp. 157–164, 2012.

[23] ASHRAE, “2009 ASHRAE Handbook - Fundamentals,” Chapter 9 Thermal Comfort, 2012.

[24] “China Passive low-energy building product catalog,” 2017. [Online]. Available: <http://www.passivehouse.org.cn/pro/555/>.

[25] J. Mlakar and J. Štrancar, “Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations,” *Energy Build.*, vol. 43, no. 6, pp. 1443–1451, Jun. 2011.

[26] N. Artmann, H. Manz, and P. Heiselberg, “Parameter study on performance of building cooling by night-time ventilation,” *Renewable Energy*, vol. 33, no. 12, pp. 2589–2598, Dec. 2008.

[27] Y. Wang, F. Y. Zhao, J. Kuckelkorn, D. Liu, J. Liu, and J. L. Zhang, “Classroom energy efficiency and air environment with displacement natural ventilation in a passive public school building,” *Energy and Buildings*, vol. 70, pp. 258-270, February 2014.FH