Analysing energy savings and overheating risks of retrofitting Chinese suburban dwellings to the Passivhaus EnerPHit standard

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ABSTRACT: Chinese suburban housing largely consists of uninsulated reinforced-concrete apartment blocks with poor insulation performance. Much energy is required to reach indoor thermal comfort in Chinese regions which have hot summer/cold winter climates. Retrofitting existing dwellings to a better energy performance standard might be preferable to new build as existing buildings are mostly structurally sound and local demand for new homes is low. This paper examines the viability and benefits of applying the German Passivhaus EnerPHit standard to a suburban dwelling in Hunan, which is in the hot summer/cold winter climate zone of China. The indoor and outdoor hygrothermal data of the dwelling was monitored for 12 months, and the dwelling was then modelled and validated against the measured data. Incremental EnerPHit retrofitting measures were applied to the modelled building, and the thermal performance of the retrofitted building was evaluated using multiple approaches, including a PMV model, the Passivhaus standard and the Chinese passive house standard. The simulation results suggest that the EnerPHit standard is achievable, producing a high energy saving efficiency. Indoor thermal comfort was hugely improved after retrofitting, but two of the multiple comfort evaluation approaches highlighted that overcooling was a bigger problem than overheating for the retrofitted dwelling.
KEYWORDS: Retrofitting, EnerPHit standard, Hot summer/cold winter climate, Thermal comfort, Overheating risk

1. INTRODUCTION

The German Passivhaus standard, with its emphasis on super-insulated and super-airtight building envelopes, is slowly being adopted in China, especially in the cold cities of northern China. However, the concept of Passivhaus in Chinese rural and suburban areas is not a familiar one, even though actual building energy use is greater in suburban China than in the cities [1]. The governance definition of rural areas in China includes both towns and villages. Much of the existing town/rural housing consists of uninsulated reinforced-concrete blocks with poor energy performance. They are structurally sound but costly to demolish and challenging to recycle. Therefore, retrofitting existing suburban dwellings to the Passivhaus EnerPHit retrofit standard may have the potential for large scale energy savings.

This paper considers the retrofitting of suburban dwellings to the EnerPHit standard in the southern Chinese province of Hunan, which experiences a hot summer/cold winter climate, with temperatures peaking around 32°C in summer and dropping down to around 2°C in winter. A typical apartment was monitored and then modelled using the software DesignBuilder, and the models were tested against the measured data. Finally, step by step EnerPHit retrofitting measures were applied to the case building, to assess the energy saving, thermal comfort and summertime overheating risk after retrofitting.

2. LITERATURE REVIEW

In China, over 100 Passivhaus projects have now been completed or are under construction, mainly in northern regions [2]. A Passivhaus dwelling built in the extremely cold northern city of Harbin generally performed well in terms of internal environmental conditions, but summer overheating was a problem [3]. The first residential Passivhaus in southern China under a hot summer/cold winter climate, the BRUCK Residence in Huzhou, was completed in 2013 [4], and achieved 95% energy savings compared to conventional dwellings [5]. For the EnerPHit retrofit project in the same climate zone, a serious overheating problem was found in the Lvyuan Passive House in Shanghai during operation [6].

3. SCOPE AND METHODOLOGY

3.1 Case study building

This study investigated a semi-detached 4-storey occupied building (Figure 1) in Huilong town in the southwest province of Hunan, built with a reinforced-concrete structure and no insulation. The ground floor is for commercial use, and the top three floors are three individual flats, each having the same layout (Figure 2). Only the residential areas were considered for the EnerPHit retrofitting in this study, so 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 DB simulations. Air temperature and relative humidity were monitored in the second-floor living room, and two bedrooms and a shaded external place for 12 months.

Figure 1: View of the case building in Hunan, China

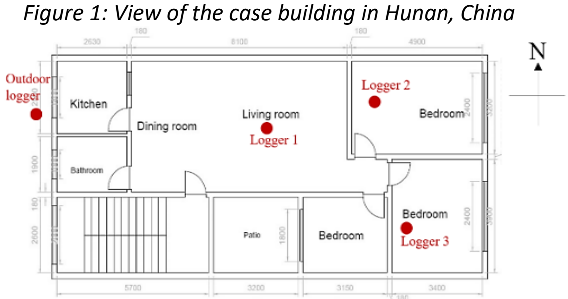

Figure 2: Floor plan and sensor locations.

3.2 The EnerPHit standard

The EnerPHit standard guides the refurbishment of existing buildings to achieve a specified Passivhaus standard. It has different energy requirements for buildings in different climates. For the studied hot summer/cold winter climate, energy demand is limited to 20 kWh/m^2 for heating, and 15 kWh/m^2 for cooling (excluding dehumidification). For thermal comfort, EnerPHit requires the same comfort temperature as the Passivhaus standard (20°C to 25°C), with no more than 10% of the hours in a year being outside this range [7].

3.3 Retrofitting strategies

The property was modelled using DesignBuilder, and the baseline model was calibrated before retrofitting. The field recorded weather data were used for calibration, and the results published in [8]. Because the aim of this retrofitting is to achieve the EnerPHit standard, the Passivhaus concept of ‘fabric first’ approach was followed, which prioritises heat retention and reduced air leakage, followed by an efficient heating and ventilation system. Rockwool insulation was chosen for the whole envelope because of its high thermal performance, and it is a commonly used in China. For external windows, triple glazed, and argon filled LoE windows were adopted. Airtightness was set to 0.6 ach, and mechanical ventilation with heat recovery (MVHR) system was modelled for the winter heating fresh air supply. For the hot summer, both active and passive cooling methods were adopted.

3.4 Thermal comfort and overheating assessment

Three evaluation approaches were used to assess the thermal comfort situation of the retrofitted building: (i) the PMV model; (ii) the Passivhaus standard and (iii) the Chinese Passive House standard. These last two standards require a similar temperature range, so the hourly simulated temperatures of the case building were compared with the two required comfort ranges.

4. RESULTS

4.1 Field measurements

The weather data were recorded from 1st July 2018 to 30th June 2019, and the dwelling was in a free-running situation. Figure 3 displays a larger outdoor hourly temperature span than the indoor hourly temperature range in the recorded period. However, the monthly mean temperature values were close, as the outdoor value changed from a peak of 31.1°C in July 2018 to a low of 6.2°C in January 2019, and the indoor value was about 1°C higher than outdoors throughout the recorded period. For recorded relative humidity, the outdoor monthly mean value was high all year at 70% to 90%, and the indoor value was only slightly lower, changing between 60% and 80%. The recorded data suggest that the indoor thermal situation of the pre-retrofit case building is quite close to the outdoor environment, and active heating and cooling is needed for indoor comfort under this climate context.

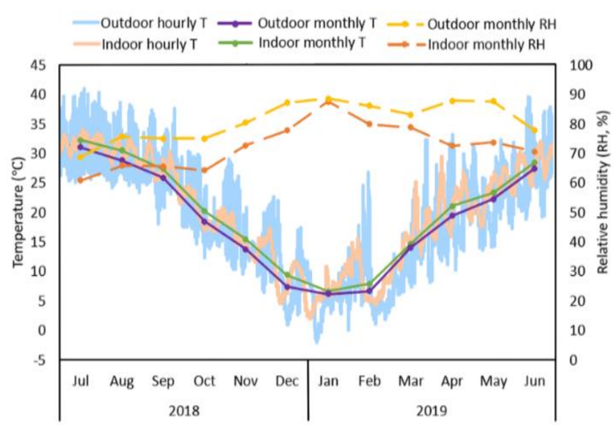

Figure 3: 12-month period measured indoor and outdoor temperature (T) and relative humidity (RH)

4.2 Comfort level before the retrofit

The comfort level of the case building before retrofitting was evaluated against the Chinese GB/T 50785 standard, which is the evaluation standard for the indoor thermal environment in civil buildings in China [9]. For free-running dwellings under the studied climate, the standard uses Equations 1 and 2 to calculate the acceptable comfort range. This calculation considers the outdoor temperatures 7 days prior to the test date, and the field recorded outdoor weather data were used to calculate the comfort range.

$$T_{upper\ limit} = 0.73\ t_{rm} + 12.72 \quad (1)$$

$$T_{lower\ limit} = 0.91\ t_{rm} - 3.69 \quad (2)$$

where 18°C ≤ $T_{upper\ limit}$ ≤ 30°C; 16°C ≤ $T_{lower\ limit}$ ≤ 28°C

Figure 4 indicates the measured indoor daily average temperature against the calculated comfort range. This range accepts a large span of indoor temperatures (16°C to 30°C) under different corresponding outdoor running mean temperatures. However, only 41% (150 days) of the days were within the range during the measured 12-month period, and 41% (150 days) were considered as cold, 18% (65 days) were hot. Thus, thermal comfort in the pre-retrofit building was unsatisfactory.

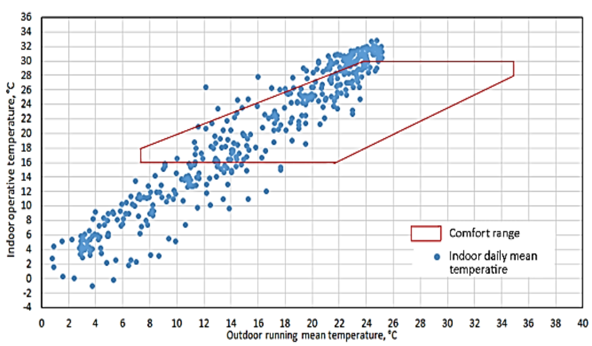

Figure 4: Recorded indoor daily mean temperatures and the Chinese GB/T 50785 standard comfort range.

4.3 EnerPHit retrofitting

For achieving the EnerPHit criteria of energy consumption, a commonly used insulation material was applied first on the inside of exterior walls, roof and floors to increase the insulation performance of the case building. Then the single glazed windows were replaced with triple glazed, argon filled low emissivity (LoE) windows. Table 1 summarises the thermal properties of the envelope before and after retrofitting. Secondly, the airtightness was reduced to 0.6 ach, and a mechanical ventilation system with heat recovery function (MVHR) was added, with a heat recovery efficiency of 0.85 and 0.80 for sensible heat and latent heat respectively. The coefficient of performance of the MVHR system for heating was increased slightly from 1.0 to 1.2, for better heating energy performance. Finally, passive methods of shading cooling and natural ventilation cooling were adopted. Simulation results showed that the energy used in cooling was lowest when the window blinds have a low slat solar reflectance level (0.2). Night-time natural ventilation can help a passive house to cool down in summer [10]. While in the studied climate, the outdoor temperature in summer is usually greater than passive house required temperature of 25°C. Thus, the natural ventilation cooling way was only used in transitional seasons.

Table 1: Thermal properties of the envelope before and after retrofitting.

	Wall	Roof	Floors	Window
Main material	180mm clay brick	100m concrete raft	100m concrete raft	Single glazing
Insulation material	Rock wool	Rock wool	Rock wool	Triple glazing LoE
Insulation thickness	250mm	250mm	250mm	-
U-value Pre-retrofit	2.3 W/m²K	1.76 W/m²K	2.85 W/m²K	5.85 W/m²K
U-value retrofitted	0.125 W/m²K	0.123 W/m²K	0.126 W/m²K	0.78 W/m²K

Figure 5 demonstrates how the energy demand changed following the EnerPHit retrofitting steps. The baseline pre-retrofit model energy demands were 150.6 kWh/m² and 42.0 kWh/m² for heating and cooling respectively - much higher than the EnerPHit standard. Retrofitting insulation and changing the glazing reduced the heating demand to 78.4 kWh/m². Figure 5 shows that the insulation did not reduce the cooling energy demand much, but the high-performance windows did. At the end of this retrofitting phase, the cooling energy demand was 29.4 kWh/m², about two-thirds of the pre-retrofit value. Reducing the air change rate to 0.6 ach was clearly very efficient, especially for heating demand, which was down to 17.4 kWh/m² (11.5% of the baseline value). The cooling demand decreased to 22.8 kWh/m² (54.3% of the baseline value). After adding the MVHR system, the heating demand finally met the EnerPHit standard, with a further decrease after the CoP for heating was slightly increased. At this retrofitting stage, the heating demand was 14.9 kWh/m² (10% of baseline demand) and cooling demand was 17.2 kWh/m² after the MVHR system was added (40.9% of baseline demand). However, the EnerPHit cooling standard was still not reached. So, passive cooling methods were utilised, and Figure 5 suggests that the shading worked efficiently, with the cooling demand dropping to 13.2 kWh/m², which successfully meets the standard. The natural ventilation cooling also contributed to cooling the building, with demand down to 12.6 kWh/m², or 30% of the baseline value. Thus, both the EnerPHit heating and cooling energy demand standards were achieved at the end of the retrofitting process.

In general, all the retrofitting measures contributed to energy saving, but to different degrees in heating and cooling consumption. The final results suggest that retrofitting the case property to meet the EnerPHit standard was achievable.

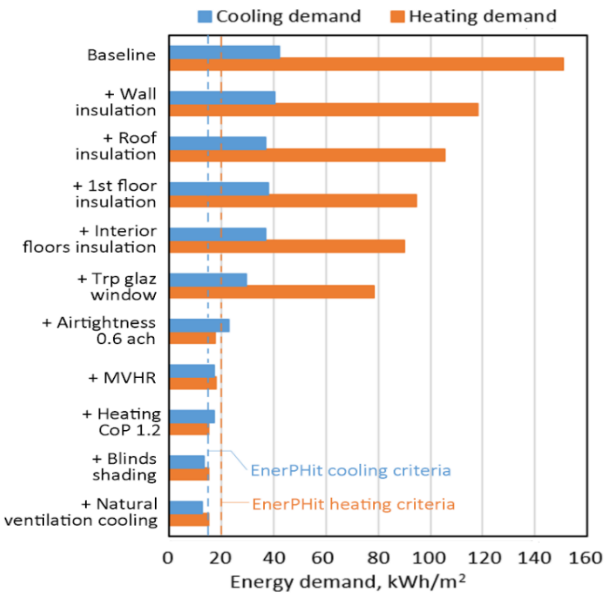

Figure 5: Heating/ cooling energy demand after retrofitting

4.4 Overheating assessment

4.4.1 Indoor comfort in the retrofitted dwelling

Before evaluating the indoor thermal environment of the retrofitted case building against any standard, the main comfort indexes of indoor temperature and relative humidity are reviewed in this section. Figure 6 indicates the monthly mean indoor temperature changed from the lowest value of 18.5°C in January to the highest of 26.0°C in July, which indicated a significant improvement in indoor comfort when compared with the pre-retrofit indoor mean temperature of 6.6°C in January and 32.3°C in July. Furthermore, the indoor environment was less humid in winter months after retrofitting, and the monthly mean relative humidity was changing between 30% and 68%.

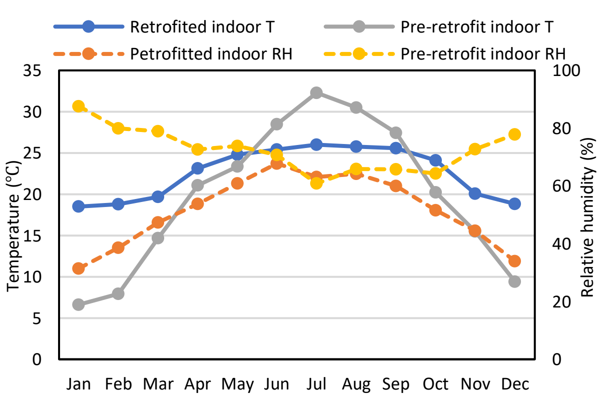

Figure 6: Comparison of retrofitted indoor mean monthly temperatures and relative humidities with pre-retrofit values.

4.4.2 Assessing thermal comfort by the PMV method

The predicted mean vote (PMV) scale ranges from -3 to +3 (very cold to very hot) and is a comprehensive method to evaluate the indoor comfort. A PMV index from +1 (slightly warm) to -1 (slightly cool) is acceptable as comfort for the actively heated and cooled buildings according to the Chinese GB/T 50785 standard [9]. The PMV results calculated by DesignBuilder assumed metabolic inputs as shown in Table 2 (middle column), and indoor clothing levels of 0.5 clo for summer and 1.0 clo for winter. Figure 7 shows the monthly PMV values of the retrofitted building. Only the months from May to October were in the comfort range, and the rest winter months were considered as cold, especially in January, the PMV index is -2.3.

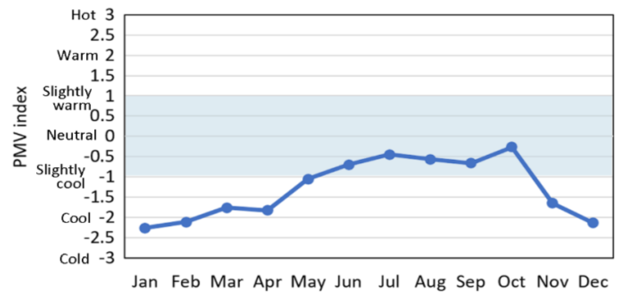

Figure 7: Monthly PMV results of the EnerPHit retrofitted case.

Table 2: Comparison of the original and ASHRAE improved metabolic rates for DesignBuilder.

Item	Original setting	Improved setting
Bedroom	0.8 met (90 W/person)	0.9 met (104 W/person)
Living room	1.0 met (110 W/person)	1.1 met (120 W/person)
Bathroom	1.1 met (120 W/person)	1.2 met (127 W/person)
Kitchen	1.4 met (160 W/person)	1.6 met (171 W/person)

However, according to ASHRAE [11], the DesignBuilder metabolic rates are slightly low and should be adjusted to slightly higher values (Table 2). Moreover, based on a previous analysis of clothing insulation [12], it is reasonable to improve the original winter clothing insulation setting from 1.0 clo to 1.2 clo. The PMV value after the metabolic rate and clothing insulation were improved is presented by the blue line in Figure 8, which suggest a significant improvement in winter indoor comfort as most of the winter months achieved reasonable comfort. Though the PMV value for the coldest month of January improved from -2.2 to -1.2, it still failed to achieve comfort. April also has a low PMV value of 1.2, which can be explained because DesignBuilder assumed less clothing insulation and less active heating would be needed as the weather got warmer in this month. To achieve further comfort, the heating setpoint temperature was increased from 20°C to 21°C, and the dashed line shows the PMV results in Figure 8. All the months achieved reasonable comfort except April because of the previously mentioned reason. However, the higher heating target temperature also led to greater heating energy demand, which increased from 14.9 kWh/m^2 to 17.5 kWh/m^2 - still within the EnerPHit standard but the residents should decide between better comfort or lower heating costs.

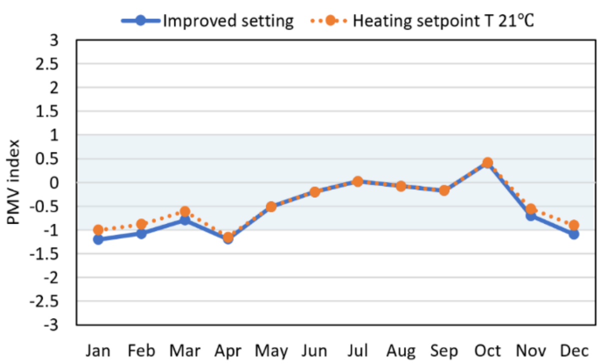

Figure 8: Monthly PMV results when metabolic and clothing insulation settings were improved, and heating target temperature is raised.

4.4.3 Assessing the thermal comfort by the Passivhaus and Chinese Passive House standards

Because the case building was retrofitted towards the Passivhaus EnerPHit standard, the indoor thermal comfort situation after retrofitting was also assessed against the Passivhaus standard as well as the Chinese Passive House Standard. The comfort level required by these two standards are very close; the first requires the indoor temperatures stay in the range of 20°C to 25°C, the second requires a temperature range of 20°C and 26°C [12]. Both of these two standards allow 10% of the time outside of this range in a year.

Table 3 illustrates the distributions of percentages of hours which are regarded as cold, comfortable and hot by the two standards for each month. Generally, most months failed to meet the comfort temperature requirement of both standards. Overall, the percentage of overcooling time in a year is 30.9% for both standards as they both require 20°C as the lower limit of the comfort range, while the overheating percentage for the Passivhaus standard (32.4%) is much higher than the Chinese Passive House Standard (9.8%), due to a different upper limit of comfort range.

For each of the months, the overcooling percentages of the months between November and March were quite high, especially in January, when 90.1% of the hours were considered as cold. However, the indoor mean temperature in January was 18.5°C, which is actually close to the required 20°C. Thus, although the indoor temperature throughout winter largely failed to meet the standards, it still should not be considered as too cold. Conversely, Table 3 illustrates overheating problems occur from May to October. July has the highest percentage of overheating, which is 91.1% by the Passivhaus standard, although only 37.4% by the Chinese standard and the monthly mean indoor temperature in this month was 26.0°C. The differences between the overheating percentages of the other overheated months are significant too when evaluated against those two standards because they have different upper limits of the comfort temperature range. These percentages shown in Table 3 were aided by the passive cooling features of window blinds shading and natural ventilation cooling. Table 4 shows that the passive cooling methods helped to reduce the overheating rate from April to October and that they appear to work more efficiently in the Chinese Passive House Standard as they are able to create a significant drop in the indoor temperatures.

Table 3: Percentages of hours which are regarded as cold, comfortable and hot in each month by the Passivhaus standard (PH) and the Chinese Passive House (CPH) standard.

	Cold		Comfort		Hot	
	PH	CPH	PH	CPH	PH	CPH
Jan	90.1%	90.1%	9.9%	9.9%	0	0
Feb	86.3%	86.3%	13.7%	13.7%	0	0
Mar	60.5%	60.5%	39.5%	39.5%	0	0
Apr	0	0	89.9%	100%	10.1%	0
May	0	0	56.9%	86.7%	43.1%	13.3%
Jun	0	0	28.1%	88.9%	71.9%	11.1%
Jul	0	0	8.9%	62.6%	91.1%	37.4%
Aug	0	0	16.3%	75%	83.7%	25%
Sep	0	0	35.1%	72.8%	64.9%	27.2%
Oct	0	0	78.2%	97.7%	21.8%	2.3%
Nov	48.8%	48.8%	51.3%	51.3%	0	0
Dec	88.2%	88.2%	11.8%	11.8%	0	0
Total	30.9%	30.9%	36.7%	59.3%	32.4%	9.8%

Table 4: Comparison of overheating percentages with and without passive cooling methods by both Passivhaus standard (PH) and 'Chinese passive house standard' (CPH).

	PH, hours % >25°C		CPH, hours % >26°C	
	No Pass C	With Pass C	No Pass C	With Pass C
April	16.1%	10.1%	0%	0%
May	48.1%	43.1%	13.7%	13.3%
Jun	89.4%	71.9%	33.2%	11.1%
Jul	90.6%	91.1%	60.8%	37.4%
Aug	90.6%	83.7%	50.5%	25%
Sep	78.1%	64.9%	29.3%	27.2%
Oct	34.8%	21.8%	4.3%	2.3%

In conclusion, both Passivhaus and Chinese Passive House standards have strict and fixed standards for indoor temperature, and only 36.7% and 59.3% of the hours in a year respectively were within their required comfort temperature range for the retrofitted building. For winter overcooling problem, both standards gauged 30.9% of the time was cold. The methods discussed in section 4.4.2 should be able to increase comfort. For the summer overheating problem, the Passivhaus standard considered 32.4% of the time as hot, which may suggest more active cooling is needed under the studied climate, while the Chinese Passivhaus standard gave only 9.8% of the time as hot, which is within the allowed overheating range.

5. CONCLUSION

This paper examines how energy savings and thermal comfort improvements can be achieved by retrofitting an ordinary suburban residential building in Hunan's hot summer/cold winter climate towards the Passivhaus EnerPHit standard and in addition the risk of overheating in summer due to the super-insulated envelope after retrofitting.

Firstly, the simulated retrofitting results proved that the strict energy requirement of the EnerPHit standard is an achievable task for this ordinary building under the challenging climate context. The achieved energy demands for heating and cooling were 14.9 kWh/m^2a and 12.6 kWh/m^2a respectively, which is only 10% and 30% of the building's energy demands before retrofitting. However, the step by step retrofitting results suggested that the increased opaque insulation levels made a substantial contribution to heating energy saving but barely affected the cooling energy usage. A super airtight building level of 0.6 ach was a key measure to keep the highly insulated envelope and the high efficiency mechanical ventilation system working together to achieve the standard. Also, the passive cooling methods of window blind shading and nature ventilation were actions to reduce the cooling energy demand to within the required EnerPHit values.

The indoor thermal comfort of the retrofitted building showed a significant improvement compared to the original dwelling. The simulated indoor monthly mean temperatures after retrofitting were 18.5°C and 26.5°C in January and July respectively, while the field recorded data showed the indoor temperature in those two months as 6.5°C and 32.2°C. However, the three approaches which are used to evaluate the indoor thermal comfort all suggested that there was a more serious overcooling problem in the retrofitted building. For example, the PMV model results showed the winter months' comfort were rated as cold, especially in January, which had a PMV of -2.3. Both the Passivhaus and Chinese Passivhaus standards assessed 30.9% of a year was cold, while the PMV model revealed that increasing the winter clothing insulation from 1.0 clo to 1.2 clo could largely improve the warm feeling in winter, and the comfort level for whole winter could fully be met after the heating setpoint temperature increased from 20°C to 21°C. Only the Passivhaus standard evaluated the overheating and overcooling problems as equally serious. On the other hand, there is no sign of overheating in the PMV model, but the Passivhaus standard assessed 32.4% within a year was hot even as the indoor monthly mean temperature in July was 26.0 °C. Thus, different evaluation approaches suggested different results and further research is required to analyse the summer comfort and limit the overheating time. Further studies, including operational performance in the long term and life-cycle carbon and cost analysis, are required to fully understand how the EnerPHit standard might benefit Chinese suburban residential buildings in this climate.

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