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Analysing the benefits and challenges of retrofitting rural dwellings in Hunan, China to the Passivhaus EnerPHit standard

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Abstract. Chinese rural housing largely consists of uninsulated reinforced-concrete apartment blocks with poor energy performance. These dwellings are structurally sound, costly to demolish and challenging to recycle. Retrofit is, therefore, potentially more worthwhile than new build. Currently, there is no Chinese standard for retrofitting dwellings. This research examined the viability of applying the German EnerPHit retrofit standard to Chinese rural dwellings in Hunan, southern China (hot summers and cold winters). Dwellings were evaluated in terms of building structure, materials and systems, and a common type of apartment was selected. The real-world thermal performance of the dwelling was monitored and then the dwelling was modelled using the dynamic thermal simulation software DesignBuilder and Passivhaus Planning Package (PHPP). Monitoring data were used to validate the software's predicted values. Next, energy-efficient EnerPHit retrofitting measures were incrementally applied to the dwelling model. Simulation results indicated that it was possible for the apartment to meet the EnerPHit standard if an optimised combination of thermal measures were applied. Good ventilation heat recovery was essential for winter comfort and minimum energy consumption; in summer, using adjustable shading and a high efficiency humidity recovery ventilation system was important. Appropriate natural ventilation schedules contributed in lowering cooling energy demand.

1. Introduction

The German Passivhaus standard, with its emphasis on super insulated and super airtight building envelopes, is a relatively new concept for China. The Hamburg House at the 2010 World Expo in Shanghai was the first certificated Passivhaus in China [1]. Currently, there are 21 certified Passivhaus buildings in China [2], with most of them located in the cold climate of northern China. However, the hot summer/cold winter climate zone covers 14 provinces in China, has one-third of the country's population and is the most economically and culturally developed region. The development of passive buildings in this region could make a great contribution to reducing China's building energy consumption. Furthermore, this region is not included in the centralized heating area plan and most buildings use high power electric heaters or split air conditioners for winter heating, resulting in high carbon emissions and energy costs and a difficulty in achieving comfort [3]. As the most densely populated area in China, many existing residential buildings have been built in recent decades, even in rural areas. Those buildings are largely uninsulated reinforced-concrete flats with no insulation applied. They are structurally sound, costly to demolish and not easy to recycle. Consequently, retrofit is a more reasonable solution than new builds.

This paper investigates the modelled energy performance of a rural dwelling in the hot summer/cold winter area of Hunan, China that was retrofitted to the Passivhaus EnerPHit standard. The real weather condition and indoor thermal comfort of this area were analysed by measured data, and the possible retrofit strategies were tested using the dynamic simulation software DesignBuilder and Passivhaus Planning Package (PHPP). The results suggest that the main challenges for rural Hunan dwellings to meet the EnerPHit standard are related to summer cooling demand rather than winter heating.

2. Literature review

Passivhaus buildings have been built in cold European climate since the 1990s and have been successful in significantly reducing heating energy demand whilst maintaining high levels of comfort. Recent Passivhaus research has been examining cooling energy savings in new and retrofit buildings for warm and hot climates [4][5]. A study of a Greek house, retrofitted to the Passivhaus EnerPHit standard, where the main challenge was to achieve summer comfort and low cooling demand, suggested that a 2kW mini split unit for space cooling, combined with shading and night ventilation cooling, could achieve indoor temperatures in summer that did not exceed 26°C [6]. In a Bulgarian study, a building used a 3 kWh air-to-air heat pump to supply active cooling and lower cooling demand. The careful design of shading for south windows and shutters and exterior blinds helped limit solar gain [7]. In China, the Passive House Database suggests that there are currently no retrofitted buildings that meet the EnerPHit standard and only five Passivhaus certificated new builds in the hot summer/cold winter region [2]. One of these certificated buildings, Lychee Garden, is a detached single-family house with an air tightness of 0.57 h^{-1} with good thermal protection and careful thermal bridge design. It uses an air-to-air heat pump for cooling and the monitored cooling load is $11W/m^2$. However, its architect acknowledged that the airtightness made the house very sensitive to occupancy activities like cooking, which could create overheating problems [8]. In conclusion, Passivhaus has been shown to provide comfortable indoor conditions at an extremely low heating and cooling load in different climates [9], while flexible design and solutions according to the exact cases and realities is the key to achieving passive standards

3. Methodology

The property investigated in this study was a semi-detached 4-storey building situated in Hunan, China. The building has multiple mixed usages, like most residential buildings in Chinese towns. The ground floor is for commercial use and the top storeys are individual flats; thus, only the flats were considered for EnerPHit retrofitting. Hunan has a hot summer/cold winter climate. The summer is hot and humid, with peak outside temperatures frequently reaching 38°C and 1175 cooling degree days against a baseline of 18°C [10]. On the other hand, the winter minimum outdoor temperature is around 0°C with 1621 heating degree days. Residents will commonly use individual radiators to heat a small area of a room while the remaining space remains cold. Figure 1 shows the floor plan and dimensions (in mm) of the flat used in the study, while Table 1 summarizes the properties.

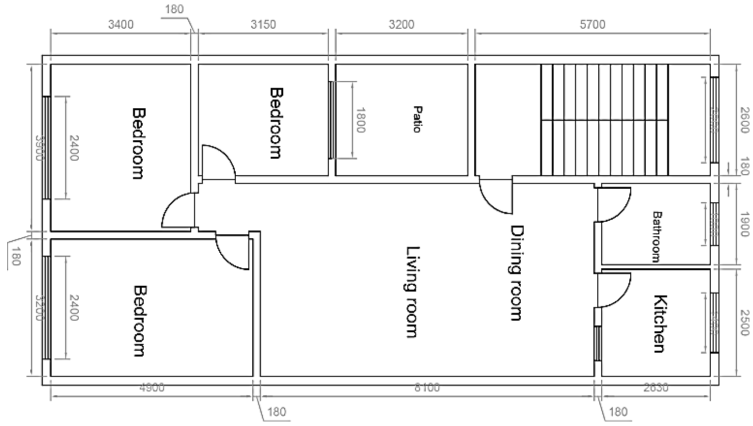

Figure 1. Floor plan of the property

Table 1. General information about the property

Location	Hunan, south China
Number of flat	3
Total treat floor area	252m^2
Floor to floor height	2.8m (1st and 2nd floors) 3.4m (3rd floor)
Total glazing area	51.8 m^2
Net volume	772.8 m^3

The property has a reinforced-concrete structure with no insulation. The building's major axis faces east-west, with the main east façade facing the main road. The three flats of this property are designed in an exact same layout, as shown in Figure 1. Each of them has a treated floor area (TFA) of 84 m^2, which does not include the patio and staircase area. Constructional and material information about the building is given in Table 2

Table 2. Properties of the building envelope

Outside wall	5mm putty paint + 10mm cement mortar + 180mm clay brick + 10mm cement mortar + 10mm outside porcelain tiles
Floors	10mm porcelain tiles + 10mm cement+ 50mm cement mortar + 100m reinforced concrete raft + 3mm putty paint
Roof	50mm cement + 100m reinforced concrete raft + 400mmair gap + 10mm wood board + 3mm putty paint
Windows	Aluminium window frame + 4mm single glass

3.1 Monitoring of the property

Two periods of indoor environmental condition measurements were made in different rooms. The indoor temperature and relative humidity in the living room and second bedroom were recorded by Rotronic TL-1D devices; a Rotronic CL11 was used to record the CO_2 levels, temperature and relative humidity in the master bedroom; finally, the outside temperature and relative humidity adjacent to the property were measured by an EasyLog EL-GFX-2. All loggers were logged at 15-minute intervals, not exposed to direct sunlight and kept away from heat sources. The two recording periods were 23rd January to 21st February 2018 (one month) and 1st July to 31st December 2018 (six months).

3.2 Software simulation

Building energy simulation of retrofitting the case study property to EnerPHit standard was done using the dynamic simulation software DesignBuilder (DB) and Passive House Planning Package (PHPP) software. The weather files used for simulation were generated by the climate database software Meteonorm. The logged data were used to calibrate the DesignBuilder base model for the different seasonal climates. Then, a series of energy efficient measures were applied on the calibrated base model to meet the standard. PHPP is an Excel based software carefully developed by the Passivhaus Institute specifically for calculating and certifying the new buildings and refurbished buildings to achieve the passive standards. It has been proven that the PHPP is an appropriate design tool in all Chinese climates [11]. Version 9 was used in this study. PHPP's interface, designPH, was used to build the model of the actual property. Then, the same energy efficient retrofit measures which were applied in DesignBuilder were simulated in PHPP, though there are some parameter settings which are different between the two software because their different calculation methods.

3.3. Proposed strategies to meet the PH standard

To retrofit the case study property to the EnerPHit standard in the model, it was important to follow the 'fabric first' approach, which prioritises heat retention and air tightness, followed by efficient heating and ventilation systems. Insulation was placed on the interior of the bricks, and this eliminated thermal bridges. Rockwool was chosen for the whole envelope because it is a common insulation material in China. Window type 'Passive 130' from Hebei Orient Sundar Co. was adopted as it is a certified passive component produced in China. Airtightness was assumed to be 0.6 ach and a mechanical ventilation with heat recovery (MVHR) system, with a heat recovery efficiency of 85% and humidity recovery efficiency of 77%, was modelled Controlled night-time natural cooling in summer was used to avoid overheating. Finally, extensive shading to exclude solar gain was employed.

4. Results and Discussion

4.1. Temperature and relative humidity data recorded in the building

Table 3 presents an overview of the monthly mean average temperatures and relative humidities for both outdoors and indoors for the two data logging periods. The indoor temperature and humidity shown are the average value of living-room and bedroom.

Table 3. Monthly temperature T (°C) and relative humidity RH (%) values

	Outside				Inside			
Month	Ave T	Max T	Min T	Ave RH	Ave T	Max T	Min T	Ave RH
23Jan-21Feb	6.8	10.9	4	70%	8.4	9.3	7.7	71%
Jul	31.0	38.1	26.5	69%	30.7	31.6	29.6	62%
Aug	28.8	34.6	25.5	76%	30.5	31.4	30.4	66%
Sep	25.8	30.8	22.4	75%	27.4	28.3	26.6	66%
Oct	18.5	23.6	15.1	75%	20.3	21.0	19.7	62%
Nov	13.8	18.4	10.8	80%	15.3	16.3	15.0	73%
Dec	7.4	9.6	5.6	87%	9.2	10.0	8.9	78%

The measured outside values show the seasonal climatic variations between winter and summer months. The measured inside values were used to assess thermal comfort in the pre-retrofit property, and Figure 2 shows the results of the analysis based on the Passivhaus standard of comfort being in the range 20℃ to 25℃. February, December, July and August had no temperature between 20℃ to 25℃, and September, October and November had 14.3%, 43.2% and 5.6% of the time in the Passivhaus standard comfort temperature range.

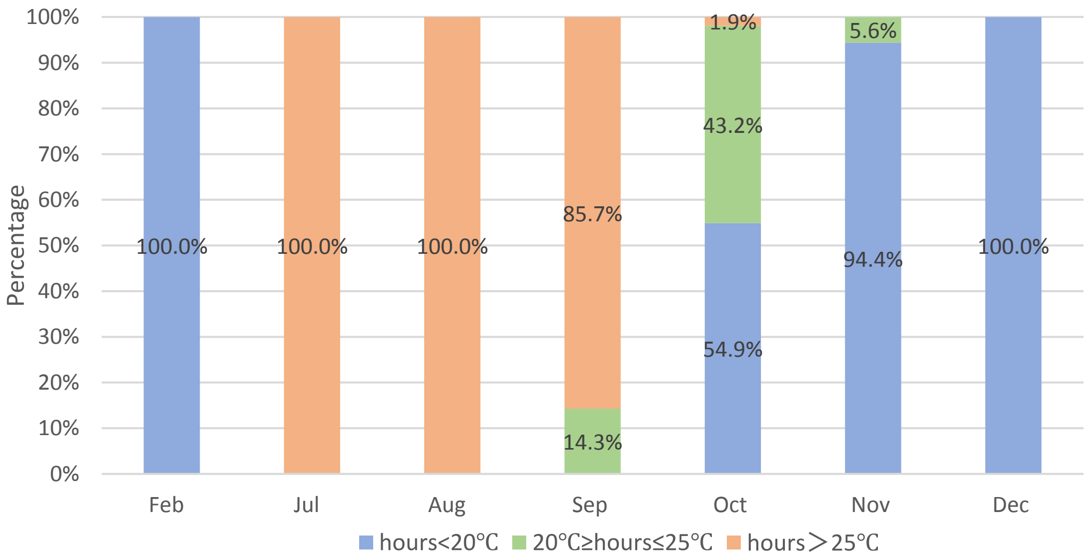

Figure 2. Percentage of comfort hours: existing property during both occupied and unoccupied hours

4.2. DesignBuilder base model calibration

The DesignBuilder base dwelling modelled the characteristics of the property, including construction materials, lights, equipment, occupancy and activity schedules. Recorded data from the two measurement periods were used to validate the DesignBuilder base model. Figure 3 displays average temperature comparisons of each hour from the recorded temperature and DesignBuilder simulated temperature in the living room. The blue dashed line shows the measured temperature data, whilst the three solid lines represent the DesignBuilder simulated results with three different envelope airtightness level: 5ach (purple); 3ach (green) and 1ach (red) respectively. Analysis of the differences between the measured and modelled data indicated a variation no greater than ±1.5°C, suggesting that the DesignBuilder model was credible.

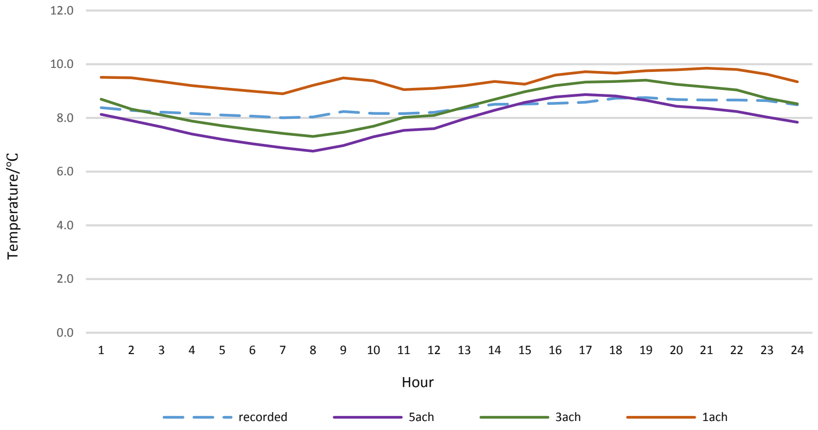

Figure 3. Hourly calibration between measured temp and DB simulated average temp in living room, based on 1, 3 and 5 ach, 23rd Jan and 21st Feb 2018

Figure 4 draws on a 6-month period (1st July – 31 Dec 2018) of measured and modelled values. The results show that a maximum temperature gap of 3°C degrees in July, which may be because the measured outside temperature was about 3°C degree higher than the DB weather file imported from Meteonorm. In the winter months, the two outside temperatures were closer, and the two inside temperature values converge. The two calibration processes were employed principally to validate the reliability of the DB base model and give confidence in the simulation of Passivhaus retrofitting.

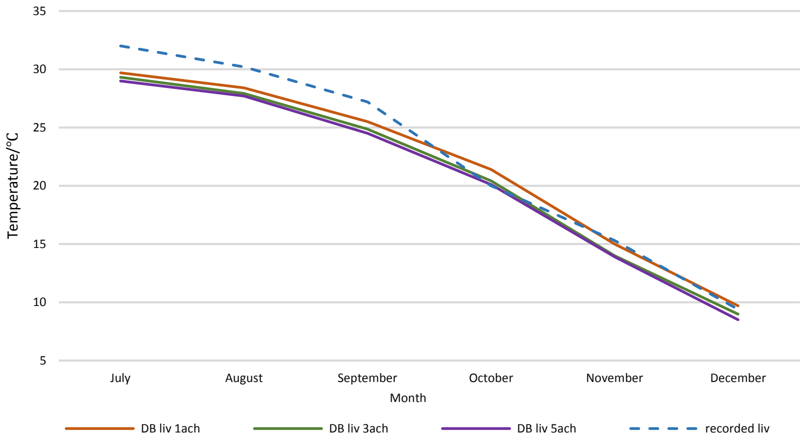

Figure 4. Monthly calibration between measured temp and DB simulated temp in living room, based on 1, 3 and 5 ach, 1st July to 31st Dec 2018

4.3. Simulation results

Table 4 shows the comparison of U-values of the dwelling's components before and after applying the Passivhaus EnerPHit standard. DesignBuilder and PHPP showed slightly different results of U-values with the exact same materials because of their different calculate methods. But both of their calculated U-values after applying 250mm rock wool were much lower than the EnerPHit standard. For the window unit, PHPP could directly use the certified 'Passive 130' window (U-value of 0.8 W/m^{2}K). A similar U-value (0.78 W/m^{2}K) was found in the DesignBuilder menu by selecting an argon-filled triple low emissivity (LoE) glazing.

The mechanical system settings of DesignBuilder and PHPP simulation are shown in Table 5. For the mechanical ventilation with heat recovery (MVHR) system, the heat recovery efficiency was set at 85% in both DesignBuilder and PHPP simulation, while the humidity recovery efficiency was 85% in DesignBuilder and 77% in PHPP. For the cooling system, the DB simulation used its default cooler with a coefficient of 2.5 controlled by room activity schedule. PHPP cooling combines recirculation cooling with additional dehumidification as the summer humidity in this area is very high, and so dehumidification is important. Both DB and PHPP have summer night-time ventilation cooling but controlled by different methods. DB controls by night-time cooling schedule and PHPP controls by temperature difference and window opening gap, so the total night ventilation value is controlled around 1.77ach. Similarly, the shading method is different between the two programmes as well - DB uses a 2 metre overhang for summer simulation and removes the overhang for winter simulation. PHPP can add a shading reduction factor only for summertime, a 10% factor is applied which could prevent 90% of solar heat from passing through the glazing.

Table 4. Comparison of pre-retrofit and retrofitted envelope U-values and the EnerPHit standard

	Existing U-value W/m^{2}K			Retrofitted U-value W/m^{2}K		EnerPHit standard W/m^{2}K
	DB	PHPP	Insulation material	DB	PHPP	
Outside walls	2.30	2.54	250mm Rockwool	0.125	0.125	0.3
Floors	2.85	3.69	250mm Rockwool	0.126	0.127	0.5
Roof	1.76	1.88	250mm Rockwool	0.123	0.125	0.3
Glazing	5.85	5.80	DB: triple glazing LoE PHPP: Orient-Passive 130	0.78	0.80	1.05

Table 5. Mechanical system inputs for DesignBuilder and PHPP

	DesignBuilder	PHPP
MVHR	Sensible heat recovery efficiency: 85% Latent heat recovery efficiency: 85% Outside air definition by zone; Outside air 1.25ac/h; Heat by MVHC	Heat recovery efficiency 85% Humidity recovery efficiency 77% Supply air: 30 m^3/ h Supply by zone; Heat by MVHC
Airtightness	0.6ach	0.6ach
Cooling	Default DB cooler with system seasonal CoP 2.5. Schedule set by room activity	Recirculation cooling with max 2.0kW cooling capacity and seasonal energy efficiency ratio 2.0. Additional dehumidification with seasonal energy efficiency ratio 3.2
Natural ventilation	Vent by zone with outside air speed 5ac/h. Night-time cooling schedule	Additional night ventilation for cooling controlled by ΔT difference. Total night ventilation value 1.77ach
Shading	Outside windows with 2m overhang in summer months; No overhang in winter months	Additional reduction factor summer shading: 10% for all outside windows

Running the PHPP software after retrofitting the Hunan dwelling to the specification shown in Tables 4 and 5 confirmed that the EnerPHit standard had been met. The EnerPHit standard criteria for Hunan's climate require a yearly energy demand for space heating of less than 20 kWh/m^2; for space cooling less than 27 kWh/m^2 and a total primary energy demand (heating, cooling, hot water and electrical appliances) of less than 120 kWh/m^2. Figure 5 shows the heating and cooling demand of the dwelling before and after the retrofit as calculated by DB and PHPP. The pre-retrofit dwelling consumed 273 kWh/m^2 of energy for heating, which is 18.9 to 21 times greater than the DB and PHPP simulated amount of the retrofitted building. Cooling energy demand pre-retrofit was 198 kWh/m^2 compared to 18.1 kWh/m^2

and 25 kWh/m^2 for the DB and PHPP retrofitted simulations respectively. Figure 6 compares the demands and compares them to the EnerPHit criteria. For the heating demand, the DB value (14.4 kWh/m^2) and PHPP (13.0 kWh/m^2) are 28% and 35% lower respectively than the criteria of 20 kWh/m^2. For the cooling demand, the DB and PHPP cooling demands are 32% and 7% lower than the criterion. For the primary energy demand, DB and PHPP both used a factor of 2.6 for electricity and factor of 1.1 for gas. The DB model just meets the primary energy criterions, whilst PHPP shows a lower demand of 108 kWh/m^2. This difference in the two calculation methods for primary energy consumption is interesting given that the same source factors were used in both models.

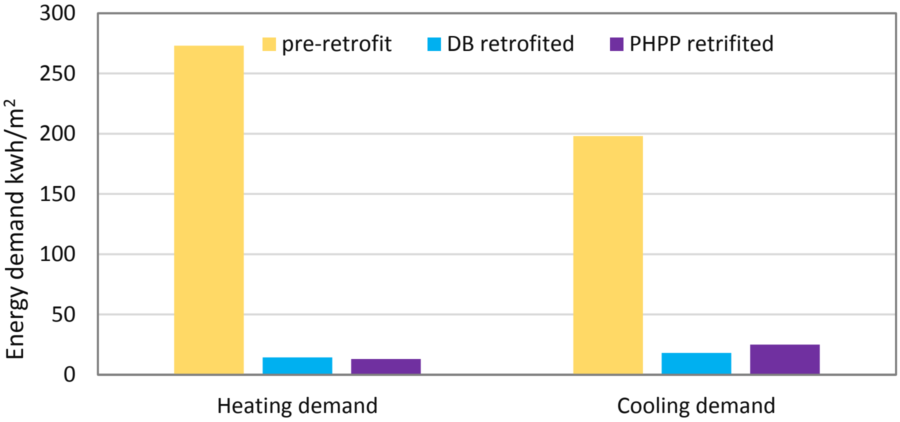

Figure 5. Comparison of modelled energy demand between pre-retrofit and retrofitted building

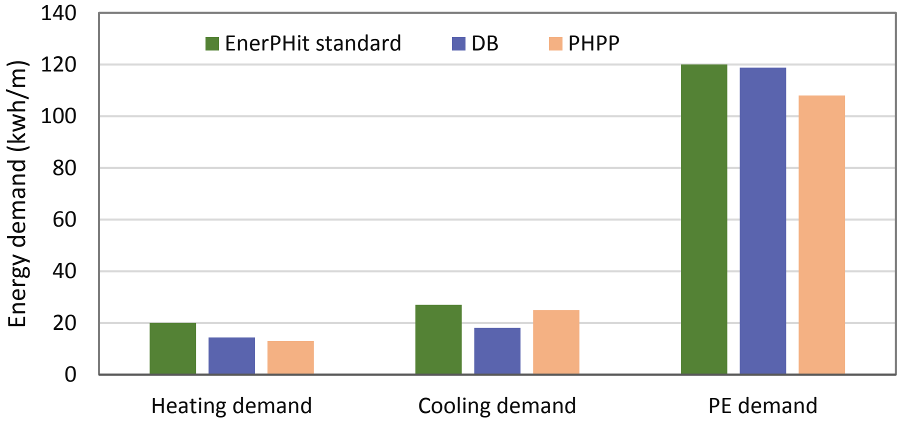

Figure 6. Comparison of predicted energy performance of the retrofitted building simulated by DB and PHPP with the EnerPHit criteria.

4.4 Main options to reduce energy demand in PHPP simulation

PHPP was used to examine the impact on energy demand of the various retrofit measures once the insulation was in place. Figure 7 shows how each measure performed. Firstly, the MVHR system, with no dehumidification, shading and summer night-time ventilation applied in the simulation, was considered. Next, summer night-time ventilation was added to the MVHR system. This produced a small drop in cooling and primary demand, but the heating demand was unchanged. Following this, dehumidification was added, which produced a considerable drop in cooling demand and primary demand. Finally, the option of shading was applied, which brought a large decrease in cooling and primary demand. From these results it appears that insulation combined with a high efficiency MVHR system are the core retrofit strategies for this property to meet the EnerPHit heating demand criterion. For the cooling demand, shading is the most efficient strategy, while dehumidification and summer night-time ventilation strategies are also important.

5. Conclusion

The results presented in this paper suggest that retrofitting an existing rural low-rise flat block in Hunan's hot summer/cold winter climate, under the constraint of the EnerPHit standard, is an achievable task. However, a series of strategies must be followed as it is necessary to deal with not only the cold winter but also the more challenging summer weather. In fact, in Hunan's climate, it is relatively easy to achieve the heating EnerPHit criterion by applying sufficient insulation materials, good windows and a high efficiency MVHS system. The simulation results from DB and PHPP both show that the heating demand is lower than the criterion after applying those measures. For summer, insulation helps to lower the cooling demand. The results show that the shading is the most efficient strategy to decrease the cooling demand. The high moisture recovery efficiency of the ventilation system is an option which will not lower the energy demand very much but will significantly increase the comfort level, as the indoor humidity is quite high. In addition, the role of summer night-time ventilation also needs attention, as it helps to reduce the cooling demand by 33% based on DB simulation.

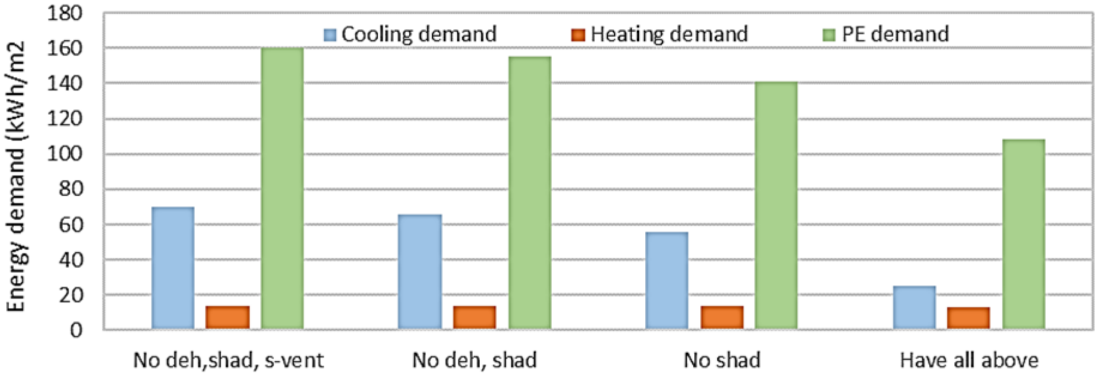

Figure 7. PHPP testing of retrofit parameters on cooling, heating and primary energy demand.

DB and PHPP simulated results for the retrofitted building for heating demand were very close, (14.4 kWh/m^2 and 13 kWh/m^2 respectively). The DB simulation showed a lower cooling demand (18.1 kWh/m^2) than PHPP (25 kWh/m^2), which may be because in the PHPP calculations there was additional dehumidification equipment. Although the retrofitted building has been investigated by two robust and extensively validated tools, DesignBuilder and PHPP, and simulations have reached the EnerPHit standard, the assessment about comfort indoor temperature and overheating risk after retrofit is inadequate. Moreover, this paper only focused on one dwelling, so the results are not sufficient to represent the feasibility of retrofitting rural housing in Hunan to EnerPHit standard. Further research, such as investigating different dwellings and post-retrofit operational performance in real-life conditions, are required to fully investigate and understand the effects of retrofitting rural housing to the EnerPHit standard on energy consumption and thermal comfort for Hunan and other hot summer/cold winter climate areas of China. Life-cycle assessment, capital expenditure and operational performance of each energy efficient retrofit measure will also be studied in the future.

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