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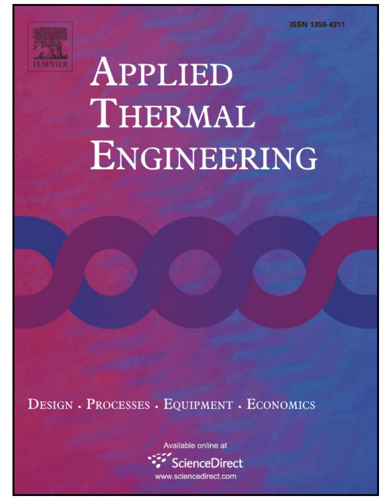

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Energy Performance of a High-rise Residential Building Retrofitted to Passive Building Standard – A Case Study

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Abstract

In China, residential building is a major energy consumer and retrofitting of existing residential buildings is considered as an effective method in achieving energy savings. This study examined a high-rise residential building located in northern China. The target-building's electricity consumption and indoor temperature were gathered and analysed. DesignBuilder software was used to conduct a numerical study on the target-building where we studied the feasibility and energy-saving potentials in retrofitting the target-building to Passivhaus standard. It was found that the energy consumption of the building reduced by 96% for heating and 8.7% for cooling; totally reduced by 78.9%. The cost for the retrofitting was estimated approximately as 18.4 years using the simple payback period method and the current price of the materials in the market. The residents could start to get profit for the remaining lifetime of the building.

Key words: High residential building, simulation, energy-saving retrofitting, Passive Building

Nomenclature:

Abbreviation

BEE Building Energy Efficiency

COP Coefficient of Performance

CV	Coefficient of Variable
EPS	Expanded polystyrene foam (insulation material)
kgce	kilogrammes of standard coal equivalent
Low-E	Low-emissivity
MVHR	Mechanical Ventilation with Heat Recovery
MBE	Mean Bias Error
NUH	Northern urban heating
RMSE	Root Mean Squared Error
SPP	Simple payback period
UPVC	Unplasticized Polyvinyl Chloride, material for window frames
VIP	Vacuum insulation panel
XPS	Extruded polystyrene foam (insulation material)
XPS-CO_2	XPS foam blown with CO2

1.0 Introduction

China is the second-largest building energy consumer in the world. The sector's energy consumption has increased by 40% since the last two decades [1]. Building stock in China accounts for 56.1 billion m² with total commercial energy consumption (includes electricity and heating) of 9,524,970,000,000 kWh in 2014. 22.5% (2,139,920,000,000 kWh) of the commercial energy usage were spent on northern urban heating (NUH) alone in 2014 [2]. The enormous heating demand in the northern region has driven the government to create initiatives to reduce the energy consumption in civil buildings [3]. One of the main initiatives developed by the government was to enforcement in Building Energy Efficiency (BEE) code which was first developed for the northern region in 1986 to achieve 30% energy reduction [3]. The potential in improving existing buildings' energy performance via retrofit to comply with the BEE was acknowledged by the Chinese government [1][4] by providing technical and financial support for building retrofits focusing on the public buildings across the country and residential buildings in northern China [1]. The BEE code for severe cold region in China was first developed in 1986 to achieve 30% energy reduction, then the code was constantly revised to achieve higher energy reduction to 50% in 1995 and 65% in 2010 [3]. The initiatives taken by the Chinese government is proven to work as the energy savings of new buildings per increased floor area per year increased from 20.4 kWh/m^2 to 28.4

kWh/m^2 [3].

The housing types in China cities is predominantly dominated by high-rise residential buildings (building with more than 8 floors) [2][4]. This type of residential normally come with 50 years to 70 years leases. To ensure that the building maintains its performance for the given lease duration and up to date with building's energy requirement, at one stage in its lifetime the building will have to go through retrofitting [4]. For the northern region alone, the average heating energy use per unit of floor area declined from 22.8 kilogrammes of coal equivalent per m^2 (kgce/m^2) in 2001 to 14.6 kgce/m^2 in 2014. This is mainly due to the improvement in building's envelopes, higher heating system's efficiency and a higher share of high efficient heating sources [2]. The increase in insulation thickness and replacement with more effective insulation materials with higher thermal resistance for building's envelope will reduce energy consumption significantly but it can be costly [5]. Another crucial position is window glazing since it has the weakest thermal properties among all building fabric elements. While an insulated opaque element (walls, floors and the roof) could have an overall heat transfer coefficient of around 0.3 W/(m^2·K), windows typically will have values more akin to 2-5 W/(m^2·K), indicating that a building could lose several times more heat through its glazing compared to an equivalent opaque surface [6]. Therefore, improving the building's fabric is one of the most effective solutions to reduce energy loss and consumption [7].

The target area (Jining City in Shandong district) is categorised as cold region where the temperature in winter can reach -10ºC and in summertime the temperatures can reach up to 37ºC [8]. The extreme weather condition in winter and summer will be tricky to define the right envelope requirement to deliver a comfortable indoor temperature in both seasons (cold winter and hot summer). Highly insulated building's envelope can reduce heating energy consumption in winter, however, it will also cause overheating during summer season which will results in the increment in cooling energy consumption. Furthermore, domestic indoor overheating also impose adverse impact on human's work performance and health and safety risks (such as accidents and injuries are likely to increase when the external temperature rises) [9]. In northern China, coal-powered district heating is widely applicable during winter time and air conditioners are generally used for summer cooling demand. The overall cooling demand for urban dwellings was 52 billion kWh of electricity and accounted for 10.4% of the total energy consumption of residential buildings [10].

Passivhaus standard is a widely known construction method that emphasize on excellent thermal performance using highly insulated building's fabric, high air-tightness and heat recovery ventilation system [11]. The standards if follows has shown to reduce building's energy consumption up to 50% compared to conventional building [4]. Retrofitting conventional building to Passivhaus standard will involve 'deep energy retrofitting' which will involve changes of the entire fabric, conventional systems of the building, and airtightness of the building. This type of retrofitting is very challenging [4]. Previous studies on Passivhaus standards are mainly focusing on the low-rise residential building and rarely on a high-rise building. Most of the studies on high-rise buildings highlighted the incorporation of passive designs in the building architecture that covers building's fabrics, thermal mass, natural ventilation, natural daylighting, passive heating/cooling [12][13][14][15][16][17][18]. Those studies used sensitivity analysis to achieve multi-objectives optimisation processes designed for early design building. This paper explores the feasibility of retrofitting a high-rise building based on the Passivhaus standard. Findings in this paper are intended to fill in the research gap in high-rise building with the Passivhaus standard. The strict regulations especially on a very low envelope's thermal conductivity can be very challenging to achieve for a retrofit case studies and low air-tightness is very challenging for high-rise buildings. The energy, indoor temperature all year round and economic analysis were presented and compared between the actual target-building and after retrofitting using Passivhaus standard.

2.0 Methods

2.1 The target-building

An 18-floor high-rise domestic tower building, located in the urban area of Jining City, Shandong Province was selected as the target-building. According to the China code for design of civil buildings [19], the area which the target-building is located is defined as the cold zone with an average temperature of -10°C to 0°C in January and 18°C to 28°C in July. As recommended in the guide [19], the buildings in cold zone should be capable of satisfying both the heating and cooling demand. The target-building with north-south exposure has 18 floors and two basement floors. The construction started in 2008 and completed in 2010. The expected building lifetime according to China

Ministry of Housing and urban and Rural Development [19] is 50 years.

With the access offered by the staff of property developers, the floor plan shown with detailed dimension information was obtained to explore internal layout of apartments and its infrastructures. As indicated in Figure 1 and 2, there are four unique apartments in each floor and a total of 72 flats in this dwelling. The width and length of each floor respectively are 36.8 m and 24.7 m, the total area of each floor is approximately 619 m^2, the conditioned space is 561 m^2. The structure drawing of the building with detailed fabric data is shown in Table 1, the U-values are calculated using DesignBuilder software [20]. It can be seen that all the needed structure information such as the thickness and materials of envelope layers was generally based on the building energy standard of Shandong Province [21] which aims to achieve 65% reduction of energy demand. However, the thermal performance of windows and ground floor are relatively poor and has higher U-values than the recommended design standard.

Figure 1: Exterior façade of the target high-rise residential building.

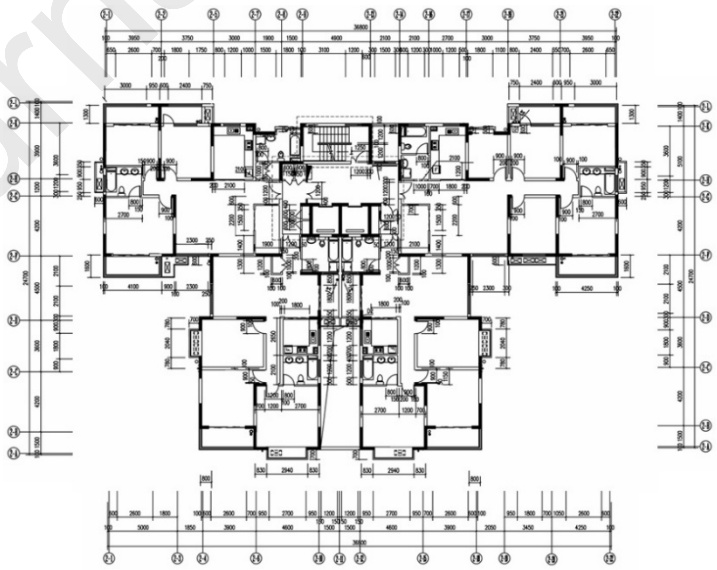

Figure 2: Typical floor plan of the studied building.

Table 1: The gathered fabric data and calculated U-values using Designbuilder

Elements	Material	Thickness (m)	U-value (W/(m2·K))
External wall	Concrete/plaster/mortar-cement screed	0.005	0.62
	XPS-CO2 blowing	0.045	
	Concrete/plaster/mortar-cement mortar	0.02	
	Concrete, reinforced (with 1% steel)	0.2	
Roof	Concrete/plaster/mortar-cement mortar	0.045	0.473
	XPS-CO2 blowing	0.055	
	Concrete/plaster/mortar-cement mortar	0.02	
	Perlite Plasterboard	0.04	
	concrete, reinforced (with 1% steel)	0.1	
Ground floor	concrete/plaster/mortar-cement mortar	0.02	3.449
	concrete, reinforced (with 1% steel)	0.12	
Window	Double glazing 6 mm/6 mm filled with air / UPVC frame		3.16
Internal partition	Concrete/plaster/mortar-cement mortar	0.021	1.094
	concrete, cast-aerated	0.1	

Heating of the whole building except basements and lobbies in every floor is supplied by a coal-fired district heating plant during winter time, and heating radiators are installed in all heating spaces. Split air conditioning systems were employed for cooling during summer in the apartments. The heating and cooling system in the building is shown in Figure 3 and Figure 4 shows the type of radiator used for rooms heating in the target-building.

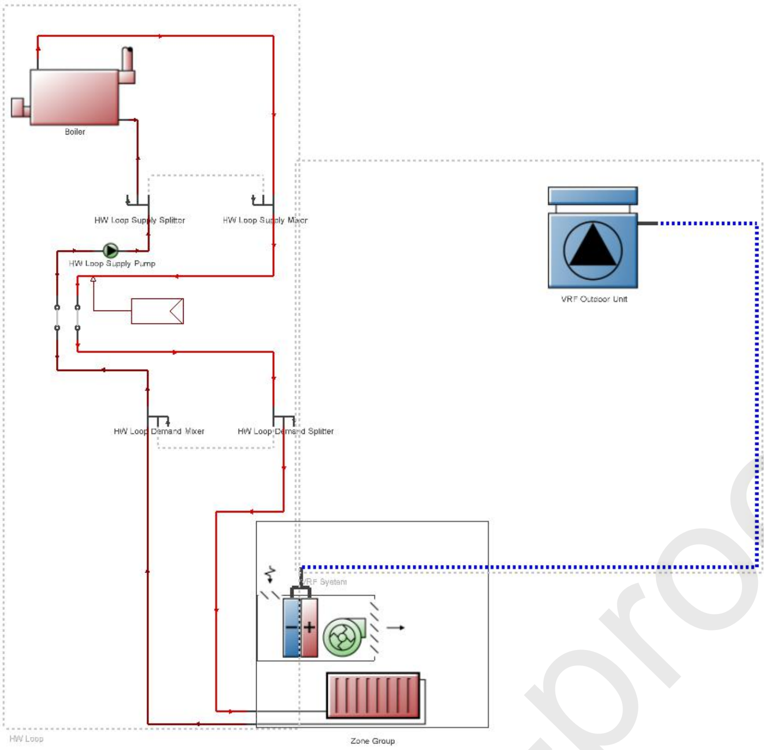

Figure 3: The target-building's heating and cooling system.

Figure 4: The radiator for room heating.

2.2 The field study

A field study was carried out to investigate the building's data (fabric, floor plan, mechanical systems and usage behaviour). Interview with the developer's staffs were conducted to gather the building's data (fabric, floor plan, and mechanical systems). A survey was conducted among the residents to explore preferences and habits of people's activities around their house and their common heating, cooling and equipment usage. The cooling schedules and preferred set point temperatures which were completely depended on individuals were gathered as well. Furthermore, for the purpose of obtaining real internal temperature data, four sets of temperature meters were set in the living rooms and bedrooms of four selected apartments on the 1st, 6th, 11th and 16th floors to monitor the variation of temperature. In addition, with the assistance of a three-member family (the most typical Chinese family formation) lived in a flat in the building, the daily electricity consumption of the flat gathered from the main electricity meter (as shown in Figure 5) was recorded from Oct 2015 to May 2016.

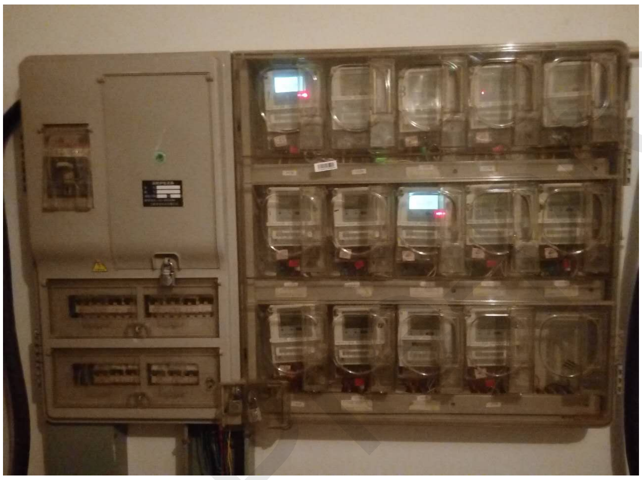

Figure 5: The combination of electricity meters in the basement.

2.3 Computational study

DesignBuilder software [20] was used for the computational study (modelling, simulation and optimisation). DesignBuilder is the most established and advanced building energy simulation tool using EnergyPlus engine [22] which provides a user-friendly interface for modelling simulation and optimisation. EnergyPlus is a very powerful simulation engine for studies of building energy including construction, HVAC, glazing, thermal mass and economic analysis. The software is widely used and validated in building energy modelling either for conventional building fabrics to a more complicated building materials such as building integrated phase change materials [23][24][25][26][27].

2.3.1 Building modelling

The CAD floor plan provided by the developer was imported into DesignBuilder as a tracing to the floor geometry. The area of each floor was divided into five closed zones including four apartments' zones and one lobby zone. The fabric data including external wall, roof, ground floor, internal partition, internal floor and window was defined exactly as the same as the real construction data gathered in the field study. The 3-D model of the whole building was established as shown in Figure 6.

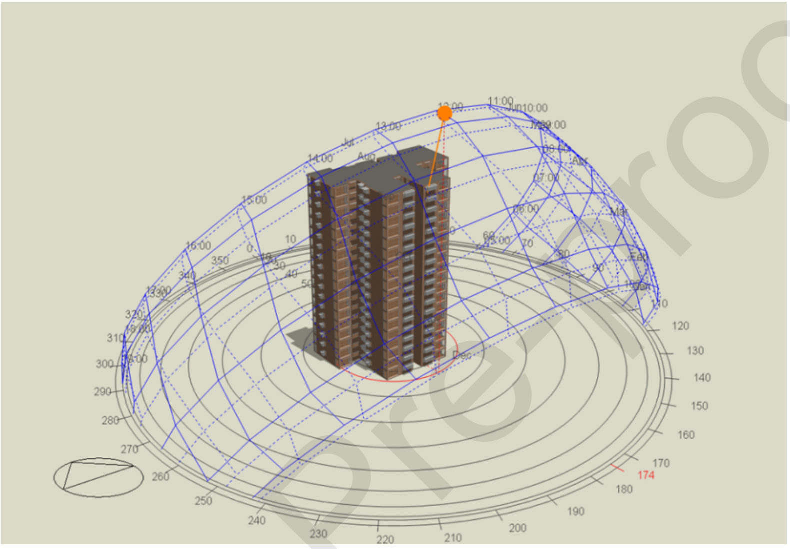

Figure 6: Visualisation of the whole building model with simulated solar radiation and sun path in summer.

Based on the collected information from the survey, the occupancy, operation schedules of heating, cooling and ventilation, and the preferred set point temperature were defined in DesignBuilder software. The heating set point temperature was set to 25 °C (the heating was set to switch on when the temperature reached 20°C) and the cooling set point temperature was set at 26 °C (the cooling was set to switch on when the temperature reached 30°C).

2.3.2 Validation

ASHRAE Guide 14 was used to validate the building model. It is an established method for measuring a model's accuracy [28,29, 30]. It is suggested that a building is considered accurate if the Mean Bias Error (MBE) of monthly values is within ±5%

and the Coefficient of Variable (Root Mean Squared Error) (CV(RMSE)) for monthly values is below +15% and [31]. The MBE and CV(RMSE) were calculated using equation (1) and (2).

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i} \left[(M_i - S_i)^2 / N_i\right]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \qquad (1)$$

$$MBE = \frac{\sum_{i=1}^{N_i} (M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \qquad (2)$$

Where, M_i and S_i respectively represents measured values and simulated values at instance i, N_i is the count of the number of values involved in the error calculation.

2.3.3 *Building optimisation- retrofitting*

The target-building base model was calibrated to follow the Passivhaus standard developed by Professors Bo Adamson of Sweden and Wolfgang Feist in Germany [32]. The actual baseline building's data and the building's requirement based on the DBJ 14-037-2012 [21] and Passivhaus standard [11] are listed in Table . The calibrated model was then simulated to evaluate its indoor temperature and energy performance.

Table 2: The actual target-building fabric elements and energy data compared to the BES for Shandong Province [21] and Passivhaus standard [11].

	Target-building	Standards	
Element	Base	DBJ 14-037-2012	Passive
Complete window installed U-value, W/(m2·K)	3.16	2.8	≤ 0.85
Air tightness, ac/h	0.5-1.5	0.5	≤ 0.6
Walls U-value, W/(m^2·K)	0.62	0.7	≤ 0.15
Floors U-value, W/(m^2·K)	3.45	0.56	≤ 0.15
Roofs U-value, W/(m^2·K)	0.47	0.45	≤ 0.15
Heating demand, kWh/m^2.year	91	n/a	≤ 15
Cooling demand, kWh/m^2.year	11	n/a	≤ 15
Primary energy demand, kWh/m^2.year	118	n/a	≤ 120

MVHR heat recovery efficiency	n/a	n/a	≥ 75%
MVHR electrical efficiency, Wh/m^2	n/a	n/a	≤ 0.45
Internal temperature	20°C - 25°C	≥18ºC	20°C - 26°C

2.4 Performance evaluation

The building's performance was assessed based on the energy performance and economic analysis. Equation (3) and (4) were used to measure the savings after retrofit and equation (5) is a simple payback period was used to as the economic indicator.

Saving (kWh) = Energy used (baseline) – Energy used (retrofit) (3)

Saving (%) = Saving (kWh) / Energy used (baseline) × 100% (4)

$$SPP = \frac{C_I}{V_E} \tag{5}$$

The C_I in the formula represents the original total investment, V_E represents the energy saving cost.

3 Results and discussion

3.1 Actual consumption

The actual electricity consumption of the target-building, as shown in Figure 7, were measured in 2016 covering winter, spring, summer and autumn seasons. The electricity consumption in summertime escalated to an average of 589 kWh a month compared to in winter, spring and autumn where the average monthly electricity consumption in those seasons were 173 kWh, 171 kWh and 204 kWh respectively. The reason is because of massive usage of electric powered cooling system during summertime. Meanwhile, in other seasons district heating was used.

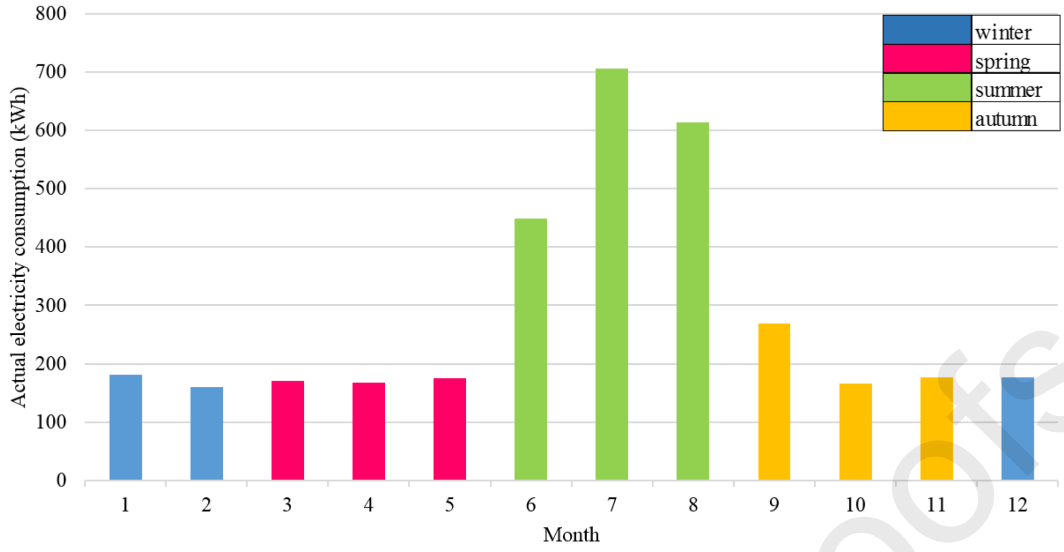

Figure 7: The target-building's monthly electricity consumption in 2016

The recorded daily electricity in one of the selected apartments shows a variation of daily electricity usage from 3 kWh to 14 kWh with the spikes of usage of more than 10 kWh occurred mainly in winter season. The electricity consumptions were exceptional high on 4 December and 9 April are because there were some relatives/friends visited the family.

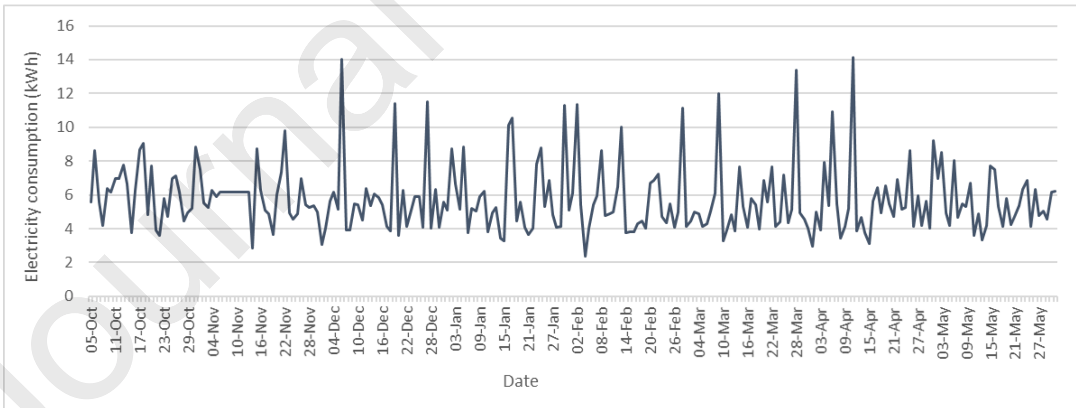

Figure 8: Recorded daily electricity consumption of a selected apartment.

Based on the survey, it is found that the heating supply is provided from 15th November to 15th March. It is noticed that some issues, for instance expensive electricity bill in summer and overheating in winter, were put forward by residents in the survey conducted. Most of the residents are workers and students with typical weekdays and weekend schedule. The residents were set to leave in the morning at 8 am and return home at 6 pm during weekdays. Approximately half of them went home for a lunch break from 12 am to 2 pm. Meanwhile on weekends and holidays, most of the residents stayed at home, spending time with their family.

From the monitored temperature data in the flats on 1st, 6th, 11th and 16th floor, it was found that approximately the room temperatures in these flats fluctuated between the peak of 25 °C and the lowest point of 20°C in winter. According to preferences of the occupants, when the temperature went up to 30 °C in summer, people would feel uncomfortable and cooling was required. On average, the cooling temperature of air conditioners was set to 26 °C.

3.2 Simulation results

The actual and simulated monthly electricity data of the target-building is shown in Figure 9 and Table 1. The result showed that the MBE for the monthly electricity consumption of the flat is -5%, the CV(RMSE) is 14.1%. Therefore, according to ASHRAE Guide 14, the building model is considered accurate.

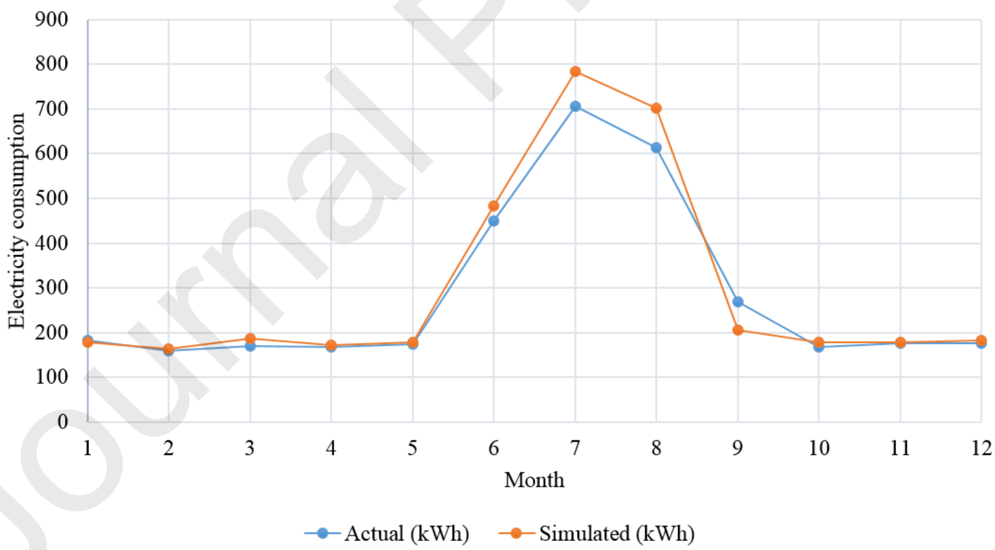

Figure 9: The actual and simulated monthly electricity consumption.

Table 1: The actual and simulated electricity consumption and the error.

Month	Actual (kWh)	Simulated (kWh)	Absolute error (kWh)	Percentage error (%)
1	182	177.6	-4.4	-2%
2	160.1	163.8	3.7	2%
3	170.2	186.4	16.2	10%

4	167.4	173	5.6	3%
5	174.9	177.6	2.7	2%
6	448.9	482.3	33.4	7%
7	705.5	783.6	78.1	11%
8	613.7	701.2	87.5	14%
9	268.7	205.6	-63.1	-23%
10	166.9	177.6	10.7	6%
11	176.7	177.4	0.7	0%
12	176.2	182	5.8	3%

Detail energy analysis of the target-building was achieved via the simulation made in DesignBuilder software. The simulation results show that the target-building consumed 324,131 kWh of electricity a year (of which 131,722 kWh was spent on summer cooling) and 1,131,519 kWh energy on heating a year. Total simulated energy (electricity and heating) consumption a year was 1,455,650 kWh. The simulated average energy intensity was 144.15 kWh/m^2.year; the average heating intensity was 112.05 kWh/m^2.year, which in the range of national statistics [33, 2]; and cooling intensity was 13.04 kWh/m^2.year. To achieve Passivhaus standard, massive heating reduction is required ($\leq$ 15 kWh/m^2.year). Most of the building's energy (87%) were spent on heating and cooling, the remaining 13% were used for other equipment (lighting, computer, refrigerator, television, kitchenware and etc.). The target-building's energy consumption by sector is shown in the Figure 10.

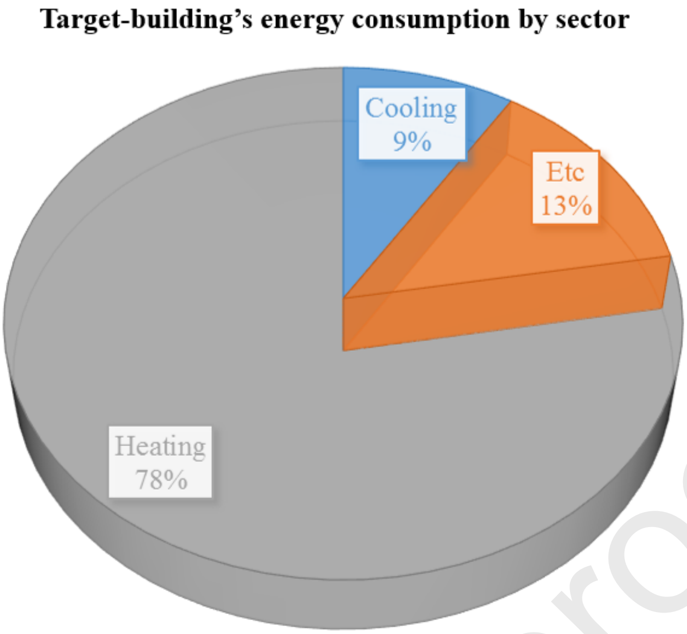

Figure 10: The target-building's energy consumption by sector.

As can be seen in Figure 11, monthly electricity consumption remains around 15,000 kWh from January to May, and then the total power consumption has increased significantly since the advent of summer with the use of air conditioners, rising from June Peaked at 68,175 kWh in July, of which 52,125 kWh was the electricity consumed by air conditioners. As the weather started to cool in September, the use of air conditioners dropped drastically and monthly power consumption dropped back to about 15,000 kWh. As mentioned earlier, the period of winter heating started from November 15 to the end of March 15 of the second year. As shown in Figure 12, monthly heating energy consumption started to rise from November and peaked at 330,790 kWh in January, Heating energy consumption in March began to drop significantly. Due to non-heating period from April to September, heating energy consumption is basically zero.

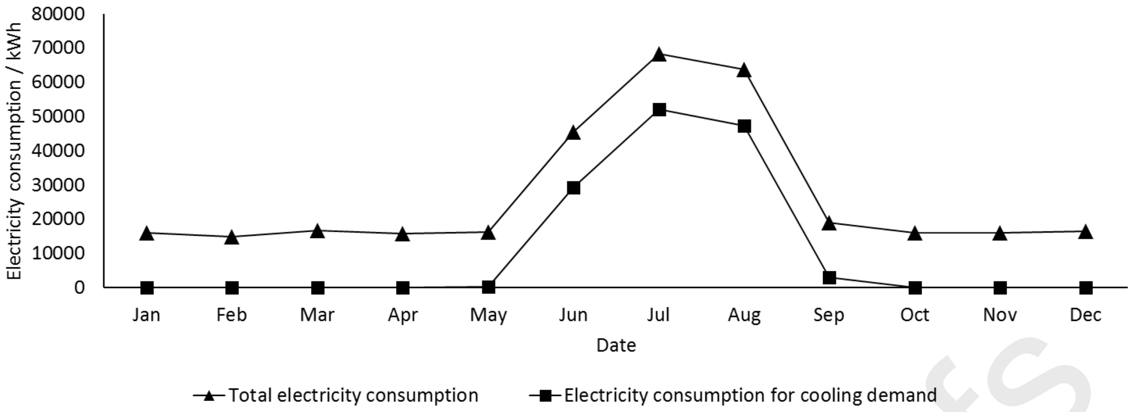

Figure 11: Simulated monthly electricity consumption and cooling consumption.

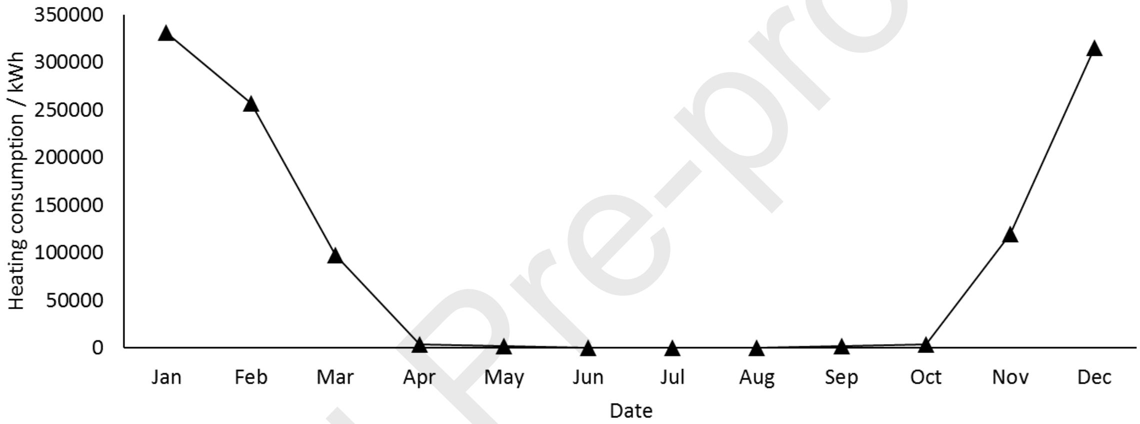

Figure 12: Simulated monthly heating consumption.

3. 3 Retrofitting approach

3.3.1 Fabric

The baseline building model was calibrated based on local Standard for Energy Efficiency of Residential Buildings (DBJ 14-037-2012) and Passivhaus standard. The building fabric's heat transfer coefficient before and after retrofitting are shown in Table 2.

Table 2: The building's fabric before and after retrofitting.

	Target building	Retrofitted target-building	
Heat transfer coefficient, W/(m2·K)	Baseline	DBJ 14-037-2012	Passivhaus
External wall	0.62	0.62	0.148

Roof	0.47	0.45	0.15
Ground floor	3.45	0.55	0.149
Window	3.16	2.71	0.786

Approaches taken to achieve the standards for the building fabrics are listed in Table 3. The target-building's external wall confirms to the DBJ 14-037-2012 standard, however, roof, ground floor and window require extra insulation to achieve the targeted heat transfer coefficient. The desired heat transfer coefficient given in the DBJ 14-037-2012 standards can be achieved by adding additional 5 mm of XPS-CO2 blowing to the roof layers, introducing 53 mm XPS-CO2 blowing to the flooring and increase the air gap between the windows' glazing to 13mm. However, to retrofit the current target-building fabrics to Passivhaus standards is rather challenging. Passive house design and planning standards put an extremely high requirements on the thermal performance of the building envelope. The actual thermal performance of the target-building is 3 to 23 times less efficient compared to the Passivhaus standards. The thermal conductivity of the conventional insulation materials such as XPS or EPS is around 0.05 W / (m • K) and to achieve 0.15 W / (m2 • K), 300 mm of the XPS/EPS is required. Installation of such insulation thickness poses a series of problems related to the difficulty of actual construction, the reduction in the strength of the external wall structure and massive losses in the indoor space as the insulation layer will be added internally. Therefore, a vacuum insulation panel (VIP) with thermal coefficient of 0.002 ~ 0.007 W / (m • K) was used in addition to the current structure. The VIP core material is usually fibre material and porous powder material. Powder silica is commonly used in construction. The core material is hermetically sealed with an airtight film wrap, typically a metal-containing polymer multilayer film [34] to maintain the vacuum state over a long period of time. The default material parameters in the DesignBuilder database do not have a vacuum insulation board and therefore need to be entered. Following material specification was entered for VIP product: thermal conductivity 0.007 W / (m • K), specific heat 850 kJ / (kg • K) with a density of 170 kg / m3 [35].

In order to improve window's thermal performance, the windows need to be replaced with argon-filled three-layer hollow low-emissivity glass. Argon is a colorless, odorless, non-toxic inert gas that has no effect on visible light penetration. Argon gas tightness of 1.7836 kg / m3 (at a temperature of 0 ° C) is greater than the air tightness, so filling argon gas in the hollow glass instead of air can reduce the thermal conductivity of the gas and reduce the heat convection [36]. Low-E glass is a thin film of one or more layers of metal or metal oxide coated on the surface of a glass to ensure visible light transmittance and high reflectivity to infrared light. Low-radiation glass in the summer can ensure enough visible light to reach the interior, and at the same time block a large amount of infrared radiation generated by external objects outdoors, thereby greatly reducing the indoor and outdoor heat exchanges. Low-radiation glass in winter reflects the thermal radiation generated by indoor electrical equipment, heating facilities, and the human body, returning it to heat the room [37]. Extra reduction in heat transfer through windows is achieved by replacing the windows frame to UPVC that can reduce the heat transfer coefficient has better air tightness.

3.3.1 Heating, cooling and ventilation

In local DBJ 14-037-2012 standards, the suggested heating set point temperature is 18 °C while in reality the residents regulated their heating to achieve 20°C to 25°C indoor temperature. Meanwhile in summer time the respondents switched on air conditioning once the indoor temperature reached 30°C. Standard cooling set point temperature wasn't given in the DBJ 14-037-2012, therefore the actual residents' preference gathered during the field study survey was taken as the cooling set point reference. Passivhaus standards requires the indoor temperature to vary between 20°C to 26°C at all time, ≥ 75% heat recovery and minimum ventilation rate per person. To ensure the building adheres to this requirement, advanced air conditioning systems supplying heating, cooling and mechanical ventilation are installed in the apartments replacing the conventional district heating, radiator and individual air conditioning used only for cooling. In this study, a Haier air conditioning system [38] with the overall Coefficient of Performance (COP) of 2.8 for cooling and 3.2 for heating was selected.

For Passivhaus retrofit, the heating set point and setback point temperature are respectively determined as 22 °C and 20 °C to avoid overheating. It was noticed that the peak temperature always occurs during late afternoon when the apartments were normally empty in the weekdays. Additionally, according to a survey aiming to investigate the optimum thermal comfort for Chinese urban residents in the cold zone [39], the range of suitable summer internal temperature for most of the residents is considered as 26.0 °C to 30.7 °C. For the purpose of both reaching Passive House standard and reducing energy consumption, the temperature range during cooling period is defined as 24 °C to 30 °C.

Table 3: The construction materials and its thicknesses for each standards.

	Retrofitted: DBJ 14-037-2012		Retrofitted: Passivhaus	
Elements	Material	Thickness (m)	Material	Thickness (m)
External wall	Concrete/plaster/mortar-cement screed	0.005	Concrete/plaster/mortar-cement screed	0.005
	XPS-CO2 blowing	0.045	Vacuum insulation panel	0.036
	Concrete/plaster/mortar-cement mortar	0.02	XPS-CO2 blowing	0.045
	Concrete, reinforced (with 1% steel)	0.2	Concrete/plaster/mortar-cement mortar	0.02
			Concrete, reinforced (with 1% steel)	0.2
Roof	Concrete/plaster/mortar-cement mortar	0.045	Concrete/plaster/mortar-cement mortar	0.045
	XPS-CO2 blowing	0.06	Vacuum insulation panel	0.032
	Concrete/plaster/mortar-cement mortar	0.02	XPS-CO2 blowing	0.06
	Perlite Plasterboard	0.04	Concrete/plaster/mortar-cement mortar	0.02
	concrete, reinforced (with 1% steel)	0.1	Perlite Plasterboard	0.04
			concrete, reinforced (with 1% steel)	0.1
Ground floor	concrete/plaster/mortar-cement mortar	0.02	concrete/plaster/mortar-cement mortar	0.02
	extruded polystyrene board	0.053	Vacuum insulation panel	0.045
	concrete, reinforced (with 1% steel)	0.12	extruded polystyrene board	0.053
			concrete, reinforced (with 1% steel)	0.12
Window	Double glazing 6 mm/13 mm filled with air / UPVC frame	0.025	13mm argon-filled three-layer hollow 3mm low-emissivity glass/ UPVC energy-saving window frame	0.022

3.3.3 Shading

In view of the climatic characteristics of most parts of China, window shade plays an important role in reducing building energy consumption and enhancing indoor thermal environment. Summer window shade helps regulate the amount of radiant heat entering the indoor which will avoid overheating and the need to use the air conditioning for cooling. A sun path simulation was made using DesignBuilder software to analyse the solar radiation in summer. As seen in Figure 13, the southern and western surfaces of the building receive the most solar radiation when the temperature was highest in the summer's afternoon. The windows on the south and west should be shaded in order to avoid too much solar heat gain through windows.

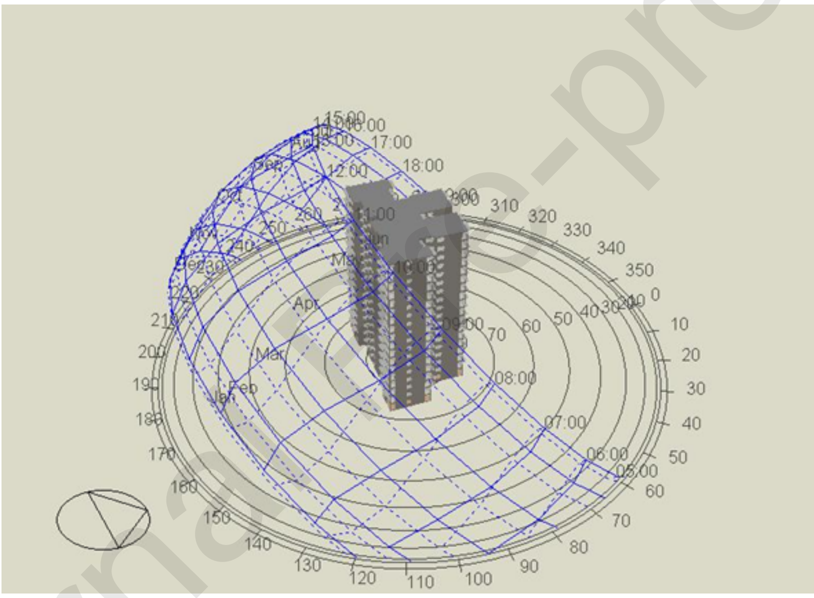

Figure 13: Analysis of the solar radiation on building envelope.

According to the study on the optimisation of shadings in Beijing area [38], no external shadings should be added outside of the balcony glazing since people would always like to enjoy enough sunlight through their balconies. Simple shadings which are only overhangs with 0.5 m of projection are applied to the windows where there are limited spaces on the southern surface. Complex shadings that are composed of overhangs with 0.5 m of projection, side-fins with 0.4 m of projection and louvres are installed outside of large windows on the southern surface. The windows on the west are added overhangs with 1.5 m of projection. Figure 14 shows the visualisation of a part of external shadings on the western and southern facades.

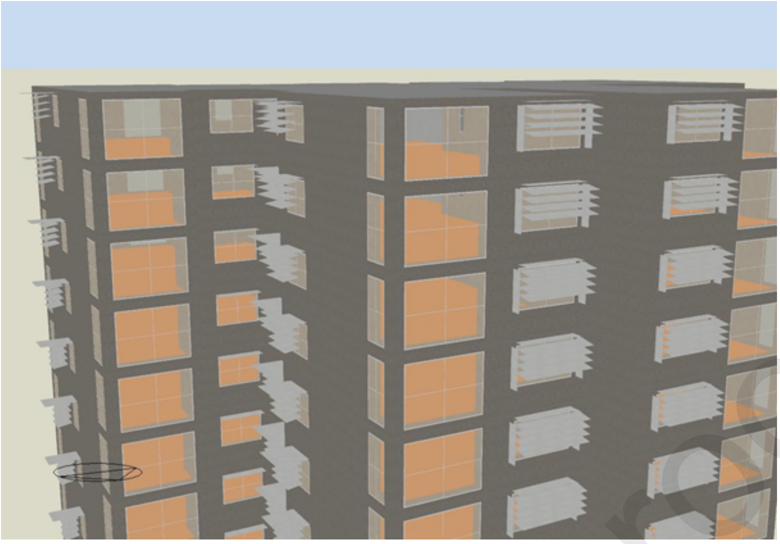

Figure 14: External shadings on the western and southern surfaces of the building.

3.4 Performance comparison

3.4.1 Energy performance

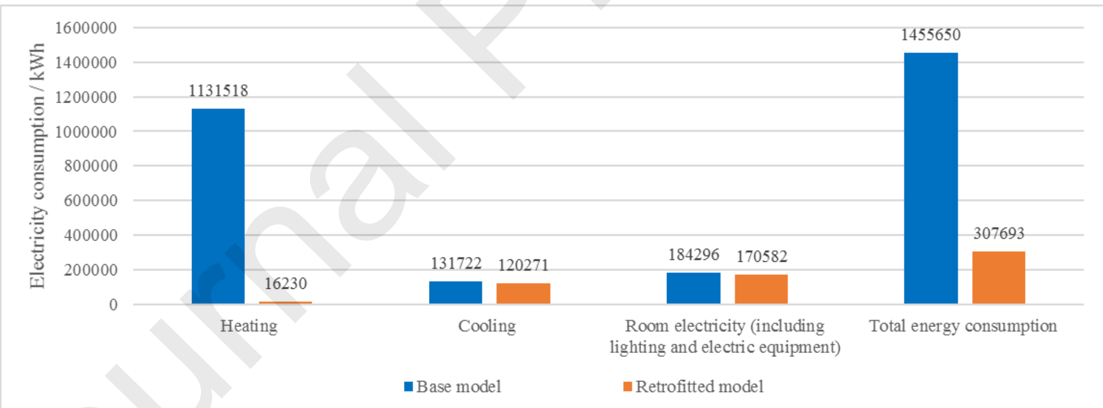

Figure 15 Summary and comparison of energy consumption

The simulated energy consumption results using retrofitted model is summarised in Figure 15 and compared to the results from the base model for the current situation of the building without retrofitting yet. From the results, it can be seen that the energy consumption for heating reduces from 1,131,518 kWh (equivalent to the standard coal consumption 13.76 kgce/m^2) per year to 16,230 kWh of electricity consumption per year. Assuming the thermal efficiency of coal power plants are 35% - 40%, the electricity consumed are equivalent to the coal consumption between 40,575 – 46,371 kWh. The primary energy consumption decreased by 95.9 - 96.4 %. The specific heating demand is between 4.02 ~ 4.59 kWh/m^2·year, reaching the requirement of Passive House. The electricity consumption for cooling reduced from 131,722 kWh per year to 120,271 kWh per year, decreased by 8.7%. The specific cooling demand is 11.9 kWh/m^2·yr, also satisfying the requirement of Passive House. Other electricity consumption used for electric appliances and lighting were reduced by 7.4% from 184,296 kWh per year to 170,582 kWh per year. The overall energy consumption was reduced from 1,455,650 kWh per year to 307,693 kWh per year, 78.9% of reduction was achieved through the retrofitting solutions. The simulated primary energy demand is 36.1 ~36.7 kWh/m^2·year, which is much lower than the Passive house standard of 120 kWh/m^2·year. Figure 16 indicates the comparison of simulated heating, cooling and overall electricity consumption. It can be seen that only a small quantity of heating is required from November to March of next year. Most of cooling occurs from March to October and reaches the peak of approximately 700 kWh per day in July. It is noted that some days in March and November that get both heating and cooling supplies are caused by outside diurnal temperature differences. Generally, the daily total electricity consumption showed a correlation with heating and cooling consumption, approximately fluctuating from 400 kWh per day to 1400 kWh per day and expressing some peaks on weekends and holidays due to people's activities at home.

Figure 17 shows the comparison of external dry-bulb temperature and internal air temperature. According to the weather data, the external temperatures could go down to -7°C in winter and reach a peak of 33°C in summer. After retrofitting, the internal temperatures of the dwelling approximately fluctuate between 22 °C and 27°C, it was a stable line for the whole year. The result indicated that the retrofitting approaches worked well on avoiding the problem of energy wasting caused by overheating in winter, the thermal comfort is improved significantly for all year round.

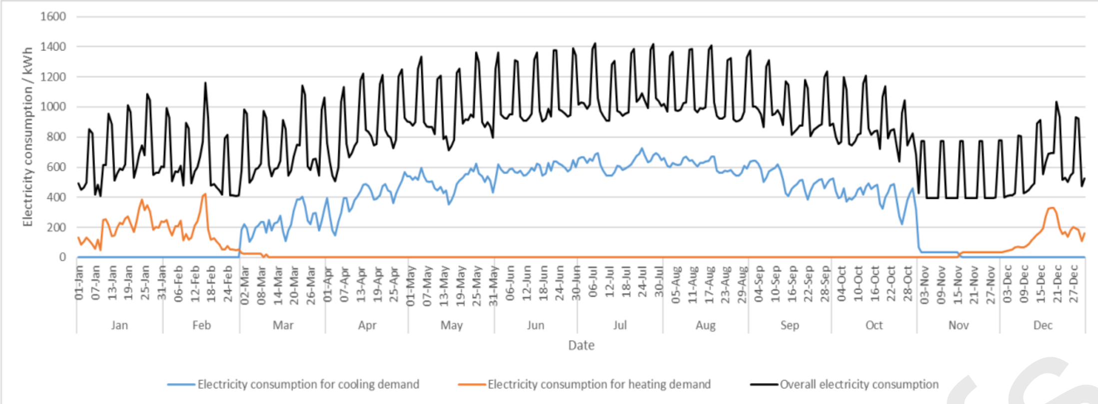

Figure 16 Simulated daily heating, cooling and total electricity consumption after retrofitting.

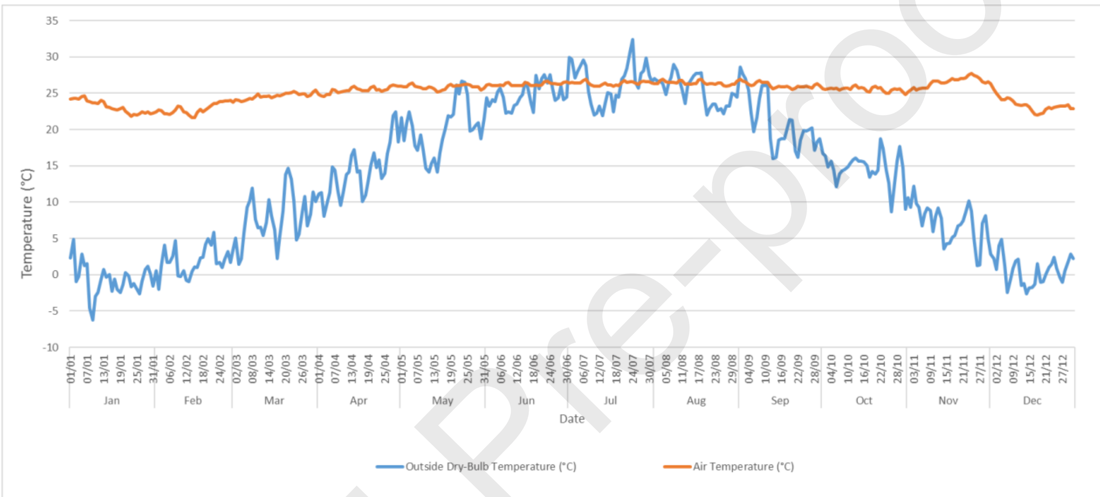

Figure 17 Comparison of internal air temperature and outside dry-bulb temperature

The results proved that the fabric retrofitting measures which lead to better insulation and the increase of thermal mass play an essential role in the reduction of energy demand in residential buildings. Meanwhile, the updated HVAC system with required 75% of heat recovery would provide reasonable scenarios of heating, cooling and mechanical ventilation based on the internal environmental conditions, resulting in the decrease of heat loss and further energy conservation. External shadings are applied outside of selected windows to avoid summer overheating and lower down cooling demand probably caused by great insulated envelope.

4. Economic analysis

The feasibility at the financial aspect is examined through a cost analysis. According to the guide [19], the designed life of residential buildings is 50 years. The target building has been occupied for 9 years since 2010, the unexpired lifetime is 41 years. The assumed investors and beneficiaries were the residents of the building. The estimated initial investment expenditure is calculated based on average market prices of Shandong Province as shown in Table 6. It is calculated that the initial investment cost is ¥ 4,069,768 in total.

Table 4 Estimation of the initial investment cost (The unit cost including labour cost)

Measures	Unit cost	Project volume	Cost
External insulation (external walls)	¥119/m^2	8451 m^2	¥1,005,669
External insulation (roof)	¥125/m^2	619 m^2	¥77,375
External insulation (ground)	¥66/m^2	619 m^2	¥40,854
Windows	¥380/m^2	2308 m^2	¥877,040
Louvres	¥370/set	90 sets	¥33,390
Overhangs and side-fins	¥120/set	162 sets	¥19,440
Air conditioning systems	¥28000/set	72 sets	¥2,016,000

According to the simulation data, 16438 kWh of electricity would be saved per year and the electricity price is ¥ 0.55/kWh, the cost of saved electricity is ¥ 9,066 per year. The heating charge is ¥ 21/m^2 and the total heating space is 10098 m^2, the cost of winter heating is ¥ 212,058 in total.

The value of saved energy is ¥ 221,124 totally. The simple payback period (SPP) is employed to carry out the cost analysis and is defined as shown in the Equation (5). Where, V_E represents the value of saved energy, C_I is the initial investment costs. The simple payback period was approximately 18.4 years. Hypothetically this retrofitting project is considered to be implemented from the beginning of 2019 and last for one year, the residents could start to turn a profit from the middle of 2037 and keep being benefited for the remaining 23years.

5 Conclusions

The simulation results from this study show that, for the studied high-rise residential building, using the retrofitting measures of the Passive House standard can lead to a 78.9% reduction of overall energy consumption in a calendar year. The heating and cooling consumption can be reduced by around 96% and 8.7 % respectively through designed updating solutions. If the studied dwelling is retrofitted to Passive House standard, 1,147,957 kWh of energy could be saved per year in total. With all the construction and energy performance updated to meet the requirements of Passive House, the living and thermal comfort would be improved for residents as well. Furthermore, the results from the cost analysis showed that the payback period was 18.4 years, and the economic benefits can be obtained in the remaining lifetime of the building.

The results of this study indicate that it is feasible to achieve the Passive House standard through the fabric refurbishment and HVAC system updating measures in an existing high-rise residential building of northern China area. The results showed a good example of energy saving by retrofitting. The methodology and retrofitting approaches can be applied to other similar existing high residential buildings in the area.

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Highlight

- This study examined a high-rise residential building located in northern China.
- The target-building's electricity consumption and indoor temperature were gathered and analysed.
- DesignBuilder software was used to conduct a computational study on the feasibility and energy-saving potentials in retrofitting the target-building to Passivhaus standard.
- It was found that the energy consumption of the building reduced by 96% for heating and 8.7% for cooling; totally reduced by 78.9%.
- The payback period was estimated as 18.4 years.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.