# Retrofit or rebuild? The future of old residential buildings in urban areas of China based on the analysis of environmental benefits

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## Abstract

From the 1970s to the 1990s, over 3.5 billion square meters of residential building areas were completed in China to accommodate the increased population in cities. Most of the constructed buildings were built without insulation and proper ventilation. Currently, these buildings are reaching the end of their designed service lifetime. Therefore, retrofitting and rebuilding represent two different options to upgrade or completely replace these old buildings. However, material utilization levels of retrofitting and the rebuilding plans are completely different, resulting in different embodied energy consumption and operation energy consumption levels. This study examines the old residential buildings located in the cold climate zone of China. The study found that rebuilding these old residential buildings normally attain higher embodied energy consumption and embodied $CO_2$ emissions due to high material input. Therefore, rebuilding plans might not be the highest priority, and government managers should consider the environmental impacts from the embodied energy consumption when formulating decisions regarding the future of these old residential buildings. Additionally, the insulation thickness is an important parameter for the main building fabrics of retrofitted and rebuilt buildings to reduce heating and cooling energy demand. Although, this study has identified that the rebuilt buildings cause higher $CO_2$ emissions than retrofitted buildings. However, various parameters, such as the materials' embodied coefficient, the carbon intensity of the operation energy sources and ratios of the surface areas of the glazing windows to the external walls, should be considered by decision-makers.

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## 1 INTRODUCTION

Buildings are responsible for more than 35% of the global energy consumption and one-third of the global greenhouse gas emissions [1]. China, as the largest building construction market in the world, ranks first in urban residential building energy consumption [2]. The residential building energy consumption in China makes up 21% of the whole national energy consumption [3]. China has unveiled a climate action plan to hit a plateau in carbon emissions by the 2030s in order to ensure national energy

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stability and solve environmental problems caused by climate change. Residential building energy use has been a crucial factor to focus on in order to achieve this aim.

Currently, the development of urban residential buildings in China can be generally categorized into three phases [4]. The phase 1 residential building development started in 1949 and ended in 1976. Under the welfare-oriented public housing distribution system, over 0.5 billion square meters of building areas was constructed by the governments or state-owned companies [4]. Currently, most of these buildings have reached the end of their designed service lifetime; therefore, they have been gradually abandoned and demolished for new urban-building developments. The second phase started in the early 1980s and ended in the late 1990s. After the implementation of market economic reforms, China has been gradually liberated from the planned economy and the scale and the pace of its urbanization has substantially increased. During this time, over 184 million people migrated to cities from rural areas, raising the urbanization rate from 18.96% to 30.40% [3]. Over the same time, the residential building areas grew from 1.4 to 4.9 billion square meters (3.5 billion square meters in total) to accommodate the increased population in cities. Moreover, ∼90% of the constructed buildings are multi-story buildings with three to six stories based on the definition provided by the 2019 Uniform Standard for Design of Civil Buildings (USDCB-2019) [5]. Currently, these buildings are still in use, although they are gradually reaching the end of their designed lifetime.

The phase 3 residential building development mainly extends from the beginning of the 21st century to the present. More than 400 million people moved to cities within this period, and approximately 24.1 billion square meters of residential building areas was completed [3]. Most of buildings are high-rise buildings with 20 to 30 stories and their types and functions are more complicated, while their structural systems are more diversified. The phase 3 residential buildings accounted for more than 50% of the building sector in China [6].

Currently, the urban residential buildings constructed in phases 2 and 3 coexist in China. These buildings have different types of the floor planning, material consumption and structure composition, as a result of the different levels of energy consumption.

The phase 2 residential buildings commonly have a square form with a layout of one staircase and two households. Each building normally has 2 or 3 units lined up in a row, and each unit houses 6 to 12 families in total. They were all constructed with brick-concrete structures, and the primary building materials were clay bricks and lime mortar, which are both cheap, sturdy and simple to make. Clay bricks and lime mortar are commonly used to build walls and they have been in use in China for thousands of years. However, clay bricks are not an eco-friendly material because their thermal conductivity reaches to 0.8 W/m$^2$K. Furthermore, the manufacture of clay bricks and lime mortar has a significant adverse impact on the climate. Clay bricks are expected to use over 1 billion square meters of clay resources per year, the equivalent of destroying 500 thousand acres of farmland [7]. Moreover, due to the low-level processing technologies, nearly 7000 tons of coal are consumed annually to manufacture clay bricks, resulting in roughly 18 thousand tons of $CO_2$ emissions [8]. As a result, China's Ministry of Housing and Urban–Rural Development issued the Clay Brick Utilization and Lime Mortar Production Regulations in 2000, with the aim of removing clay bricks and lime mortar from construction sites. Apart from these two non-eco-friendly materials, the phase 2 residential buildings also have few energy-saving physical features. Before 1986, China had no energy-saving requirements for urban residential buildings. Therefore, the residential buildings constructed before 1984 normally possess no external insulation and double-glazing windows. In 1986, the first building energy savings standard, i.e. the Energy Saving Standard for Civil Buildings (JGJ26-86), was implemented by the central government of China. The standard required that residential buildings have to save 30% more energy than buildings constructed in the early 1980s. However, due to economic conditions and low environmental protection awareness, most urban residential buildings were still built without insulation in the 1990s. Thus, the phase 2 residential buildings always attain high levels of heating and cooling energy consumption to achieve a thermally comfortable indoor environment.

The phase 3 residential buildings normally are high-rise buildings with a layout of one staircase and 4 to 6 households. Therefore, these buildings have a high occupancy density, and each of them can house 80 to 180 families. Their form is more complex than that of the phase 2 residential buildings to achieve better lighting conditions and ventilation performance for all the families on each floor. The main forms include the butterfly shape, T shape and slab shape. Residential communities with high-rise buildings could save more land for landscaping, parking areas and activity venues. Most phase 3 residential buildings are built with reinforced concrete structures, and the main materials used are concrete and steel. In addition, the walls are constructed with aerated concrete blocks because they are more environmentally friendly than clay bricks. Aerated concrete blocks are solid, lightweight, precast concrete blocks that contain air bubbles throughout the material to generate a low-density lightweight material with autoclave ovens. Moreover, the aerated concrete blocks have an incredibly high insulation value, thus improving the building energy efficiency by reducing the heating and cooling loads (thermal conductivity: 0.2 w/m$^2$·K). The Zhiyan Consulting Group reported that the annual production of aerated concrete blocks has increased from 12 to 178 m$^3$ between 2005 and 2018 [9]. Apart from the switch from clay bricks to aerated concrete blocks, the amount of insulating material used in phase 3 residential buildings also increased to meet the current energy-saving criteria. After China entered the new century, the central government introduced a new version of JGJ26-86, requiring urban residential buildings to save 50% of energy based on phase 2 residential building energy usage levels. In 2018, this standard has been updated again (JGJ26-2018) and the number has increased to 75% [10]. Local governments have also adopted their own energy-saving guidelines for urban residential buildings, which are generally more stringent than national standards. For example, the government of Beijing introduced its own energy conservation standard in 2020 (DB11/891-2020), with the aim of reducing energy consumption by more than 5% while adhering to national standards (80%) [11]. Therefore, phase 3 residential buildings normally have a thick external insulation and energy-efficient external windows. As a result, compared to the phase 2 residential buildings, the energy consumption of the phase 3 residential buildings is substantially reduced.

Considering the phase 2 residential buildings, governments normally have two kinds of plans to improve the energy performance of these buildings, i.e. retrofitting plans and rebuilding plans. For most of them, governments may demolish these buildings directly and build high-rise residential buildings to accommodate the occupants of the old residential buildings. In addition, land areas can be released since high-rise residential buildings have a low land occupation density, and these released lands can be used for new projects and promote the replacement of industry. For a few old residential buildings, governments may take measures to retrofit them, such as adding external insulation and replacing single-glazing windows with double-glazing windows.

Therefore, governments rarely consider the future of these residential buildings from an ecological point of view and prefer to rebuild phase 2 residential buildings because this normally can generate more economic benefits. However, the material utilization levels of retrofitting and rebuilding plans are completely different, resulting in different embodied energy consumption and operation energy consumption levels. Moreover, the indoor thermal comfort performance might also be different due to the different material utilization levels in these two plans. Currently, few studies compare the eco-benefits of rebuilding and retrofitting phase 2 residential buildings, and the relationship between material utilization, indoor thermal comfort and associated energy input (embodied energy and operation energy) of these two plans has not been identified. Therefore, the purpose of this paper is to investigate the energy currently consumed by these buildings and quantify the material utilization and associated energy input levels for retrofitting and rebuilding plans, respectively. The findings of this study may help governments formulate decisions on the future of these old residential buildings from an ecological point of view.

## 2 ASSOCIATED ENERGY INPUTS

Generally, a building's lifespan is divided into three stages: preoccupancy, post-occupancy and demolishment [6]. Preoccupancy often involves the energy used for material extraction, production and transportation. Moreover, the energy used for construction process also takes place in this stage. The post-occupancy phase mainly involves the energy consumed for the heating, cooling and systems' maintaining of buildings. The demolishment stage normally involves the energy consumption for the demolishment activities, i.e. demolishing buildings, waste material transportation and recycling. The above three steps are included in a full lifespan environmental impact study, which considers building environmental performance from upstream (extraction, processing, transportation) to downstream (decommissioning and disposal) processes. It should be noted, however, that the demolishment process is not included in this study due to a lack of data.

The term 'embodied energy' is used to describe the energy absorbed during the preoccupancy period. It refers to the energy used in the extraction, manufacturing and transportation of materials, as well as the construction of buildings [12]. In addition, there are two forms of embodied energy: initial embodied energy and recurring embodied energy. The energy used to build the structure is referred to as initial embodied energy. The recurrent embodied energy, on the other hand, relates to the energy used in the refurbishment of buildings over time. Currently, embodied energy is a primary evaluating indicator for pre-occupancy building environmental study.

In the post-occupancy stage, energy is primarily used to build a pleasant indoor atmosphere, which includes the thermal, visual and acoustic environments. This research mainly investigates the correlation between the energy consumption and thermal comfort performance, therefore, the energy used for visual environment and acoustic environment is not considered.

## 3 INDOOR THERMAL COMFORT

The term 'thermal comfort' refers to the state of satisfaction with the thermal environment [13]. It has a huge effect on the mental and physical health of inhabitants, as well as their working efficiency [14, 15]. Normally, people prefer to associate the thermal comfort directly with the surrounding environment, particularly air temperature [16]; however, many researchers have identified that six indicators have a major impact on the evaluation of thermal comfort, they are metabolic rate, clothing levels, the movement of air (m/s), the mean radiant temperature (°C), the air temperature (°C) and the relative humidity [17]. An acceptable indoor environment can only be created when a proper balance is established between these six indicators. Currently, two co-existing models are available to assess indoor thermal comfort: Fanger's predicted mean vote (PMV) model [18] and the adaptive model [19]. Fanger's PMV model evaluates the thermal comfort based on a combination of the six indicators. It provides a rating score from response of a group of occupants based on the thermal sensation scale defined by the ASHRAE [13]. Generally, PMV between −0.5 and 0.5 refers to an ideal thermal environment for comfort. In practice, PMV indexes ranged from −1 to 1 are also acceptable [6]. Currently, the PMV model is widely used in the evaluating indoor thermal comfort because it is cost effective and time saving. Thermal simulation software, such as Integrated Environment Solutions (IES) and Energy-plus, can directly provide the calculation results of PMV model.

The adaptive model is developed based on field studies to analyses the real comfort level of the thermal environment. It is affected significantly by the specific thermal context, the occupants' behaviors and the occupants' expectations [16]. An adaptive model

**Figure 1.** *The selected residential community.*

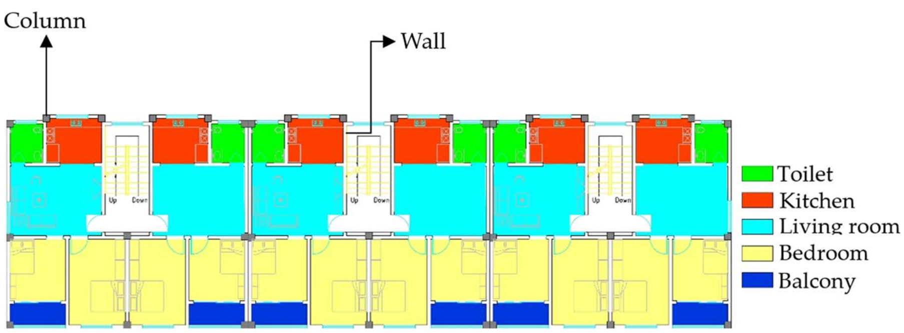



**Figure 2.** *The floor planning of building 1.*

would normally provide more reliable information about the actual comfort level and more accurate interacting parameters for naturally ventilated buildings [20]. The adaptive model, on the other hand, usually necessitates a significant amount of time and human resources because all of the data is gathered through field studies such as surveys, interviews, field measurements and questionnaires.

# 4 RESEARCH METHODS

## 4.1 Case study building

A case study can typically provide in-depth analysis; thus, a phase 2 residential community located in the cold climate zone of China was selected (Figure 1). This community occupies 14428 m$^2$ of land area and has 8 residential buildings that accommodate 240 units totaling approximately 770 local residents. All the buildings are identical and have a square form with five floors and three units. Each unit has a layout of one staircase and two households. Thus, one building houses 30 families in total. Figure 2 shows the floor plan of building 1. It is noted that each household has two bedrooms, one living room, one toilet and one kitchen. Two bedrooms have a south orientation, and the toilet and the kitchen have a north orientation. The floor areas for each household and the whole building are 73 and 2190 m$^2$, respectively.

These buildings were built in 1990 and have no external insulation and energy-efficient windows. Currently, only 10 years are left before they reach the end of their designed structural lifespan (the required lifetime for residential buildings in China is 50 years). The main construction materials were clay bricks and lime mortar. Reinforced concrete was only used for the columns and beams. All the rooms are heated by wall-mounted gas boilers in winter and cooled by air conditioners in summer. Thus, the main energy sources are natural gas and electricity, respectively. Moreover, hot water is normally provided by electric hot water heaters.

Field surveys were conducted in the form of a WeChat questionnaire to investigate the energy currently consumed by the

**Table 1.** *WeChat questionnaire.*

| Questions | Data format |
|---|---|
| Q 1. What period will the gas boiler be used? | Months |
| Q 2. How long should the heating system run per day? | Hours |
| Q 3. How much of natural gas is consumed per month? | $m^3$ |
| Q 4. What period will air conditioner be used? | Months |
| Q 5. How long should the air conditioners run per day? | Hours |
| Q 6. How much of electricity is consumed per month? | kWh |

occupants. The questionnaire contained six questions (Table 1). In total, 200 copies of the questionnaire were distributed to the residents in the case study community and 182 valid copies were retrieved. In addition, the households in unit 1 of building 1 were selected as representative households of this residential community.

## 4.2 Retrofitting plan

To extend the lifespan of these old residential buildings, a retrofitting plan can be designed based on the requirements of the Technical Specifications for Seismic Strengthening of Buildings (JGJ116-2009) and Residential Building Energy Saving Standards (DB375026-2014). Table 2 summarizes the construction specifications of the retrofitting plan. The lifespan of these buildings can be extended by 20 years by adding reinforced concrete walls 50 mm in thickness to the existing walls. Insulation (90 mm insulation applied to the external walls and 100 mm insulation to the roofs) and double-glazing windows are used to reduce the building energy consumption.

The quantity of material utilization in the retrofitting plan can be estimated based on a model built in REVIT (left in Figure 3). Table 3 summarizes the material utilization of the retrofitting plan. It is worth noting that the material density was calculated based on the data from the Thermal Design Code for Civil Buildings of China (GB5176-2016).

To investigate the indoor thermal comfort performance and the energy consumption of the retrofitted building, a simulation program, i.e. Integrated Environmental Solutions Virtual Environment (IESVE) was selected to conduct the calculations (right in Figure 3). Published studies have found that IESVE offers a high accuracy and interoperability. For example, Attia et al. [21] compared ten software packages and found that IESVE performs the best due to its usability, graphical visualization and interface management. Good agreement was observed between the IESVE simulation results and experimental data [22, 23]. Attia and De Herde [24] stated that IESVE can estimate and predict the building performance at a reasonable level of accuracy. In addition, IESVE has been tested and verified by both the CIBSE and ASHRAE. The construction specifications and the retrofitting material utilization were input into the model in IESVE, and the thermal comfort levels and operation energy consumption levels were obtained. To quantify the effects of material utilization on the thermal comfort performances, thermal comfort simulations were conducted with no active system installed in the studied building. Ventilation only relies on infiltration, and an exchange rate of 0.5 was adopted for the simulation based on the recommendation from the Code for Design of Heating, Ventilation and Air Conditioning of China (GB50019-2003). In addition, the thermal comfort simulations mainly focused on the performance in winter and summer because residential buildings in transition seasons usually attain a suitable comfort performance since the ambient temperature is within the comfort range. According to the utilization habits of occupants, windows were opened to introduce fresh air in the summer simulations, and in the winter simulations, all the windows remained closed to keep the building interior warm.

## 4.3 Rebuilding plan

Currently, the local government is implementing a plan to rebuild this community with high-rise residential buildings, and the released land will be used for new commercial development. The rebuilding plan is shown in Figure 4, as six high-rise residential buildings will be built to accommodate occupants. These 6 buildings have 20 floors, and each story has a layout consisting of one elevator and four households. The floor area for each building is 4704 $m^2$. The main construction materials used are cement mortar, reinforced concrete and aerated concrete blocks. Table 4 summarizes the main construction specifications of the new high-rise buildings.

Based on the model built in REVIT (left in Figure 5), the quantity of material utilization in the rebuilding plan is summarized in Table 5. The listed material density was calculated based on the data from the Thermal Design Code for Civil Buildings of China (GB5176-2016).

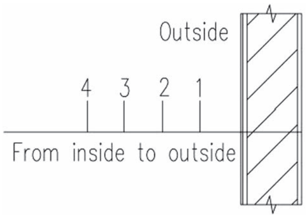
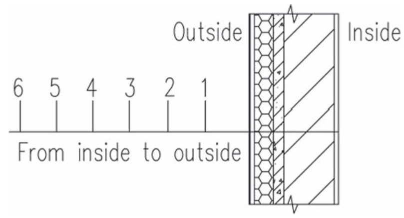
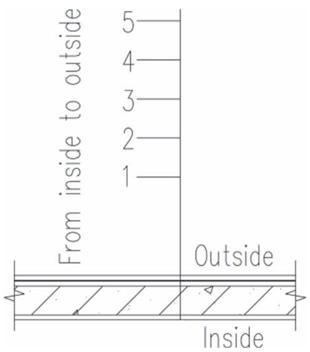
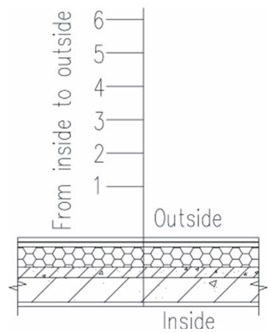
The indoor thermal comfort and operation energy consumption of the new high-rise residential buildings were also quantified based on IESVE simulations (right in Figure 5). The construction specifications were input in the rebuilding model, and the heating and cooling settings were kept the same as those in the retrofitting model. Moreover, the active system was also deactivated for the thermal comfort simulations.

# 5 RESULTS OF ENERGY CONSUMPTION

## 5.1 Energy currently consumed

According to the WeChat questionnaire, all the investigated families normally use their heating system from the middle of November until the middle of March of the following year. In the hot season, the air conditioners are always used between July and September. Additionally, the occupants prefer to operate their heating systems throughout the day. In contrast, they only use air conditioners when they are at home in the cooling season. Figure 6 shows the average gas and electricity consumption levels per month. The natural gas consumption in March, November and winter months was much higher than that in other months. During the non-heating season, natural gas was mainly used for cooking, and the average gas consumption per month was 32 $m^3$. In contrast, the average gas consumption per month in the heating

**Table 2.** *Construction specifications.*

| | Original construction specifications | Construction specifications of the retrofitting planning |
|---|---|---|
| Wall | <br>1. Lime mortar (20 mm); 2. Clay bricks (240 mm); 3. Lime mortar (20 mm) | <br>1. Cement mortar (20 mm); 2. Clay bricks (240 mm); 3. Reinforced concrete wall (50 mm); 4: Extruded polystyrene board (90 mm); 5. Cement mortar (20 mm) |
| Roof | <br>1. Lime mortar (20 mm); 2. Reinforced concrete slab (120 mm); 3: Lime mortar (20 mm); 4. Waterproof material (3 mm); 5. Lime mortar (20 mm) | <br>1. Cement mortar (20 mm); 2. Extruded polystyrene board (100 mm); 3. Reinforced concrete slab (30 mm); 4. Cement mortar (20 mm); 5. Reinforced concrete slab (120 mm); 6. Cement mortar (20 mm) |
| Window | Single glazing | Double glazing (6 + 12A + 6) |

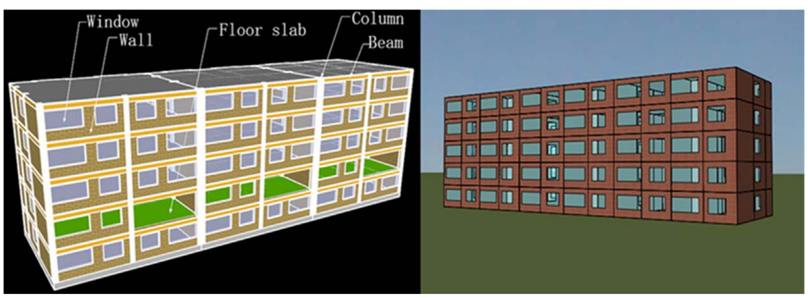



**Figure 3.** *Models of the retrofitted building in Revit (left) and IESVE (right).*

**Table 3.** *Materials utilization of retrofitting plan.*

| | | Added reinforced concrete wall | Added insulations of external walls | Added cement mortar of external walls | Added insulations of roof | Added reinforced concrete slab of roof | Added cement mortar of roof | Double glazing |
|---|---|---|---|---|---|---|---|---|
| Surface areas ($m^2$) | South | 482.4 | 482.4 | 482.4 | 511.5 | 511.5 | 511.5 | 216 |
| | North | 554.6 | 554.6 | 554.6 | | | | 175.5 |
| | East | 174.3 | 174.3 | 174.3 | | | | 13.5 |
| | West | 174.3 | 174.3 | 174.3 | | | | 13.5 |
| Thickness (m) | | 0.05 | 0.09 | 0.02 | 0.1 | 0.03 | 0.02 | 0.012 |
| Volume ($m^3$) | | 69.3 | 124.7 | 27.7 | 51.2 | 15.3 | 10.2 | 5.0 |
| Density ($kg/m^3$) | | 2500 | 29 | 1800 | 29 | 2500 | 1800 | 2500 |
| Mass (kg) | | 173200 | 3616.4 | 49881.6 | 1483.4 | 38250 | 18360 | 12500 |

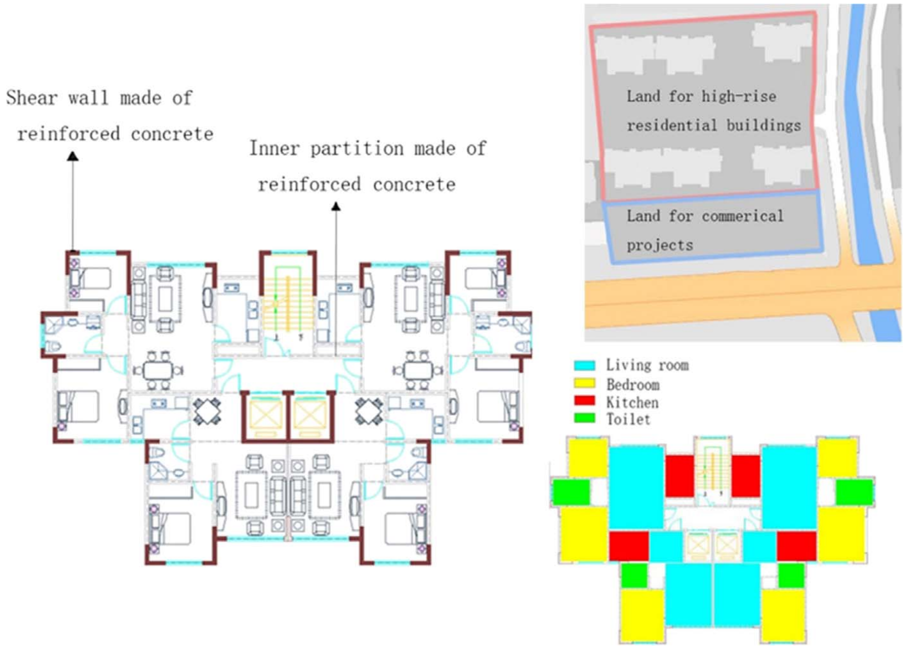



**Figure 4.** *The floor planning of the rebuilt high-rising residential buildings.*

**Table 4.** *Construction specifications of high-rising residential buildings.*

| Building fabrics | Construction specifications | |
|---|---|---|
| Wall | Shear wall | 1. Cement mortar (20 mm); 2. Reinforced concrete wall (200 mm); 3. Rock wool board (110 mm); 4. Cement mortar (20 mm) |
| | Block wall | 1. Cement mortar (20 mm); 2. Aerated concrete block (200 mm); 3. Rock wool board (110 mm); 4. Cement mortar (20 mm) |
| Roof | 1. Cement mortar (20 mm); 2. Reinforced concrete slab (120 mm); 3. Extruded polystyrene board (120 mm); 4. Cement mortar (20 mm) | |
| Windows | Double glazing (6 + 12A + 6) | |
| Inner partitions | 1. Cement mortar (20 mm); 2. Reinforced concrete wall (200 mm); 3. Cement mortar (20 mm) | |
| Floor slab | 1. Cement mortar (20 mm); 2. Reinforced concrete slab (100 mm); 3. Extruded polystyrene board (20 mm); 4. Cement mortar (20 mm) | |
| Ground floor | 1. Cement mortar (20 mm); 2. Reinforced concrete slab (120 mm); 3. Rock wool board (80 mm); 4. Cement mortar (20 mm) | |

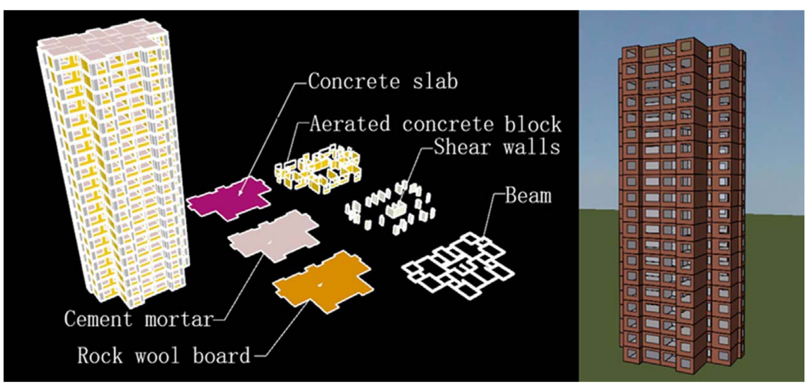



**Figure 5.** *Models of the rebuilt building in Revit (left) and IESVE (right).*

season was 191 $m^3$. Therefore, it can be estimated that the natural gas consumption for the heating demand was 159 $m^3$ per month, and the total gas consumption throughout the heating season was 795 $m^3$ for each family.

In July, August and September, the electricity consumption was much higher than that in other months and the average consumption was 421 kWh per month per family. In the other months, the consumption was 103 kWh for one family. Thus,

**Table 5.** *Quantity of materials utilization of rebuilding plan.*

| Building fabrics | Materials | Volume ($m^3$) | Density ($kg/m^3$) | Mass (kg) |
|---|---|---|---|---|
| Wall | Aerated concrete blocks | 1079 | 700 | 756000 |
| | Shear wall (reinforced concrete) | 546 | 2500 | 1365000 |
| | Cement mortar | 174 | 1800 | 313200 |
| Windows | Glass | 10.6 | 2500 | 26500 |
| Doors | Timber | 40.8 | 500 | 20400 |
| Ground floor | Cement mortar | 5.7 | 1800 | 10260 |
| | Rock wool board | 22.7 | 140 | 3178 |
| | Concrete slab | 34.07 | 2500 | 85175 |
| | Cement mortar | 5.7 | 1800 | 10260 |
| Floor slab | Cement mortar | 114 | 1800 | 205200 |
| | Extruded polystyrene board | 114 | 29 | 3306 |
| | Concrete slab | 566 | 2500 | 1415000 |
| | Cement mortar | 114 | 1800 | 205200 |
| External insulation and mortar | Cement mortar | 82 | 1800 | 147600 |
| | Rock wool board | 456 | 140 | 63840 |
| | Cement mortar | 82 | 1800 | 147600 |
| Roof | Cement mortar | 114 | 1800 | 205200 |
| | Concrete slab | 682 | 2500 | 1705000 |
| | Extruded polystyrene board | 680 | 29 | 19720 |
| | Cement mortar | 114 | 1800 | 205200 |

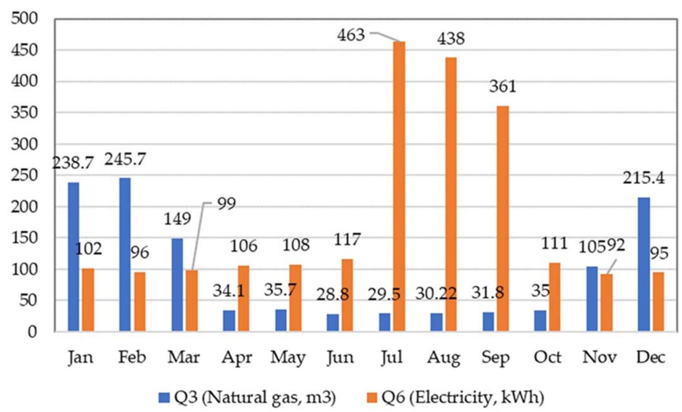



**Figure 6.** *Energy consumption currently for one family per month.*

each family normally consumes 318 kWh electricity per month in summer to cool their indoor environment and ∼954 kWh of electricity was consumed in total.

The Energy Department of China recommends that one cubic meter of natural gas consumption normally generates ∼10 kWh of electricity [25]. Thus, for the old residential buildings, the annual heating and cooling energy consumption levels in terms of electricity were 108.9 and 13.1 kWh/$m^2$, respectively. The carbon emissions can be estimated based on the carbon intensity of the energy source. According to the recommendation of the National Development and Reform Commission, the complete combustion of one cubic meter of natural gas usually generates 1.946 kg $CO_2$ emissions [26]. In the cold climate zone of China, the energy source of electricity production is coal. Additionally, the transfer coefficients between coal and electricity and the carbon intensity of coal are 0.323 and 3.67, respectively [27]. Therefore, the annual $CO_2$ emissions of the old residential building associated with the energy consumption for heating and cooling were estimated as 21.2 kg/$m^2$ and 10.4 kg/$m^2$, respectively.

## 5.2 Embodied energy consumption

Currently, very little data related to the energy intensity of construction materials are available in China [28, 29]. Thus, this study adopted the University of Bath's Inventory of Carbon and Energy (ICE) database to quantify the embodied energy consumption of the construction materials used in the retrofitted and rebuilt buildings. ICE is a comprehensive database that records over 1,700 materials and their embodied energy and carbon factors [30]. Therefore, many studies have used this database to estimate the embodied energy consumption of the construction materials in China [28]. Based on the material utilization in Tables 3 and 5 and the embodied factors provided by ICE, the embodied energy consumption and embodied carbon emissions of the retrofitted and rebuilt buildings were summarized in Tables 6 and 7, respectively. With an extended 40-year lifetime, the annual embodied energy consumption of the retrofitted building was 2.33 kWh/$m^2$, resulting in embodied $CO_2$ emissions of 0.17 kg/$m^2$. In contrast, the rebuilt building has a higher annually embodied energy consumption and embodied carbon emissions, with values of 13.5 kWh/$m^2$ and 1.48 kg/$m^2$, respectively.

## 5.3 Operation energy consumption

Based on the simulation results, the heating and cooling energy demands of the retrofitted and rebuilt buildings are summarized in Table 8. The retrofitted building consumed 74.7 kWh/$m^2$ of natural gas for heating and 10.4 kWh/$m^2$ of electricity for cooling. The rebuilt building has a lower heating energy consumption level than that of the retrofitted building, at 52.5 kWh/$m^2$. However,

**Table 6.** *Embodied energy consumption of the retrofitted building.*

| Retrofitted building (floor areas: 2190 m$^2$) | | | | |
|---|---|---|---|---|
| | Reinforced concrete | Extruded polystyrene board | Cement mortar | Glazing |
| Mass (kg) | 211450 | 5099.8 | 68241.6 | 12500 |
| Embodied energy coefficient (MJ/kg) | 1.11 | 88.6 | 1.4 | 15 |
| Embodied carbon intensity (Kg$CO_2$/kg) | 0.16 | 2.5 | 0.213 | 0.85 |
| Embodied energy consumption in total (MJ) | 234709.50 | 451842.28 | 95538.24 | 187500.00 |
| Embodied $CO_2$ emissions in total (kg) | 33832.00 | 12749.50 | 14535.46 | 10625.00 |
| Embodied energy consumption per square meter of floor area (kWh/m$^2$) | 22.58 | 43.48 | 9.19 | 18.04 |
| Embodied $CO_2$ emissions per square meter of floor area (kg/m$^2$) | 3.26 | 1.23 | 1.40 | 1.02 |
| Lifespan after retrofitting | 40 years | | | |
| Annually embodied energy in total (kWh/m$^2$·a) | 2.33 | | | |
| Annually embodied $CO_2$ emissions (kg/m$^{2\cdot}$·a) | 0.17 | | | |

**Table 7.** *Embodied energy consumption of the rebuilt building.*

| | Rebuilt building (floor areas: 4704m$^2$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Aerated concrete block | Reinforced concrete | Rock wool board | Timber | Extruded polystyrene board | Cement mortar | Glazing |
| Mass (kg) | 756000 | 4570175 | 67018 | 20400 | 23026 | 1449720 | 26500 |
| Embodied energy coefficient (MJ/kg) | 0.67 | 1.11 | 16.8 | 8.5 | 88.6 | 1.4 | 15 |
| Embodied carbon intensity (Kg$CO_2$/kg) | 0.06 | 0.16 | 1.05 | 0.46 | 2.5 | 0.213 | 0.85 |
| Embodied energy consumption in total (MJ) | 506520 | 5072894.25 | 1125902.4 | 173400 | 2040103.6 | 2029608 | 397500 |
| Embodied $CO_2$ emissions in total (kg) | 45360 | 731228 | 70368.9 | 9384 | 57565 | 308790.4 | 22525 |
| Embodied energy consumption per square meter of floor area (kWh/m$^2$) | 30.15 | 301.96 | 67.02 | 10.32 | 121.43 | 120.81 | 23.66 |
| Embodied $CO_2$ emissions per square meter of floor area (kg/m$^2$) | 2.70 | 43.53 | 4.19 | 0.56 | 3.43 | 18.38 | 1.34 |
| Lifespan | 50 years | | | | | | |
| Annually embodied energy in total (kWh/m$^2$·a) | 13.5 | | | | | | |
| Annually embodied $CO_2$ emissions (kg/m$^2$··a) | 1.48 | | | | | | |

the cooling energy consumption level of the rebuilt building was slightly higher than that of retrofitted building, at 11.3 kWh/m$^2$. In total, the retrofitted building consumed 21.3 kWh/m$^2$ more energy than the rebuilt building, leading to slightly higher $CO_2$ emissions (17.2 kg/m$^2$ to 16.2 kg/m$^2$).

# 6 ANALYSIS AND DISCUSSION

## 6.1 Energy consumption for heating and cooling

Figure 7 shows a comparison of the energy consumption levels for heating and cooling between the current old building and the retrofitted and rebuilt buildings. It is clear that the retrofitting measures have considerably decreased the annual heating energy consumption from 108.9 to 74.7 kWh/m$^2$. The annual cooling energy consumption was also decreased by 2.7 kWh/m$^2$. In the rebuilt building, the heating energy consumption was further decreased by 22 kWh/m$^2$ based on the level of the retrofitted building. However, the annual cooling energy consumption of the rebuilt building was 1 kWh/m$^2$ higher than the level of the retrofitted building. There is no doubt that both the retrofitted and rebuilt buildings attain a notably reduced the energy consumption for heating and cooling, mainly due to the thick external insulation and energy-efficient double-glazing windows. As Figure 8 shows, the retrofitted and rebuilt buildings realize lower U-values than the existing building for the external walls, roofs and external windows. It should also be emphasized that the lowest U-values

**Table 8.** *Operation energy consumption of the retrofitted building and the rebuilt building.*

| Months | Retrofitted building | | Rebuilt building | |
|---|---|---|---|---|
| | Heating energy consumption (MWh) | Cooling energy consumption (MWh) | Heating energy consumption (MWh) | Cooling energy consumption (MWh) |
| Jan 01–31 | 51.9432 | 0 | 81.0563 | 0 |
| Feb 01–28 | 36.9162 | 0 | 55.9423 | 0 |
| Mar 01–31 | 10.2075 | 0 | 13.8174 | 0 |
| Apr 01–30 | 0 | 0 | 0 | 0 |
| May 01–31 | 0 | 0 | 0 | 0 |
| Jun 01–30 | 0 | 0 | 0 | 0 |
| Jul 01–31 | 0 | 9.3036 | 0 | 19.8724 |
| Aug 01–31 | 0 | 8.1981 | 0 | 19.5357 |
| Sept 01–30 | 0 | 5.2515 | 0 | 13.7659 |
| Oct 01–31 | 0 | 0 | 0 | 0 |
| Nov 01–30 | 17.0937 | 0 | 21.8449 | 0 |
| Dec 01–31 | 47.4999 | 0 | 74.131 | 0 |
| Summed total | 163.6605 | 22.7529 | 246.7918 | 53.1739 |
| Annually Energy consumption per square meter of floor area (kWh/m$^2$) | 74.7 | 10.4 | 52.5 | 11.3 |
| Annually $CO_2$ emissions per square meter of floor area (kg/m$^{2\cdot}$) | 12.1 | 4.1 | 11.3 | 5.9 |
| Annually Energy consumption per square meter of floor area in total (kWh/m$^2$) | 85.1 | | 63.8 | |
| Annually $CO_2$ emissions per square meter of floor area in total (kg/m$^{2\cdot}$) | 16.2 | | 17.2 | |

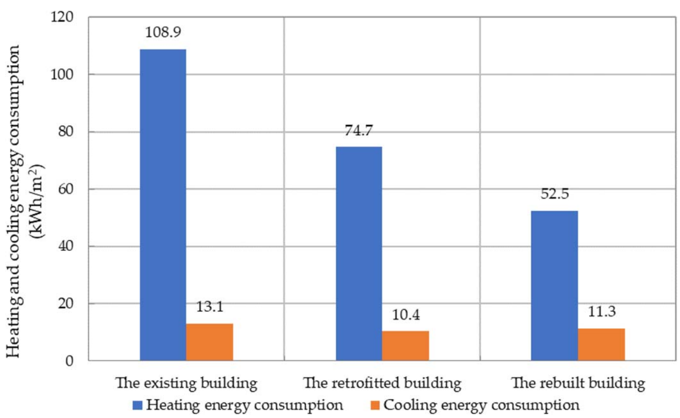



**Figure 7.** *Energy consumption for heating and cooling.*

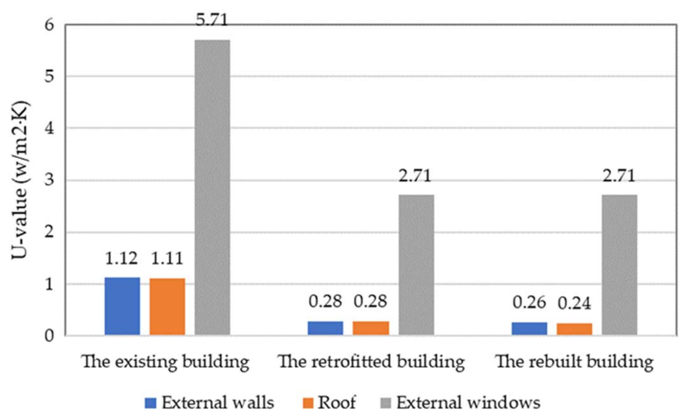



**Figure 8.** *U-values of main building fabrics.*

for the walls and roof of the rebuilt building were attributed not only to the thicker insulation applied to the external walls and roof, but also to the lower thermal conductivity of the aerated concrete blocks (compared to the clay bricks).

The rebuilt building, on the other hand, consumes significantly more cooling energy than the retrofitted building, despite having the lowest U-values for the external walls and roof. This phenomenon might be explained by the ratios of the external glazing windows. Figure 9 shows that the rebuilt building has a higher ratio in the south façade than that of the retrofitted building (0.33 vs 0.31), which might lead to greater solar heat gains in summer. As a result, the rebuilt building requires more energy for cooling to reach the same thermal comfort level as the retrofitted building.

## 6.2 Embodied energy consumption

As Figure 10 shows, the high material input of the rebuilt building led to an embodied energy consumption that was 6 times that of the retrofitted building (13.51 vs 2.33 kWh/m$^2$·a). For example, the insulating material for the external walls of the retrofitted building (extruded polystyrene board) has a much higher embodied energy coefficient than the materials used in the rebuilt building (rock wool board) (88.6 vs 16.8 MJ/kg). However, the rock wool board consumption in the rebuilt building was 13 times that of the extruded polystyrene board in the retrofitted building (in terms of the weight), which led to an embodied energy consumption of the rock wool board that was 5.5 times that of the extruded polystyrene board in the retrofitted building.

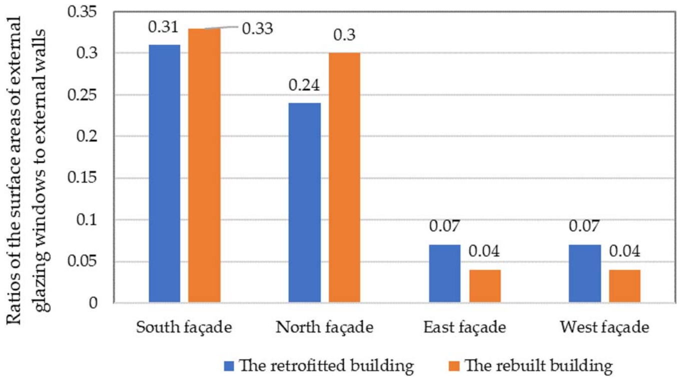



**Figure 9.** *Ratios of surface areas of external glazing windows to external walls.*

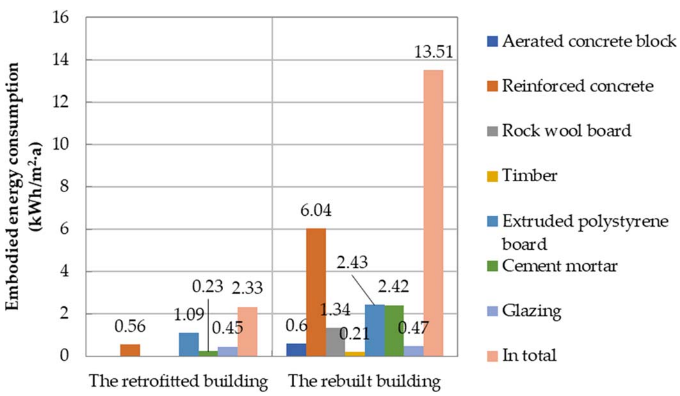



**Figure 10.** *Embodied energy consumption.*

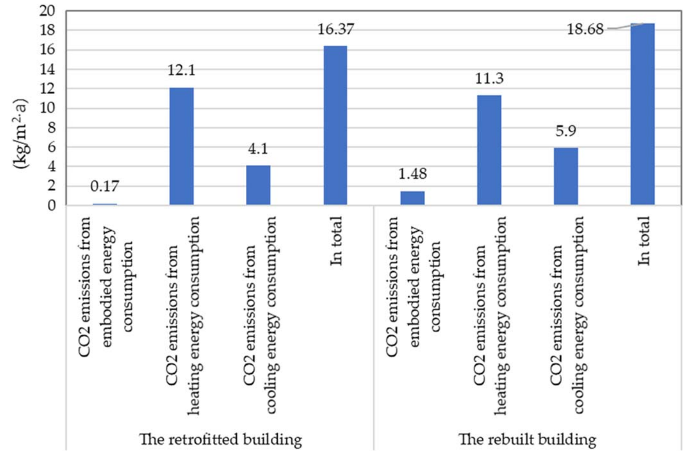



**Figure 11.** *$CO_2$ emissions of the retrofitted building and the rebuilt building.*

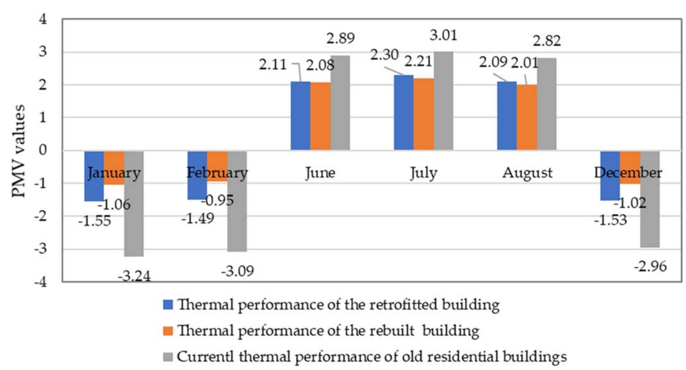



**Figure 12.** *The simulation results of average PMV values.*

Therefore, it is clear that the embodied energy coefficient is not the sole parameter that affects the embodied energy consumption, and the quantity of material input might be a more important determinant.

## 6.3 $CO_2$ emissions

Figure 11 shows the $CO_2$ emissions of the retrofitted and rebuilt buildings. Owing to the high material input in the construction phase, $CO_2$ emissions from the embodied energy consumption of the rebuilt building were approximately 9 times those from the embodied energy consumption of the retrofitted building. Additionally, the retrofitted building emitted only 0.8 kg/m$^2$ more $CO_2$ annually than the rebuilt building, even though it consumed 22.2 kWh/m$^2$ more heating energy. In contrast, the rebuilt building achieved an increase in annual $CO_2$ emissions of 1.8 kg/m$^2$ due to the lower by 1 kWh/m$^2$ energy input for the cooling demand. This difference can be explained by the different carbon intensities of the energy sources for heating and cooling energy consumption. The energy source for the heating demand is natural gas, and its carbon intensity is 0.4484 kg/kg [31]. However, the energy source for the cooling demand is coal because electricity is normally generated by the combustion of coal in North China. Moreover, the carbon intensity of coal is 0.7559 kg/kg [31], which is 1.7 times that of natural gas and resulting in higher $CO_2$ emissions.

Thus, due to the higher carbon intensity of the cooling energy source and the very high material input for the construction, the rebuilt building emitted more $CO_2$ than the retrofitted building in total.

## 6.4 Indoor thermal comfort

Figure 12 shows the simulation results of the indoor thermal performances. The PMV values of the old residential buildings ranged from −3.24 to −2.96, indicating a considerably uncomfortable indoor environment. The retrofitted building performed better than the existing residential buildings as the PMV values increased to approximately −1.50. The rebuilt building performed the best, and particularly in February, the PMV value was −0.95, within the acceptable range of the thermal performance.

In summer, all the PMV values were notably higher than 1, indicating a hot indoor environment. The old residential building attains the worst performance, with the PMV values ranging from 2.82 to 3.01. The retrofitted building and rebuilt building performed similar, as the PMV values approached 2.13 on average. The retrofitted building and the rebuilt building substantially improved the thermal performance based on the level of the old residential building due to the updated construction specifications (added insulation and replacement of the external windows). However, the identical output of the retrofitted building and rebuilt building in the IES simulations can be explained by the continuously opened windows, as more air can be exchanged with the ambient environment.

In winter, the improvement of the thermal performance from the old residential building to the retrofitted and rebuilt buildings could be attributed to the added insulation to the external walls and roofs and the replacement of the external windows.

## 7 CONCLUSION

This study investigated the energy currently consumed by the residential buildings built between the 1970s and the 1990s. Additionally, the environmental impacts of retrofitting and rebuilding plans were analyzed. The following points summarize the main findings of this research:

- The rebuilt buildings normally attain a notably higher embodied energy consumption and embodied $CO_2$ emissions due to the high material input. Therefore, government managers should consider the material embodied energy consumption and carbon emissions when formulating decisions regarding the future of old residential buildings.
- The insulation thickness is an important parameter for the main building fabrics of retrofitted and rebuilt buildings to achieve low $U$-values. Subsequently, the heating and cooling energy demands can be reduced. However, the ratios of the surface areas of the glazing windows to the external walls should also be minimized to avoid increasing the operation energy consumption in the rebuilt buildings.
- From an ecology point of view, rebuilding old residential buildings might not be the highest priority. This study has identified that the rebuilt buildings cause higher $CO_2$ emissions than retrofitted buildings. Various parameters, such as the material embodied coefficient, carbon intensity of the operation energy sources and the ratio of the surface area of the glazing windows to the external walls should be considered by decision-makers.

This study only selected one case study residential building and evaluated the ecological impacts of one rebuilding plan and one retrofitting plan. In the future work, comparative research should be conducted on more types of residential buildings in different climate areas. Moreover, the environmental impacts of renewable energy systems, such as heat pumps, photovoltaics and wind turbines, should be considered for the rebuilding and retrofitting plans.

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## CONFLICTS OF INTEREST

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.

## AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Dr. Zhen Peng. The first draft of the manuscript was written by Dr. Zhen Peng and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

## REFERENCES

[1] United Nations Environment Programme. Global Status Report for Buildings and Construction: towards a zero-emission, efficient and resilient buildings and construction sector, 2020. Nairobi, 2020.

[2] Sga B, Da YA, Shan HA, Yang ZA. Modelling building energy consumption in China under different future scenarios. *Energy* 2021;**214**. https://doi.org/10.1016/j.energy.2020.119063.

[3] CNSB. 2019. *China Statistical Yearbook*. Beijing: China Statistical Press.

[4] Hu R, Zhou Y. 2018. *Principles of Residential Building Design*3rd edn. Beijing, China: China Architecture & Building Press.

[5] Yang X. Study on the habitability transformation and utilization of urban multi-storey residential buildings. *Dissertation*. Chang'an University 2019.

[6] Deng W, Xie J, Peng Z. Material transitions and associated embodied energy input of rural buildings: case study of Qinyong Village in Ningbo China. *Sustainability* 2018;**10**:2016. https://doi.org/10.3390/su10062016.

[7] Peng Z, Deng W, Hong Y. Materials consumption, indoor thermal comfort and associated energy flows of urban residential buildings. *Int J Build Pathol Adapt* 2019;**37**:579–96.

[8] China Coal Information Institute. 2015. *China Statistic Yearbook of Coal Industry*. Beijing: Coal Industry Press.

[9] Zhiyan Consulting Group. 2018. *China Aerated Concrete Block Industry Market Analysis, Forecast and Investment Prospect Analysis Report, 2018–2024*. Beijing: Zhiyan Consultation. 1–117.

[10] Chinese Academy of Building Sciences. 2018. *Design Standard for Energy Efficiency of Residential Buidings in Severe Cold and Cold Areas*. China Construction Industry Press.

[11] Beijing Institute of Architectural Design (Group) Co., Ltd. 2018. *Design Standard for Energy Efficiency of Residential Buildings*. China Construction Industry Press.

[12] Alwan Z, Nawarathna A, Ayman R *et al.* Framework for parametric assessment of operational and embodied energy impacts utilizing BIM. *J Build Eng* 2021;**1**:102768.

[13] ASHRAE. 2010. *ASHRAE Standard 55-010 Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[14] Taylor P, Fuller R, Luther M. Energy use and thermal comfort in a rammed earth office building. *Energy Build* 2008;**40**:793–800.

[15] Wagner A, Gossauer E, Moosmann C *et al.* Thermal comfort and workplace occupant satisfaction—results of field studies in German low energy office buildings. *Energy Build* 2007;**39**:758–69.

[16] Djongyang N, Tchinda R, Njomo D. Thermal comfort: a review paper. *Renew Sust Energ Rev* 2010;**14**:2626–40.

[17] Ji W, Zhu Y, Cao B. Development of the predicted thermal sensation (PTS) model using the ASHRAE global thermal comfort database. *Energy Build* 2020;**211**:109780. https://doi.org/10.1016/j.enbuild.2020.109780.

[18] Fanger P. 1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering*. McGraw-Hill, New York, NY. 1–244.

[19] Humphreys MA, Nicol JF, Raja IA. Field studies of indoor thermal comfort and the progress of the adaptive approach. *Adv Build Energy Res* 2007;**1**:55–88.

[20] Nicol J, Humphreys M. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings* 2002;**34**:563–72.

[21] Attia S, Beltrán L, Herde A, Hensen J. 2009. Architect friendly: a comparison of ten different building performance simulation tools. In *Eleventh International IBPSA Conference Glasgow: Building Simulation*. 1–8.

[22] Hamza N. Double versus single skin facades in hot arid areas. *Energy Build* 2008;**40**:240–8.

[23] Chinnayeluka S. Performance Assessment of Innovative Framing Systems through Building Information Modelling Based Energy Simulation. Master. B.E: Osmania University, 2011.

[24] Attia S, De Herde A. 2011. Early design simulation tools for net zero energy buildings: a comparison of ten tools [online]. In *Building Simulation*. Sydney. 204–11 http://ibpsa.org/proceedings/BS2011/P_1148.pdf (27 February 2019, date last accessed).

[25] Yafei Zhang WX, Li J. Current situation and analysis of natural gas power generation in China. *Dongfang Electric Review* 2021;**02**:38–40.

[26] NBS and NDRC. 2016. *China Energy Statistics Yearbook*. NBS and NDRC, Beijing. Table 1-10 and Table 4-14.

[27] China Electric Power Enterprise Association. *China Electric Power Development Report*. China Electric Power Enterprise Association, Beijing. 2016. 25–70.

[28] Deng W, Prasad D, Osmond P, Li FT. Quantifying life cycle energy and carbon footprints of China's residential small district. *J Green Build* 2011;**6**:96–111.

[29] Fridley DG, Zheng N, Zhou N. 2008. *Estimating Total Energy Consumption and Emissions of China's Commercial and Office Buildings*. Lawrence Berkeley National Laboratory: Berkeley, CA, USA.

[30] Hammond G, Jones C. 2008. *Inventory of Carbon & Energy, Sustainable Energy Research Team*. Bath Avon: Department of Mechanical Engineering, University of Bath.

[31] Zhao M, Zhang W, Yu L. Carbon emission analysis of energy consumption in Shanghai. *Res Environ Sci* 2019;**22**:985–9.