energies

Article

Assessing the Energy Performance and Retrofit Potential of the 1980–1990s' Residential Building Stock in China's Jiangsu Province: A Simulation-Based Study

Xi Chen [1,*], Marco Cimillo [1,*], David Chow [2] and Bing Chen [3]

[1] Department of Architecture, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China
[2] School of Architecture, University of Liverpool, Liverpool L69 3BX, UK; david.chow@liverpool.ac.uk
[3] Department of Urban Planning and Design, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China; bing.chen@xjtlu.edu.cn
* Correspondence: xi.chen1704@xjtlu.edu.cn (X.C.); marco.cimillo@xjtlu.edu.cn (M.C.)

Abstract: The building operation sector in China represents 22% of the national energy consumption and 22% of the carbon emission, of which urban residential buildings accounted for 24% in 2019. Such figures for the housing sector are projected to increase sharply in the near future, while China aims to peak CO_2 emissions by 2030 and reach neutrality before 2060. To reduce the impacts of the urban housing sector and address the energy use and waste generated by large-scale demolition and reconstruction, the central government started promoting the energy retrofit of urban residential buildings, raising such policies to the national strategic level. Jiangsu Province is one of the most urbanised, with a rapid growth in the energy consumption of residential buildings. The Multi-Danyuan and Single-Danyuan Apartment built in 1980–1999 are the most representative residential types in its urban areas. While still adequate functionally, they were designed and built to low energy standards and show significant potential for energy retrofit. Nonetheless, their current performance and energy-saving potential are under-researched, while more detailed and reliable data would be critical to support retrofit design and policy making. This study investigates and characterises the typical use and energy performance of the two building types. Additionally, seven measures and six retrofit scenarios were identified based on the optimal energy reductions and regulations from selected countries. The simulations indicate that, without intervention, the energy consumption of the typical urban residential buildings can reach 122 kWh/m^2 under the typical high-energy user scenario. By selecting a set of effective energy-saving measures, the operational energy use for heating and cooling can be reduced by up to 52.4%. Current local standards prove cost-efficient, although less effective in reducing energy use compared to international best practices, indicating potential improvements to the contribution of building retrofit towards achieving the national carbon reduction goals.

Keywords: energy retrofit; residential building stock; building energy simulation; carbon peak; carbon neutrality; China's hot summer–cold winter zone

Citation: Chen, X.; Cimillo, M.; Chow, D.; Chen, B. Assessing the Energy Performance and Retrofit Potential of the 1980–1990s' Residential Building Stock in China's Jiangsu Province: A Simulation-Based Study. *Energies* **2024**, *17*, 1260. https://doi.org/10.3390/en17051260

Academic Editors: Massimiliano Manfren, Maurizio Sibilla and Esra Kurul

Received: 31 December 2023
Revised: 25 February 2024
Accepted: 1 March 2024
Published: 6 March 2024

1. Introduction

The International Energy Agency (IEA) reported in 2021 that the building construction and operation sectors accounted globally for the most significant shares of the total final energy use in 2020, namely 37% of energy and process-related carbon dioxide (CO_2) emissions [1]. Residential building operations alone represent 22% of the final energy use and 17% of the energy-related CO_2 emissions [1]. While the total global energy demand fell by 1% in 2020 due to the pandemic, the changes in the energy usage patterns caused an increase in the building sector in the same period. The pandemic also caused a decline in the construction of new buildings, which resulted in a 10% drop in total carbon emissions in 2020 [1]. According to the Statistical Review of World Energy 2021, China contributed

26.1% of the total global energy consumption in 2020, making China the largest energy-consuming country in the world [2]. Tsinghua University Building Energy Research Center (THUBERC) calculated that the building construction and operation sectors combined used 33% of the total national energy consumption in 2019, including 11% from the building construction sector and 22% from the building operation sector [3]. The shares of carbon emissions from the building construction and operation sectors were 16% and 22% of the national total, totalling 38% [3]. The energy consumption and carbon emissions from the building operation sector, each accounting for 32% of the total, rank second only to the industry sector [3]. Therefore, the building operation sector is a significant part of China's national macro goals for energy conservation and emission reduction.

China's dynamics have also been characterised by a fast development of the economy and a substantial improvement in people's living standards, resulting in higher requirements for the indoor living environment and increasing demands for domestic energy use. In addition, rapid urbanisation led to unprecedented growth in the total building floor area, aggravating energy use and carbon emissions. At the 75th session of the United Nations General Assembly in September 2020, the country announced that it would aim to peak CO_2 emissions by 2030 and reach carbon neutrality before 2060 [4]. Although the building construction and operation section will necessarily be required to play a key role, there are no specific energy consumption and carbon emission targets. Comprehensive and systematic studies on the energy consumption and carbon emission control targets for the building sector seem insufficient, and the demand for viable targets on the overall consumption of energy use and carbon emissions is impending.

The urban residential sector is identified as one of the most rapidly developing and most significant energy-consuming segments of the building sector. The total floor area of civil buildings in China reached 64.4 billion m^2 by the end of 2019, 43.8% of which was concentrated in the urban areas. Different studies predict a peak between 2030 at 35 billion m^2 [3], and 2040 at 38.4 billion m^2 [5], and then a gradual reduction to 33.2 billion m^2 in 2060.

At the same time, the energy consumption of the construction of urban residential buildings in China took the most significant proportion (69%) of total energy use in the construction of city buildings in 2019 [3]. As for the energy consumption of building operations, in 2019, the urban residential building sector represented around 24% of the total civil buildings (including urban residential, rural residential, public buildings and central-heated buildings in northern China). Moreover, the average energy intensity of urban residential households increased quickly, at an average rate of 8% in the past twenty years [3]. In particular, the energy use for winter heating in the urban housing in the hot summer–cold winter zone (HSCW zone) increased at an average annual rate of 15–21% in the past twenty years and should be at the centre of the strategy for the reduction of urban residential energy use and emissions. Various institutes have different prediction models for future energy consumption and carbon emissions situations in the building construction and operation sector. It is projected that China's energy consumption in the building sector may double or triple in the next five to ten years, and the carbon emissions in the building sector will increase by 20% to 100% [5].

Jiangsu Province is one of the most urbanised regions in the southeast China. The total urban residential area accounts for almost 9% of the national total, with over 38% of the existing urban residential buildings being built before 2000 [6], when the local energy efficiency design standards were not mandatorily implemented, determining rather poor thermal performance of building envelope [7–10]. The statistics also indicate that the majority of the existing residential buildings in urban Jiangsu feature brick and reinforced concrete structures with no insulation layers. These are also the most commonly found in buildings constructed in the 1980s and 1990s [11]. Previous studies found that the indoor temperature in winter ranged between 6 to 20 °C, with an average of 13.9 °C, while the summer temperature could be very close to the outdoor air temperature [12]. Moreover, the minimum indoor temperature of urban housing can be as low as 1.5 °C in winter and reach 38.7 °C in summer without air conditioning systems [3], which poses risks to occupants' health and increases the potential energy use for space heating and cooling. The bursting demand for a better indoor thermal environment in fact increased energy use for distributed space heating and cooling facilities. The energy consumption for air conditioning has shown a trend of exponential growth since 2001 in the HSCW zone. The electricity use in 2019 on space heating in winter was 4.5 times that of 2001 [3], showing a continuously growing trend. China Association of Building Energy Efficiency (CABEE) reported that, compared with other provinces in China, the energy consumption and carbon emissions of Jiangsu Province rank fifth and sixth nationally, only lower than some of the heavy-industry provinces [13]. The energy conservation and carbon emissions reduction in Jiangsu Province bear national and international significance.

Although the national government has devoted substantial effort to building energy efficiency and conservation research and achieved satisfactory general results, the implementation of urban residential retrofit work did not meet expectations by 2020. The average annual retrofitted area was 200 million m^2 from 2011 to 2015 but dropped sharply by 74% from 2016 to 2020, with an average reduction of 52.45 million m^2 per year due to the lack of State financial subsidy [5]. As a result of the pandemic, retrofit activities have been essentially stagnant since 2020. The progress of urban residential retrofit in HSCW was even more unpromising. To respond to the national energy conservation and carbon emissions reduction strategy, Jiangsu Province also promoted the old urban residential retrofit from 2016 to 2020. A national-focused residential retrofit plan started in 2017. By the end of 2020, the average retrofit area was 60 million m^2 per year, just slightly higher than the annual average retrofit area of the cold and severe cold zone [14]. However, rather than focusing on energy, the primary retrofit strategies have focused on updating the ageing facilities, improving the community living environment, improving fire safety, and upgrading the general infrastructure.

The energy retrofit of the urban residential building stocks is regarded as a high-potential strategy for energy efficiency and carbon mitigation. However, the implementation of urban retrofit seems inadequate, and the anticipated results are yet to be achieved [5]. The obstacles to promoting urban residential retrofit have been widely discussed and researched. On the one hand, previous research indicated that the current regulations were not sufficiently developed to meet the changing needs of rapid urbanisation and that the national-level guidelines do not address specific needs at regional or local levels. Many researchers also point out issues such as inconsistent definitions or content overlap among different standards and the difficulty of adapting to the evolving forms and functions of housing, with revisions to regulations often being delayed [15–20]. On the other hand, specific operational guidelines and technical support are required, especially considering the carbon peak and neutrality targets and the potential aggravation determined by climate change. Some pilot-retrofit projects also pointed out that lacking records of building construction information, building drawings, and measured data posed additional challenges for the building performance assessment in preparation for effective retrofit strategies [21]. In addition, the financial support and funding provided by the government are insufficient to support large-scale or in-depth urban housing renovation.

Blueprints for future developments are offered by developed countries where research on the energy retrofit of residential buildings started earlier, resulting in today's well-established laws, regulations, and standards. Examples include the United States' ASHRAE and LEED systems for building retrofit and maintenance, the UK's BREEAM system for residential retrofit, Germany's EnerPHit standards for building energy retrofit, and the specifications in Japan's CASBEE [22,23]. The objectives related to residential energy retrofit have evolved from the promotion of basic energy-saving measures to more ambitious performance standards, such as net-zero energy buildings and active energy-producing buildings. The transition involved establishing detailed energy models to quantitatively assess the potential energy consumption in different scenarios [24–27].

To extend the scope of building simulation at the stock level, the building typology approach has been proven feasible and effective in the past few decades with national, regional, or municipal scopes, with advanced developments, particularly in European countries, including key projects like TABULA (2009–2012) and EPISCOPE (2013–2016). Applications to residential building stocks enable systematic research on energy use for space conditioning and hot water systems of both existing and newly built buildings. The representative building types, complemented with the national statistics on building stocks, can be used for developing bottom–up models of the national residential building sector for predicting energy consumption [28]. Apart from the TABULA project, which sets a pretty comprehensive framework for cross-country comparisons of different indexes, including building features, measures and energy performance, many researchers also used similar research approaches to classify existing building types and further analyse and predict the energy consumption and successfully quantified the predicted energy use of the residential buildings [29–37].

In China, research in this area started relatively late and has only received sufficient attention in recent years. Additionally, more emphasis has been placed on energy retrofit in northern China, with limited attention given to Jiangsu Province [38,39], where studies are in the early stages. They often focus on individual energy-saving measures, while more systematic quantitative analyses of energy performance or improvements in thermal comfort were not commonly undertaken [7,8,40,41], and have focused on public structures such as offices and industrial heritage buildings [42,43]. Tsang developed a comprehensive building energy model for residential retrofit in the HSCW zone, covering multiple areas. However, it only included one city in Jiangsu Province, and the selection of typical Jiangsu residential building types and climate differences between the northern and southern parts of Jiangsu Province was not taken into account [44].

Similarly, research at the residential building stock scale developed later, is less comprehensive and systematic, and not always intended for practical applications. Initially, most Chinese scholars researching urban architectural typology investigated aspects such as historical background, urban population, and family morphology, exploring topics related to social development and historical changes [11,45–47]. Some energy-related studies on building types analysed residential or public buildings in north- and southwest China [48,49], and a few studies chose to focus on one typical residential building in hot summer and cold winter areas [50,51]. Gui has developed a housing typology system for the HSCW zone with relevant parameters [52]; however, it does not specifically address the existing building stock requiring retrofit, and the selected city has a different climate from Jiangsu Province.

In summary, two main gaps emerged from the review of the existing literature: (1) The classification of Jiangsu urban residential building types is still generic and lacks of a systematic database, which would allow more informed and targeted decision and policy making; (2) there is limited research on the retrofit of existing residential stock in Jiangsu Province, and a lack of energy models and quantitative studies to assess the energy-saving potential specifically to different climates and building types.

This study addresses these gaps by conducting a literature review and on-site investigation of the existing residential stock in urban areas of Jiangsu Province, selecting representative building types, and conducting detailed surveys and documentation of the physical performance, energy usage, user behaviour patterns, and other relevant parameters for studying energy performance, possible retrofit measures, and related energy-saving potential. The data informed the development of a detailed energy model, with simulations conducted in the two normative climate zones of the province: the HSCW Zone, covering the vast majority of its territory, and the Cold Zone, occupying the northernmost areas. More in particular, the research focused on the most substantial part of the stock constructed between 1980 and 1999, still adequate functionally but designed and built to low energy standards, and therefore with a significant potential for retrofit. Individual measures and aggregate scenarios were selected and built based on the current literature and on the most consolidated international benchmarks.

2. Materials and Methods

2.1. Bottom–Up Energy Modelling and Simulation

This paper posits that bottom–up building energy models are a reliable and effective way to investigate energy demand under different conditions [53]. Therefore, the study adopts this approach to explore the predictions of building energy consumption and carbon at the current status and the potential of energy retrofit measures. Developing a detailed building energy model of representative residential building types in Jiangsu Province also lays the foundation for future studies with potentially broader and more articulated building stock models. The method has seen numerous developments worldwide in the residential building sector since the 1990s [53–61]. China counts several applications since 2000, but mainly concerned with the northern regions or with specific buildings, and with insufficient consideration of future climate scenarios [12,44,59,62–64].

For this research, the individual building types are modelled and simulated using DesignBuilder, EnergyPlus, and jEPlus. EnergyPlus is one of the most commonly used whole-building energy simulation programs and has undergone extensive validation [65–67]. DesignBuilder is a user graphical interface specially developed for EnergyPlus, and incorporating all building construction, activities, opening, lighting, and HVAC input sections, as well as a vast database including, among others, building and structural materials, lighting units, windows and aerated glass, curtains, and shading. jEPlus_v2.1.0 is used to simplify and support the parametrical simulation process. jEPlus is able to assist in setting up parametric runs with EnergyPlus models and to perform large sets of simulations in "parallel" mode [68]. It can simplify the process of inputting model parameters, make the process more time-efficient, and reduce the probability of operational errors and repetitive work to the minimum extent.

The climate files for the simulations were retrieved from SWERA and CSWD databases through the EnergyPlus website. They include the cities of Suzhou and Xuzhou as representative of southern (HSCW) and northern (Cold) regions. Given the distinctive characteristics and requirements in the two zones, the respective residential energy demands will be discussed separately.

2.2. Building Carbon Emission Calculation Method

In 2021, the Ministry of Housing and Urban-Rural Development (MOHURD) issued the National standard "General Code for Energy Efficiency and Utilization of Renewable Energy application in Buildings GB 55015-2021", which came into force on 1 April 2022 [69], as the prescribed method for the calculation of building carbon emission. The emissions of the two building types under different scenarios are estimated according to this standard for the operational energy. Although its results may not be entirely accurate in absolute terms due to the assumptions in the input data, it allows a useful comparative analysis of different retrofit and climate scenarios. Carbon emission is calculated as follows:

$$C_M = \frac{\left[\sum_{i=1}^{n}(E_i EF_i) - C_p\right]y}{A^-}, \quad (1)$$

$$E_i \sum_{j=1}^{n}(E_i, j - ER_i, j), \quad (2)$$

where: C_M: Carbon emission per unit building area for building operation ($kgCO_2/m^2$); E_i: Annual Type i energy consumption in buildings (unit/a); EF_i: Carbon emission factor of Type i energy; $E_{i,j}$: Class i energy consumption of class j systems; $ER_{i,j}$: Type j systems consumption of Type i energy provided by renewable energy systems (units/a); i: Type of terminal energy consumed by the building; j: Building energy system; C_p: Annual carbon reduction by carbon sink system of building green space; y: Designed lifespan of the building; and A: building area (m^2).

As for the carbon emission factor of electricity in China, various authorities have provided inconsistent definitions, and Yin highlights that the carbon emission of China's electricity varies according to the local power generation mix [70]. By analysing the power generation technology of the East China regional power grid where Jiangsu Province is located, he calculated that the carbon emission factor of Jiangsu Province should be 0.6826. This value is adopted for the calculations in this subsection. This research does not include renewable energy generation and the carbon sink systems.

2.3. Retrofit Measure Selection

The retrofit measures simulated in this study were chosen based on previous research and existing standards, regulations, and construction guidebooks, including the 'Technical guide for Green Renovation of existing residential buildings' and the 'Technical Specification for energy efficiency retrofitting of existing residential buildings' [3,10,40,41,44,71–78].

Li concluded that improving wall insulation should be the priority for retrofitting [72], while other researchers emphasised improving roof insulation [79–81] or window components [8,72,82]. Several studies tested the impacts of adding window shading devices, arguing that a certain depth of overhang shading has a significant effect on reducing cooling demands in the HSCW zone, while the effect of adjustable shadings largely depends on the occupants' preferences and control patterns [8,72,83,84]. Enclosing open staircases was also recognised as one of the most cost-effective measures to improve indoor thermal performance and reduce energy demands [8,10,85].

Prioritising the criteria of applicability, operability effectiveness in reducing energy use, the following seven measures were selected: adding external insulation; adding roof insulation; window upgrading (including double-glazed and triple-glazed windows); air tightness improvement; changing external wall reflective paint/coating; adding external window overhang; and enclosing the currently open staircases.

Each is tested in up to three variations with different impacts on energy use (Table 1). The incremental improvement of each variation is determined so that compliance with different standards can be achieved by materials and components commercially available in the province. This resulted in 21 basic configurations and 1536 combinations under one climate context and one energy-user scenario for one city. EnergyPlus was used to set up the basic configurations, and jEPlus to process all resulting combinations to be run in parallel simulations.

Table 1. Input configurations and code names of pre-retrofit and retrofit measures.

Retrofit Component	Code Name	Configuration	Properties
wall	pre-wall	no insulation (original)	U-value: 1.951 W/m^2K
	WallSce_1	EPS 30 mm	U-value: 0.695 W/m^2K
	WallSce_2	EPS 60 mm	U-value: 0.440 W/m^2K
	WallSce_3	EPS 90 mm	U-value: 0.322 W/m^2K
roof	pre-roof	no insulation (original)	U-value: 3.231 W/m^2K
	RoofSce_1	XPS 30 mm	U-value: 0.598 W/m^2K
	RoofSce_2	XPS 60 mm	U-value: 0.383 W/m^2K
	RoofSce_3	XPS 90 mm	U-value: 0.282 W/m^2K
window	Win Single	single glazing + Aluminum window frame without thermal break (original)	U-value: 5.9 W/m^2K, SHGC: 0.75
	Win Dbl	double glazing-Argon gas + Aluminum window frame with thermal break	U-value: 2.9 W/m^2K, SHGC: 0.67
	Win_Dbl low-E	double low-E glazing-Argon gas + UPVC window frame	U-value: 2.0 W/m^2K, SHGC: 0.62
	Win_Trp low-E	triple low-E glazing-Argon gas + UPVC window frame	U-value: 0.8 W/m^2K, SHGC: 0.58

Table 1. *Cont.*

Retrofit Component	Code Name	Configuration	Properties
air infiltration	1.5 ACH 1.0 ACH 0.5 ACH	1.5 ACH (original) 1.0 ACH 0.5 ACH	1.5 ACH 1.0 ACH 0.5 ACH
External wall façade reflectivity	Ref_0.4 Ref_0.8	0.4 (original) 0.8	0.4 0.2
south window overhang	none 0.5 m	none (original) 0.5 m	None 0.5 m
staircase enclosure	semi-open closed	semi-open closed	semi-open closed

3. Results

3.1. Building Types and Baseline Model Development

3.1.1. Representative Building Types in Urban Areas of Jiangsu Province

Building classification assists with estimating energy performance, for it correlates with multiple parameters, including the construction year, surrounding situation, geometry, envelope characteristics, energy supply, and other energy-related systems. Thus, when the existing buildings are well classified into building typologies according to these features, it is possible to efficiently estimate the energy performance and provide recommendations for building retrofit strategies [28].

The selection of building types in urban regions of Jiangsu Province is based on the four most impactful parameters: construction year, plane form, storey numbers and building structure. The National Population Census 2020 contains information on the conditions of the existing residential building stock in the urban areas of Jiangsu Province. Figure 1 shows that 35% of the stock was built from 1980 to 1999. These are also the main subjects of recent renewal research in China [86]. The hybrid structure, a combination of brick and reinforced concrete, is the most common type among residential buildings from this period [11]. Moreover, the majority of these buildings are developed in one to seven storeys.

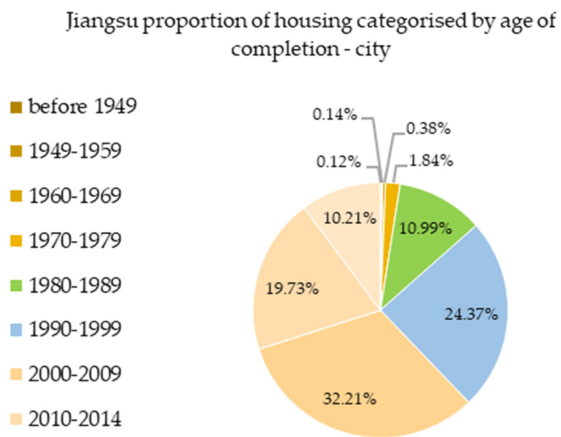
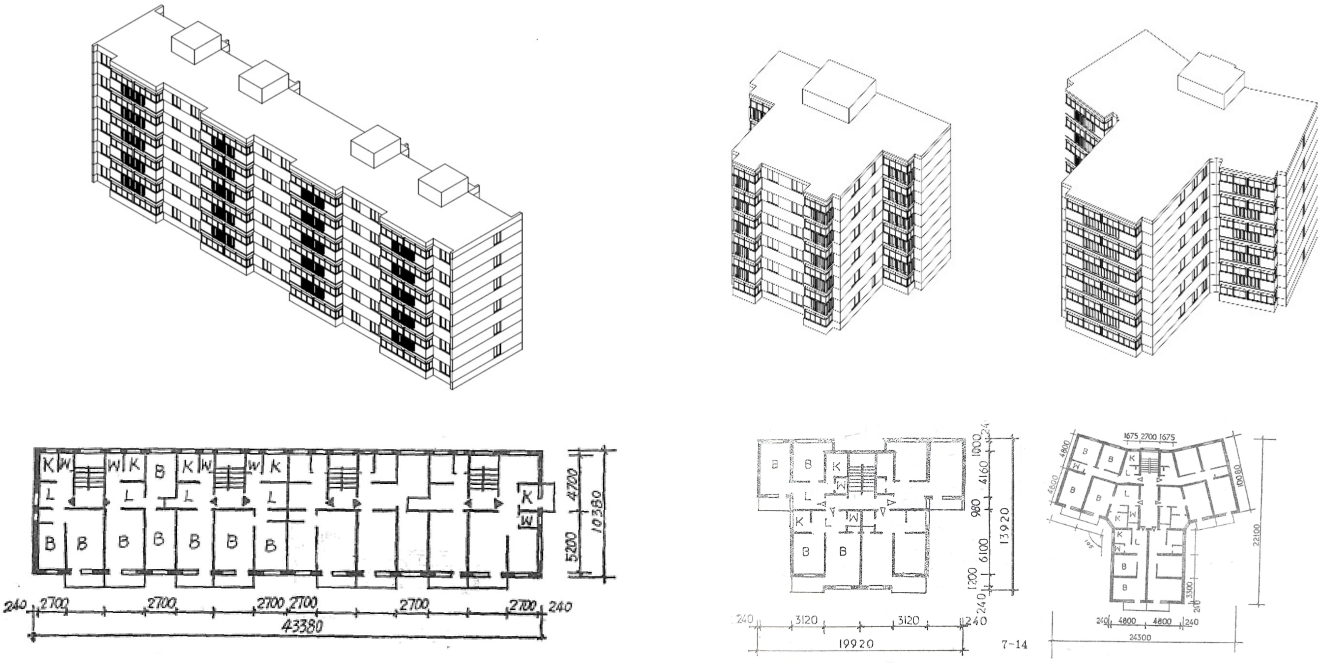


Figure 1. Proportion of housing stock by the age of completion Jiangsu—urban region. Data from China Population Census [6,86].

Based on their floor plan, the two main types can be defined as linear-shaped and tower-shaped buildings. This paper will refer to them as Multi-Danyuan Apartment and Single-Danyuan Apartment, respectively. "Danyuan" refers to a staircase shared by two to four households on one floor, with apartments accessed directly from the landing. Based on the survey of governmental city record statistics, community management information, online renting advertisements, recent photos from housing intermediaries and digital Map app, and field visits, the average proportion of the Multi-Danyuan Apartment is 85%;

meanwhile, the Single-Danyuan Apartment accounts for the remaining 15%. The typical geometry forms and plans of the selected two building types are illustrated in Figure 2.



Multi-Danyuan Apartment   Single-Danyuan Apartment

Figure 2. Typical geometry forms and plans of the two representative building types [87].

The buildings are typically supported by simple brick and concrete structures with mixed mortar as an interior and exterior wall finish and no insulation layers, resulting in inferior physical features of the envelope and overall thermal performance. In addition, they usually have no insulation layer on the roof, poor-quality windows and frames, poor air tightness, no shading devices, and low-efficient electric facilities. The thermal properties of the buildings and the input parameters for the development of the baseline model are summarized in Table 2.

Table 2. Thermal characteristics of the building envelope of the two building types [44,88–90].

Component	Thickness	U-Values [W/m^{2}K]
Exterior wall	0.24–0.28 m	1.951
Roof	0.18–0.22 m	3.231
Partition wall	0.24–0.28 m	2.721
Internal floor	0.15–0.22	2.753
Window	Single glass with timber or aluminium frames	5.90
airtightness	1.5 ACH	
Shading devices	no shading or foldable rain shed	
Staircase	Semi-open	

The main energy-consuming systems in the urban residential building stock are space heating in winter, air conditioning (AC) in summer, home appliances, cooking, domestic hot water (DHW), and lighting. Home appliances account for the most sizeable proportion, which is predicted to keep growing in the future with the rising living standards. Similarly, space-cooling and -heating take a big share, and show a significant increasing trend, especially the heating section, which has been growing at an annual rate of 15% to 21% in the past 20 years [3].

Distributed heating is the most widespread heating system in the HSCW zone, most commonly in the form of split AC units and portable electric heaters. AC systems are still the most owned and installed heating equipment in the HSCW zone, even though the residents tend to consider them as inefficient energetically and often resulting in excessively low indoor humidity. Moreover, residents have a consolidated habit of regularly opening windows for ventilation, increasing heat loss, and requiring extended use of AC systems, contributing to the perception that they are outperformed by portable equipment in ensuring minimum comfort levels. The residents in urban regions of Jiangsu Province use heating equipment for two months per year on average, and the majority of the residents choose to use heating only when strictly necessary and deactivate it when leaving the room or before bedtime [12].

The indoor space cooling in the urban residential buildings of China relies primarily on decentralised AC and electric fans. However, even within the same climate zone, the electricity consumption of AC would vary significantly due to the different lifestyles and AC-using patterns of different households [91]. According to the National Census 2015, 70% of the occupants prefer to turn on the AC only when necessary, including 50% of them who only activate the AC when they feel extremely hot indoors. Only 8% of the residents prefer keeping all rooms conditioned, while 90% choose to condition the occupied rooms [12].

3.1.2. Case Study and On-Site Investigation

The on-site investigation was conducted to improve the integrity and accuracy of the database for the development of the baseline model and input parameters. In addition, the simulation results were calibrated and validated against the measured data collected from the monitoring of the case study.

One apartment unit in a typical Multi-Danyuan building with an elderly couple as the residents was selected for this research. A set of on-site investigations on the neighbourhood and the building was conducted, in addition to the indoor temperature monitoring and interviews with the residents. The target apartment is located south of the old town of Suzhou city, showing the typical climate features of the hot summer–cold winter zone. The photos of the case study apartment building and unit are shown in Figure 3. The basic building information is shown in Table 3. There are no available architectural drawings, construction specifications or archives for the building. Therefore, the assumptions of building envelopes are made based on the building construction codes, residential design atlas, and the experience of engineering practices widely accepted by local architects. The specific assumptions for the modelling are summarised in Table 2.

Figure 3. Photos of the case study apartment building and unit.

Table 3. Descriptive statistics for the case building.

Building Property Information	
Construction Year	1986
Floors	6
Number of Staircase (Danyuan)	4
Dwelling Unit per Danyuan	2
Number of apartments	48
Area per storey (sqm)	470
Orientation	E-W
Surface area to volume (S/V) ratio	0.42
Window-to-wall ratio	26.3% (north façade), 34.0% (south façade), 5.6% (east and west façades)
Average storey height (m)	2.9 m
Central heating	No

The case-study apartment is on the fourth floor of the building, the east unit of the Danyuan (highlighted in Figure 4). It consists of a living room without a window surrounded by three bedrooms, one bathroom, and one kitchen.

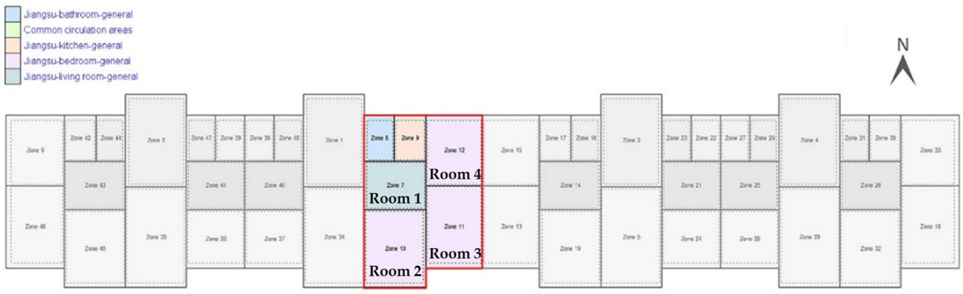


Figure 4. The layout plan of the case study building and apartment unit (zones 1, 2, 3, and 4 are staircases).

The primary cooling methods are natural and mechanical ventilation, such as ceiling fans and portable electrical fans. The residents typically use air conditioners for indoor space cooling during the extremely hot months of July and August. Their use pattern for AC reflects the habits of most Chinese urban residents, turning on the AC only when necessary, and turning it off when they feel comfortable enough.

The use of space heating in the wintertime is similarly frugal and need-driven but more frequent due to poor thermal insulation. The interviewees indicated that the free-run indoor temperature in the winter is similar to the outdoor temperature and, therefore, excessively uncomfortable, particularly between December and February. Nevertheless, they barely use the central AC system, preferring movable electric heaters/radiators and even electric blankets. The use pattern for heating equipment (electric heaters and electric blankets) is to turn it on only when necessary and off when comfort levels are acceptable.

In addition, the apartment is equipped with a gas water heater to provide domestic hot water for daily use. The interviewees routinely cook at home three times a day. The primary energy source for cooking is natural gas, but they use electric cookers sometimes as well. No televisions, computers or other facilities were observed.

The onsite indoor temperature monitoring was carried out from 17 July 2019 until 24 August 2019, during which the AC was functioning between 24th July and 2nd August. iButtons temperature sensors and loggers were used as monitoring tools to collect the indoor air temperatures hourly. The loggers were placed in the main living areas of the apartment, namely Rooms 1–4, shown in Figure 4. They were suspended around a height of 1.8 to 2.0 metres above the floor avoiding direct influence from solar radiation, external walls, air conditioning devices, and electric appliances that generate heat. Between 17 and 23 July and from 3–24 August, the HVAC cooling of all rooms was constantly off, while natural ventilation was used in each room according to the users' preference. AC was on from 24 July–2 August, when all rooms were conditioned in the hottest hours, excluding natural ventilation. The monitoring and collecting of the outdoor temperature and relative humidity were also conducted with iButtons. The sensors were suspended in the middle of an instrument shelter/thermometer screen, which can protect the instrument from strong breeze and precipitation, block direct solar radiation, and provide ventilation, allowing for more accurate recordings. The logger and shelter were fixed on the open top floor terrace of a 5-storey building, away from building facades and heat-generating equipment.

More comprehensive real-time meteorological data of this period were obtained from the Suzhou weather station, including dry bulb temperature (°C), dew point temperature (°C), relative humidity (%), direct normal radiation (Wh/m^2), diffuse horizontal radiation (Wh/m^2), wind direction (o), and wind speed (m/s).

The bi-monthly utility bills, including electricity consumption and cost of the case study apartment for two years—from November 2017 to October 2019—were obtained from the local electricity supplier, State Grid Suzhou Power Supply Company. The urban residential gas consumption was not gained directly from the gas supplier but calculated from the cost charged to the bank account, which is also charged every two months. The bi-monthly utility bills are provided in Table A1 in Appendix A.

3.1.3. Baseline Model Development

The case study building is modelled according to an on-site survey, and assumptions are made based on design regulation and academic research as detailed in Section 2. The model includes adjacent buildings affecting the solar heat gains. Figure 5 shows the baseline model for the Multi-Danyuan Apartment and an outline of the Single-Danyuan Apartment in DesignBuilder. The thermal characteristics of the building fabric are shown in Table 2.

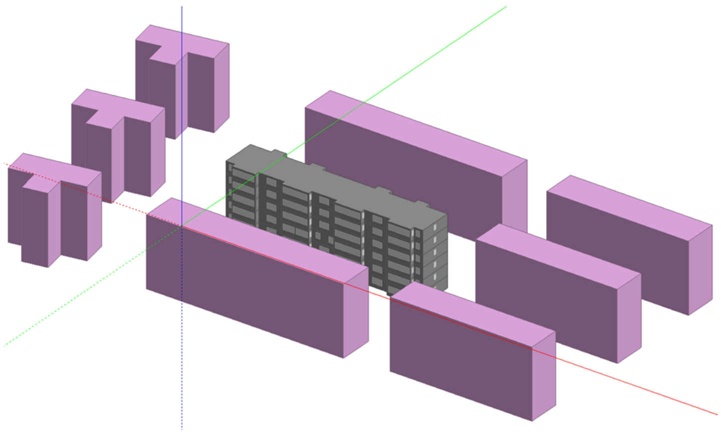


Figure 5. Case building and adjacent buildings in DesignBuilder.

With regard to set-point temperatures for the AC, the Design standard for energy efficiency of residential buildings in the Hot Summer and Cold Winter Zone [92] recommends 18 °C for heating and 26 °C for cooling. This standard also indicates that the heating and cooling COP of air source heat pumps should be 2.3 and 1.9, respectively.

Multiple studies conducted surveys on the hourly operation of AC systems for heating and cooling for a typical day in sample cities belonging to the HSCW zone [93–96], as illustrated in Figure 6.

Although the details vary, similar trends are recognizable in all studies. For heating, they show an evident rise in the operation rate at 16:00, with a peak between 19:00 and 23:00. The usage of AC cooling rises sharply between 12:00–15:00 and 18:00–22:00 and peaks between 20:00 and 22:00.

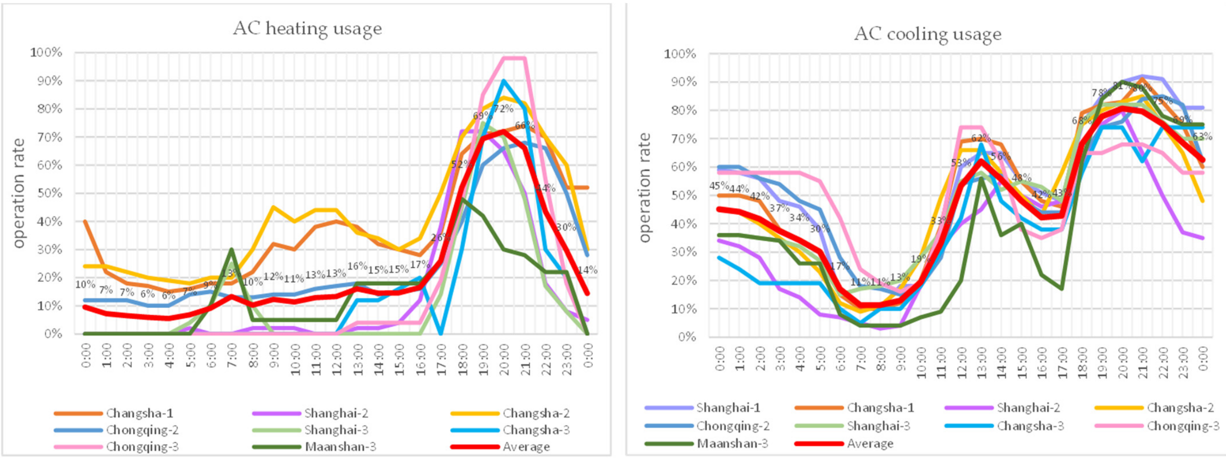


Figure 6. The hourly usage rate of air conditioner for cooling and heating on a representative weekday in summer for an urban residential apartment in different cities in the HSCW zone. Adapted from [44,93–96].

An hourly AC operation schedule based on the data from the above studies is produced as the input parameter for the AC schedule of each zone in the energy model. The method to define the AC operation schedule of different types of residents was introduced by Tsang [44], grouping the residents with different operation hours into three categories: low-energy, medium-energy, and high-energy users, as defined by different operation ratios. The operating ratios for the three scenarios are 70% (low-energy user scenario), 50% (medium-energy user scenario), and 20% (high-energy user scenario). That is, for the medium energy-using scenario, AC is active when the value is above 50%. To provide a second example, at 13:00, the operating ratio is 65% for summer cooling and 16% for winter heating; thus, int the high-energy user scenario, cooling is operated, but heating remains inactive. As seen in Figure 7, for the high-energy user scenario, the operating times for AC are 0:00 to 6:00, 10:00 to 24:00 in summer (assuming 10:00 to 21:00 in the living room and 21:00 to 6:00 am in the bedroom), and 16:00–24:00 pm in winter, a total of 20 h in summer and 8 h in winter. The same method is applied to the low-energy user scenario, resulting in a total operation hour of 4 h in summer and 4 h in winter.

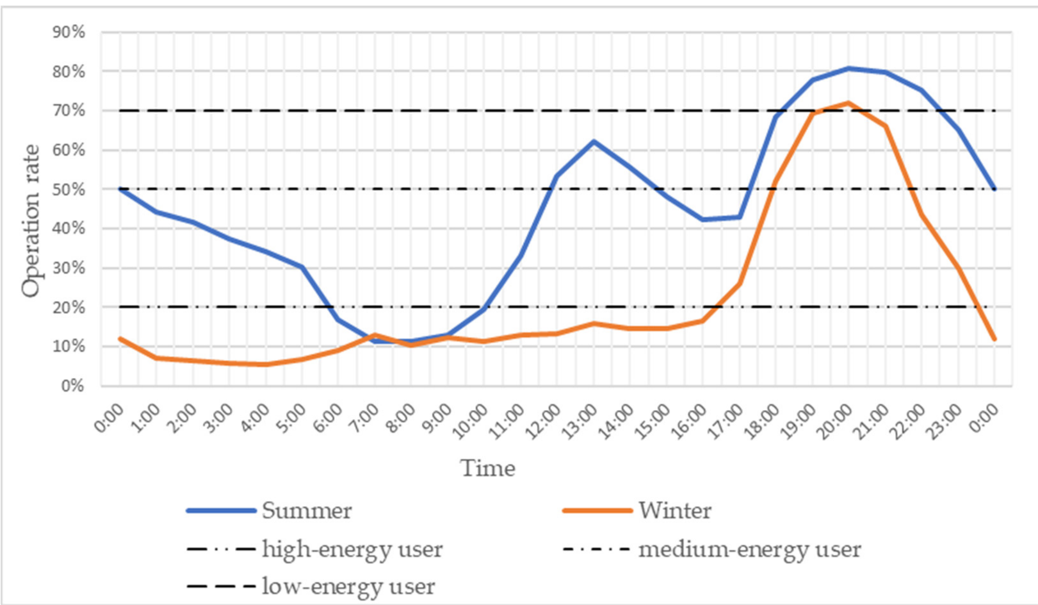


Figure 7. Hourly usage of air conditioner for cooling and heating on a representative weekday.

The energy demand under low-energy and high-energy user scenarios will be tested in this paper to provide a range of energy use possibilities and to discuss the energy-reducing potentials by applying different retrofit approaches. The detailed AC usage schedule of the three scenarios is shown in Table 4 (A more detailed AC schedule can be found in Table A2 in Appendix B).

Table 4. AC operation schedule of a typical urban residential household in HSCW.

0:00		**6:00**	**10:00**	**16:00**	**18:00**	**19:00**	**21:00**	**22:00**	**23:00**	**0:00**	**Sum**
summer	low					Living room		Bedroom			4 h
	high	Bedroom			Living room				Bedroom		20 h
winter	low						Living room	Bedroom			4 h
	high					Living room			Bedroom		8h

In addition, the internal heat gains were determined according to the design standard for HSCW residential buildings [92] as 4.3 W/m^2, which refers to the internal heat gains from equipment and home appliances, including television, computers and other appliances. The lighting gains are set at 6 W/m^2 according to the standard for the lighting design of residential buildings [97]. The schedule and energy use density of cooking are usually excluded from relevant research because of the high uncertainty caused by diverse preferences on cooking methods, tools, and schedules. This paper adapted Yu's research, which identifies 18:00–19:00 for cooking, with internal heat gains assumed to be 10.8 W/m^2 [98].

3.1.4. Baseline Model Calibration

Given the availability of reliable and high-quality input data, building energy models show enormous potential for investigating various specific design strategies and retrofit measures, as well as providing detailed predictions about building performance. However, discrepancies between simulation results and actual measured data are inevitable, and significant errors lead to decreased confidence in the model's reliability and are detrimental to the capability of investigating different scenarios. Such discrepancies can be reduced by calibrating the model predictions against the measured building performances.

The Coefficient of Variation in the Root–Mean–Square Error (CV RMSE) expresses how well a building energy model describes the variability in measured data, as per Equation (3). ASHRAE Guideline 14-2014 is one of the most widely used methodologies for building energy model calibration and provides criteria to measure accuracy, which are also used in this paper. The acceptance threshold for CV RMSE based on ASHRAE Guideline 14 is within 15% for monthly simulation and 30% for hourly simulation. Below these limits, a model can be regarded as calibrated and reliable.

$$CV\ RMSE(\%) = \frac{\sqrt{\sum_{i=1}^{N_P} (m_i - s_i)^2 / N_P}}{\overline{m}} \tag{3}$$

The measured data used to calibrate simulation results include bimonthly electricity use from November 2017 to November 2019, and the monitored hourly indoor air temperature of each room from 24 July–2 August 2019. During the calibration process, the model adjustments were conducted manually, introducing multiple iterations each time with a specific change in input parameters to minimise the variability between simulated and measured data. The adjustments include the set-point temperature, occupants and AC schedules, and the hourly climate data for the monitored 38 days.

The CV RMSE value of the bimonthly energy consumption of the case apartment was calibrated to fall within 15% by adjusting the preferences of the usage of AC. By adjusting the usage of winter heating in the bedrooms, the CV RMSE value can reach between 12.82% and 14.04%. Such adjustments are consistent with the preferences of the residents of the case apartment. Moreover, the temperature monitoring period included situations with AC in on and off modes, and the CV RMSE values in both modes were within 7% for all rooms in all periods. The highest and lowest values are 6.76% and 2.95%, with an average of 3.8%, indicating that the model is highly accuracy.

The subsequent development for the Single-Danyuan Apartment is based on the calibrated baseline model of the Multi-Danyuan Apartment, as both share the same construction and thermal characteristics, occupant behaviour and AC schedules and settings.

3.2. Pre-Retrofit Energy Demand

Since this research focuses on building demand for environmental control and operates under fixed assumptions for the use of gas and home appliances, the energy user scenarios only affect heating and cooling intensity.

Tables 5 and 6 show the annual energy consumption for the low and high-energy use of the two building types of in the south and north Jiangsu region. The simulation results indicate that the potential energy demand per conditioned floor area ranges from 91.7 to 149.52 kWh/m^2 in south Jiangsu and 89.46 to 155.52 kWh/m^2 in north Jiangsu.

Table 5. Current annual energy consumption for low-energy and high-energy user scenarios of the multi-Danyuan and Single-Danyuan Apartment in the south Jiangsu region.

South Jiangsu Region		Utility se Per Conditioned Floor Area [kWh/m^2]			Total Site Energy per Total Building Area [kWh/m^2]
		Heating Demand	Cooling Demand	Total Energy Demand per Conditioned Area	
Multi-Danyuan apartment	Low-energy user	39.62	23.70	100.81	74.08
	high-energy user	72.86	39.18	149.52	109.88
Single-Danyuan apartment	Low-energy user	37.30	29.40	91.70	72.80
	high-energy user	77.25	43.77	146.02	115.93

Table 6. Current annual energy consumption for low-energy and high-energy user scenarios of the Multi-Danyuan and Single-Danyuan Apartment in the north Jiangsu region.

North Jiangsu Region		Utility se Per Conditioned Floor Area [kWh/m^2]			Total Site Energy per Total Building Area [kWh/m^2]
		Heating Demand	Cooling Demand	Total Energy Demand per Conditioned Area	
Multi-Danyuan apartment	Low-energy user	42.96	19.05	99.49	73.11
	high-energy user	85.3	32.73	155.52	114.28
Single-Danyuan apartment	Low-energy user	41.35	23.12	89.46	71.03
	high-energy user	92.7	35.68	153.37	121.77

They also show an overall similar energy demand for the Multi-Danyuan Apartment and Single-Danyuan Apartment for both low-energy and high-energy user scenarios. In both cases, the heating demand is higher than the cooling demand under all circumstances, ranging between 40 and 60% of the total, with the maximum occurring in the north region for the Single-Danyuan apartment in the high-energy user. This outcome differs from available statistics estimating heating energy at about 11% of the total end-use electricity in urban residential buildings in 2019 [3]. The statistical data may be underestimated due to the widespread use of plugged devices (see Section 1) and indicate that a large number of residents in the HSCW zone so far has under-used heating at the expense of indoor comfort. However, with an average annual growth rate of 15–21% in the past twenty years (see Section 1), space heating will likely become the dominant energy use in the existing housing stock.

The fact that the Multi-Danyuan Apartment has higher total energy demand per conditioned area but lower total site energy per total building area reflects a larger proportion of the unconditioned communal area of the whole building compared to the Single-Danyuan type.

3.3. Post-Retrofit Energy Demand: Single Retrofit Measures

As described in Section 2.3, the energy retrofit measures for the typical residential types mainly aim to improve the thermal envelope, with a focus on seven aspects of the building fabric: the external wall, roof, window components, air tightness, external wall façade reflectivity, south window overhang, and communal staircase. This section investigates the energy reduction potential by examining the energy demands after applying every measure independently.

Through the analysis in the previous section, both types were found to have similar heating and cooling energy demands and overall proportions in southern and northern Jiangsu. Since this section focuses on the variations in heating, cooling, and total energy, the buildings in southern Jiangsu will be assumed as representative of the whole province. The assumption will be verified by further simulation in the next step of the research. In consideration of the above-mentioned trends in energy use, and in order to make the variations determined by each measure more distinct, the simulation and analysis will be carried out based on the high-energy user patterns.

Considering both building types in south Jiangsu, the variations in heating, cooling, and total energy are summarised in Table 7. While individual measures for wall and roof insulation, windows, air tightness, south window overhanging shading, and common staircases can reduce the total energy consumption by 4-18%, increasing external wall façade reflectivity shows no measurable effect in this case.

Table 7. Heating, cooling demand (per conditioned floor area) and total building energy demand (per total building area) reduction to the pre-retrofit energy use (%).

Energy Demand Reduction (%)	Retrofit Configuration Code Name	Heating Reduction		Cooling Reduction		Total Reduction	
		Multi	Single	Multi	Single	Multi	Single
Original	pre-retrofit	-	-	-	-	-	-
wall	WallSce_1	7.48%	10.60%	4.59%	7.38%	4.85%	7.82%
	WallSce_2	9.51%	13.59%	5.54%	8.98%	6.08%	9.89%
	WallSce_3	10.50%	15.08%	6.00%	9.80%	6.68%	10.92%
roof	RoofSce_1	7.14%	6.77%	7.02%	7.97%	5.31%	5.98%
	RoofSce_2	8.03%	7.64%	7.63%	8.73%	5.92%	6.67%
	RoofSce_3	8.48%	8.08%	7.94%	9.09%	6.22%	7.00%
window	Win Dbl	1.67%	1.20%	4.06%	2.83%	1.88%	1.49%
	Win_Dbl low-E	2.29%	1.67%	5.54%	3.91%	2.57%	2.06%
	Win_Trp low-E	4.10%	3.02%	6.53%	4.66%	3.71%	3.00%
air infiltration	1.0 ACH	8.83%	8.78%	6.18%	6.79%	5.92%	6.68%
	0.5 ACH	17.94%	17.90%	14.22%	16.08%	12.47%	14.30%
external wall façade reflectivity	Ref_0.2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
south window overhang	Ref_0.8	−2.55%	−1.13%	5.90%	1.96%	0.30%	0.00%
staircase enclosure	closed	2.92%	3.91%	−0.05%	0.00%	2.07%	2.07%

Improving the air tightness of buildings proved to be the most effective single retrofit measure that can benefit both heating and cooling demand. When reducing the air tightness from 1.5 ACH to 1.0, the total energy demand can be reduced by 6–7%, while the heating and cooling demand is also reduced by almost 9% and 6.8%, respectively. When the air tightness is further improved to 0.5 ACH, the heating and cooling demand is significantly reduced by 17.94% and 16.08% at most, respectively, and the total energy demand is reduced by nearly 15%. A total energy demand reduction of 6% to 14.3% can be achieved by a single measure alone.

Adding insulation on the external walls and roof are the next best measures, with reductions between 4.85% and 10.50% for the Multi-Danyuan and between 6.22% and almost 11% for the Single-Danyuan. Although the marginal benefit of adding extra insulation decreases gradually as the thickness increases for both external walls and roofs, the solutions with higher insulation are the only ones that reduce energy use to a level comparable with the European standards used as references in this research.

Changing the window components with better insulation properties and lower solar transmittance also reduces heating, cooling, and total energy, but to a lesser extent. This can be partially explained by the design of the buildings, with most transparent surfaces concentrated on the south façade and therefore performing reasonably well in terms of energy balance. It should also be considered that replacing windows influences airtightness, which has already been identified as the single most effective intervention.

Window overhangs on the southern façades can moderately reduce the cooling intensity, but the worsening in the winter performance almost completely outweighs the advantage. Thus, this will not be regarded as an effective retrofit measure for these buildings.

Similarly, enclosing a semi-open staircase shows limited impacts on the total energy demand, as it reduces heating energy in winter (already identified as a priority) while slightly increasing cooling needs in summer. Like for the windows, the enclosure also contributes to improving air tightness. Additionally, part of the interest in this measure lies in its contribution to other aspects connected with building retrofit, including safety and security, environmental comfort, and hygiene of the common spaces, building facade continuity and correction of thermal bridges, and overall quality standards of the residential communities.

3.4. Development of Retrofit Scenarios

Retrofit Measures and Scenario Development

All measures in all configurations were simulated parametrically to obtain all possible combinations. Such an approach enables the assessment of all possible interactions among measures and to identify the most effective and efficient scenarios. For the purpose of this analysis, six scenarios are considered, in addition to the original pre-retrofit situation (named SCE_0_Pre-retrofit):

1. Three combinations of measures are selected based on the following regulations: JGJ 134-2010 Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone, China [92]; The Building Regulations 2010 L1B Conservation of fuel and power in existing dwellings, UK [99]; and Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, Germany [100]. The China -based scenario assesses the potential of adapting the obsolete building types to the most current local standards. The UK and Germany-based scenarios assess the potential of implementing the best international practices and to evaluate their suitability in the local context. The thermal requirements of the two standards are not strictly complied with in this research; minor deviations were deemed tolerable to align the scenarios to the local specifications of materials and components. The three scenarios are named SCE_1_CN (China), SCE_2_UK (UK), and SCE_3_GER (Germany), respectively. Their configurations are summa-rised in Table 8.
2. After the simulations, three additional combinations achieving the lowest total energy demand, heating demand, and cooling demand were selected regardless of retrofit costs, regulations, or other constraints. The scenarios were named SCE_4_BT (best total), SCE_5_BH (best heating), and SCE_6_BC (best cooling). Their configuration can vary depending on the building types, as shown in Table 9. It should be noted that for the Single-Danyuan Apartment, SCE_3_GER and SCE_4_BT coincide. That is, the optimal total energy demand reduction is achieved by meeting the German EnerPHit standard.

The combination of measures to achieve the best heating, cooling, and total energy demand reduction for both types of buildings are remarkably similar, all featuring the most stringent thermal configurations for walls, roof, air tightness and window components. The only differences occur in the specific settings for the south window overhang and staircase enclosure. For the best total energy reduction, the multi-Danyuan Apartment needs a 0.5-m-deep overhang on the south-facing window, while no overhang should be added for the Single-Danyuan Apartment. Moreover, for the best cooling energy demand, the Single-Danyuan Apartment should enclose the staircase, while the other building type should keep the staircase semi-open.

Table 8. Building characteristics in the different retrofit scenarios.

	China Standard	UK Standard	Germany Standard
Retrofit Component	**SCE_1_CN**	**SCE_2_UK**	**SCE_3_GER**
Wall U-value [W/m^{2}K]	0.695	0.440	0.322
Roof U-value [W/m^{2}K]	0.598	0.383	0.282
Window U-value [W/m^{2}K]	2.9	2.0	0.8
Window SHGC	0.67	0.62	0.58
Air infiltration	1.5 ACH	1.0 ACH	0.5 ACH
External wall façade reflectivity	0.8	0.8	0.8
South window overhang	none	none	none
Staircase enclosure	closed	closed	closed

Table 9. Input parameters of three retrofit scenarios for the Multi and Single-Danyuan Apartment.

Retrofit Component	Multi-Danyuan Apartment			Single-Danyuan Apartment		
	SCE_4_BT	**SCE_5_BH**	**SCE_6_BC**	**SCE_4_BT**	**SCE_5_BH**	**SCE_6_BC**
Wall U-value [W/m^{2}K]	0.322	0.322	0.322	0.322	0.322	0.322
Roof U-value [W/m^{2}K]	0.282	0.282	0.282	0.282	0.282	0.282
Window U-value [W/m^{2}K]	0.80	0.80	0.80	0.80	0.80	0.80
Window SHGC	0.58	0.58	0.58	0.58	0.58	0.58
Air infiltration	0.5 ACH	0.5 ACH	0.5 ACH	0.5 ACH	0.5 ACH	0.5 ACH
External wall façade reflectivity	0.8	0.4	0.8	0.8	0.4	0.8
South window overhang	0.5 m	none	0.5 m	none	none	0.5 m
Staircase enclosure	closed	closed	semi-open	closed	closed	closed

Different retrofit scenarios will result in variations in retrofit costs. Table 10 summarises the costs of the materials for the renovation measures according to Liu [101], the project valuation quota issued by the Jiangsu Provincial Government [102], and the data observed in the local market. It should be noted that maintenance and demolition of old building components, labour, and material transportation are not included in this table. The costs are estimated for comparative purposes and should be intended as indicative.

Table 10. Material prices estimation for the retrofit scenarios.

Material Prices Estimation (RMB/m^2)	Multi-Danyuan Apartment	Single-Danyuan Apartment
SCE_1_CN	1095.10	1095.10
SCE_2_UK	1198.55	1198.55
SCE_3_GER	1427.00	1427.00
SCE_4_BT	1470.00	1427.00
SCE_5_BH	1427.00	1427.00
SCE_6_BC	1220.00	1470.00

3.5. Post-Retrofit Energy Demand under Six Scenarios

3.5.1. Total Energy Demand Reduction

Tables 11 and 12 summarise the total energy demands of all cases of the two building types, including the low and high-energy user scenarios and the south and north Jiangsu regions. The total energy use of the Multi-Danyuan type ranges from 56 to 84.93 kWh/m^2 and from 49.1 to 83.67 kWh/m^2 for the Single-Danyuan type.

Table 11. Multi-Danyuan Apartment energy use per total building area of pre- and post-retrofit.

Total Site Energy per Total Building Area [kWh/m^2]				
Multi-Danyuan Apartment	**Low-Energy**		**High-Energy**	
	South	**North**	**South**	**North**
Pre-retrofit	74.08	73.11	109.88	114.28
SCE_1_CN	65.63	64.70	84.36	84.93
SCE_2_UK	59.44	58.77	70.07	69.78
SCE_3_GER	57.22	56.34	65.26	64.37
SCE_4_BT	56.85	56.00	64.62	63.77
SCE_5_BH	57.35	56.47	65.47	64.60
SCE_6_BC	59.07	58.57	69.15	69.25

Table 12. Single-Danyuan Apartment energy use per total building area of pre- and post-retrofit.

Total Site Energy per Total Building Area [kWh/m^2]				
Single-Danyuan Apartment	**Low-Energy**		**High-Energy**	
	South	**North**	**South**	**North**
Pre-retrofit	72.8	71.03	115.93	121.77
SCE_1_CN	61.35	59.82	82.4	83.67
SCE_2_UK	52.67	51.98	63.76	64.15
SCE_3_GER	49.96	49.10	58.18	57.95
SCE_4_BT	50.17	49.33	58.53	58.33
SCE_5_BH	49.97	49.14	58.18	58.02
SCE_6_BC	72.8	71.03	115.93	121.77

The following commentary will focus on the performance of the high-energy user scenario as the most likely one in the upcoming years, according to the trends discussed in Section 1.

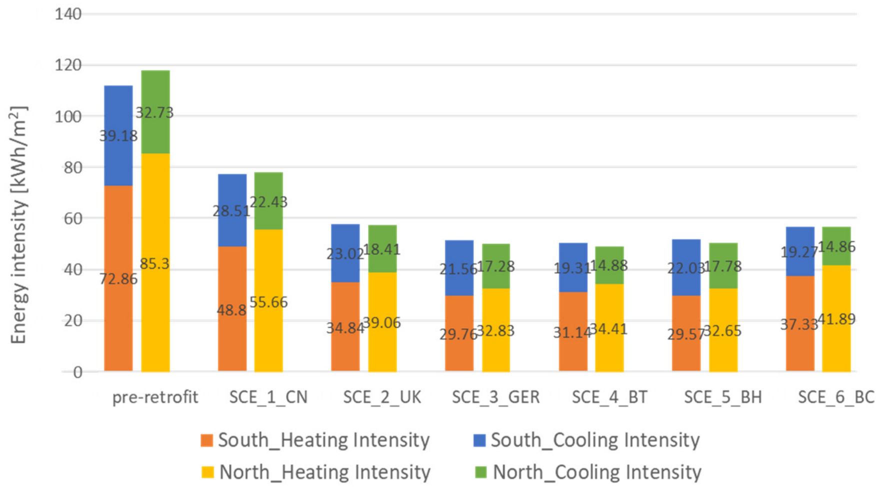
The results indicate that the energy reduction potential for the retrofit of the Multi-Danyuan Apartment ranges from 23.2% to 44.2%, and that of the Single-Danyuan Apartment ranges from 28.9% to 52.4%. The overall energy reduction in the Single-Danyuan Apartment is more significant than that of the Multi-Danyuan Apartment due to lower compactness and the consequent stronger influence of the building envelope. The overall energy reduction after the retrofit of the building in northern Jiangsu, due to the higher weigh of the heating component, is more significant than that of southern Jiangsu.

SCE_3_GER, SCE_4_BT, SCE_5_BH and SCE_6_BC produce the best contributions to the total energy reduction. They feature remarkably similar retrofit measures and subtle differences in energy performance. Thus, they can all be regarded as equivalent energy-optimal retrofit scenarios. This result also points to Germany's EnerPHit as the most effective standard in terms of energy reduction in this specific context.

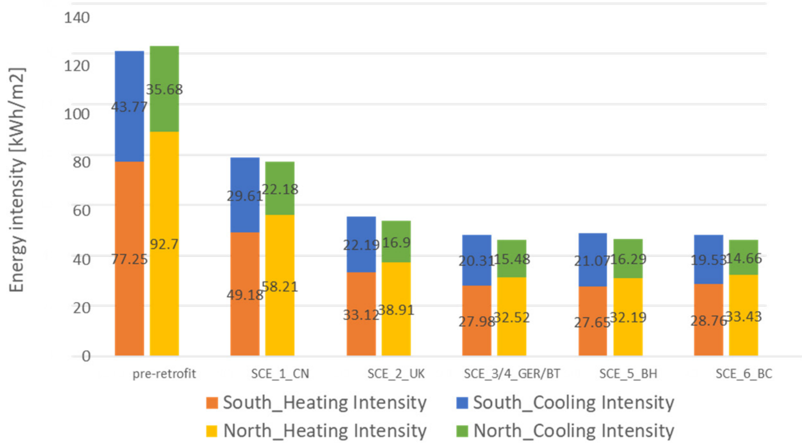
Although SCE_1_CN and SCE_2_UK do not achieve the most significant energy reductions, their 38.9% and 47.3% for the two building types confirm the effectiveness of the two standards. The scenarios feature different configurations, with costs 16–23% lower than the EnerPHit solution, and can be regarded as particularly cost-effective.

3.5.2. Heating and Cooling Demand Reduction

Figure 8 illustrates the heating and cooling energy demand of the two building types in south and north Jiangsu Province and their changes in different retrofit scenarios under a high-energy user assumption.



Multi-Danyuan Apartment



Single-Danyuan Apartment

Figure 8. Heating and cooling demand [kWh/m^2] of Multi-Danyuan Apartment and Single-Danyuan Apartment with pre-retrofit and different retrofit scenarios under current climate scenario (high-energy user scenario).

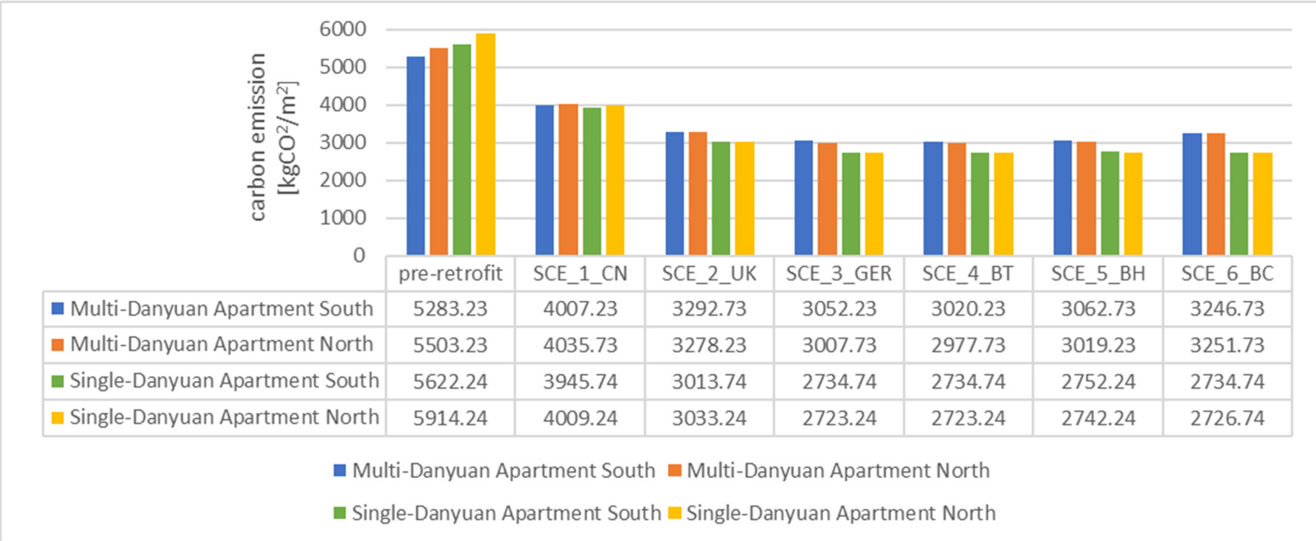
The heating intensity of the two buildings is similar in the pre-retrofit configuration (6–9% variance), while differences are more apparent after retrofit, with 20–23% in the most advanced scenario. The opposite happens with cooling, which shows differences of 9–12% (it can reach 21–24% in the low-energy user scenario) before retrofit and only 1–10% after the retrofit. This may be partially explained by the reduction in SHGC and U-values, which reduces the form advantage of the Multi-Danyuan Apartment with lower surface-to-volume ratio and proportionally larger transparent surfaces facing due south.

Both types of buildings have the lowest reduction under SCE_1_CN, with a total energy intensity slightly below 80 kWh/m^2. More advanced retrofit scenarios can reduce the total heating and cooling energy to less than 60 kWh/m^2, with 33–65.3%. savings on heating and 27.2–58.9% savings on cooling. All retrofit scenarios produce a higher percentage reduction in heating energy than in cooling energy, except for the "Best Cooling" scenario, but only for the Multi-Danyuan typology, with a larger amount of shaded south-facing windows.

From the perspective of the regional division, the energy intensity ratio of heating and cooling in southern and northern Jiangsu are distinct. However, the total energy use is relatively close and experiences similar reductions under different retrofit scenarios.

3.5.3. Carbon Emission Reduction

The total energy use in this study refers to the sum of power used by the HVAC system, lighting, home appliances, DHW and cooking. The energy of cooking is natural gas, and the rest is electricity. The cooking energy use is unaffected by the retrofit scenarios, which only impact heating and cooling, which are electricity-consuming. Therefore, this section will only discuss the carbon emissions of electricity consumption to investigate the carbon reduction potential with the high-energy user scenario. Figure 9 shows the carbon emissions of two building types in different retrofit scenarios in the south and north Jiangsu regions. Due to the correlation between carbon emissions and energy consumption, the decreasing trend in post-retrofit carbon emissions follows a pattern similar to the previously discussed reduction in energy consumption.



	pre-retrofit	SCE_1_CN	SCE_2_UK	SCE_3_GER	SCE_4_BT	SCE_5_BH	SCE_6_BC
Multi-Danyuan Apartment South	5283.23	4007.23	3292.73	3052.23	3020.23	3062.73	3246.73
Multi-Danyuan Apartment North	5503.23	4035.73	3278.23	3007.73	2977.73	3019.23	3251.73
Single-Danyuan Apartment South	5622.24	3945.74	3013.74	2734.74	2734.74	2752.24	2734.74
Single-Danyuan Apartment North	5914.24	4009.24	3033.24	2723.24	2723.24	2742.24	2726.74

Figure 9. Carbon emissions of two building types in Jiangsu in different retrofit scenarios.

Although the proportion of heating and cooling is different between southern and northern Jiangsu after retrofit, there is a minor difference in the overall building energy consumption and carbon emissions.

On the other hand, there are significant differences in carbon emissions between building types. Under different retrofit scenarios, the reduction in carbon emission of the Multi-Danyuan Apartment can reach 24% to 46%; the reduction in the Single-Danyuan Apartment carbon emissions could be between 30% and 54%, indicating higher carbon-reducing potential.

3.5.4. Thermal Comfort

In order to assess the effectiveness of the retrofit measures in improving thermal comfort, the number of hours outside CEN15251 Category III acceptability limits was simulated in all scenarios for both building types and in both climate zones. CEN15251 uses an adaptive model which estimates comfort temperatures based on the running mean outdoor air temperature and assumes a certain flexibility of the occupants in adapting their clothing. Category III expresses 65% acceptability. Adaptive models were originally developed for naturally ventilated buildings, but previous studies have supported their applicability also for mixed-mode buildings, where they are preferable to static models such as PMV, in spite of their limitations [103]. The model was deemed adequate for this study, which aims to draw an indicative comparison among the different scenarios rather than attempting a detailed discomfort analysis. Furthermore, in the specific case, the assumptions closely reflect the actual situation, in which residents tend to limit the use of heating and cooling to the periods during which acceptable comfort conditions cannot be achieved by other means.

Table 13 summarises the results of the simulations by listing the average number of discomfort hours in each scenario for both building types and in each climate zone. The averages are calculated on all occupied zones and compared with the pre-retrofit scenario in terms of per cent reduction (in brackets).

Table 13. Annual average of hours outside CEN15251 Category III Acceptability Limits.

	Pre-Retrofit	**SCE_1_CN**	**SCE_2_UK**	**SCE_3_GER**	**SCE_4_BT**	**SCE_5_BH**	**SCE_6_BC**
Multi-Danyuan Apartment South	1254 (100%)	1139 (−9.2%)	884 (−29.5%)	706 (−43.7%)	896 (−28.5%)	834 (−33.5%)	1130 (−9.9%)
Multi-Danyuan Apartment North	1141 (100%)	1022 (−10.4%)	697 (−38.9%)	505 (−55.7%)	760 (−33.3%)	587 (−48.5%)	1021 (−10.4%)
Single-Danyuan Apartment South	1486 (100%)	1351 (−9.1%)	1144 (−23.0%)	1000 (−32.7%)	1000 (−32.7%)	937 (−36.9%)	1104 (−25.7%)
Single-Danyuan Apartment North	1268 (100%)	1220 (−3.8%)	1008 (−20.5%)	827 (−34.8%)	827 (−34.8%)	750 (−40.6%)	984 (−22.4%)

The data show reductions in discomfort hours between 9.1 and 55.7%. Interestingly, the best results in terms of thermal comfort do not coincide with the largest reductions in energy use. The most effective sets of measures are found instead in either Scenario 5, the best performing for heating demand, or Scenario 3, based on the German Standard and also predominantly geared towards winter energy use (as shown in Figure 8). More specifically, the Best-Heating scenario is the most effective for the Multi-Danyuan type, while the slightly more balanced German standard works best for the Single-Danyuan. Such results are not entirely surprising and confirm that most discomfort hours occur in winter rather than summer, consistently with the current energy use, which shows a heating-dominated breakdown. It should be noted that discomfort hours include both conditioned and free-running periods in the different zones. As a result, heating-focused retrofit measures may be preferable for low-income residents (more likely to refrain from using climatization), as they guarantee overall better comfort conditions.

3.5.5. Limitations

This paper acknowledges its limitations in the research process. Firstly, due to the non-disclosure of personal information regarding households and energy consumption, it was not possible to monitor temperatures and collect energy consumption data for the entire building and all apartment units. Consequently, a small sample size became an unavoidable limitation in this study. Additionally, the impact of the global pandemic hindered the ability to conduct long-term data monitoring. These limitations are expected to be addressed and supplemented in future research. Finally, this study did not undertake instrumental measurements of the thermal conductivity of the building envelope and the air tightness of the apartments. However, a sensitivity analysis was conducted to assess the uncertainty determined by these limitations, which was estimated in the range of −12.4 to +9.5%. Moreover, the specific performance of the survey building is less critical for a stock model trying to achieve the best assumptions for a representative typology rather than an individual structure.

4. Conclusions

This investigation is conducted on a selection of the most representative urban residential building types in Jiangsu Province. By developing a dynamic energy model for the selected building types, the current energy demand and carbon dioxide emissions of the existing urban housing stock in Jiangsu Province are estimated. The model constitutes the initial core of a bottom–up stock model for the residential buildings in the province. Several aspects developed within the research can be applied directly to the modelling of most residential buildings, including occupancy, and user behaviour, range of retrofit measures and the structure of the parametric model itself. Others can be extended to all typologies of the same period, including the physical characteristics of the buildings, or be adapted to other vintages built in adjoining periods. The model has been validated against statistical data and field measurements within the scope of this project.

Multi and Single-Danyuan Apartment show similar energy demands in the current situation. The potential energy demand per conditioned floor area ranges from 91.7 to 149.52 kWh/m^2 and in the south Jiangsu region from 89.46 to 155.52 kWh/m^2 in the north Jiangsu region. Under all conditions, the heating demand exceeds the cooling demand, constituting the largest share of total energy consumption, with the highest percentage peaking at 60%.

Among the selected retrofit measures, improving the airtightness of the building proved the most effective individually, enhancing both winter (−17.94%) and summer (−16.08%) performance. Similarly, increasing external wall and roof insulation can reduce total energy demand by 7–11% and 6–7%, respectively. Upgrading the window components not only enhances their thermal properties but also improves airtightness, justifying its inclusion among the most effective measures.

Six scenarios including multiple measures were defined based on their efficacy in reducing energy use and on their compliance with local and international regulations. Among them, SCE_4_BT is the most effective in reducing total energy consumption by 41–44% for Multi-Danyuan Apartments and 50–52% for Single-Danyuan Apartments. The carbon emissions reduction for the two types of buildings can reach 43–46% and 51–54%, respectively. The scenario is remarkably similar (when not identical) to SCE_3_GER, reflecting the prescriptions of the EnerPHit Standard [100].

The scenario based on the British standard [99] was found to be particularlycost-effective, reducing the total energy demand by up to 47% for a capital cost on materials 16% lower than the energy optimal retrofit scenarios.

Similarly, the Chinese standard [92] produces more limited benefits (−39% energy) at a lower cost. While this has the advantage of promoting more extensive interventions on the building stock, it also underlines significant room for improvement to gradually align with international best practices, particularly in consideration of the ambitious goals set by the country on carbon emission peak and neutrality.

The model also provides insights on thermal comfort, indicating that the measures targeting winter energy uses perform better in improving overall indoor conditions both in free-running and conditioned modes. Although without a direct impact on energy and carbon emission in the model, it should be noted that better internal comfort can contribute to limiting the use of heating and cooling systems, while also ensuring more liveable buildings in cases when the use of active conditioning systems is restricted by financial hardship.

Further research will focus on investigating the energy performance of these two types of buildings under various future climate change scenarios, as well as exploring potential retrofit measures that offer optimal energy efficiency and cost-effectiveness. Finally, dynamic aspects related to users' behaviour (and determined by broader socio-economic factors) were not included in this research scope, so they could also be further investigated and integrated with the projections of the model.

Author Contributions: Conceptualization, X.C., M.C., D.C. and B.C.; methodology, X.C., M.C., D.C. and B.C.; software, X.C. and M.C.; validation, X.C.; formal analysis, X.C.; investigation, X.C.; resources, X.C.; data curation, X.C.; writing—original draft preparation, X.C.; writing—review and editing, X.C., M.C., D.C. and B.C.; visualization, X.C.; supervision, M.C., D.C. and B.C.; project administration, X.C. and M.C.; funding acquisition, M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Research Development Fund granted by Xi'an Jiaotong-Liverpool University (grant number RDF16-01-46), the Technology Development Consultation Project granted by Xi'an Jiaotong-Liverpool University Urban and Environmental Studies University Research Centre (grant number RDS10120210101), and the Key Program Special Fund granted by Xi'an Jiaotong-Liverpool University (grant number KSF-E-58).

Institutional Review Board Statement: The study was reviewed and approved by the Ethical Committee of Xi-an Jiaotong-Liverpool University.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ACH	Air Changes per Hour
CABEE	China Association of Building Energy Efficiency
CSWD	Chinese Standard Weather Data
CV RMSE	Coefficient of Variation in the Root–Mean–Square Error
HSCW zone	Hot summer–cold winter zone of China's architecture climatic regions
IAMs	Integrated Assessment Models
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Pathways
SWERA	Solar and Wind Energy Resource Assessment
THUBERC	Tsinghua University Building Energy-saving Research Center
TMY	Typical Meteorological Year

Appendix A

Table A1. Bimonthly electricity (kWh) and gas (cubic metre) usage of the case apartment.

Period	Electricity Use (KWh)	Gas Consumption (m^3)
November, December	280	16.94
January, February 2018	563	27.02
March, April	339	27.02
May, June	291	29.03
July, August	300	25.09
September, October	271	24.36
November, December	356	28.73
January, February 2019	610	27.27
March, April	334	35.27
May, June	292	38.91
July, August	324	22.91
September, October	206	30.18

Appendix B

Table A2. AC operation schedule of a typical urban residential household in Jiangsu Province.

<table>
<tr><th>Summer</th><th>S-Low</th><th>S-Medium</th><th>S-High</th></tr>
<tr><td>0:00</td><td rowspan="19">off</td><td rowspan="13">off</td><td rowspan="7">bedroom</td></tr>
<tr><td>1:00</td></tr>
<tr><td>2:00</td></tr>
<tr><td>3:00</td></tr>
<tr><td>4:00</td></tr>
<tr><td>5:00</td></tr>
<tr><td>6:00</td></tr>
<tr><td>7:00</td><td rowspan="4">off</td></tr>
<tr><td>8:00</td></tr>
<tr><td>9:00</td></tr>
<tr><td>10:00</td></tr>
<tr><td>11:00</td><td rowspan="11">living room</td></tr>
<tr><td>12:00</td></tr>
<tr><td>13:00</td><td rowspan="3">Living room</td></tr>
<tr><td>14:00</td></tr>
<tr><td>15:00</td></tr>
<tr><td>16:00</td><td rowspan="2">off</td></tr>
<tr><td>17:00</td></tr>
<tr><td>18:00</td><td rowspan="4">living room</td></tr>
<tr><td>19:00</td><td rowspan="3">living room</td></tr>
<tr><td>20:00</td></tr>
<tr><td>21:00</td></tr>
<tr><td>22:00</td><td>bedroom</td><td rowspan="3">bedroom</td><td rowspan="3">bedroom</td></tr>
<tr><td>23:00</td><td rowspan="2">off</td></tr>
<tr><td>0:00</td></tr>
<tr><td>Totol hour</td><td>4</td><td>10</td><td>20</td></tr>
</table>

<table>
<tr><th>Winter</th><th>S-Low</th><th>S-Medium</th><th>S-High</th></tr>
<tr><td>0:00</td><td rowspan="20">off</td><td rowspan="19">off</td><td rowspan="17">off</td></tr>
<tr><td>1:00</td></tr>
<tr><td>2:00</td></tr>
<tr><td>3:00</td></tr>
<tr><td>4:00</td></tr>
<tr><td>5:00</td></tr>
<tr><td>6:00</td></tr>
<tr><td>7:00</td></tr>
<tr><td>8:00</td></tr>
<tr><td>9:00</td></tr>
<tr><td>10:00</td></tr>
<tr><td>11:00</td></tr>
<tr><td>12:00</td></tr>
<tr><td>13:00</td></tr>
<tr><td>14:00</td></tr>
<tr><td>15:00</td></tr>
<tr><td>16:00</td></tr>
<tr><td>17:00</td><td rowspan="5">living room</td></tr>
<tr><td>18:00</td></tr>
<tr><td>19:00</td><td rowspan="3">living room</td></tr>
<tr><td>20:00</td><td rowspan="2">living room</td></tr>
<tr><td>21:00</td></tr>
<tr><td>22:00</td><td rowspan="2">bedroom</td><td rowspan="2">bedroom</td><td rowspan="3">bedroom</td></tr>
<tr><td>23:00</td></tr>
<tr><td>0:00</td><td>off</td><td>off</td></tr>
<tr><td>Totol hour</td><td>4</td><td>5</td><td>8</td></tr>
</table>

References

1. United Nations Environment Programme. *2021 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2021.
2. BP PLC. *Statistical Review of World Energy 2021*; bp p.l.c.: London, UK, 2021.
3. THUBERC. *Annual Report on China Building Energy Efficiency 2021*; China Architecture & Building Press: Beijing, China, 2021; p. 261.
4. Zhou, L. China's Carbon Peak and Neutrality Goals Show Its Resolve to Address Climate Change. Available online: http://www.china.org.cn/opinion/2021-05/03/content_77451598.htm (accessed on 3 January 2022).
5. Liang, J. *Research on the Implementation Path of Carbon Peaking and Carbon Neutralization in the Construction Sector*; Architecture & Building Press: Beijing, China, 2021.
6. Office of The State Council Leading Group for the Seventh National Census. *China Population Census Yearbook 2020*; China Statistics Press: Beijing, China, 2022.
7. Ji, X.; Zhang, B.; Chen, Z.; Jia, W. Reconstruction of existing dwellings in Northern Jiangsu for energy-saving. *J. Harbin Inst. Technol.* **2003**, *35*, 1320–1353. [CrossRef]
8. Bai, J.-B.; Shen, B.-a.; Zhang, Y.; Rui, W.-W.; Yang, J.-J.; Zhang, J.-Y.; Wu, H.-J. Energy-saving Retrofit Integrated Technology System and Energy Consumption Evaluation of Existing Residential Buildings of Old District in the South of Jiangsu. *Build. Sci.* **2012**, *28*, 59–65. [CrossRef]
9. Xu, L.; Liu, J.; Pei, J.; Han, X. Building energy saving potential in Hot Summer and Cold Winter (HSCW) Zone, China—Influence of building energy efficiency standards and implications. *Energy Policy* **2013**, *57*, 253–262. [CrossRef]
10. Tian, G.-H.; Ji, X.; Liu, W.; Liu, P.; Zhang, L.-J. Energy-consumption Survey and Energy-saving Retrofitting of Existing Residential Buildings in Xuzhou. *Build. Energy Effic.* **2018**, *46*, 79–84.

11. Lv, J.; Rowe, P.G.; Zhang, J. *Modern Urban Housing in China 1840–2000*; Prestel: Munich, Germany; London, UK; New York, NY, USA, 2001.
12. THUBERC. *Annual Report on China Building Energy Efficiency 2017*; China Architecture & Building Press: Beijing, China, 2017.
13. CABEE. China Building Energy Consumption Research Report 2019. Available online: https://www.cabee.org/site/content/23565.html (accessed on 9 May 2022).
14. The Standing Committee of Jiangsu Provincial People's Congress. Research Report on the Improvement of Old Residential Areas in Cities and Towns. Available online: http://www.jsrd.gov.cn/zyfb/rdcwhsyyj/202106/t20210629_530508.shtml (accessed on 6 January 2022).
15. Xue, Y. Residential building design code research. *Constr. Mater. Decor.* **2013**, 12–14.
16. Chai, H.; Song, W. Residential building design code research. *Theor. Res. Urban Constr. Digit.* **2013**.
17. Liu, B. Residential building design code research. *Technol. Outlook* **2014**, 2.
18. Hu, Z. Residential building design code research. *Chin. Dwell.* **2014**, 94–95.
19. Xie, Y. Study on design code of residential building. *Real Estate Inf. China* **2019**, 96.
20. Zhang, D.; Fan, L. The Development of Our Country City Residential Standard Revision and Residential Buildings. *Chin. Overseas Archit.* **2013**, *6*, 56–57.
21. Liu, X.-x.; Li, Y.-l. Inquiry on energy-saving transformation problems and causes of existing residential building. *Shanxi Archit.* **2014**, *40*, 205–207.
22. Liu, G.; Peng, C.; Liu, J. Study on the development history and trend of building energy efficiency standards abroad. *Constr. Sci. Technol.* **2015**, 16–21. [CrossRef]
23. Wang, J.; Wang, Q.; Ye, L. *Existing Building Green Renovation Standards and Case Studies in Foreign Counturies*; China Architecture & Building Press: Beijing, China, 2016.
24. Fotopoulou, A.; Cattani, E.; Gulli, R.; Ferrante, A.; Semprini, G.; Schihin, Y.; Weyer, J. Deep renovation in existing residential buildings through façade additions: A case study in a typical residential building of the 70s. *Energy Build.* **2018**, *166*, 258–270. [CrossRef]
25. Brambilla, A.; Salvalai, G.; Imperadori, M.; Sesana, M.M. Nearly zero energy building renovation: From energy efficiency to environmental efficiency, a pilot case study. *Energy Build.* **2018**, *166*, 271–283. [CrossRef]
26. Akhozheya, B.; Syam, M.; Abdelghani, R.; Aoul, K.A.T. Retrofit evaluation of a residential building in UAE: Energy efficiency and renewable energy. In Proceedings of the 2018 5th International Conference on Renewable Energy: Generation and Applications (ICREGA), Al Ain, United Arab Emirates, 25–28 February 2018; pp. 238–242.
27. Kavgic, M.; Mavrogianni, A.; Mumovic, D.; Summerfield, A.; Stevanovic, Z.; Djurovic-Petrovic, M. A review of bottom-up building stock models for energy consumption in the residential sector. *Build. Environ.* **2010**, *45*, 1683–1697. [CrossRef]
28. Loga, T.; Diefenbach, N.; Wittchen, K.B.; Kragh, J.; Balaras, C.; Dascalaki, E.; Zavrl, M.Š.; Rakušček, A.; Corrado, V.; Corgnati, S.; et al. *Use of Building Typologies for Energy Performance Assessment of National Building Stocks. Existent Experiences in European Countries and Common Approach. First TABULA Synthesis Report*; Institut Wohnen und Umwelt GmbH (IWU): Darmstadt, Germany, 2010.
29. Vissilia, A.-M. Evaluation of a sustainable Greek vernacular settlement and its landscape: Architectural typology and building physics. *Build. Environ.* **2009**, *44*, 1095–1106. [CrossRef]
30. Dascalaki, E.G.; Droutsa, K.G.; Balaras, C.A.; Kontoyiannidis, S. Building typologies as a tool for assessing the energy performance of residential buildings—A case study for the Hellenic building stock. *Energy Build.* **2011**, *43*, 3400–3409. [CrossRef]
31. Filogamo, L.; Peri, G.; Rizzo, G.; Giaccone, A. On the classification of large residential buildings stocks by sample typologies for energy planning purposes. *Appl. Energy* **2014**, *135*, 825–835. [CrossRef]
32. Kragh, J.; Wittchen, K.B. Development of two Danish building typologies for residential buildings. *Energy Build.* **2014**, *68*, 79–86. [CrossRef]
33. Santos, C.; Ferreira, T.M.; Vicente, R.; Mendes da Silva, J.A.R. Building typologies identification to support risk mitigation at the urban scale—Case study of the old city centre of Seixal, Portugal. *J. Cult. Herit.* **2013**, *14*, 449–463. [CrossRef]
34. Cuerda, E.; Pérez, M.; Neila, J. Facade typologies as a tool for selecting refurbishment measures for the Spanish residential building stock. *Energy Build.* **2014**, *76*, 119–129. [CrossRef]
35. Kavgic, M. City Scale Physically Disaggregated Bottom-Up Energy Model: Technical Options for Decarbonising Belgrade Residential Stock. Ph.D. Thesis, Bartlett School of Graduate Studies, University College London, London, UK, 2013.
36. Filippi Oberegger, U.; Pernetti, R.; Lollini, R. Bottom-up building stock retrofit based on levelized cost of saved energy. *Energy Build.* **2020**, *210*, 109757. [CrossRef]
37. De Oliveira Fernandes, M.A.; Keijzer, E.; van Leeuwen, S.; Kuindersma, P.; Melo, L.; Hinkema, M.; Gonçalves Gutierrez, K. Material-versus energy-related impacts: Analysing environmental trade-offs in building retrofit scenarios in the Netherlands. *Energy Build.* **2021**, *231*, 110650. [CrossRef]
38. Song, R.; Fan, Y.; Wang, X.; Zhao, Y. The Study on the Design Mode of the Existing Residential Building Regeneration: Taking 1980s Existing Residential Buildings in Jinan as an Example. In Proceedings of the China Urban Housing Seminar and Sustainable Housing Construction Industrialization Forum, Hefei, China, 1 December 2009.
39. Huang, J.e.; Lyu, H.; Feng, W.; Chen, Y.; Zhou, T. Thermal Properties Optimization of Envelope in Energy-Saving Renovation of Existing Residential Building. *J. Chongqing Jianzhu Univ.* **2013**, *35*, 118–124. [CrossRef]

40. Peng, C.; Liu, X.; Cao, S.; Lin, J. Research on The Rebuilding Technology of Energy Efficiency for the Existing Residential Buildings in A Region of Hot Summer and Cold Winter. *Ind. Constr.* **2003**, *33*, 19–22. [CrossRef]
41. Rui, W.-W.; Bai, J.-B.; Yang, J.-J.; Zhang, Y.; Zhang, J.-Y.; Wu, H.-J. Energy Saving Renovation for Existing Residential Houses in the South of Jiangsu. *Jiangsu Constr.* **2012**, 101–115. [CrossRef]
42. Peng, C.; Wang, L.; Zhang, X. DeST-based dynamic simulation and energy efficiency retrofit analysis of commercial buildings in the hot summer/cold winter zone of China: A case in Nanjing. *Energy Build.* **2014**, *78*, 123–131. [CrossRef]
43. Li, Y.; Ren, J.; Jing, Z.; Jianping, L.; Ye, Q.; Lv, Z. The Existing Building Sustainable Retrofit in China-A Review and Case Study. *Procedia Eng.* **2017**, *205*, 3638–3645. [CrossRef]
44. Tsang, C. Energy-Saving Retrofits for Residential Buildings in the Hot Summer and Cold Winter Zone in China. Ph.D. Thesis, Loughborough University, Loughborough, UK, 2020. [CrossRef]
45. Zou, D.-N. *A History of Chinese Modern Architecture*; Tianjin Science and Technology Press: Tianjin, China, 2001.
46. Liu, Y. *Chinese Housing 60 Years (1949–2009) Look Back at the Past*; China Architecture & Building Press: Beijing, China, 2009.
47. Deng, Y. Urban housing system reform and real estate market development in China. *Hous. Financ. Int.* **2017**, 15–17.
48. Pu, Q. *Research on Prediction Model and Influencing Factors of Urban Residential Building Energy Consumption*; Chongqing University: Chongqing, China, 2012.
49. Yang, X. *Study of China's Building Energy Efficiency Based on Energy Data*; Tsinghua University: Beijing, China, 2009.
50. Yao, R.; Costanzo, V.; Li, X.; Zhang, Q.; Li, B. The effect of passive measures on thermal comfort and energy conservation. A case study of the hot summer and cold winter climate in the Yangtze River region. *J. Build. Eng.* **2018**, *15*, 298–310. [CrossRef]
51. Dong, X. *Research on the Hot Summer and Cold Winter Zone Residential Heating and Energy Saving Design*; Xi'an University of Architecture and Technology: Xi'an, China, 2016.
52. Gui, X.-C.; Ma, Y.-T.; Chen, S.-Q.; Ge, J. The methodology of standard building selection for residential buildings in hot summer and cold winter zone of China based on architectural typology. *J. Build. Eng.* **2018**, *18*, 352–359. [CrossRef]
53. Loga, T.; Stein, B.; Diefenbach, N. TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable. *Energy Build.* **2016**, *132*, 4–12. [CrossRef]
54. Shorrock, L.D.; Dunster, J.E. The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock. *Energy Policy* **1997**, *25*, 1027–1037. [CrossRef]
55. Boardman, B.; Darby, S.; Killip, G.; Hinnells, M.; Jardine, C.N.; Palmer, J.; Sinden, G.; Lane, K.; Layberry, R.; Wright, A.; et al. *40% House*; Environmental Change Institute, University of Oxford: Oxford, UK, 2005.
56. Natarajan, S.; Levermore, G.J. Predicting future UK housing stock and carbon emissions. *Energy Policy* **2007**, *35*, 5719–5727. [CrossRef]
57. Cheng, V.; Steemers, K. Modelling domestic energy consumption at district scale: A tool to support national and local energy policies. *Environ. Model. Softw.* **2011**, *26*, 1186–1198. [CrossRef]
58. Huang, Y.J.; Brodrick, J. A bottom-up engineering estimate of the aggregate heating and cooling loads of the entire U.S. building stock. In Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 20–25 August 2000.
59. Zhou, Y.; Gurney, K. A new methodology for quantifying on-site residential and commercial fossil fuel CO_2 emissions at the building spatial scale and hourly time scale. *Carbon Manag.* **2010**, *1*, 45–56. [CrossRef]
60. Cerezo Davila, C.; Reinhart, C.F.; Bemis, J.L. Modeling Boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets. *Energy* **2016**, *117*, 237–250. [CrossRef]
61. Yang, X.; Hu, M.; Tukker, A.; Zhang, C.; Huo, T.; Steubing, B. A bottom-up dynamic building stock model for residential energy transition: A case study for the Netherlands. *Appl. Energy* **2022**, *306*, 118060. [CrossRef]
62. Hogan, J.; Watson, R.; Huang, Y.J.; Lang, S.; Fu, X.; Lin, H. *Development of China's Energy-Efficiency Design Standard for Residential Buildings in the "Hot-Summer/Cold-Winter" Zone*; China Energy Group, International Energy Analysis Department, Energy Analysis and Environmental Impacts Division: Berkeley, CA, USA, 2001.
63. Niu, J.; Liao, Z. Forecasting Residential Energy Demand in China: An approach to technology impacts. *J. Asian Archit. Build. Eng.* **2002**, *1*, 8. [CrossRef]
64. Wei, F.; Khanna, N.; Fridley, D.; Ke, J.; Huang, K.; Zhou, N. Impact Analysis of Developing Net Zero Energy Buildings in China. In Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar Conference Center, Pacific Grove, CA, USA, 21–26 August 2016.
65. Crawley, D.B.; Hand, J.W.; Kummert, M.; Griffith, B.T. Contrasting the capabilities of building energy performance simulation programs. *Build. Environ.* **2008**, *43*, 661–673. [CrossRef]
66. Boafo, F.E.; Ahn, J.-G.; Kim, J.-T.; Kim, J.-H. Computing Thermal Bridge of VIP in Building Retrofits using DesignBuilder. *Energy Procedia* **2015**, *78*, 400–405. [CrossRef]
67. Liu, Y.; Chen, H.; Zhang, L.; Feng, Z. Enhancing building energy efficiency using a random forest model: A hybrid prediction approach. *Energy Rep.* **2021**, *7*, 5003–5012. [CrossRef]
68. Zhang, Y.; Korolija, I. Performing complex parametric simulations with jEPlus. In Proceedings of the 9th International Conference on Sustainable Energy Technologies, Shanghai, China, 24–27 August 2010.
69. MOHURD. *General Code for Energy Efficiency and Utilization of Renewable Energy Application in Buildings GB 55015-2021*; MOHURD: Beijing, China, 2021.
70. Yin, S. Study of Life-Cycle Carbon Emission in Buildings. Master's Thesis, Harbin Institute of Technology, Harbin, China, 2012.

71. Jiang, Y. *Residential Energy Conservation*; China Architecture & Building Press: Beijing, China, 2006.
72. Li, X. *Technical Guide for Green Renovation of Existing Residential Buildings*; China Architecture & Building Press: Beijing, China, 2016.
73. *JGJ/T 129-2012*; Technical Specification for Energy Efficiency Retrofitting of Existing Residential Buildings. China Architecture & Building Press: Beijing, China, 2012.
74. Zhang, X.; Zhang, Y. *Building Energy Saving Technology and Materials*; Zhang, X., Zhang, Y., Eds.; Chemical Industry Press: Beijing, China, 2009.
75. *GB 21455-2019*; Minimum Allowable Values of the Energy Efficiency and Energy Efficiency Grades for Room Air Conditioners. China Architecture & Building Press: Beijing, China, 2019.
76. Bai, J.-b.; Zhang, Y.; Lu, J.; Li, L.-h.; Wu, H.-j.; Zhang, J.-y. Energy Efficiency Retrofit of Existing Residential Buildings in the South of Jiangsu Based on Life Cycle Assessment. *Build. Sci.* **2013**, *29*, 59–64.
77. Yang, J.; Cong, G.; Peng, J. The impact of the external window shading on residential energy consumption in Hot summer and cold winter areas. *Constr. Wall Innov. Build. Energy Sav.* **2009**, 48–50. [CrossRef]
78. General Administration of Quality Supervision Inspection and Quarantine of China; Standardization Administration of China. *The Minimum Allowable Values of the IPLV and Energy Efficiency Grades for Multi-Connected Air-Conditioning (Heat Pump) Unit GB 21454-2008*; China Architecture & Building Press: Beijing, China, 2008.
79. Wang, X.; Lu, M.; Mao, W.; Ouyang, J.; Zhou, B.; Yang, Y. Improving benefit-cost analysis to overcome financing difficulties in promoting energy-efficient renovation of existing residential buildings in China. *Appl. Energy* **2015**, *141*, 119–130. [CrossRef]
80. Gou, S.; Li, Z.; Nik, V.M.; Scartezzini, J.L.; Zhao, Q. Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand. *Energy Build.* **2018**, *169*, 484–506. [CrossRef]
81. Yu, J.; Xu, X.; Wang, J.; Tian, L.; Yang, C. Optimum insulation thickness of residential roof with respect to solar-air degree-hours in hot summer and cold winter zone of China. *Energy Build.* **2011**, *43*, 2304–2313. [CrossRef]
82. He, Q.; Ng, S.T.; Hossain, M.U.; Skitmore, M. Energy-efficient window retrofit for high-rise residential buildings in different climatic zones of China. *Sustainability* **2019**, *11*, 6473. [CrossRef]
83. Li, X. *Green Retrofitting for Existing Reidential Building-Technical Guide*; China Architecture and Building Press: Beijing, China, 2016.
84. Xiao, X.; Cao, Y.; Li, D.; Liang, Y. Relationship between the Depth of Horizontal Shading Board and Building Energy Consumption in Hot Summer and Cold Winter Zone. *Ind. Constr.* **2014**, 49–89. [CrossRef]
85. Jiang, D.-m.; Liu, H.-c. Study on the Energy-saving Reconstruction to the Open-styled Staircase of the Existing Residential Buildings in Hot-summer and Cold-winter Region. *Build. Energy Effic.* **2008**, *36*, 32–34. [CrossRef]
86. Suo, J.; Wu, D.; Tian, D. *Study on Sustainable Renovation of Urban Existing Housing in China*; China Architecture & Building Press: Beijing, China, 2015.
87. Engineering Earthquake Resistance Institute of China Academy of Building Research. *Residential Building Graphic Design Reference Atlas/Zhu Zhai Jian Zhu Ping Mian She Ji Can Kao Tu Ji*; Engineering Earthquake Resistance Institute of China Academy of Building Research, 1992.
88. *GB 50176-1993*; Code for Thermal Design of Civil Building. China Architecture & Building Press: Beijing, China, 1993.
89. *GB 50176-2016*; Code for Thermal Design of Civil Building. China Architecture & Building Press: Beijing, China, 2016.
90. *DBJT03-22-2005*; 05 Series Building Standard Design Atlas, 05J1-3. Shanxi Architectural Engineering Design Co.; China Architecture & Building Press: Beijing, China, 2005.
91. Chen, B.; Kang, J. Low Carbon Architecture in the UK: Research and Development (R&D) from an Integrated Perspective. *World Archit.* **2010**, 54–59.
92. *JGJ 134-2010*; Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone. China Architecture & Building Press: Beijing, China, 2010.
93. Chen, S.; Li, N.; Yoshino, H. Statistical analyses on summer energy consumption characteristics of residential buildings in some cities of China. *Energy Build.* **2010**, *42*, 136–146. [CrossRef]
94. Chen, S.; Li, N.; Yoshino, H.; Guan, J.; Levine, M.D. Statistical analyses on winter energy consumption characteristics of residential buildings in some cities of China. *Energy Build.* **2011**, *43*, 1063–1070. [CrossRef]
95. Yoshino, H.; Yoshino, Y.; Qingyuan, Z.; Mochida, A.; Nianping, L.I.; Zhenhai, L.I.; Miyasaka, H. Indoor thermal environment and energy saving for urban residential buildings in China. *Energy Environ. Resid. Build. China* **2006**, *38*, 1308–1319. [CrossRef]
96. Djamila, H.; Chu, C.-M.; Kumaresan, S. Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia. *Building Environ.* **2013**, *62*, 133–142. [CrossRef]
97. *GB 50034-2013*; Standard for Lighting Design of Buildings. China Architecture & Building Press: Beijing, China, 2013.
98. Yu, J.; Yang, C.; Tian, L. Low-energy envelope design of residential building in hot summer and cold winter zone in China. *Energy Build.* **2008**, *40*, 1536–1546. [CrossRef]
99. HM Government. *The Building Regulations 2010 L1B Conservation of Fuel and Power in Existing Dwellings*; RIBA Workshop: London, UK, 2010.
100. Passive House Institute. *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, Version 9f, Revised 15 August 2016*; Passive House Institute: Darmstadt, Germany, 2016.
101. Liu, X.e. *Jiangsu Province Housing Renovation Project Valuation Table (Civil Engineering) 2009 Edition*; Southeast University Press: Nanjing, China, 2010.

102. Jiangsu Provincial Department of Housing and Urban-Rural Development. *Jiangsu Province Construction and Decoration Engineering Valuation Quota*; Jiangsu Science and Technology Press: Nanjing, China, 2014.
103. Parkinson, T.; de Dear, R.; Brager, G. Nudging the adaptive thermal comfort model. *Energy Build.* **2020**, *206*, 109559. [CrossRef]