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Review

A Review of Building Energy Retrofit Measures, Passive Design Strategies and Building Regulation for the Low Carbon Development of Existing Dwellings in the Hot Summer–Cold Winter Region of China

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Abstract: Retrofitting buildings to achieve improved levels of energy performance is a key strategy in the transition to a low-/net zero carbon future. In China, there has been an enormous growth in residential construction in recent decades in response to the country's economic development and population growth. However, although these buildings are structurally solid and have long functional life spans, most have very poor thermal performance. Therefore, they would be very suitable for energy retrofitting. Because of the variety of retrofitting options, it is important to review the retrofit measures, regulations and possible outcomes to find effective, long-term solutions that strike a balance between the energy saved, the carbon emitted and the financial costs over a building's lifetime. This paper reviews suitable retrofit measures for the hot summer–cold winter region of China, because this is an area with huge numbers of residential buildings that are suitable for energy retrofitting. The study explores the current conditions of targeted residential buildings, retrofit schemes, building regulations, and policy gaps towards achieving China's 2060 carbon neutrality goal. The review indicates that current mandatory building energy regulations in this region are not ambitious enough to achieve a significantly lower carbon future, and one-step deep Passivhaus retrofit schemes are recommended to achieve decarbonization goals.

Keywords: energy retrofitting measures; building decarbonization; policy gap; building regulation; hot summer–cold winter climate

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1. Introduction

Improving the energy efficiency of buildings is a potential way to mitigate climate change, because the building sector has been a major energy consumer and contributor to greenhouse gas emissions. The International Energy Agency stated that buildings, together with the construction industry, consume about 30% of global energy production and are responsible for approximately 27% of global carbon emissions [1]. It is also illustrated by the IEA that all new buildings, and 20% of the existing building stock, need to be highly energy efficient by 2030 to achieve a net zero emission scenario by 2050 [2].

China is the biggest energy consumer in the world, and is responsible for about 26.5% of the world's primary energy consumption [3]. The building sector in China accounts for 45.5% of the country's yearly national energy consumption and is responsible for around 50.9% of national carbon emissions [4]. This suggests that changes in the building sector are particularly urgent for China. However, it is also challenging, since China is still undergoing urbanization and, together with the increasing expectation of thermal comfort, Chinese building operational energy consumption has been experiencing a rapid growth in many regions.

It is essential for new buildings to be built with a high level of energy performance, since this will affect the energy consumption in the following decades. In China's context, although the new construction area is expanding every year, the existing building stock had reached 69.6 billion square meters in 2020 [5]. More than 90% of these existing buildings have poor energy performance, including many of those that were built in recent years [6]. Their inadequate energy performance has placed tremendous pressures on energy resource conservation, such that retrofitting these existing buildings to improve their energy performance is a solution to moderate this pressure and make efforts towards more sustainable building development [7]. The Chinese Ministry of Housing and Urban–Rural Development divides China into five major climate zones based on the main climate features. The hot summer cold–winter climate zone, located in the central–southern part of China, experiences weather conditions during which the mean outdoor temperature is usually between 25 and 30 °C in summer and 0 and 10 °C in winter. Residential buildings in this region require particular attention for retrofitting, because about 40% of China's population is living here and they deal with very poor thermal conditions of hot and humid summers and damp cold winters. This region is currently responsible for around 45% of the total building-related energy consumption in China, and higher consumption is expected due to the higher thermal comfort expectations of the residents [8].

However, retrofitting buildings in this climatic region can be very challenging considering the large scale, harsh climate, and that the construction industry is not familiar with energy retrofits. On the other hand, it is a necessary step towards a net zero future, and it should be done in a sustainable and efficient way that keeps on track with the national plan of decarbonization. The Chinese government plans to achieve the country's carbon emission peak in 2030 and then be "carbon neutral" (net zero carbon) by 2060 [9]. Therefore, the realistic planning of efficient building retrofit schemes, which holistically consider the climate features, building status, retrofit methods and predicted results, should be made for this ambitious goal to be met.

This study aims to assess the retrofitting measures made for the existing residential buildings under the hot summer–cold winter climate region, and to identify the potential retrofit methods that are able to fill the gap between current poor energy performance buildings and the net zero building goal. For this purpose, a comprehensive review of retrofit measures and their outcomes is provided in this paper. Additionally, the study considers the climate characteristics and energy and thermal performance of the existing buildings, as well as examining passive retrofit measures suitable for these buildings. Furthermore, this study reviews current mandatory and voluntary building regulations and policies, and compares them with advanced international building standards. Finally, the paper discusses policy gaps and retrofit suggestions to provide a clear insight into and recommendations for retrofitting existing residential buildings in hot summer–cold winter climate regions, with a focus on enhancing energy performance and moving towards net zero building goals. By adopting this research process, the study should provide a thorough analysis of retrofitting measures, consider the local climate and building characteristics, and examine the effectiveness of existing policies and regulations. The outcome of this study is a set of recommendations that can be applied to improve the energy performance of existing residential buildings in the hot summer–cold winter climate region, and contribute towards achieving net zero building goals.

2. Review on Retrofit Approaches

2.1. Retrofit Measures

There are many types of retrofit measures that can improve the energy efficiency of existing buildings. Wang and He have summarized these practical and applicable measures from examples of retrofitting in China, and grouped them into three main categories [10,11]. Figure 1 illustrates the three categories, which are linked with the three main aims of achieving energy conservation, energy generation and energy management in building retrofitting.

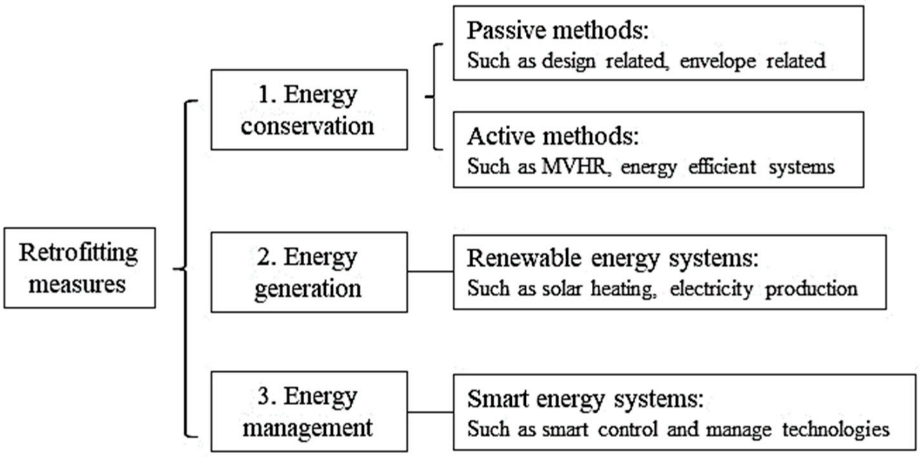


Figure 1. Retrofitting measures categorized by different purposes [10,11].

2.1.1. Energy Conservation-Related Passive Measures

Among all the different retrofitting measures, those related to reducing the energy demand and consumption in buildings should be the most essential measures because they directly reduce greenhouse gas emissions. The energy conservation-related measures could be categorized into the two aspects of passive measures and active measures. The passive measures are climate- and location-related, and each building is worth individual analysis when deciding on the suitable passive measures [12]. Building geometric design, such as the building shape factor, could significantly impact on a building's energy performance and thermal comfort in regions with hot summers and cold winters, because it affects the amount of heat gain and loss through the building's surface. Buildings with a large surface area relative to their volume may require more energy to maintain indoor comfort during summer and winter. Similarly, building orientation and window size are also significant because these significantly affect the solar gain from the sun, natural ventilation efficiency and natural lighting in buildings [13–15]. In retrofitting projects, it could be quite challenging to improve those geometric features because of the physical limitations of the existing structure [16]. However, Felius studied building forms in terms of low-energy retrofitting, and found that apartment buildings are relatively cheaper to retrofit because the external walls and roofs already have higher energy efficiencies than other building elements [17]. Apartment buildings are the main residential building type in China as a result of the demand for quick development to cope with population growth.

Passive heating and cooling methods, that assist with solar heat gain in winter and avoid excessive heat gain and overheating in summer, are significant approaches in building retrofitting. With those passive measures, it is possible to decrease the energy consumption of active heating and cooling [18]. The selection of passive heating and cooling measures is highly influenced by the climate type in which the building is located. The suitable measures for the target climate in this paper are reviewed in a later section.

Passive measures for improving the envelope thermal performance usually involve insulating the exterior walls, roof and ground floor, and utilizing the better thermal performance of windows, which all promotes an enclosure that significantly decreases the thermal heat transfer between the indoor and outdoor environments, so that more stable and comfortable indoor thermal conditions can be maintained, and the energy demand of the conditioning system is decreased [19]. Insulating the building envelope has been considered as an efficient method in cold climates, and helps with reducing the cooling demand in places with hot climates. The thermal insulation layer could separate the indoor conditioned air from the high outdoor temperature, and reduce cooling energy dissipation. Insulating the building envelope is usually a key measure that is required in deep energy retrofitting, which aims to achieve very low energy consumption, as it also assists in creating a steady indoor environment that allows other systems to work at a more desired efficiency [20]. However, within a climate warming scenario, it is important to include future climate possibilities in decisions on the insulation material's thickness, for the sake of avoiding overheating in the future [21,22]. This is also relevant to minimizing the initial carbon emissions from the retrofitting, as insulating materials account for a big part of the carbon emissions that result from manufacturing retrofit-related materials [23].

Currently, mineral and fossil fuel-derived insulation materials, such as stone wool, glass wool and XPS, are the most commonly used materials because of their good thermal performance in terms of costs [24]. The novel material aerogel is considered as an optimal insulation due to its outstanding thermal conductivity (~0.013 W/mK) and comprehensive performance in terms of acoustics and fire resistance [25]. Silica aerogels are increasingly used in building insulation, with opaque blankets and renders being common. Aerogel glass bricks are a novel, highly insulating, and translucent building component that provides new design opportunities for increasing daylight inside buildings [26]. However, aerogels are vapor-permeable and have a relatively high embodied energy when compared to the common conventional insulation materials [25]. In addition, Icynene, an open-cell spray foam, has a better overall performance due to its combined benefits in terms of high vapor-permeability, low density and low embodied energy [27]. Gianluca compared over 20 insulation materials and concluded that traditional insulation materials, such as stone wool and glass wool, are still very competitive due to their fire resistance, waterproofing properties, and less restricted durability. Natural insulation materials have a higher percentage of renewable embodied energy and carbon sink properties, making them competitive. However, innovative high-performance insulation materials, such as aerogel, have high environmental impacts, hindering their application in the buildings sector. Standardization and transparency in manufacturing and information conveyed by program operators are desirable for all insulation materials [28].

Windows are a significant part of a building's façade, and while they typically represent a smaller area than the external opaque walls, they generally lose a greater amount of heat. Research about the function of windows discussed a case study building wherein the windows accounted for only 14% of the total external walls and roof area, while the heat loss from the windows was 48% of the total loss [29]. Upgrading to triple-glazed windows is a high efficiency retrofit measure that improves the thermal performance, and visual and acoustic comfort, as well as decreasing the condensation risk and air leakage [27]. However, the change to high-efficiency windows is a relatively costly retrofit measure, whereby the cost benefit is less than its carbon-saving benefit [30].

Airtightness is another factor that influences the envelope performance. It is a measure of the amount of intended (ventilation) or unplanned (infiltration) airflow between an enclosure and the outdoor environment. The worse the airtightness performance is, the more the thermal (heating or cooling) demand is increased [31]. There are many factors that influence a building's airtightness level. Martin summarized them into four categories of geometry, technology/material, guidance, and other, in which highly significant factors included envelope structure, building method, ventilation system and workmanship in relation to the design target [32]. The author also highlighted the lack of effective tools available to help designers and other actors in decision-making for airtightness design. The lack of standardization and the difficulty of modeling the parameter of workmanship are reasons that hinder the development of new tools [32]. Nevertheless, there are tools available, such as PHPP, a modeling tool that been highly recommended by the AECB Retrofit Standard in the UK for minimizing thermal bridge and airtightness design [33].

2.1.2. Energy Conservation-Related Active Measures

Active measures related to energy conservation are used to improve the efficiency of energy use in buildings, such that the total amount of energy consumed can be decreased. Standard measures include improving the energy efficiency of building systems, such as heating and cooling systems, adopting heat recovery systems, and improving lighting efficiency and the efficiency of other assistive applications [10]. For example, low-energy efficiency boilers could be replaced with modern high-energy efficiency boilers, thereby saving energy for the same activity [11]. A mechanical ventilation system with a heat recovery (MVHR) function can be adopted in deep retrofitting, such as buildings targeted for Passivhaus retrofitting to the EnerPHit standard, or low-/zero-energy buildings. However, a well-insulated envelope with a very low air infiltration rate is usually required as a foundation for an MVHR system to achieve its designed efficiency in operation [34]. Replacing traditional lighting with LED (light-emitting diode) lighting is another energy-efficient step, as the energy efficacy (emitted luminous flux in lumens to the expended electric power in watts) of an LED lamp is about 150 to 200 lm/W, while that of a traditional type of compact fluorescent lamp is about 50 to 100 lm/W. However, the price of LED lighting is about three times higher than traditional lighting in many parts of China [11,35].

Upgrading existing building systems and equipment is a straightforward way to improve energy efficiency. Dubois reviewed over 160 research articles and stated that the current knowledge about the actual energy performance of existing equipment is quite limited, and therefore, the users are unclear about the energy saving potential the new equipment could represent, and they tend instead to exchange applications at the end of their equipment's life [36]. More attention should be paid to the optimization of individual replacements integrated into the whole building system, which considers the occupants behavior and their control of the indoor thermal environment, in order to minimize the predicted and actual energy saving in retrofits [37].

2.1.3. Energy Generation Related Measures

The integration of renewable energy measures into building retrofitting is a common approach to achieving low- or zero-carbon energy targets, where the renewable energy generated can offset the consumed energy. In China, the most commonly used renewable sources include solar hot water, solar photovoltaic PV, wind power and hydroelectric [38]. However, due to factors such as site access, neighboring surroundings, and building function, rural residential buildings typically have a greater potential for adopting renewable energy technologies than urban residential buildings. This is because these conditions are often lacking in highrise residential buildings in densely populated urban areas [11].

To promote the use of renewable energy in buildings, especially in rural and remote areas, the Chinese government has issued a series of policies encouraging the application of renewable energy technologies such as biomass, household solar energy, small-scale wind energy, and hydropower. These policies have also been incorporated into building energy-efficient design and assessment codes, which consider the different climatic characteristics of various climate zones in China [39]. However, the key barriers to renewable development in China include immature technology, a lack of complete national and industrial standards for related technologies and products, a lack of security architecture for products and facilities, high initial development costs compared to conventional energy, the limited availability of raw materials, the inadequate supply chain, lower profit levels of the solar PV industry, and insufficient policy support from the government [39]. The utilization of wind energy in buildings is still at an exploratory stage; the current trend of wind energy systems development includes building integrated vertical-axis wind turbines, power windows, wind-induced vibration-based wind energy harvesters, double skin and other innovative building façade systems, and wind source exploration [40].

Local renewable energy generation is considered as a significant step towards sustainability. A study about the optimization of PV, wind and diesel hybrid energy systems suggested that energy decentralization has great potential benefits in energy usage efficiency, cost and carbon saving [41]. Heat pumps and solar photovoltaics are the most applicable renewable energy technologies for thermal conditioning and electricity generation in buildings. However, they require storage systems to improve their efficiency. While electricity storage batteries have the drawbacks of high cost and low efficiency, phase change materials have great potential for heat storage because they allow heat to be accumulated during low consumption periods and recovered during high consumption periods [42]. For historic buildings, solar and wind energy may not be acceptable due to technical, economical, informative, and legislative barriers. Geothermal energy, on the other hand, is more acceptable in historic buildings, but there is currently limited literature on its specific application in this context [43].

2.1.4. Energy Management-Related Measures

Energy management-related measures are technologies capable of smart monitoring, managing and controlling the building systems and applications to reduce energy consumption in buildings [10]. Sensor control for lighting is a relatively advanced technology that allows lighting energy consumption reduction while providing lighting comfort to residents [44]. Wireless technologies linked with smartphones give occupants a more convenient way to manage household devices and applications [45]. Moreover, the development of big data and data management, as well as research and development into data analysis, decision-making and event management, are possible means to provide better efficiency in energy usage in the future [46]. Whole-building smart energy management systems have the potential to optimize energy saving and thermal comfort control in buildings though the use of Building Information Modeling (BIM) and smart sensor systems. Building users should not lose the control of their building environment, but their behavior could be assessed by the real-time energy use feedback from the smart system [47]. However, this requires further research, in which machine learning models should play an important role because they have been more deeply developed with massive building operational data in the past few decades [48].

2.2. Retrofit Outcomes

Energy saving, environmental impact reductions and improvements in thermal comfort during the operational energy period are the most direct and desired outcomes from building energy retrofitting [49]. However, many factors need to be considered in achieving a significant retrofitting result, such as climate characteristics, existing building conditions, and retrofitting targets and budgets. Therefore, according to the specific context of each building, the combined adoption of a selection of retrofitting measures is usually required for boosting the retrofitting outcome by the thermodynamic performance and physical interactions between the different measures [16]. Many multi-objective retrofitting studies have looked at optimal retrofit strategies, and some examples of recent comprehensive reviews into this can be found in [50,51]. A recent study in northern China used a multi-objective optimization framework to evaluate retrofitting options for rural dwellings. The framework considered carbon emissions, indoor thermal comfort, and cost-effectiveness, and identified prioritized factors for the Hebei area as sunspace, insulation thickness, south-facing external window material, porch overhang depth, and roof PV panel area and angle. The optimal results showed significant reductions in carbon emissions and indoor thermal discomfort time, but also an increase in global costs [52]. In addition, the building regulations or assessment criteria that the retrofits seek to achieve are directly correlated with the outcomes in energy savings and greenhouse gas reductions after the retrofit is completed [38]. Similarly, shallow and deep retrofits are referred to in practices based on the selection of retrofit measures and expected outcome.

2.2.1. Shallow Retrofit

A shallow retrofit usually refers to basic and traditional measures that alter the existing building to improve building or system efficiency, and retrofit decisions are usually made with the awareness of the users. Typical retrofit measures include the changing of an old boiler or lights at their life end [27]. The outcome of shallow retrofits could vary depending on the measures and conditions of the building. For example, applying insulation to different building components can result in different energy saving outcomes, and the availability of existing building conditions, such as cavity spaces in walls or an attic space in the roof, may limit the insulation application. Simple retrofits are less costly and more likely to yield faster cost payback than deep retrofits [53].

2.2.2. Deep Retrofit

A deep retrofit includes a holistic approach that aims to achieve large improvements in the building's energy efficiency through applying multiple measures, which include building envelope thermal performance improvements and building system upgrades. A deep retrofit usually benefits from dynamic building energy simulations in order to plan a reliable and explicable retrofit approach in which interactions between many parameters are considered for a comprehensive building performance upgrade. One study compared a simple retrofit approach that replaced old equipment with new equipment that met local standard efficiency requirements, via an integrated deep retrofit approach. It was concluded that energy savings of up to 84% could be achieved with the deep approach, while only a 13% saving was achieved with the simple approach [37]. A deep retrofit that plans to meet targets such as the zero-energy building standard or the Passivhaus Plus standard could achieve even higher energy conservation or generation results with the integration of renewable energy systems. In addition, some governments consider deep retrofitting as the only way to achieve their carbon reduction targets. For example, the Scottish government reported that a deep retrofit approach including envelope improvements and the use of new systems is needed for achieving their program of bringing residential energy efficiency up to Energy Performance Certificate EPC level C or higher [54].

3. China's Hot Summer–Cold Winter Climate and the Housing Situation

3.1. The Hot Summer–Cold Winter Climate

Adaptation to climate is one of the most critical principles for low-energy buildings. Therefore, it is important to first understand the specific characteristics of the climate in the target area before developing any strategy for the retrofitting of buildings to save energy. This section aims to provide an overview of the climate characteristics of the hot summer–cold winter climate, which is prevalent in a large area of central and southern China. According to the Chinese Ministry of Housing and Urban–Rural Development, this climate type covers 14 of the country's 22 provinces, as shown in Figure 2 [55]. The main indicator that [56] identified for this climate regionalization was based on the outdoor monthly mean temperatures in January (the coldest month) and July (the hottest month), which should be within the ranges of 0–10 °C and 25–30 °C, respectively. Another significant characteristic of this climate region is the high relative humidity level, with the yearly mean value usually around 70–80%. The hot summer–cold winter climate zone is a large geographical area, and therefore incorporates differences in local climates. For example, the eastern region faces the sea and is generally windier, while the middle region has a relatively more humid summer, and the western part has less solar radiation [56]. However, the common features of extreme temperatures and relative humidity contribute to significant challenges in this large region in terms of buildings performing well in terms of both thermal comfort [57] and energy conservation [58].

The software Climate Consultant 6.0 (SBSE, 2021), which employs the typical meteorological year (TMY) weather data from the China Meteorological Administration [59], was used to review the overall outdoor dry bulb temperature and relative humidity for five typical and major cities in the studied climate region. Figure 3 shows the common characteristics of a wet cold winter and humid hot summer. The temperatures in the five cities are distributed between 4 and 8 °C in January and 25 and 29 °C in July, and the relative humidity levels all trend flatly all year round at 80%. A study [60] compared eight capital cities in provinces under this climate region using weather data from the Meteorological Information Centre in China. The results show that the number of days in which the temperature was above 35 °C in a year was between 16 and 30 days, while the number of days below 5 °C in a year was between 45 and 83 days.

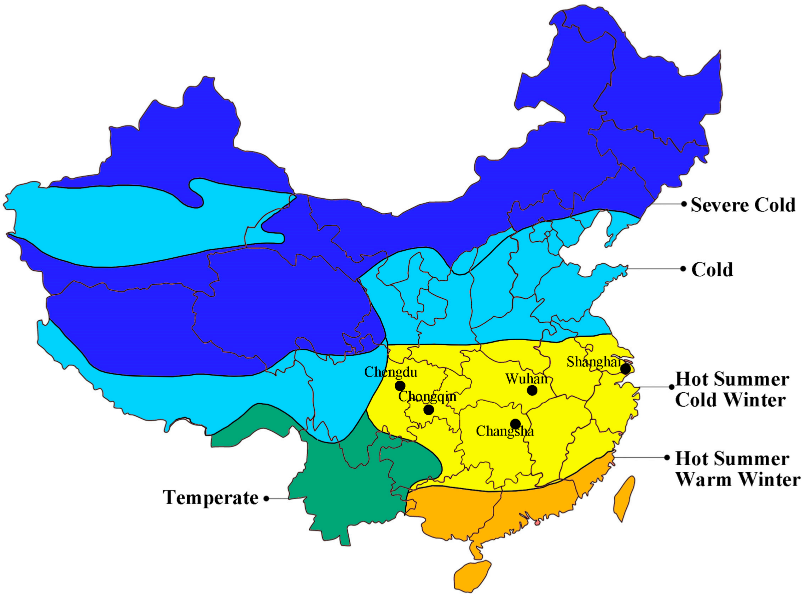


Figure 2. The climate regionalization in relation to architecture and province division in China [56].

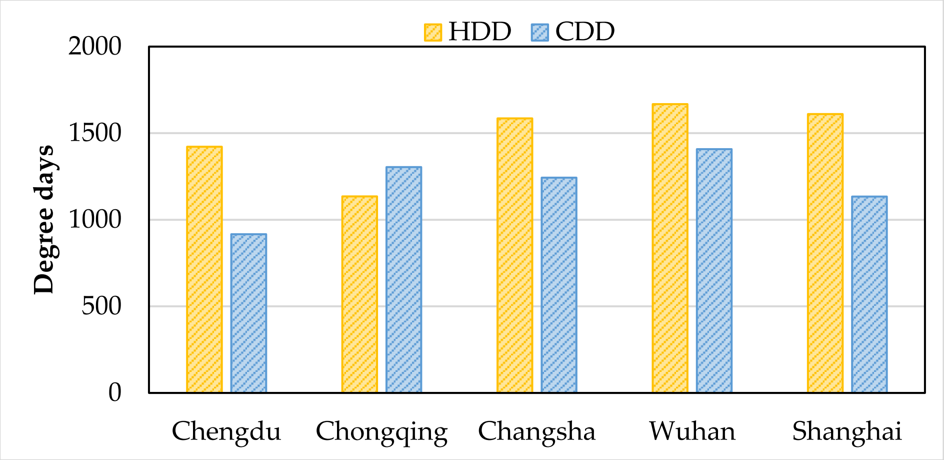


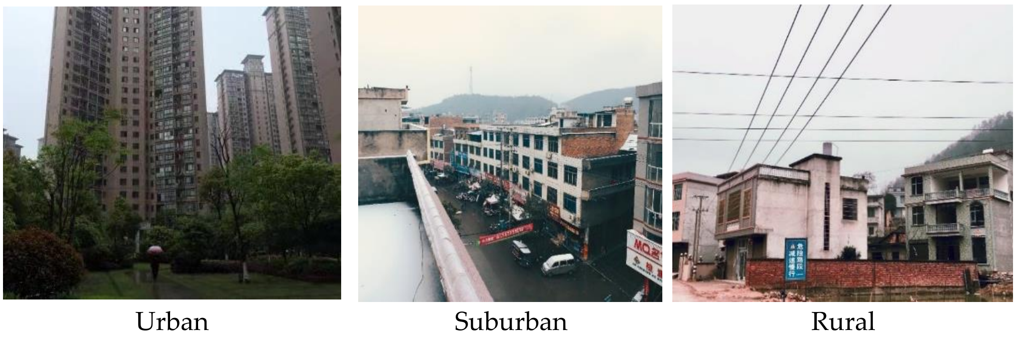
Figure 3. Yearly HDD and CDD in five main hot summer–cold winter climate cities [61].

Heating degree days (HDD) and cooling degree days (CDD) are common measures used to represent climatic conditions, and so the HDD and CDD were derived in this study for five cities in the hot summer–cold winter zone using the global Klimaat Consulting database, which considers a baseline of 18 °C for both HDD and CDD [61]. Figure 3 shows an HDD distribution of 1135–1668 degree days, and a CDD distribution of 917 to 1408 degree days. However, the Chinese code for the thermal design of a civil building considers a much hotter baseline for CDD, which is 26 °C. Therefore, the CDD number would be significantly decreased. As an example, for a typical city in the studied climate region, Changsha, its CDDs decreased from 1243 to 230 [55]. However, Changsha's heating requirement is still considered moderate compared with northern Chinese cities such as Beijing (2450 HDDs) under the same baseline, and those of many European countries [62]. In conclusion, this region experiences relatively extreme temperatures and high humidity, which leads to high energy consumption in residential buildings due to the dual demand of space heating and cooling. Understanding the climate characteristics and requirements of the region is essential for developing effective strategies to retrofit buildings and improve energy efficiency.

3.2. Housing Situation

Understanding the general housing situation and energy consumption patterns in the hot summer–cold winter climate in China is crucial for developing effective strategies to retrofit buildings and improve energy efficiency. According to a report from the China Association of Building Energy Efficiency (CABEE) in 2022, there was a total of 69.6 billion m^2 of existing building floor area in China, of which 32 billion m^2 (46%) and 23.3 billion m^2 (34%) were in urban and non-urban areas, respectively [63]. The hot summer–cold winter climate region is a relatively densely populated region in China, and there is massive existing residential building stock in both urban and rural areas. As regards residential buildings, the differences between them more concern geometry, size and design, rather than building materials and thermal performance.

The modern urban residential structures are mostly high-rise apartment buildings (more than 10 stories) with several flats on each floor, and they are usually situated within densely populated surroundings. In suburban areas, most modern residential structures are low-rise and medium-rise apartment buildings, which usually only have one flat on each floor, and are usually built in rows along the street. For rural areas, most residential buildings are low-rise dwellings in which the layout of function rooms may be scattered on different floors, and they usually have more open surroundings. Figure 4 shows examples of these buildings. In terms of building materials, their structures are mostly built with concrete and steel, and brick is the primary material for the envelope; the windows mostly consist of a single layer of glass [64]. According to [63], steel and cement are the two most common materials associated with carbon emissions, and are responsible for 45.5% and 21.3% of the total embodied carbon of national building material production. Fortunately, those existing residential buildings built in the past several decades are structurally sound and are expected to function for many years. Thus, the proper retrofitting of those buildings to suit occupants' increasing expectations regarding the comfort of modern life could represent the most sustainable means to make the best use of those energy-intensive building materials.



Urban Suburban Rural

Figure 4. Examples of modern residential buildings in different locations.

3.2.1. Energy Consumption of Existing Housing

As an overview of the building sector in China, the energy consumed during the operational stage was responsible for 21.7% (about 1 billion tons coal equivalent) of the 2020 national energy consumption, in which urban and rural housing accounted for about 42% and 20%, respectively [63]. In China, the northern regions (including both cold and severe cold climate regions) have the largest proportional energy consumption, but this proportion has been declining in the last two decades because of the increase in energy consumption in the southern hot climate regions, with the hot summer–cold winter climate regions having an energy consumption average growth rate of 6.5% between 2010 and 2020. In 2020, the energy consumption in the hot summer–cold winter climate regions was responsible for 33% of total national building-related energy consumption [63]. In addition, considering that the need for active heating and cooling is increasing in this climate region, its energy demand is expected to show a significant increase in the near future [58].

In the hot summer–cold winter climate regions, split air conditioning units are the main method of supplying both heating and cooling, and it is assisted by electric fans in summer and plug-in heaters in winter [58]. Figure 5 shows the average number of air conditioners per 100 households in China, which in both urban and rural areas was increasing in the period between 2014 and 2020. For urban areas, this figure is double that of rural areas, suggesting the energy consumption and thermal comfort difference could be significant between them [65]. The carbon emissions produced by space heating and cooling increased nearly threefold in urban areas, and slightly more than doubled in rural areas, in the period between 1996 and 2012 [66].

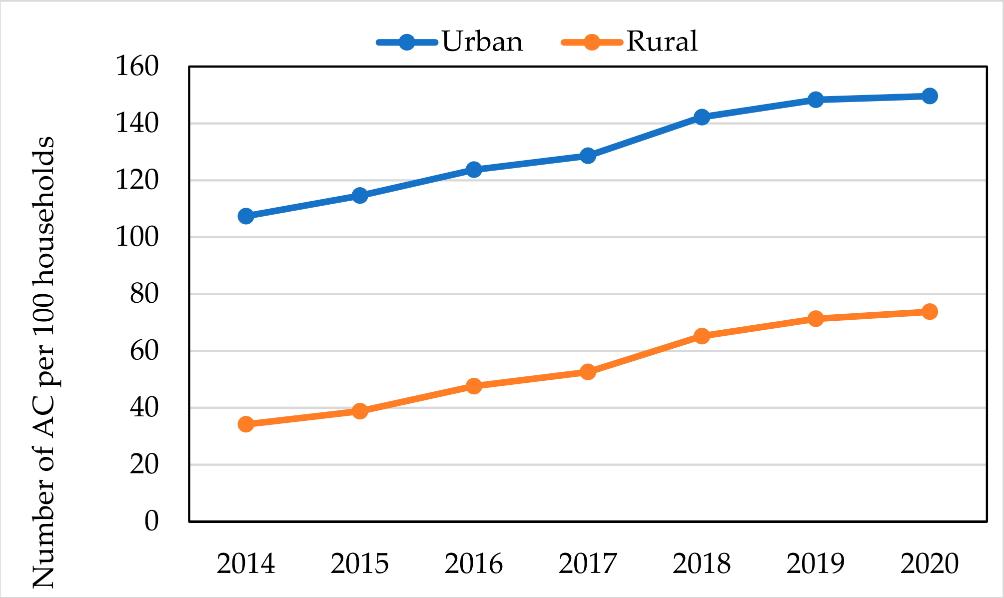


Figure 5. The growth in air conditioners per 100 households in China 2014–2020—adapted from [61].

Wang carried out a large-scale heating demand study based on the onsite measurement of 1075 households in the hot summer–cold winter climate area during the winter period between 31 December and 28 February. The findings show an average yearly winter electricity heating demand of 654.19 kWh per household and 662.5 kWh per household at the 50th percentile, and the demand ranged up to 4867 kWh. The households using split AC and distributed electricity heaters consumed, on average, 133 kWh and 62 kWh electricity yearly more than the households without heating at the 10th percentile. The author concluded that households with a large size, more elderly family members, and high income tended to consume higher amounts of electricity for heating, and that energy retrofits applied to residential buildings in this climate region should be accelerated [67].

3.2.2. Thermal Comfort of Existing Housing

Due to the heating policy in China, under which central heating systems are not provided in the hot summer–cold winter climate region, the residents in this region have for a long time had to adapt themselves to the extreme weather. As living standards improve, air conditioning is becoming the main active method that the occupants utilize to condition the poor indoor thermal environment resulting from the hot summer–cold winter climate, and consequently, the energy consumption for heating and cooling has been increasing [68]. However, Wang investigated 513 households' energy consumption and concluded that (i) 84% of the household occupants chose to turn on the air conditioner in winter when they were at home and feeling cold; (ii) 90% of the study's occupants felt cold when the indoor temperature dropped below 12 °C, and (iii) 73% of them selected to turn off the air conditioner for heating during sleep. This suggests that the hours during which the occupants had a relatively comfortable conditioned indoor environment were not long, and the overall comfort level should not be considered satisfactory compared with many international standards [68].

For the actual indoor thermal environment under the studied climate region, on-site indoor temperature data were recorded in an urban and a rural residential building, which were built before 2005 and 2010, respectively [63]. Both types of buildings were measured under a mixed-mode situation in which the buildings operated under free-running conditions most of the time, and the air conditioner was turned on when the occupants felt it was required. Figure 6 shows a summary of the recorded data, where the indoor mean temperatures for both the urban and rural housings were around 30 °C and 10 °C in summer and winter, respectively, and the difference between indoor and outdoor environments was not significant. A study measured 152 households in major cities in China, and the findings suggest the average indoor temperatures of the 26 measured households in the hot summer–cold winter cities were 3–6 °C lower than in the cities in other parts of the country in winter, and the indoor thermal comfort was far below the ASHRAE comfort zone [69]. A study investigating occupants' thermal feelings under this climate through 2171 questionnaires (with 513 responses), showing that the rural residents had a higher tolerance of the indoor thermal conditions than the urban residents. However, both groups showed a strong preference for cooler summer and warmer winter indoor environments [59].

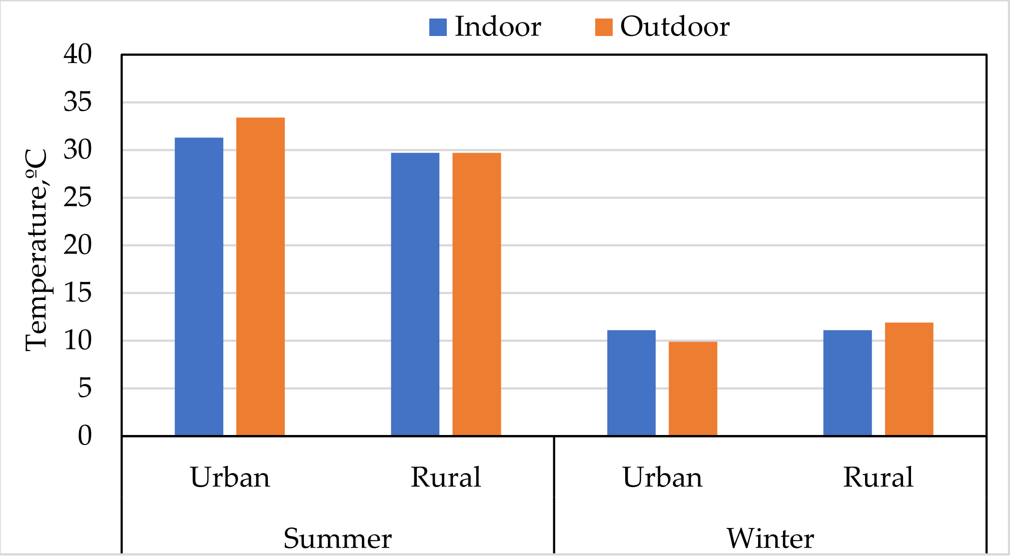


Figure 6. Measured indoor and outdoor average air temperatures in existing residential buildings in hot summer–cold winter climate regions, from [63].

In general, the level of indoor thermal comfort within the hot summer–cold winter climate could be considered poor. A large-scale field survey on indoor thermal environments concluded that the thermal comfort in this climate region was the worst among China's five climate zones [70]. There is no doubt that the residents in this climate region urgently need improvements in indoor thermal comfort. However, with the current poor thermal performance of buildings, energy consumption will significantly increase if active heating and cooling are operated to maintain a relatively good indoor comfort level when the building is occupied. Retrofitting those dwellings to improve building thermal and energy efficiency is an ideal solution for this issue. Retrofitting can provide occupants with a more comfortable indoor environment, reduce energy consumption, and improve their quality of life. These benefits should increase the willingness of the residents to engage in retrofitting their dwellings.

3.3. Passive Measures Suitable for this Climate

The Climate Consultant software program provides a quick way to the assess the general comfort level of residential buildings at a selected location based on the ASHRAE Standard 55-2010, and gives recommendations on strategies for improving the thermal comfort. Therefore, Climate Consultant was applied to weather data for the five cities mentioned in Section 3.1 for an overview of the studied climate. The results suggest that the dwellings in these five cities have poor thermal comfort ranges, as only 19% to 22% of the hours in a year met the comfort level. Suggestions for thermal comfort improvement measures are given and ranked by their effectiveness as follows:

- Active heating;
- Active cooling;
- Retain internal heat gains;
- Use fan-forced ventilation cooling;
- Use active dehumidification;
- Natural ventilation cooling;
- Sun shading of windows;
- High thermal mass;
- Thermal window with passive solar control;
- Two-stage evaporative cooling.

These measures cover both active and passive measures, and active heating and cooling are considered as the most effective measures that align with the climate features discussed earlier in the paper. Retaining internal heat gains is also recommended—an approach that is only achievable with an insulated building envelope. Related measures also produce good results according to Climate Consultant, including using high thermal mass and thermal windows. To achieve thermal comfort levels suitable for modern life while using as little energy as possible, the interaction between various measures should be well-planned to achieve the best effect. Although active heating and cooling are unavoidable in this climate, their energy loads could be reduced using adequate passive strategies to maximize low-carbon living [71]. Based on a review of recent studies on passive cooling and heating methods in different climate backgrounds, several passive methods were found with high potential to lower the energy demand for buildings in the studied climate region [72,73].

3.3.1. Passive Cooling Methods

For passive cooling, solar and wind control-related methods are frequently utilized in hot and humid climates. Shading is one of the most commonly considered passive solar cooling strategies, particularly for hot areas, and shading elements are designed in many shapes to suit the local surroundings and building geometry [74]. For example, Yu and Tian evaluated the performance of shading methods, including (i) horizontal/vertical overhangs, (ii) four types of window inner shading and (iii) outer louvre shading, on a six-floor residential building located in Changsha (a typical city in the studied climate region). The results show that the outside louvre shading was the most efficient type, allowing a 17.87% decrease in cooling energy consumption [75]. Similar research in Singapore, which has a hot and humid climate, showed energy savings ranging 2.6–10.1% after 0.3–0.9 m horizontal shading devices were applied [76], and this shading method reduces the indoor temperature by about 1 °C according to an earlier study by the same researcher [77]. The solar chimney is another solar cooling method, which utilizes the buoyancy effect whereby hot air rises out of the top of the chimney and cool air enters the building at lower levels. Passive downdraught evaporative cooling systems integrate a water system (a spray or wet pads) at the top of a tower to create a down flow of cooled air. However, it has been reported that this method works much less efficiently in a hot and humid climate than in a hot and dry climate [72]. A case study in Thailand's hot and humid climate suggested that indoor temperature decreased by between 2 and 6.2 °C in a wooden structure cell room that adopted a solar chimney with a dampened roof [78]. For the very hot and dry climate, the results measured at a Saudi Arabian library, which utilized two cooling towers that contain wet pads, showed a significant passive cooling effect, as the indoor air temperature was cooled to 25.8 °C when the outdoor dry bulb temperature was 46 °C [79].

Natural ventilation is an efficient method for diminishing the heat stored inside a building. Its efficiency is influenced mainly by the air temperature difference between indoor and outdoor environments, wind velocity and direction, and relative humidity [80]. For a hot summer–cold winter climate, however, this method is not highly recommended, as the indoor and outdoor temperature difference is slight in the summer period, even at night time [81], but it may still be a suitable approach during inter-season months [82]. A few published case studies have presented how this method works for a hot and humid climate, such as for a standard public housing block in Hong Kong, which reported an indoor temperature drop of 5 °C [83], while for two other cases, temperature decreases of 4 °C and 2 °C were recorded in traditional houses in India [84] and Beijing [85], respectively.

Radiative cooling is a method that utilizes cold water placed on a heated surface, such as a roof during the night time. Thus, the stored heat inside the building could be transferred into the water, and the water then dissipates the heat to the cooler air in the night time. This method was reviewed by [72] under a different type of climate, and the results suggest that its efficiency is quite high for hot and humid climates, as an energy-saving ratio between 8.2% and 44% was found in the reviewed cases. However, Zhao highlighted that this cooling method is only appropriate for buildings with large levels of surface area exposure to solar radiation and high interior wall temperatures, and so this method would have a lower efficiency in medium- or high-rise residential building cases [86].

3.3.2. Passive Heating Methods

Insulating the building envelope is one of the most common ways to improve heating efficiency in a cold climate, and it also contributes to the cooling efficiency in hot climates. For example, a study evaluated wall insulation in the hot summer–cold winter climate city of Shanghai, with results showing that both heating and cooling energy decreased, although heating energy decreased to a greater degree [87]. High-performance windows are highly regarded for decreasing the amount of heat escaping from the envelope in the winter time. However, research shows that they also contribute to improving the cooling efficiency in a hot climate [88], and that triple-glazed windows were more effective than double-glazed windows regarding energy demand for various window-to-floor ratios within the hot and humid climate of Malaysia [83]. Moreover, a decrease of between 3.4% and 6.4% in cooling energy was achieved by replacing single-glazing with double low-E glazing, as was recorded in a similar study from Malaysia [89].

In conclusion, by combining these passive cooling and heating techniques, it is possible to create a comfortable living environment while reducing the need for energy-intensive heating and cooling systems under this climate context. The factors that need to be considered when deciding on a passive retrofit strategy are the climate condition of a given location, and the specific building geometry and surrounding environment [76].

4. Building Standard, Retrofit Schemes in HSCW Climate

4.1. The Building Standards in this Climate

Building regulations provide a legal basis for guaranteeing that buildings have been constructed or retrofitted in a way that meets the requirements; therefore, setting suitable regulations that match the national energy conservation and carbon reduction targets is critical for the targets to be achieved. This section reviews the existing mandatory and voluntary building regulations in the studied climate region and international low-energy building standards, and makes suggestions related to building retrofitting in the studied climate with the aim of a low-carbon future.

4.1.1. Mandatory Building Regulations

China's first mandatory building energy saving regulation (code: JGJ 26-86) was issued in 1986, and focused exclusively on residential buildings in northern China, as this part of China is supplied with district heating that consumes a large amount of coal. The requirements of this regulation mainly focus on building geometry designs and the use of insulation materials. Since then, the building energy regulations have improved over time. Currently, three national regulations are mandatory for residential buildings within the different climate regions in China. For the climate studied in this research, the regulation "Design standard for energy efficiency of a residential building in hot summer–cold winter zone (JGJ 134-2010)" has been applied to residential building types, including new builds, retrofits and extensions. This regulation was first released in 2001 (version code of JGJ134-2001) and the renewed version (JGJ 134-2010) has been enforced since 2010. Apart from the national regulation, the provincial governments have also formulated local mandatory regulations according to the national regulations and the situation of the province. These local regulations are mostly addressed within "Design standard for energy efficiency of residential buildings", and they are supposed to be strictly enforced in conjunction with the current national regulation. They have been renewed comparatively recently, and four of the five provinces whose areas are completely under this climate had their local regulations renewed between 2014 and 2019, with the exception of Hubei province, as in that case, the first version from 2005 was not renewed, and it lapsed when the national regulation was renewed in 2010. There is also an upcoming revision of national regulation, as a new version has been drawn up that is adapted from the one current enforced (JGJ 134-2010). This was opened up to public review in 2020, but has still not been officially released. The currently enforced and upcoming national and local regulations are reviewed, and their main mandatory requirements summarized, in Table 1.

As shown in Table 2, the mandatory requirements for the residential buildings under the studied climate region mainly refer to building designs and envelope thermal performance. The building design requirements are basically the same between the national and the local provincial regulations, while in terms of the envelope thermal performance, the most recently released provincial regulations generally have higher requirements. Anhui province has the newest regulations compared with the other provinces, and its thermal requirements are appreciably higher than those set out in the national regulations, especially for tall buildings, for which the shape factor (the ratio of the external envelope area to the inner volume of a building) must be equal to or less than 0.4. For comparison, in Anhui's regulations, the roof and wall U-values are required to be in the range of 0.6–1.1 W/m^2K, while the range is 0.8–1.5 W/m^2K in the national regulations. More significantly, the U-value for windows is limited to the range of 0.26–2.4 W/m^2K in the Anhui regulation for various window-to-wall ratio conditions, while the national regulation has a much looser requirement of 2.8–4.7 W/m^2K. The requirements of the Anhui regulation are actually very similar to those of the upcoming national regulation, which could be because they were published at a similar time. The official release of the upcoming national regulation and its stricter requirements are expected to have a significant influence on the new builds in this climate region, because all the new builds should adhere to both national and local mandatory regulations. Moreover, the provincial regulations are also expected to be updated in order to be consistent with the new national standard, and together they will work more effectively towards building energy conservation. In terms of building energy performance, buildings that adopt the required energy-efficient design and envelope thermal performance measures of either of the current national or provincial regulations are expected to achieve 65% annual energy savings related to active heating and cooling compared to the buildings that do not meet those requirements. However, this energy conservation goal is only an expected result, rather than a mandatory requirement of those regulations.

Table 1. The main requirements of the mandatory national and provincial building regulations for residential buildings within the hot summer–cold winter climate zone.

	JGJ 134-2010 (National)	**DBJ43/001-2017 (Hunan)**	**DBJ/T36-024-2014 (Jiangxi)**	**DB34/1466-2019 (Anhui)**	**DB33/1015-2015 (Zhejiang)**	**New National (Review Stage)**
Building shape factor						
≤3 floors	0.55	0.55	0.55	0.55	0.55	0.57
4–11 floors	0.40	0.4	0.40	0.40	0.40	0.4
≥12 floors	0.35	0.35	0.35	0.35	0.35	0.4
Window-to-wall ratio (WWR)						
North	0.4	-	0.40	0.30	0.40	0.4
East and West	0.35	-	0.35	0.2/0.3	0.20	0.35
South	0.45	-	0.45	0.45	0.45	0.45
Heat transfer coefficient (shaper factor ≤ 0.4); Anhui: ≤6 floors/>6 floors						
Roof (D ≤ 2.5)	U ≤ 0.8	U ≤ 0.6	U ≤ 0.8	U ≤ 0.6/0.6	U ≤ 0.6	U ≤ 0.4
Roof (D > 2.5)	U ≤ 1.0	U ≤ 0.8	U ≤ 1.0	U ≤ 0.6/0.6	U ≤ 0.7	U ≤ 0.4
Wall (D ≤ 2.5)	U ≤ 1.0	U ≤ 0.8	U ≤ 1.0	U ≤ 0.8/0.9	U ≤ 1.0	U ≤ 0.6
Wall (D > 2.5)	U ≤ 1.5	U ≤ 1.1	U ≤ 1.5	U ≤ 1.0/1.1	U ≤ 1.2	U ≤ 1.0
Window (conditioned by different WWR range, noted in brackets)	U ≤ 4.7 (≤0.2)	U ≤ 3.6 (≤0.2)	U ≤ 4.7 (≤0.2)	U ≤ 2.6 (≤0.2)	U ≤ 2.8 (≤0.2)	U ≤ 2.8 (≤0.25)
	U ≤ 4.0 (0.2–0.3)	U ≤ 3.2 (0.2–0.35)	U ≤ 4.0 (0.2–0.3)	U ≤ 2.6 (0.2–0.3)	U ≤ 2.8 (0.2–0.3)	U ≤ 2.5 (0.25–0.4)
	U ≤ 3.2 (0.3–0.4)	U ≤ 2.8 (0.35–0.45)	U ≤ 3.2 (0.3–0.4)	U ≤ 2.6 (0.3–0.4)	U ≤ 2.6 (0.3–0.4)	U ≤ 2.2 (0.4–0.6)
	U ≤ 2.8 (0.4–0.45)	U ≤ 2.5 (≥0.45)	U ≤ 2.8 (0.4–0.45)	U ≤ 2.4 (0.4–0.45)	U ≤ 2.4 (0.4–0.45)	-
Envelope heat transfer coefficient (shaper factor > 0.4); Anhui: ≤6 floors/>6 floors						
Roof (D ≤ 2.5)	U ≤ 0.5	U ≤ 0.5	U ≤ 0.5	U ≤ 0.5/0.5	U ≤ 0.5	U ≤ 0.4
Roof (D > 2.5)	U ≤ 0.6	U ≤ 0.6	U ≤ 0.6	U ≤ 0.5/0.5	U ≤ 0.6	U ≤ 0.4
Wall (D ≤ 2.5)	U ≤ 0.8	U ≤ 0.9	U ≤ 0.8–0.95	U ≤ 0.6/0.8	U ≤ 0.8	U ≤ 0.6
Wall (D > 2.5)	U ≤ 1.0	U ≤ 1.0	U ≤ 1.0–1.2	U ≤ 0.8/1.0	U ≤ 1.0	U ≤ 1.0
Window (conditioned by different WWR range, noted in brackets)	U ≤ 4.0 (≤0.2)	U ≤ 3.2 (≤0.2)	U ≤ 4.0 (≤0.2)	U ≤ 2.6 (≤0.2)	U ≤ 2.8 (≤0.2)	U ≤ 2.8 (≤0.25)
	U ≤ 3.2 (0.2–0.3)	U ≤ 2.8 (0.2–0.35)	U ≤ 3.2 (0.2–0.3)	U ≤ 2.6 (0.2–0.3)	U ≤ 2.6 (0.2–0.3)	U ≤ 2.5 (0.25–0.4)
	U ≤ 2.8 (0.3–0.4)	U ≤ 2.5 (0.35–0.45)	U ≤ 2.8 (0.3–0.4)	U ≤ 2.6 (0.3–0.4)	U ≤ 2.4 (0.3–0.4)	U ≤ 2.2 (0.4–0.6)
	U ≤ 2.5 (0.4–0.45)	U ≤ 2.3 (≥0.45)	U ≤ 2.5 (0.4–0.45)	U ≤ 2.4 (0.4–0.45)	U ≤ 2.2 (0.4–0.45)	-
Airtightness level						
1–6 floors	≤class 4	-	≤class 4	≤class 6	≤class4	≤class 6
≥7 floors	≤class 6	-	≤class 6	≤class 6	≤class 6	≤class 6

U: heat transfer coefficient, W/m^{2}K; D: index of thermal inertia; WWR: window-to-wall ratio; Class 4 airtightness level: air penetration per unit area ≤ 7.5 m^3/m^{2}h; Class 6 airtightness level: air penetration per unit area ≤ 4.5 m^3/m^{2}h.

Table 2. Green building evaluation score system.

Elements	**Basics Requirements**	**Safety and Durability**	**Health and Comfort**	**Convenience**
Points	400	100	100	100
Elements		Energy conservation	Environment	Innovation
Points		200	100	100

In addition, the mandatory policies in China currently put greater emphasis on new buildings than retrofits. For example, the national mandatory policy of the “five-year plan” between 2020 and 2025 aims to achieve green buildings in all new urban residential areas, and at least 50 million m^2 of new ultra-low energy or near-zero-energy building floor area, while the retrofit goal is 350 million m^2 of residential area [90]. For a comparison, the total new residential construction area in 2020 was 2244 million m^2 [91]. As for the key energy efficiency requirement, this policy aims to achieve a 30% energy efficiency improvement in new buildings compared with the average energy efficiency level in 2020, and there is no specific energy target for the retrofits [90]. The local provincial governments set their mandatory policies in line with the national goal. For example, the “five-year plan” policy (for 2020 to 2025) in Hunan province has set out that all new buildings should be green buildings, with 10% of the new built areas achieving green building level one, and 5% meeting green building level two or three standards [92]. Hunan’s energy target is more ambitious as it aims to achieve a 65% energy efficiency improvement in new buildings compared with the 2020 level.

However, “Green Building” certification in China involves marking many elements, such as basic requirements, safety and geometry design. The factor of energy saving only accounts for about 18% of the certification (see Table 2). The criterion for the basic level of green building is achieving only 400 points within the basic requirements, and achieving levels 1, 2 and 3 requires no less than 600, 700 and 850 points, respectively. The requirements for the factor of energy saving in this certification are mostly associated with envelope thermal performance, rather than acting as a clear indicator of energy consumption or saving [93]. Therefore, these mandatory policies’ building energy conservation targets should not be considered straightforward goals, and the green building certification system in China should not be considered in line with the low-carbon building goal.

4.1.2. Voluntary Building Regulations

Building energy conservations and green buildings have been seen as important factors in China’s sustainable development by the Chinese Ministry of Housing Development. The growth of high-energy-efficiency voluntary building regulations in China is actually faster than the development of mandatory regulations. There have been many green building policies and voluntary building regulations published in the multi-level governance context [94]. Among these, the technical guidelines for passive ultra-low-energy green building and the technical standards for nearly-zero-energy buildings (GB/T 51350-2019) are the two key regulations that have been developed. They are based on advanced international standards and targeted at achieving outstanding energy-saving outcomes. These two regulations have different criteria when applied to different climate types in China. For the hot summer–cold winter climate we studied, Table 3 illustrates the main technical measures, including thermal envelope, airtightness level and building system. Table 4 shows the energy criteria, whereby the requirements for heating demand are strict in both standards (10 kWh/m^2a or less), and the requirements for cooling demand include more consideration of weather factors, and therefore differ according to location. The cooling demands demonstrated in Table 4 were calculated using a typical city (Changsha) in this climate region, and are around 30 kWh/m^2a under both standards. In addition, both regulations consider the comfortable indoor air temperature to be 20 °C or higher in winter and 26 °C or lower in summer.

These two voluntary regulations involve significantly higher requirements regarding the envelope thermal performance when compared with the mandatory regulations for residential buildings in the same climate region. Moreover, the two voluntary regulations also place requirements on airtightness level and the usage of heat recovery mechanical ventilation systems to improve energy efficiency. In terms of the estimated energy conservation results, the two voluntary regulations state that a passive ultra-low-energy building should achieve at least an energy saving of 85% in active heating; the near-zero-energy building should achieve an energy saving between 60% and 75% in overall building energy consumption; and the ultra-low-energy building should achieve an overall energy saving of 50%, compared with buildings meeting the mandatory regulations and reviewed earlier [95,96]. These two voluntary regulations currently do not provide specific guidance or set out requirements for new builds compared to retrofits.

Table 3. Comparison of main technical measures for the hot summer–cold winter climate region between two voluntary regulations in China [95,96].

	Technical Guidelines for Passive Ultra-Low-Energy Green Building	Technical Standard for Nearly Zero-Energy Buildings
Roof	U: 0.20~0.35	U: 0.15~0.35
Exterior wall	U: 0.20~0.35	U: 0.15~0.40
Ground floor	-	-
Exterior window	U: 1.0~2.0	U: $\leq$2.0
MVHR system	Sensible heat recovery 75% Enthalpy heat recovery 70%	Sensible heat recovery 75% Enthalpy heat recovery 70%
Airtightness	0.6 ach	1.0 ach

U: U-value, W/m^{2}K.

Table 4. Comparison of energy criteria for the hot summer–cold winter climate region between two voluntary regulations in China [95,96].

	Technical Guidelines for Passive Ultra-Low-Energy Green Building	Technical Standard for Nearly Zero Energy Buildings	
		NZE Building	ULE Building
Heating energy	5 kWh/m^{2}a	8 kWh/m^{2}a	10 kWh/m^{2}a
Cooling energy *	$3.5 + 2.0 \times WDH_{20} + 2.2 \times DDH_{28}$ (34.1 kWh/m^{2}a)	$3 + 1.5 \times WDH_{20} + 2.0 \times DDH_{28}$ (27 kWh/m^{2}a)	$3.5 + 2.0 \times WDH_{20} + 2.2 \times DDH_{28}$ (34.1 kWh/m^{2}a)
Sum of heating, cooling and lighting	60 kWh/m^{2}a	-	-
Sum of heating, cooling, hot water and lighting	-	55 kWh/m^{2}a	65 kWh/m^{2}a

NZE: nearly zero-energy; ULE: ultra-low-energy; WDH$_{20}$: wet bulb degree hours for a baseline of 20 °C; DDH$_{28}$: dry bulb degree hours against baseline of 28 °C; * Cooling energy: demonstration calculations based on the typical city Changsha.

Until now, most of the provincial governments in the hot summer–cold winter climate region have issued voluntary building regulations, which are similar to the two national regulations reviewed above. This is expected to play a foundational role in the future in promoting the development of low-carbon buildings aimed at achieving the final goal of carbon neutrality in China in 2060. The policies of the "five-year plan" are China's short-term development strategy. All five of the provincial governments in the studied climate region have included developing ultra-low-energy buildings in their current five-year plan (between 2020 and 2025). For example, the provinces of Jiangsu, Hunan and Jiangxi aim to build five million, one million and half a million m^2 of ultra-low-energy buildings, respectively, in those five years [92,97,98]. Anhui and Hubei provinces aim to finish the development of their local voluntary regulations related to ultra-low-energy building and near-zero-energy buildings, and construct a batch of demonstration buildings [99,100]. These plans related to building low-energy buildings are small compared to the overall annual volume of new buildings built in China, but they are meaningful as demonstrations for the entire construction industry.

4.2. International Low-Energy Building Standards

From a global perspective, developed countries in Europe have recognized the environmental consequences, and undertaken the development of sustainable building relatively early. Several essential policies intent on reducing building energy consumption have been formulated, among which the Energy Performance of Building Directives (EPBD) set out by the European Commission is a leading policy action [101]. A critical measure that EPBD set up for building energy conservation was the implementation of nearly zero-energy buildings (NZEBs), with new buildings for public authorities being required to be NZEBs since 31 December 2018, and all new buildings have had the NZEB requirement since 31 December 2020. For existing buildings, the EPBD requires national support policies be set to encourage deeper refurbishment to NZEB levels, but no target dates or minimum energy performance requirements were set [102].

Each member state is required to detail the definition of NZEBs and to establish a plan for NZEB implementation according to their national or regional conditions [103]. Therefore, the definition and criteria for NZEBs differ slightly from country to country, but, in general, NZEBs should have a very high level of energy efficiency and very low energy consumption requirements for operation. A study has collected the numeric indicators of energy performance for NZEBs expressed as primary energy among different European countries, and grouped by climate types and building type [104]. Table 5 shows the indicators for dwellings, which are applied to the cumulative energy used for heating, cooling, ventilation, hot water and lighting.

Table 5. NZEBs levels of energy performance for residential buildings within different European climates [104].

Climate, and Representative Cities	Primary Energy (kWh/m^{2}a)	On-Site Renewable Energy (kWh/m^{2}a)	Net Primary Energy * (kWh/m^{2}a)
Mediterranean (Catania, Athens, etc.)	50–65	50	0–15
Oceanic (Paris, London, etc.)	50–60	35	15–30
Continental (Budapest, Milan, etc.)	50–70	30	20–40
Nordic (Stockholm, Helsinki, etc.)	65–90	25	40–65

* Off-set between the primary energy and on-site-generated energy.

The energy requirements of the Chinese voluntary low-energy standards and of the European Commission NZEBs standards cannot be compared directly because of the different climate contexts and energy criteria metrics (measured in secondary and primary energy). However, a big difference to note is that for the inclusive consideration of renewable energy harvesting, the European Commission standards considered the net primary energy balanced with renewable generation, and as a result, the requirements regarding energy demand are much stricter than those in the Chinese voluntary standard that does not include renewable generation.

In summary, the advanced building concepts are fundamentally all designed to achieve as little energy consumption in building operation as possible, and some consider producing energy from suitable renewable energy sources on-site or nearby to offset the small amount of energy consumed partly or fully. Unrequired energy may even be returned to the grid. Among all of these advanced concepts, achieving very low building energy consumption is fundamental.

As for ways to achieve these low- and zero-energy building targets, the Passivhaus concept is certainly one of the most important guides, and this concept is in line with many low-energy building standards [104]. The Passivhaus method is an integrated solution using the interaction of five key energy saving measures to minimize the building energy usage, and it creates an efficient environment in combination with renewable energy generation systems [105]. The five key measures are: (1) adequate insulation in the entire opaque envelope, where the U-value should be no greater than 0.15 W/m^{2}K; (2) high-performance windows with particularly low U-values of between 0.70 and 0.85 W/m^{2}K;

(3) super airtight envelope wherein the airtightness level should be no more than 0.6 air changes per hour (ach); (4) mechanical ventilation system with heat recovery function with at least a 75% efficiency, and (5) no thermal bridges, so that the interior envelope surface temperatures can always be kept above 13 °C to avoid a cold bridge.

Accordingly, the energy criteria set out by the Passivhaus standard are also very strict, with the heating and cooling demands both limited to no more than 15 kWh/m^{2}a, excluding dehumidification, for all new builds no matter the climate type. For retrofits, the heating energy requirements are more generous and allow for differences related to climate classifications, but the cooling energy requirement is kept the same as in the new builds. The Passivhaus energy criteria can be compared easily with the two voluntary Chinese low-energy building standards, which largely learn from the Passivhaus standard and measure conservation with the same metric. For the climate type studied in this paper, a big difference that has been found is that the Chinese regulations require even lower heating demands (5 to 10 kWh/m^{2}a), but allow a more liberal cooling demand (around 30 kWh/m^{2}a). The Passivhaus performance is globally evaluated positively overall for various important aspects of construction, especially in terms of achieve significant energy saving while maintaining a good level of thermal performance [106]. However, the embodied carbon involved here is significantly more than for conventional buildings, and represents a significant share of the building's lifetime energy use. Recent research has focused on optimizing initial material inputs to reduce the embodied carbon load [107,108].

5. Discussion and Suggestions

This review is aimed at providing an overview of building retrofit measures and directions for the retrofitting of existing residential buildings within China's hot summer–cold winter climate region, aiming at a decarbonized future. The objectives of the review include researching the retrofitting measures and their outcomes, understanding the current conditions of the targeted residential buildings, and assessing the building regulations and retrofit schemes set for them. Accordingly, some insights can be gained regarding the policy gaps within the Chinese government's 2060 carbon neutrality goal, and directions for efficient retrofitting can be derived.

According to the reviewed Chinese mandatory regulations, the current government's focus has mainly been on new buildings. There are still considerable numbers of new residential buildings being built every year, and the current policy requires 100% of the new constructions to be built as green buildings, which is a policy improvement, because much lower percentages were required in the past policies. However, energy saving is not really counted as one of main values in the green building evaluation system in China, and therefore the energy conservation rate of 65% outlined by the mandatory regulations is not guaranteed. This leads to a gap in the energy performance of these new buildings, and it is reasonable to estimate that the retrofitting of buildings will be needed following decarbonization developments in the future. Under the current retrofit scheme, both central and local governments only plan to retrofit certain amounts of residential areas, which represent small portions when compared with the new residential areas being built every year. China is planning to reach its emission peak in 2030. Afterwards, the speed of construction should significantly slow down, and the focus of the government should be moved towards the existing buildings. Utilizing this period to plan retrofit schemes that are suitable for the situations in existing housing could be essential in order to meet the government's goal of carbon neutrality by 2060.

In Section 3 of this paper, the characteristics of the hot summer–cold winter climate region, and the residential buildings that are prevalent in this region, were described. Most existing buildings in this climate have poor energy performance, resulting in subpar indoor thermal comfort. As a result, the residents experience poor thermal comfort and have a strong desire for more comfortable indoor environments. Given the current state of these buildings, is it almost certain that the energy consumption will keep growing, as more active heating and cooling are used. Large amounts of carbon emissions were released when those existing buildings were constructed, given that the main materials used (steel, concrete and brick) have high embodied energies. Therefore, retrofitting and maintaining these buildings to ensure lifespans that are as long as possible represents the best way to neutralize the carbon emissions created during their construction. There are many retrofitting measures in place for this purpose, as reviewed in Section 2 of this paper. Guidance on the selection of a combination of retrofit measures that can facilitate significant energy conservation in existing residential buildings is missing from the current Chinese mandatory regulations and policies. As per the retrofit outcomes that have been reviewed in Section 2.2, the energy conservation results that shallow retrofits could achieve would be very different based on the applied measures and building or climate conditions, but in general, the resulting conservation would be much less significant than that which deep retrofitting could bring. When planning a retrofit scheme, it is recommended that passive retrofit measures are included, because these enable the adapting of the buildings to weather, and the improving of thermal comfort or decreasing of energy demand directly.

Deep retrofit plans that include suitable passive measures are considered ideal ways for residential buildings to achieve very low energy demand, and to meet the ambitious decarburization goals that many governments have set out. However, deep retrofits are prohibitively expensive, and thus often not included in the chosen schemes. The Chinese government updates the building regulations regularly every ten years or so, and new buildings always need to meet the requirements of the new regulations. Some challenges are expected if similar policies are put in place for retrofits. It might be difficult to decide which retrofit measures should be adopted first. For example, choosing active measures, such as adopting higher-efficiency heating and cooling systems, would result in significant energy savings. However, these measures might not be enough to achieve the current decarbonization goals, especially given the poor energy performance standards of buildings in the studied climate region. Additional measures, such as insulation, will be needed, necessitating the reconfiguration of mechanical systems. Furthermore, as the cost of renewable energy generation systems decreases, they are becoming an increasingly popular way to achieve low carbon, but they typically require specific surroundings (such as a lack of over-shading), and many of them (such as heat pumps) work more efficiently in insulated buildings.

Therefore, deciding which method to choose for renovation often causes some controversy. This study recommends that policy-makers adopt one-step deep retrofit schemes, because in this way, the decarbonization goal could be achieved in a shorter time, and they can avoid issues related to small-scale retrofit measures. Bite-size retrofitting may lead to more costs because of the need for multiple re-retrofits over the next few decades [27]. Among the low-energy regulations that can be adopted via one-step deep retrofit schemes, the Passivhaus standard could be an ideal approach for the policy-makers to consider in China's future. This is because the Passivhaus standard comes with straightforward guidance on how to achieve its ultra-low-energy criteria, which is missing from current Chinese policies and regulations related to retrofitting. Most importantly, similar voluntary building regulations have been published in China by multi-level authorities, with plans for demonstration projects to be built in following years. All this should help with adapting industries and markets to easily promote low-carbon developments.

6. Conclusions

The energy retrofitting of existing dwellings is a significant step towards sustainable development, so many improvements in retrofitting technologies and energy-saving targets have been seen across the world. This study focuses on the retrofitting of existing residential buildings in China's hot summer–cold winter climate region to improve energy performance and move towards low-energy building goals. To provide an insight into the gap between existing building performance in this region and the government's targets related to a net zero-carbon future, this study provides a comprehensive review of general retrofit and passive measures, the climate and building features, and the building regulations and policies in the studied region. Discussions and suggestions are also provided in this study to uncover potential approaches to retrofitting that will bridge the gap between current poor energy performance buildings and the net zero building goal. The findings from this review can be summarized as follows:

- Based on the studied climate, the most effective passive cooling methods are the use of shading elements and natural ventilation. In addition, radiative cooling can be particularly effective for buildings with large surface areas that are exposed to solar radiation and have high interior wall temperatures. For passive heating, it is recommended to insulate the building envelope and install high-performance windows;
- There are many building retrofit measures that could allow both energy saving and increased thermal comfort in residential buildings, but shallow retrofits in general have much less effect than deep retrofitting in terms of building performance improvements;
- Deep retrofitting will be needed if the studied residential buildings are to achieve significant energy savings, and making good use of passive measures that suit the hot summer–cold winter climate could reduce the need for active heating and cooling;
- Local renewable energy generation is important to achieving low carbon emissions, especially as the cost of renewable generation systems continues to decrease. Solar photovoltaics and heat pumps are the most applicable renewable energy technologies. However, it is important to note that certain renewable energy systems are more efficient in insulated buildings. Therefore, retrofit projects involving insulation may be made more effective by adopting these technologies;
- The current mandatory building regulations and policies set out in the studied region are still a long way from achieving the country's target for decarbonization, and so deep retrofit schemes will be necessary to achieve the decarbonization goals on time;
- Compared to retrofitting existing building several times to meet the updating Chinese regulations, a one-step deep retrofit approach is recommended, which can achieve the decarbonization goal in a shorter time;
- The Passivhaus standard is a method with good potential and that policy-makers should consider, given its ultra-low-energy criteria, as yielded by comprehensive evaluations of its performance and demonstration projects in China.

Based on the research presented, there are several areas that will be beneficial for further study. Cost is always a limiting factor in ambitious decision-making, hence it is imperative to conduct cost–benefit analyses of Passivhaus retrofit schemes and other standard retrofit schemes to determine the most cost-effective approaches to ensuring the energy efficiency of existing residential buildings in hot summer–cold winter climate regions. Such research should include pre- and post-retrofit evaluations and monitoring analyses of the renovation projects implemented in this climate region. Furthermore, it is recommended to investigate the barriers and challenges faced by policy-makers and building owners in implementing deep retrofit schemes. Conducting long-term benefit and cost-effectiveness analyses can provides valuable insights for future policy development.

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References

1. Buildings–Analysis-IEA. Available online: https://www.iea.org/reports/buildings (accessed on 3 March 2023).
2. International Energy Agency (IEA). Net Zero by 2050-A Roadmap for the Global Energy Sector. 2021. Available online: www.iea.org/t&c/ (accessed on 14 February 2023).
3. British Petroleum. BP, Statistical Review of World Energy 2022. Available online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjWv5aHr-X-AhXNOcAKHdreADMQFnoECBAQAQ&url=https%3A%2F%2Fwww.bp.com%2Fcontent%2Fdam%2Fbp%2Fbusiness-sites%2Fen%2Fglobal%2Fcorporate%2Fpdfs%2Fenergy-economics%2Fstatistical-review%2Fbp-stats-review-2022-full-report.pdf&usg=AOvVaw1M37wlAu6qujo7XTIb-KW8 (accessed on 3 March 2023).
4. CABEE. China Association of Building Energy Efficiency. Research Report of China Building Energy Consumption and Carbon Emissions. 2022. Available online: https://carbon.landleaf-tech.com/report/4621/ (accessed on 6 March 2023).
5. National Bureau of Statistics. Yearly New Construction Areas. 2021. Available online: https://data.stats.gov.cn/easyquery.htm?cn=C01 (accessed on 9 September 2021).
6. Lin, Y.; Zhong, S.; Yang, W.; Hao, X.; Li, C.-Q. Towards zero-energy buildings in China: A systematic literature review. *J. Clean. Prod.* **2020**, *276*, 123297. [CrossRef]
7. Liu, G.; Li, X.; Tan, Y.; Zhang, G. Building green retrofit in China: Policies, barriers and recommendations. *Energy Policy* **2020**, *139*, 111356. [CrossRef]
8. 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]
9. China.gov. Carbon Neutrality Implementation Plan for Science and Technology to Support Carbon Peak (2022–2030). 2022. Available online: http://www.gov.cn/zhengce/2022-08/18/content_5705885.htm (accessed on 6 March 2023).
10. Wang, Y.; Mauree, D.; Sun, Q.; Lin, H.; Scartezzini, J.; Wennersten, R. A review of approaches to low-carbon transition of high-rise residential buildings in China. *Renew. Sustain. Energy Rev.* **2020**, *131*, 109990. [CrossRef]
11. He, Q.; Hossain, U.; Ng, S.T.; Augenbroe, G. Identifying practical sustainable retrofit measures for existing high-rise residential buildings in various climate zones through an integrated energy-cost model. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111578. [CrossRef]
12. Zhao, X.; Tan, Y.; Shen, L.; Zhang, G.; Wang, J. Case-based reasoning approach for supporting building green retrofit decisions. *Build. Environ.* **2019**, *160*, 106210. [CrossRef]
13. Jalal, S.J.; Bani, R.K. Orientation modeling of high-rise buildings for optimizing exposure/transfer of insolation, case study of Sulaimani, Iraq. *Energy Sustain. Dev.* **2017**, *41*, 157–164. [CrossRef]
14. Gan, V.J.; Wong, H.; Tse, K.; Cheng, J.C.; Lo, I.M.; Chan, C. Simulation-based evolutionary optimization for energy-efficient layout plan design of high-rise residential buildings. *J. Clean. Prod.* **2019**, *231*, 1375–1388. [CrossRef]
15. Xue, P.; Li, Q.; Xie, J.; Zhao, M.; Liu, J. Optimization of window-to-wall ratio with sunshades in China low latitude region considering daylighting and energy saving requirements. *Appl. Energy* **2018**, *233*, 62–70. [CrossRef]
16. Gorse, C.; Johnston, D.; Glew, D.; Fylan, F.; Thomas, F.; Shenton, D.M.; Fletcher, M.; Erkoreka, A.; Stafford, A. Monitoring and Measuring Building Performance. In *Building Sustainable Futures*; Dastbaz, M., Strange, I., Selkowitz, S., Eds.; Springer: Cham, Switzerland, 2015; pp. 35–61. [CrossRef]
17. Felius, L.C.; Hamdy, M.; Dessen, F.; Hrynyszyn, B.D. Upgrading the Smartness of Retrofitting Packages towards Energy-Efficient Residential Buildings in Cold Climate Countries: Two Case Studies. *Buildings* **2020**, *10*, 200. [CrossRef]
18. Chan, H.-Y.; Riffat, S.B.; Zhu, J. Review of passive solar heating and cooling technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 781–789. [CrossRef]
19. Aditya, L.; Mahlia, T.; Rismanchi, B.; Ng, H.; Hasan, M.; Metselaar, H.; Muraza, O.; Aditiya, H. A review on insulation materials for energy conservation in buildings. *Renew. Sustain. Energy Rev.* **2015**, *73*, 1352–1365. [CrossRef]
20. Pérez-Carramiñana, C.; González-Avilés, B.; Galiano-Garrigós, A.; Lozoya-Peral, A. Optimization of Architectural Thermal Envelope Parameters in Modern Single-Family House Typologies in Southeastern Spain to Improve Energy Efficiency in a Dry Mediterranean Climate. *Sustainability* **2022**, *14*, 3910. [CrossRef]
21. Li, X.; Tingley, D.D. A whole life, national approach to optimize the thickness of wall insulation. *Renew. Sustain. Energy Rev.* **2023**, *174*, 113137. [CrossRef]
22. Bojic, M.; Yik, F.; Leung, W. Thermal insulation of cooled spaces in high rise residential buildings in Hong Kong. *Energy Convers. Manag.* **2002**, *43*, 165–183. [CrossRef]
23. Hu, M. An evaluation of the retrofit net zero building performances: Life cycle energy, emissions and cost. *Build. Res. Inf.* **2022**, 1–13. [CrossRef]
24. Pavel, C.C.; Blagoeva, D.T. *Competitive Landscape of the EU's Insulation Materials Industry for Energy-Efficient Buildings Revised Edition*; Report; European Commission: Brussels, Belgium, 2018. [CrossRef]
25. Baetens, R.; Jelle, B.P.; Gustavsen, A. Aerogel insulation for building applications: A state-of-the-art review. *Energy Build.* **2011**, *43*, 761–769. [CrossRef]
26. Jia, G.; Li, Z. Influence of the aerogel/expanded perlite composite as thermal insulation aggregate on the cement-based materials: Preparation, property, and microstructure. *Constr. Build. Mater.* **2021**, *273*, 121728. [CrossRef]

27. Alabid, J.; Bennadji, A.; Seddiki, M. A review on the energy retrofit policies and improvements of the UK existing buildings, challenges and benefits. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112161. [CrossRef]
28. Grazieschi, G.; Asdrubali, F.; Thomas, G. Embodied energy and carbon of building insulating materials: A critical review. *Clean. Environ. Syst.* **2021**, *2*, 100032. [CrossRef]
29. Urbikain, M.K. Energy efficient solutions for retrofitting a residential multi-storey building with vacuum insulation panels and low-E windows in two European climates. *J. Clean. Prod.* **2020**, *269*, 121459. [CrossRef]
30. Luo, X.; Oyedele, L.O. Assessment and optimisation of life cycle environment, economy and energy for building retrofitting. *Energy Sustain. Dev.* **2021**, *65*, 77–100. [CrossRef]
31. Fine, J.P.; Gray, J.; Tian, X.; Touchie, M.F. An investigation of alternative methods for determining envelope airtightness from suite-based testing in multi-unit residential buildings. *Energy Build.* **2020**, *214*, 109845. [CrossRef]
32. Prignon, M.; Van Moeseke, G. Factors influencing airtightness and airtightness predictive models: A literature review. *Energy Build.* **2017**, *146*, 87–97. [CrossRef]
33. BSI. PAS 2035/2030: Retrofitting Dwellings for Improved Energy Efficiency-Specification and Guidance. Publishing and Copyright Information. 2022. Available online: https://knowledge.bsigroup.com/products/retrofitting-dwellings-for-improved-energy-efficiency-specification-and-guidance-3/standard (accessed on 3 March 2023).
34. Crawley, J.; Wingfield, J.; Elwell, C. The relationship between airtightness and ventilation in new UK dwellings. *Build. Serv. Eng. Res. Technol.* **2019**, *40*, 274–289. [CrossRef]
35. Akil, Y.S.; Mawar, S.; Mangngenre, S.; Amar, K. Hasniaty LED lighting in Indonesian residential electricity sector: A user's behavior analysis for energy saving. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *575*, 12227. [CrossRef]
36. Dubois, M.-C.; Bisegna, F.; Gentile, N.; Knoop, M.; Matusiak, B.; Osterhaus, W.; Tetri, E. Retrofitting the Electric Lighting and Daylighting Systems to Reduce Energy Use in Buildings: A Literature Review. *Energy Res. J.* **2015**, *6*, 25–41. [CrossRef]
37. Regnier, C.; Sun, K.; Hong, T.; Piette, M.A. Quantifying the benefits of a building retrofit using an integrated system approach: A case study. *Energy Build.* **2018**, *159*, 332–345. [CrossRef]
38. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing building retrofits: Methodology and state-of-the-art. *Energy Build.* **2012**, *55*, 889–902. [CrossRef]
39. Yuan, X.; Wang, X.; Zuo, J. Renewable energy in buildings in China—A review. *Renew. Sustain. Energy Rev.* **2013**, *24*, 1–8. [CrossRef]
40. Kwok, K.; Hu, G. Wind energy system for buildings in an urban environment. *J. Wind. Eng. Ind. Aerodyn.* **2023**, *234*, 105349. [CrossRef]
41. Nsafon, B.E.K.; Owolabi, A.B.; Butu, H.M.; Roh, J.W.; Suh, D.; Huh, J.-S. Optimization and sustainability analysis of PV/wind/diesel hybrid energy system for decentralized energy generation. *Energy Strat. Rev.* **2020**, *32*, 100570. [CrossRef]
42. Zhang, S.; Ocłoń, P.; Klemeš, J.J.; Michorczyk, P.; Pielichowska, K.; Pielichowski, K. Renewable energy systems for building heating, cooling and electricity production with thermal energy storage. *Renew. Sustain. Energy Rev.* **2022**, *165*, 112560. [CrossRef]
43. Lucchi, E. Renewable Energies and Architectural Heritage: Advanced Solutions and Future Perspectives. *Buildings* **2023**, *13*, 631. [CrossRef]
44. Zou, H.; Zhou, Y.; Jiang, H.; Chien, S.-C.; Xie, L.; Spanos, C.J. WinLight: A WiFi-based occupancy-driven lighting control system for smart building. *Energy Build.* **2018**, *158*, 924–938. [CrossRef]
45. Silva, B.N.; Khan, M.; Han, K. Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities. *Sustain. Cities Soc.* **2018**, *38*, 697–713. [CrossRef]
46. Silva, B.N.; Khan, M.; Han, K. Big Data Analytics Embedded Smart City Architecture for Performance Enhancement through Real-Time Data Processing and Decision-Making. *Wirel. Commun. Mob. Comput.* **2017**, *2017*, 1–12. [CrossRef]
47. Habibi, S. Micro-climatization and real-time digitalization effects on energy efficiency based on user behavior. *Build. Environ.* **2017**, *114*, 410–428. [CrossRef]
48. Chen, Z.; Xiao, F.; Guo, F.; Yan, J. Interpretable machine learning for building energy management: A state-of-the-art review. *Adv. Appl. Energy* **2023**, *9*, 100123. [CrossRef]
49. Jagarajan, R.; Asmoni, M.N.A.M.; Mohammed, A.H.; Jaafar, M.N.; Mei, J.L.Y.; Baba, M. Green retrofitting–A review of current status, implementations and challenges. *Renew. Sustain. Energy Rev.* **2017**, *67*, 1360–1368. [CrossRef]
50. Costa-Carrapiço, I.; Raslan, R.; González, J.N. A systematic review of genetic algorithm-based multi-objective optimisation for building retrofitting strategies towards energy efficiency. *Energy Build.* **2020**, *210*, 109690. [CrossRef]
51. Chang, S.; Castro-Lacouture, D.; Yamagata, Y. Decision support for retrofitting building envelopes using multi-objective optimization under uncertainties. *J. Build. Eng.* **2020**, *32*, 101413. [CrossRef]
52. Gao, Y.; Luo, S.; Jiang, J.; Rong, Y. Environmental-thermal-economic performance trade-off for rural residence retrofitting in the Beijing–Tianjin–Hebei region, Northern China: A multi-objective optimisation framework under different scenarios. *Energy Build.* **2023**, *286*, 112910. [CrossRef]
53. Dowson, M.; Poole, A.; Harrison, D.; Susman, G. Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. *Energy Policy* **2012**, *50*, 294–305. [CrossRef]
54. 4 Objectives-Energy Efficient Scotland Programme: Analysis of Delivery Mechanism-gov.scot. Available online: https://www.gov.scot/publications/energy-efficient-scotland-strategic-outline-case-proposed-development-national-delivery-mechanism/pages/6/ (accessed on 14 February 2023).

55. Ministry of Housing and Urban-Rural Development MOHURD People's Republic of China. Thermal Design Code for Civil Building (GB 50176-2016) 2016. Available online: http://www.mohurd.gov.cn/wjfb/201702/t20170213_230579.html (accessed on 15 February 2023).
56. National Bureau of Technical Supervision of PRC, Ministry of Construction of PRC. *GB50178-93*; Standard of Climatic Regionalization for Architecture. China Planning Press: Beijing, China, 1993. (In Chinese)
57. Li, B.; Li, W.; Liu, H.; Yao, R.; Tan, M.; Jing, S.; Ma, X. Physiological Expression of Human Thermal Comfort to Indoor Operative Temperature in the Non-HVAC Environment. *Indoor Built Environ.* **2010**, *19*, 221–229. [CrossRef]
58. Wang, Z.; Zhao, Z.; Lin, B.; Zhu, Y.; Ouyang, Q. Residential heating energy consumption modeling through a bottom-up approach for China's Hot Summer–Cold Winter climatic region. *Energy Build.* **2015**, *109*, 65–74. [CrossRef]
59. Song, F.; Zhu, Q.; Wu, R.; Jiang, Y.; Xiong, A.; Wang, B.; Zhu, Y. Meteorological Data Set for Building Thermal Environment Analysis of China. In Proceedings of the IBPSA 2007-International Building Performance Simulation Association, Beijing, China, 4–6 September 2007; pp. 9–16.
60. Li, B.; Yu, W.; Liu, M.; Li, N. Climatic Strategies of Indoor Thermal Environment for Residential Buildings in Yangtze River Region, China. *Indoor Built Environ.* **2011**, *20*, 101–111. [CrossRef]
61. Available online: https://klimaat.ca/epw/ (accessed on 25 August 2021).
62. Atalla, T.; Gualdi, S.; Lanza, A. A global degree days database for energy-related applications. *Energy* **2018**, *143*, 1048–1055. [CrossRef]
63. Xiong, Y.; Liu, J.; Kim, J. Understanding differences in thermal comfort between urban and rural residents in hot summer and cold winter climate. *Build. Environ.* **2019**, *165*, 106393. [CrossRef]
64. CABEE China Association of Building Energy Efficiency. China Building Energy Research Report 2020. Available online: https://www.cabee.org (accessed on 6 March 2023).
65. National Bureau of Statistics. *China Statistical Yearbook 2020*; National Bureau of Statistics: Beijing, China, 2020.
66. Fan, J.-L.; Yu, H.; Wei, Y.-M. Residential energy-related carbon emissions in urban and rural China during 1996–2012: From the perspective of five end-use activities. *Energy Build.* **2015**, *96*, 201–209. [CrossRef]
67. Wang, X.; Fang, Y.; Cai, W.; Ding, C.; Xie, Y. Heating demand with heterogeneity in residential households in the hot summer and cold winter climate zone in China -A quantile regression approach. *Energy* **2022**, *247*, 123462. [CrossRef]
68. Delmastro, C.; Lavagno, E.; Mutani, G. Chinese residential energy demand: Scenarios to 2030 and policies implication. *Energy Build.* **2015**, *89*, 49–60. [CrossRef]
69. Yoshino, H.; Yoshino, Y.; Zhang, Q.; Mochida, A.; Li, N.; Li, Z.; Miyasaka, H. Indoor thermal environment and energy saving for urban residential buildings in China. *Energy Build.* **2006**, *38*, 1308–1319. [CrossRef]
70. Li, B.; Du, C.; Yao, R.; Yu, W.; Costanzo, V. Indoor thermal environments in Chinese residential buildings responding to the diversity of climates. *Appl. Therm. Eng.* **2018**, *129*, 693–708. [CrossRef]
71. Campaniço, H.; Hollmuller, P.; Soares, P.M. Assessing energy savings in cooling demand of buildings using passive cooling systems based on ventilation. *Appl. Energy* **2014**, *134*, 426–438. [CrossRef]
72. Bhamare, D.K.; Rathod, M.K.; Banerjee, J. Passive cooling techniques for building and their applicability in different climatic zones—The state of art. *Energy Build.* **2019**, *198*, 467–490. [CrossRef]
73. Tejero-González, A.; Andrés-Chicote, M.; García-Ibáñez, P.; Velasco-Gómez, E.; Rey-Martínez, F.J. Assessing the applicability of passive cooling and heating techniques through climate factors: An overview. *Renew. Sustain. Energy Rev.* **2016**, *65*, 727–742. [CrossRef]
74. Kirimtat, A.; Koyunbaba, B.K.; Chatzikonstantinou, I.; Sariyildiz, S. Review of simulation modeling for shading devices in buildings. *Renew. Sustain. Energy Rev.* **2016**, *53*, 23–49. [CrossRef]
75. 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]
76. Wong, N.; Li, S. A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore. *Build. Environ.* **2007**, *42*, 1395–1405. [CrossRef]
77. Wong, N.H.; Istiadji, A.D. Effects of external shading devices on daylighting and natural ventilation. In Proceedings of the Eighth International IBPSA Conference, Eindhoven, The Netherlands, 11–14 August 2003; pp. 475–482.
78. Chungloo, S.; Limmeechokchai, B. Application of passive cooling systems in the hot and humid climate: The case study of solar chimney and wetted roof in Thailand. *Build. Environ.* **2007**, *42*, 3341–3351. [CrossRef]
79. Alshenaifi, M.A.; Sharples, S. A parametric analysis of the influence of wind speed and direction on the thermal comfort performance of a Passive Downdraught Evaporative Cooling (PDEC) system–field measurements from a Saudi Arabian library. *IOP Conf. Series: Earth Environ. Sci.* **2019**, *329*, 012042. [CrossRef]
80. Santamouris, M.; Kolokotsa, D. Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy Build.* **2013**, *57*, 74–94. [CrossRef]
81. Givoni, B. Indoor temperature reduction by passive cooling systems. *Sol. Energy* **2011**, *85*, 1692–1726. [CrossRef]
82. Bulut, H.; Aktacir, M.A. Determination of free cooling potential: A case study for İstanbul, Turkey. *Appl. Energy* **2011**, *88*, 680–689. [CrossRef]
83. Yik, F.W.; Lun, Y.F. Energy Saving by Utilizing Natural Ventilation in Public Housing in Hong Kong. *Indoor Built Environ.* **2010**, *19*, 73–87. [CrossRef]

84. Priya, R.S.; Sundarraja, M.C.; Radhakrishnan, S. Experimental study on the thermal performance of a traditional house with sone-sided wind catcher during summer and winter. *Energy Effic.* **2012**, *5*, 483–496. [CrossRef]
85. Ji, Z.; Su, Y.; Khan, N. Performance Evaluation and Energy Saving Potential of Windcatcher Natural Ventilation Systems in China. *Int. J. Arch. Eng. Constr.* **2012**, *1*, 84–95. [CrossRef]
86. Zhao, K.; Liu, X.-H.; Jiang, Y. Application of radiant floor cooling in large space buildings–A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 1083–1096. [CrossRef]
87. Pan, D.; Chan, M.; Deng, S.; Lin, Z. The effects of external wall insulation thickness on annual cooling and heating energy uses under different climates. *Appl. Energy* **2012**, *97*, 313–318. [CrossRef]
88. Tahmasebi, M.M.; Banihashemi, S.; Hassanabadi, M.S. Assessment of the Variation Impacts of Window on Energy Consumption and Carbon Footprint. *Procedia Eng.* **2011**, *21*, 820–828. [CrossRef]
89. Sadrzadehrafiei, S.; Sopian, K.; Mat, S.; Lim, C. Application of advanced glazing to mid-rise office buildings in Malaysia. In Proceedings of the 9th WSEAS International Conference on Environment, Ecosystems, and Development, Montreux, Switzerland, 29–31 December 2011; pp. 197–201.
90. MOHURD. 14th Five-Year Plan on Building Energy Conservation and Green Building Development Plan. 2022. Available online: https://www.mohurd.gov.cn/gongkai/zhengce/zhengcefilelib/202203/20220311_765109.html (accessed on 27 February 2023).
91. National Bureau of Statistics. National Real Estate Development Investment and Sales from January to December 2020. 2021. Available online: http://www.stats.gov.cn/tjsj/zxfb/202101/t20210118_1812429.html (accessed on 27 February 2023).
92. Hunan.gov. Hunan Province's "14th Five-Year Plan" on Building Energy Conservation and Green Building Development. 2022. Available online: http://www.hunan.gov.cn/zqt/zcsd/202203/t20220314_22704357.html (accessed on 27 February 2023).
93. MOHURD (Ministry of Housing and Urban-Rural Development). Assessment Standard for Green Building. 2018. Available online: https://www.mohurd.gov.cn/gongkai/fdzdgknr/zqyj/201809/20180921_237690.html (accessed on 6 March 2023).
94. Hu, Q.; Xue, J.; Liu, R.; Shen, G.Q.; Xiong, F. Green building policies in China: A policy review and analysis. *Energy Build.* **2023**, *278*, 112641. [CrossRef]
95. MOHURD. Technical Standard for Nearly Zero Energy Buildings. 2019. Available online: https://www.mohurd.gov.cn/gongkai/zhengce/zhengcefilelib/201905/20190530_240712.html (accessed on 6 March 2023).
96. MOHURD. Technical Guidelines for Passive Ultra-Low Energy Green Building. 2015. Available online: https://www.mohurd.gov.cn/gongkai/zhengce/zhengcefilelib/201511/20151113_225589.html (accessed on 6 March 2023).
97. Jiangxi.gov. Jiangxi Province's "14th Five-Year Plan" on Building Energy Conservation and Green Building Development Plan, 2022. Available online: http://zjt.jiangxi.gov.cn/art/2022/9/13/art_40687_4139446.html (accessed on 6 March 2023).
98. Jiangsu Province's "14th Five-Year Plan" on Building Energy Conservation and Green Building Development Plan. 2022. Available online: http://www.jiangsu.gov.cn/art/2022/7/21/art_59167_10549023.html (accessed on 27 February 2023).
99. Building Energy Conservation and Green Building Standard System in Hubei Province. 2022. Available online: http://zjt.hubei.gov.cn/zfxxgk/zc/zcjd/202212/t20221229_4469403.shtml (accessed on 27 February 2023).
100. Anhui Province's "14th Five-Year Plan" on Building Energy Conservation and Green Building Development Plan. 2022. Available online: https://www.masys.gov.cn/stqq/stzc/18639651.html (accessed on 27 February 2023).
101. Economidou, M.; Todeschi, V.; Bertoldi, P.; D'Agostino, D.; Zangheri, P.; Castellazzi, L. Review of 50 years of EU energy efficiency policies for buildings. *Energy Build.* **2020**, *225*, 110322. [CrossRef]
102. European Commission. European Commission Guidelines for the Promotion of Nearly Zero-Energy Buildings and Best Practices to Ensure that, By 2020, All New Buildings are Nearly Zero-Energy Buildings. 2016. Available online: http://www.sciencedirect.com/science/article/pii/S0306261911007811/ (accessed on 27 February 2023).
103. European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast), EPBD Recast. 2010. Available online: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32010L0031 (accessed on 11 September 2021).
104. D'Agostino, D.; Mazzarella, L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *J. Build. Eng.* **2018**, *21*, 200–212. [CrossRef]
105. PHI. Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, Passive House Institute. 2016, pp. 1–27. Available online: https://passiv.de/downloads/03_building_criteria_en.pdf (accessed on 25 August 2021).
106. Wang, Y.; Kuckelkorn, J.; Zhao, F.-Y.; Spliethoff, H.; Lang, W. A state of art of review on interactions between energy performance and indoor environment quality in Passive House buildings. *Renew. Sustain. Energy Rev.* **2017**, *72*, 1303–1319. [CrossRef]
107. Sierra-Pérez, J.; Rodríguez-Soria, B.; Boschmonart-Rives, J.; Gabarrell, X. Integrated life cycle assessment and thermodynamic simulation of a public building's envelope renovation: Conventional vs. Passivhaus proposal. *Appl. Energy* **2018**, *212*, 1510–1521. [CrossRef]
108. Annibaldi, V.; Cucchiella, F.; De Berardinis, P.; Rotilio, M.; Stornelli, V. Environmental and economic benefits of optimal insulation thickness: A life-cycle cost analysis. *Renew. Sustain. Energy Rev.* **2019**, *116*, 109441. [CrossRef]