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# Energy-Saving Potential of Applying Prefabricated Straw Bale Construction (PSBC) in Domestic Buildings in Northern China

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**Abstract:** The Prefabricated Straw Bale Construction (PSBC) has been proven as one of the most efficient construction methods to achieve low-energy buildings with low environmental impacts. This research presents analysis of the rationale for using straw bale constructions in northern China and a discussion of feasible constructions of PSBC to meet the local building codes following evaluations of potential energy performance of domestic buildings with PSBC in severe cold regions and cold regions in China. The results show that the buildings with PSBC reduce both heating and cooling energy uses, as well as heating intensities across the severe cold and cold regions, compared to the domestic buildings with conventional constructions. The findings of this research will contribute to reducing energy consumption in building industries in China.

**Keywords:** low-carbon design; bio-based building materials; straw bale; prefabricated straw bale construction (PSBC); operational energy; energy simulation

## 1. Introduction

### *1.1. Research Background*

As an outcome of the boom in economic development over the last two decades, China has experienced a rapid increase in urbanization. Urbanization has increased from 46% in 2008 to a predicted value of 60% by 2020 [1]. During the urbanization process, the major energy source has been coal [1]. Due to the inevitable increase in energy demand from the urbanization process, Green House Gas emissions in China will continue to increase significantly until this urbanization process is completed [2]. Energy consumption in residential buildings makes a significant contribution to the GHG emissions generated by the urbanization process in China [3]. As a result, the building industry has been a major obstacle in reducing energy consumption and GHG emissions from China [4,5]. The current situation with building energy efficiency levels is to ensure high energy efficiency standards for new construction [6]. However, the rapid growth of energy demand in Northern China may make it more difficult to achieve these standards [7].

To deliver the commitment that the Chinese government made in the Paris Agreement, policies adopted by the building industry have largely been defined and supervised by the Ministry of Housing and Urban–Rural Development of the People's Republic of China (MOHURD). The majority of policies are enacted through statutory and industrial standards [8]. The strategies to reduce GHG emissions caused by the building industry focus on increasing the energy efficiency levels of existing buildings and reducing energy use in newly built buildings [6]. The strategies for increasing the energy efficiency levels of existing buildings involve refurbishment of existing buildings and replacing existing building service systems [8]. The reductions in energy use in newly built buildings involve higher standards of energy efficiency levels, encouraging the use of prefabricated construction in buildings and promoting the number of green buildings amongst newly built buildings [8]. These strategies have been applied as a priority in northern China due to the higher energy reduction potential in this region compared to those in other regions [9,10].

Nearly Zero-Energy Buildings (NZEBs) are defined as low-energy buildings with superior building performances than conventional buildings, and renewable energy resources are often applied to meet the energy requirements of NZEBs [11,12]. As the ultimate target of NZEBs is to achievable zero energy consumption, the designs and constructions of NZEBs require high energy efficiency levels of the NZEB and passive strategies for improving the energy efficiency levels [13]. As part of the passive strategies for improving energy efficiency levels of NZEBs, the building envelopes have notable impact on both the built environment and methods of building designs and constructions [14].

### *1.2. Climatic Features and Energy Consumptions of Buildings in Northern China*

The climate in China encompasses a wide range of air temperatures and humidity. MOHURD published the national code for thermal design of civil buildings, which identifies a number of different climatic regions [15]. The design and construction of buildings in China is informed by five climate regions differentiated by the climatic characteristics of the regions (Figure 1). Northern China is in the climatic areas defined as "Severe Cold" and "Cold". In these two regions, the primary energy demand in buildings is for winter heating [15].

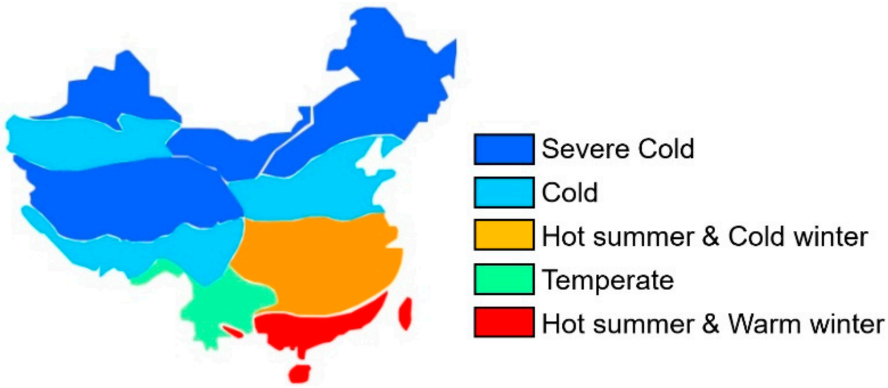


**Figure 1.** Climatic regionalization in the GB50178-93 (reproduced from [15]).

Both severe cold and cold regions are in the "Temperate" monsoon climate. The climatic features of the two climatic regions represent two typical climatic characteristics [15]: Firstly, both the air temperature and humidity are at high levels in summer months. The daily high temperatures are around 30 °C in summer months in severe cold regions, whereas they are over 30 °C in cold regions. Rainfalls are expected mostly in summer months, and they lead to the high air humidity. Secondly, the air temperatures are expected to be below freezing during the whole winter period in the two climatic regions, and highest monthly air humidity levels are present during the same period of time. However, the high air humidity levels do not result in a humid environment inside and outside buildings. As the low temperatures decrease absolute water vapor pressures in the air, the relative humidity levels in winter months are significantly higher than other months annually in the severe cold and cold regions.

The need for improved building energy efficiency is most critical in northern China due to the high winter heating demand caused by the regional climatic conditions. The Climate Policy Initiative established that the floor area of urban residential buildings has doubled between 2000 and 2008 [16]. As a result, residential buildings are expected to account for up to 90% of total building floor area in

China by 2030 [16]. Due to this dominant position of domestic buildings, end-use energy consumption is a significant contributor to the total in-use energy of buildings in China (Figure 2). According to the predictions for 2021, in comparison with the 1996 energy consumption levels, energy use increased at its most rapid rate in China in 2008 [16]. The heating energy demand by domestic buildings more than doubled between 1996 and 2008, and has become the most crucial factor for energy use in domestic buildings in China.

Heating demand is notably high in northern China due to the requirement for thermal comfort in the winter months. As a result, in this region, the proportion of energy consumption associated with heating is much greater than the national average. The latest versions of building regulations commit to a reduction of 50% in the heating energy consumption of buildings against the 1980 levels in northern China [17,18]. The regulations specify the thermal conductivity of the building envelope, with U-values ranging from 0.25 to 0.7 $W/m^2K$, depending on the heights and locations of residential buildings in northern China [17,18].

### *1.3. Rationale for Straw Bale Construction in Northern China*

Straw bale construction uses agricultural co-products in the construction of buildings. It was originally developed due to a shortage of building materials in Nebraska in the late 19$^{th}$ century [19]. Straw bale buildings were originally used as temporary buildings [20]. This building type was replaced through the development of more industrialized building materials in the Mid-West of America in the early 20th century [19]. In the 1970s, the oil crisis prompted the development of concepts for more energy-efficient buildings in the USA [19]. Straw bale buildings are characterized by a combination of low cost, quick construction process, and high thermal insulation [20]. This construction technique was re-introduced in the 1980s in west America, and the construction method has since become popular worldwide [21]. Straw bale construction is now recognized globally and has developed into a contemporary building typology and construction method in the Western world [19]. The construction technique was initially introduced to northern China by the Adventist Development and Relief Agency (ADRA) in 1998 [22]. This project was funded by the ADRA/China, Central Government, and Local Government in northern China, and more than 600 straw bale buildings were completed by 2006 [23]. Informed by the practices of the ADRA project, a different design for straw bale buildings was developed in Jilin province [24].

There are three significant advantages to straw bale construction in the context of conditions in China.

First of all, straw bales are a carbon-sink building material with significantly low embodied energy and embodied carbon [25]. The atmospheric $CO_2$ is sequestered in the body of the plant through the process of photosynthesis [25–28]. It can be calculated through stoichiometry that 1 kg of carbon sequestered in the straw stems requires the removal of 3.67 kg of $CO_2$ from the atmosphere. This amount of adsorbed carbon will not be released into the atmosphere until the straw bale buildings are demolished [29].

Secondly, due to the high thermal insulation properties of straw bale walls, straw bale houses have low heating energy demand [30]. The U-value of typical prefabricated straw bale walls can be as low as from 0.11 to 0.19 $Wm^2K^{-1}$ for 450 mm thick wall panels [31]. In comparison with the thermal performance stipulated in current Chinese standards for walls, the thermal resistances of these panels are 50–300% better than those of standard wall constructions. Air pollution is also exacerbated by the use of coal to heat buildings in Northern China [32–34]. The high thermal insulation properties of straw bale buildings notably decrease heating demand; therefore, less coal is required for winter heating in northern China.

Thirdly, the use of straw in the building industry will benefit the agricultural economy of northern China. Straw is considered a waste material in the farming process for rice and wheat in northern China [35]. The total annual rice production in northeast China is approximately 203 million metric tons [36]. Due to the associated large amount of waste straw, disposal of the material has been a concern in China for decades. Currently, the most common approach for disposal of the straw is for it to be burnt in fields [37]. This issue demands more environmentally friendly disposal solutions for straw as an alternative to burning [37].

*1.4. Prefabricated Straw Bale Construction (PSBC)*

Prefabricated Straw Bale Construction (PSBC) is a prefabricated construction technique for utilizing straw bales in buildings [38]. This building technique combines conventional straw bales with the superior characteristics of controlled prefabricated construction processes [38]. In comparison with conventional straw bale construction, the main benefit of PSBC is that this construction technique minimizes the risks associated with wet weather on construction sites. It also offers better quality control than onsite construction of straw bale walls [39]. Additional benefits of PSBC include a reduction in onsite construction time, no site waste removal, and lower risks of fire on the construction site due to elimination of loose straw [38].

ModCell is one of the first companies to produce PSBC. This PSBC is in the form of PSBC panels. The panels typically consist of engineered timber frames, in-fill straw bales, and lime render [39]. The dimensions of the engineered frames are typically 100 x 480 mm to accommodate the dimensions of the in-fill straw bales. The sizes of the panels vary according to different building projects, but are typically 3.0 (width) × 3.2 m (height). The in-fill straw bales are stacked to form walls of densities of around 110 kg/m$^3$ [39], and these are pre-compressed during the process to increase stability and reduce thermal bridging arising from gaps between the bales and the frames [40]. The bales are finished with a 30 mm lime render, which is the minimum thickness of lime render possible without the use of a rain screen in the climatic environment of the UK [41].

The ModCell panels have been used in several projects. One of the more high-profile applications of this product was in the construction of the Low-Impact Living Affordable Community (LILAC) project in Leeds. This project included a 20 household community in Bramley, west Leeds on a former school site [42]. The ModCell PSBC panels were used for the walls of the domestic buildings in the LILAC project. The project featured low-energy-consumption residential buildings [42]. The average energy use in the LILAC buildings can be categorized as follows: 35.73 kWh/m$^2$ for space heating, 39.22 kWh/m$^2$ for domestic hot water, and 30.00 kWh/m$^2$ for lighting [43]. Comparison between these energy demands and other benchmarks shows that the energy consumption level of the LILAC project residences is greatly superior to the Chartered Institution of Building Services Engineers (CIBSE) Guide F benchmarks, and is comparable to PassivHaus standards in terms of space heating energy demand (Figure 2).

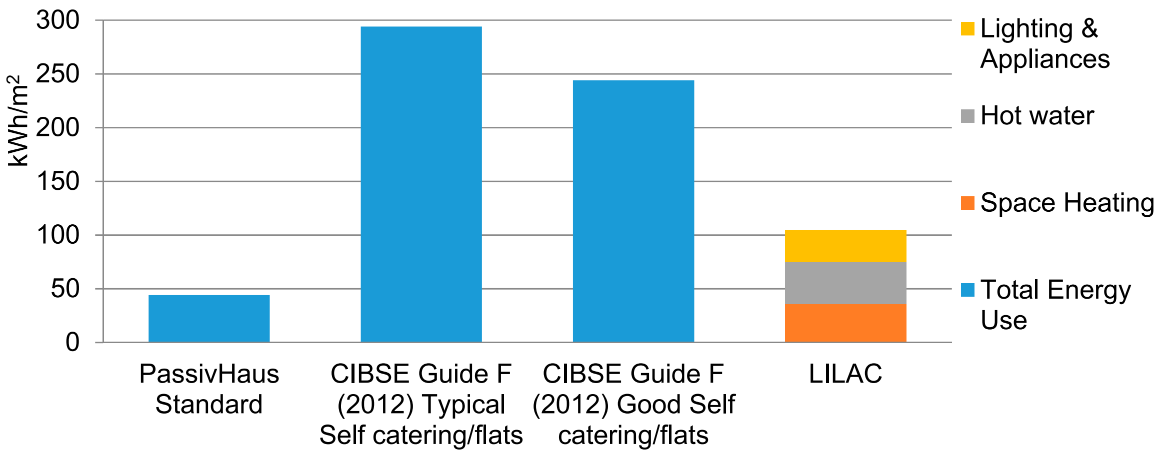


**Figure 2.** Comparative energy consumption of Low-Impact Living Affordable Community (LILAC) and other benchmarks (data of benchmarks from [44]).

Apart from the ModCell PSBC, another prefabrication method for straw bales was developed by Ecococon in Lithuania. The Ecococon prefabrication system consists of in-fill straw, timber frames, and a plastering and rendering layer. The assembly of the PSBC walls required only simple tools and standard screws for the building of Ecococon walls [45]. The prefabricated Ecococon panels use in-fill loose straw rather than straw bales. Straw stems are stacked in several layers on the timber frames and compressed during the stacking process [45]. According to Ecococon, this stacking method can effectively reduce the gaps between the straw and results in a high uniform density of the in-fill bale walls [45].

The design of the in-fill method of straw and the design of the timber frames results in a high thermal resistance for the Ecococon PSBC panels. Typical U-values for the ModCell panels are 0.190 W/m$^2$K [40]. The thermal conductivity of the Ecococon products is 0.056 W/mK, with a resulting overall U-value of 0.107 W/m$^2$K [45]. The panels were certified as PassiveHaus building materials, as they meet the PassiveHaus standards [45].

### *1.5. Research Scope and Objective*

With a relatively long history of straw bale buildings, Prefabricated Straw Bale Construction (PSBC) has developed in recent years. Current research verifies the rationale for applying straw bale buildings in accordance with the policies and climatic features of northern China. However, the discussion of feasibility and the potential benefits of this relatively innovative walling construction method has been limited.

This research discusses the feasibility of PSBC in residential buildings to reduce energy consumption in this building type in northern China. In order to establish overall estimates of the energy consumption of residential buildings with PSBC, this research discusses the operational energy load (heating and cooling) of reference buildings in the climatic conditions for fifteen major cities in northern China. This is followed by a comparison of the operational heating and cooling energy demand of buildings with PSBC and with standard wall construction.

## 2. Research Methodology

This study commences by determining the reference buildings and the application methods for PSBC in the reference buildings. Energy modeling and the simulation processes for the reference buildings are based on the IESVE-2018, which is computational simulation software produced by the Integrated Environmental Solutions Limited (Glasgow, UK). The detailed research methods are as follows.

### *2.1. Typical Residential Buildings*

In the urban environment of China, the majority of residential buildings are multiple-floor apartment buildings and high-rise apartment buildings [46,47]. There are two types of typical layouts for high-rise domestic building designs in northern China. The first layout consists of several apartment blocks [48]. In each block, stairs and lifts are available to every apartment on each floor [48]. The second layout is for tower-type high-rise residential buildings [48]. The floor plan for these tower-type residential buildings is more centralized than that for the block-type high-rise residential buildings, and is generally suitable for the design of small apartments. However, in practice, since the floor area of residential buildings has been increasing since the 1980s [46], the block layout for residential buildings is most common.

In order to representing the most common form of residential buildings, this research is based on apartment residential buildings of different building heights. The reference floor plan consists of two blocks with two one-bedroom apartments and one two-bedroom apartment (in blue and green), with a corridor and stairs (in red) to each apartment in the building (Figure 3). As required by GB50096-2011, residential buildings with less than six floors are identified as multiple-floor residential buildings, whereas high-rise buildings have more than seven floors [48]. Skyscraper residential buildings are defined in the standard as being over 100 m high [48]. However, due to the severe requirements for fire evacuation and the related economic implications, this type of residential building is not widely constructed in China. As a result, the reference building heights for this study are defined as 6, 12, and 18 floors.


**Figure 3.** Typical floor plan of the reference residential building in this research (corridor space in red; flat space in blue and green).

## 2.2. *Application of PSBC*

The method of application of PSBC wall panels is referenced from the standard building details in 16J110-2/16G333. This standard building detail was published by the MOHURD in 2008. This published standard introduces the standard construction details for application methods for prefabricated concrete wall systems in China [49]. Based on the 16J110-2/16SG333, the PSBC wall panels can be used for in-fill construction between building frames. In this technique, the PSBC wall panels are directly placed between the main structural frames (Figure 4). The weight of the PSBC walling panels is directly contained by the main structure. As a result, metal connections are only required to fix the PSBC wall panels to the structural frame of the building. The structural frame requires a separate layer of thermal insulation materials in the in-fill PSBC walling façade.

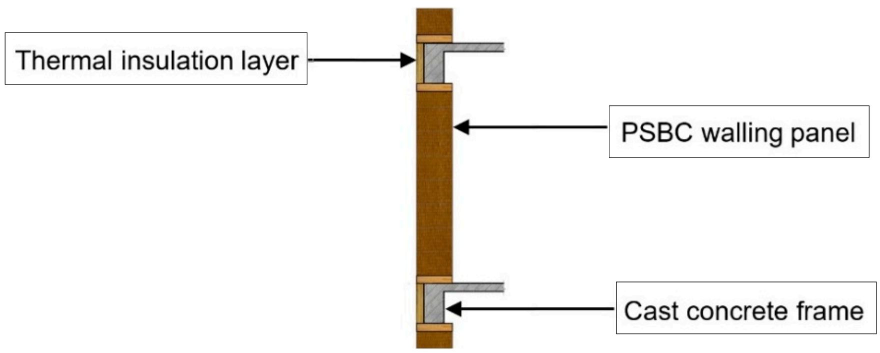


**Figure 4.** Construction of a Prefabricated Straw Bale Construction (PSBC) walling façade with in-fill PSBC panels.

The detail designs between the PSBC wall panels and the structural frame can be referenced from standard designs for metal fixing in 16J110-2/16G333. One detail design for metal fixing is shown in Figure 5. The metal fixings include three components, which are the part embedded in the concrete frame, the part embedded in the prefabricated wall panels, and the connection between the prefabricated wall panels and the cast concrete frame. In consideration of infiltration issues and the fire resistance requirements for the prefabricated wall panels, fire resistance materials are applied between the prefabricated wall panels.

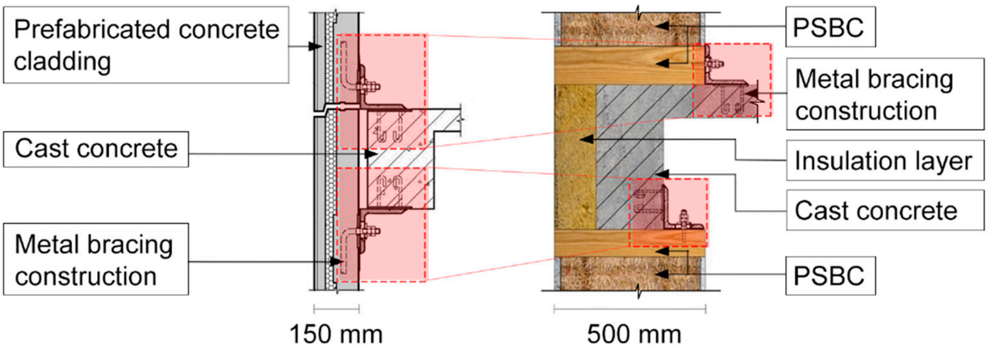


**Figure 5.** Detailed design of PSBC walling in reference building (right) from the 16J110-2/16G333 (left) [49].

The construction of the in-fill PSBC wall panels is different from that of the prefabricated concrete wall panels. As a result, the detailed connections between the cast concrete frame and the PSBC wall panels are modified from the standard metal fixing designs in the 08SJ110-2/08SG333. Since the PSBC panels are in-filled in the space between the concrete frames, there is no need for fire resistance sealing between these walling panels. The in-fill construction of the PSBC wall façade requires a thermal insulation layer on the external surface of the concrete frames. The U-value of the thermal insulation layer can be referenced from the design U-value of the PSBC walling panels to avoid thermal bridging through the concrete frames.

There are two locations for the metal fixing between the PSBC wall panels and the structural frames. The metal fixing should be applied both between the top plate of the structural frames for the PSBC wall panels and the cast concrete frame, and between the base plate of the structural frames for the PSBC wall panels and the cast concrete frame. The embedded parts for metal fixing of the wall panels are different to accommodate the different construction processes for prefabricated concrete wall panels and PSBC wall panels. The embedded parts for the PSBC wall panels are screws rather than the rebar used in prefabricated concrete wall panels. The screws have an M30 thread and are 80 mm long [49].

As per the design for the PSBC wall construction, there are two potential thermal bridging concerns. The first is the linear bridging between the PSBC wall panels and the thermal insulation layer. The second is the timber frame for the PSBC wall panels. The linear bridging issues can be solved through proper sealing between the insulation layers and the PSBC wall panels during installation of the wall panels. For the timber frame bridging, due to the relatively low thermal conductivity of timber, the bridging may not be significant.

### *2.3. IESVE Simulation Process*

The simulation process is based on the IESVE-2018, which is widely used in accessing the energy efficiency levels of building projects for research purposes. There are three key elements in the modeling process in this research: The choosing of simulated cities, construction details of reference buildings, and the occupancy behaviors. Each element is discussed as follows.

The reference buildings will be examined in 15 major cities across the severe cold regions and the cold regions (Table 1). In the simulation process, each sub-region contains three examined cities to provide more accurate estimation of the energy requirements of reference buildings in the region. For the same reason, the examined cities are also selected across both longitude and latitude of the severe cold regions and the cold regions in the simulation process.

**Table 1.** Examined cities of the IESVE-based simulation of reference buildings.

| **15 Study Cities by Climate Zones** | | | | | |
|---|---|---|---|---|---|
| **Climatic Regions** | **Sub-Regions** | **Index of Heating Degree Day (HDD) and Cooling Degree Day (CDD) (JGJ26-2010)** | **City** | **Longitude** | **Latitude** |
| Severe Cold Regions | Region 1A | 6000 ≤ HDD18 | Mohe | 122.53° E | 52.97°N |
| | | | Hailar | 119.70° E | 49.25°N |
| | | | Nenjiang | 125.23° E | 49.17°N |
| | Region 1B | 5000 ≤ HDD18 < 6000 | Dunhua | 128.20° E | 43.37°N |
| | | | Qiqihar | 123.92° E | 47.24°N |
| | | | Harbin | 126.57° E | 45.93°N |
| | Region 1C | 3800 ≤ HDD18 < 5000 | Changchun | 125.68° E | 44.00°N |
| | | | Shenyang | 123.52° E | 41.73°N |
| | | | Wulumuqi | 87.62° E | 43.78°N |
| Cold Regions | Region 2A | 2000 ≤ HDD18 < 3800, CDD26 ≤ 90 | Taiyuan | 112.63° E | 37.75° N |
| | | | Lanzhou | 103.88° E | 36.05°N |
| | | | Dalian | 121.54° E | 38.97°N |
| | Region 2B | 2000 ≤ HDD18 < 3800, CDD26 > 90 | Beijing | 116.59° E | 40.08°N |
| | | | Shijiazhuang | 114.35° E | 38.07°N |
| | | | Ji'nan | 116.98°E | 36.68°N |

In the simulation process, thermal properties of the building materials are referenced from the IESVE-2018 database. Due to the lack of the data of straw bales in the software, the data are from existing researches. Considering the property differences of straw bales in different researches [40,50,51], the thermal conductivity of straw bale is designated as 0.700 W/mK. Existing researches confirmed the high thermal mass of straw bale walls [29,52] with specific thermal heat capacity ranging from 1388–2000 J/(kgK) [53,54]. As a result, the heat capacity of the PSBC is designated as 2000 J/(kgK) in the simulation process.

Detailed constructions and the requirements of design U-values of the building components are referenced from the standard JGJ-26-2010 [17]. According to the standard, the buildings require highly demanding U-value designs in the climatic regions that feature high HDD and vice versa [17]. Considering the practices of residential buildings in the climatic regions, detailed U-values of reference buildings are listed in the Table 2. There are two walling constructions of the reference building with PSBC walls: The original-thickness construction (OTC) and the reduced-thickness construction (RTC). The OTC features a walling thickness which is similar to that of the existing PSBC, whereas the RTC has a similar walling thickness to that of the typical walling constructions required in the JGJ26-2010.

There are two major aspects in deciding the occupancy factors: The heating and cooling modes and the residential behaviors. As the city levels of district heating systems have been widely used in the climatic regions since the 1950s, the heating periods of the reference buildings are subject to the heating requirements in each city. The heating periods and cooling periods of different cities are developed from the HDD index introduced in the JGJ-26-2010 (Table 3). The cooling requirements in the researched climatic regions are mainly achieved by using separate air conditioning units on a flat basis; there are no fixed cooling periods in this research. The cooling requirements are set 26 °C outside the heating periods in the flats of the reference buildings [17]. For the residential behaviors, the residential periods would be mainly based on the individual life styles of the people living in the flats; this research provides estimations of residential behaviors of working people on average (Table 4). The appliances are considered to be the most essential ones in flats.

**Table 2.** U-values of reference buildings in different climatic regions.

| Climatic Regions | Sub-Regions | U-Value (W/(m$^2$·K)) | | | |
|---|---|---|---|---|---|
| | | Building Construction | Simulated Standard Construction | PSBC (OTC) | PSBC (RTC) |
| Severe Cold | Region 1A | Roof | 0.199 | 0.199 | 0.199 |
| | | Wall | 0.242 | 0.150 | 0.168 |
| | | Window | 1.600 | 1.600 | 1.600 |
| | | Door | 1.436 | 1.436 | 1.436 |
| | Region 1B | Roof | 0.243 | 0.243 | 0.243 |
| | | Wall | 0.436 | 0.150 | 0.221 |
| | | Window | 1.600 | 1.600 | 1.600 |
| | | Door | 1.436 | 1.436 | 1.436 |
| | Region 1C | Roof | 0.243 | 0.243 | 0.243 |
| | | Wall | 0.436 | 0.150 | 0.221 |
| | | Window | 1.600 | 1.600 | 1.600 |
| | | Door | 1.436 | 1.436 | 1.436 |
| Cold | Region 2A | Roof | 0.389 | 0.389 | 0.389 |
| | | Wall | 0.573 | 0.150 | 0.245 |
| | | Window | 1.600 | 1.600 | 1.600 |
| | | Door | 1.692 | 1.692 | 1.692 |
| | Region 2B | Roof | 0.389 | 0.389 | 0.389 |
| | | Wall | 0.573 | 0.150 | 0.245 |
| | | Window | 1.600 | 1.600 | 1.600 |
| | | Door | 1.692 | 1.692 | 1.692 |

**Table 3.** Settings of heating periods in the IESVE-2018.

| Sub-Climatic Regions | Region 1A | Region 1B | Region 1C | Region 2A | Region 2B |
|---|---|---|---|---|---|
| Heating period | 1 October−30 April | 10 October−10 April | 20 October−31 March | 10 November−20 March | 15 November−15 March |
| Heating temperature | 20 °C in flat (required 18 °C in JGJ 26-2010) and 12 °C in corridors (required 12 °C in JGJ 26-2010) | | | | |

**Table 4.** Occupancy factors in the IESVE-2018 simulation in this research.

| | Bedroom | | Living room | Bathroom | Kitchen |
|---|---|---|---|---|---|
| Occupied period | Weekday | 24:00−7:00 | 7:00−9:00 and 17:00−24:00 | 7:00−7:30 and 22:00−22:30 | Randomly 1 h between 17:00−19:00 |
| | Weekend | 24:00−9:00 | 0:00−24:00 | Randomly 1 h between 0:00−24:00 | Randomly 1 h between 0:00−24:00 |
| Lighting | 60 W | | 180 W | 40 W | 40 W |
| Occupancy density | 2 persons/room | | 2 persons | 2 persons | 2 persons |
| Equipment | 300 W | | 200 W | 2000 W | 2600 W |

## 3. Research Results and Discussions

The energy-saving potentials of PSBC are estimated through the heating energy requirements of the flats and the heating and cooling energy loads in the reference buildings. The heating energy intensities of residential buildings are standardized in the JGJ-26-2010. To compare the energy intensity of the standard constructed walls and the PSBC walls, the heating energy loads are examined in the simulation processes of the reference buildings with the standard construction. The heating energy demand and the cooling energy demand are based on the results of energy consumption in the simulation processes of the reference buildings across climatic regions in this research. Due to the uncertainty of energy efficiency of the heating and cooling systems in different cities, the energy efficiency levels are set at 100% [55]. The following estimations of energy demand are based on the energy requirements of the reference buildings with the standard construction and the PSBC.

### *3.1. Heating Load*

Detailed heating loads of reference buildings are shown in Table 5. The heating loads of the reference buildings with the standard construction are notably higher than those of the standard requirements. The higher heating loads of the reference buildings would be the result of the higher indoor temperature set-up than the standard requirements. The indoor temperature of the reference buildings is set at 20 °C during the simulation process, whereas the standard (JGJ-26 2010) requires 18 °C for the flat spaces. As the 20 °C indoor temperature is widely applied in existing practices in northern China [56–58], the standard heating load may underestimate the heating load in practices in Mohe, Harbin, and Changchun (Table 5). In the three cities, the gaps of heating load are between 2–4 W/m$^2$ in the simulation results of reference buildings with standard constructions. Higher heating loads in real practices in these cities may also confirm the gaps of heating demands [59].

**Table 5.** Heating loads in severe cold regions and cold regions in China.

| Climatic Area | Cities | Heating loads (W/m$^2$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | JGJ26-2010 Requirements | | | Simulated Standard Construction | | | PSBC (OTC) | | | PSBC (RTC) | | |
| | | 6F | 12F | 18F | 6F | 12F | 18F | 6F | 12F | 18F | 6F | 12F | 18F |
| Region 1A | Mohe | 23.1 | 20.9 | 20.6 | 24.96 | 23.11 | 22.71 | 23.5 | 21.6 | 21.2 | 23.9 | 21.9 | 21.51 |
| | Hailar | 20.9 | 18.9 | 18.8 | 20.8 | 19.2 | 18.90 | 19.4 | 17.9 | 17.6 | 19.8 | 18.1 | 17.8 |
| | Nenjiang | 20.7 | 18.6 | 18.5 | 19.8 | 18.3 | 18.02 | 18.5 | 17.1 | 16.8 | 18.9 | 17.3 | 17.0 |
| Region 1B | Dunhua | 18.0 | 16.5 | 15.2 | 21.6 | 19.3 | 18.55 | 18.0 | 15.6 | 14.9 | 19.0 | 16.6 | 16.0 |
| | Qiqihar | 19.8 | 18.1 | 16.7 | 21.3 | 19.0 | 18.20 | 17.7 | 15.3 | 14.6 | 18.7 | 16.3 | 15.7 |
| | Harbin | 20.0 | 18.3 | 16.9 | 21.0 | 18.7 | 18.01 | 17.4 | 15.1 | 14.4 | 18.4 | 16.0 | 15.5 |
| Region 1C | Chang chun | 19.9 | 18.6 | 16.3 | 22.9 | 20.5 | 19.97 | 19.2 | 16.7 | 16.2 | 20.1 | 17.7 | 17.1 |
| | Shen yang | 17.2 | 15.9 | 13.9 | 16.9 | 14.9 | 14.44 | 13.8 | 11.8 | 11.3 | 14.6 | 12.6 | 12.1 |
| | Wulu muqi | 18.7 | 17.4 | 15.4 | 19.8 | 17.5 | 16.93 | 16.4 | 14.1 | 13.5 | 17.2 | 15.0 | 14.4 |
| Region 2A | Taiyuan | 15.4 | 14.1 | 12.5 | 14.4 | 12.5 | 11.99 | 10.6 | 8.6 | 8.1 | 11.5 | 9.5 | 9.0 |
| | Lan zhou | 14.4 | 13.1 | 11.7 | 14.6 | 12.6 | 12.04 | 10.8 | 8.8 | 8.2 | 11.7 | 9.7 | 9.1 |
| | Dalian | 14.3 | 13.0 | 11.5 | 16.8 | 15.0 | 14.58 | 12.6 | 10.7 | 10.3 | 13.6 | 11.7 | 11.3 |
| Region 2B | Beijing | 15.0 | 13.4 | 12.1 | 14.1 | 12.3 | 11.77 | 10.3 | 8.4 | 7.9 | 11.1 | 9.2 | 8.8 |
| | Shijia zhuang | 14.6 | 13.1 | 11.6 | 13.6 | 11.8 | 11.34 | 10.0 | 8.2 | 7.7 | 10.8 | 9.0 | 8.5 |
| | Ji'nan | 13.2 | 11.7 | 10.5 | 11.6 | 10.0 | 9.62 | 8.3 | 6.7 | 6.3 | 9.0 | 7.4 | 7.0 |

□ 5.00–9.99 W/m$^2$ □ 10.00–14.99 W/m$^2$ □ 15.00–19.99 W/m$^2$ ■ 20.00–24.99 W/m$^2$.

The simulation results show that the heating loads of the simulated standard constructions are from −14.4% to 26.2% in comparison to the data from the JGJ-26-2010 (Table 6). The simulation results indicate that the standard data overestimate the heating load by around 10% across the cities in the climatic region 2B. The heating load is subjective to the situation of each city in other climatic regions. The heating loads of standard requirements overestimate the heating loads of reference buildings in Taiyuan, Shenyang, and Nenjiang. However, the simulation results of heating loads are higher than those of the standard requirements in other cities in the climatic regions 1A, 1B, 1C, and 2A. Compared to the simulation results, the underestimations of heating loads are more than 15% in Dunhua, Changchun, and Dalian.

**Table 6.** Comparison of heating loads of simulated buildings with standard construction.

| Climatic Area | Cities | Comparison of Heating Requirements with Standard Requirements in JGJ26-2010 (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Simulated Standard Construction | | | PSBC (OTC) | | | PSBC (RTC) | | |
| | | 6F | 12F | 18F | 6F | 12F | 18F | 6F | 12F | 18F |
| Region 1A | Mohe | +8.1 | +10.6 | +10.3 | +1.6 | +3.5 | +3.1 | +3.5 | +4.8 | +4.4 |
| | Hailar | −0.7 | +1.6 | +0.5 | −7.1 | −5.4 | −6.5 | −5.2 | −4.1 | −5.1 |
| | Nenjiang | −4.3 | −1.5 | −2.6 | −10.4 | −8.3 | −9.4 | −8.5 | −7.0 | −8.1 |
| Region 1B | Dunhua | +20.2 | +17.1 | +22.0 | +0.2 | −5.6 | −2.0 | +5.7 | +0.4 | +5.1 |
| | Qiqihar | +7.6 | +4.8 | +9.0 | −10.4 | −15.5 | −12.6 | −5.5 | −10.2 | −6.2 |
| | Harbin | +4.9 | +2.3 | +6.6 | −13.0 | −17.8 | −14.7 | −8.0 | −12.4 | −8.3 |
| Region 1C | Chang chun | +15.1 | +10.3 | +22.5 | −3.7 | −10.1 | −0.7 | +0.9 | −5.1 | +5.0 |
| | Shen yang | −1.5 | −6.1 | +3.9 | −19.6 | −25.9 | −18.7 | −15.1 | −20.9 | −13.1 |
| | Wulu muqi | +5.7 | +0.7 | +9.9 | −12.3 | −18.9 | −12.1 | −7.8 | −14.0 | −6.6 |
| Region 2A | Tai yuan | −6.2 | −11.2 | −4.1 | −31.2 | −38.9 | −35.2 | −25.6 | −32.6 | −28.1 |
| | Lan zhou | +1.3 | −3.9 | +2.9 | −24.7 | −32.9 | −29.6 | −18.8 | −26.2 | −22.1 |
| | Dalian | +17.4 | +15.4 | +26.8 | −11.9 | −17.7 | −10.6 | −5.3 | −10.1 | −2.0 |
| Region 2B | Beijing | −6.2 | −8.6 | −2.7 | −31.6 | −37.5 | −34.7 | −26.1 | −31.1 | −27.7 |
| | Shijia zhuang | −6.6 | −9.6 | −2.2 | −31.3 | −37.7 | −33.9 | −25.9 | −31.4 | −26.8 |
| | Ji'nan | −12.5 | −14.4 | −8.4 | −37.4 | −43.1 | −40.2 | −31.9 | −36.6 | −33.1 |

< −20% −10% ~ −20% −9.9% ~ −0.1% 0% ~ +9.9% +10% ~ +20% > +20%.

Due to relatively low standards of thermal insulative properties of walling constructions in the cold regions, the PSBC has more reductions of heating load than the ones in the severe cold regions. In the region of 2B, the two types of PSBC are estimated to lower the heating loads of reference buildings by more than a quarter compared to the reference buildings with standard constructions. As the PSBC (RTC) has a similar walling thickness to that of the standard constructions, the applications of the PSBC will significantly lower the heating loads of the heating systems and maintain similar levels of indoor space to the reference buildings with standard constructions.

The applications of the two types of PSBC have significant impact on reducing the heating loads of reference buildings in the severe cold regions as well. As the setups of the indoor temperatures are higher than the standard requirements in JGJ-26-2010, the existing heating systems may not meet the heating loads of reference buildings with standard constructions in the severe cold regions. The applications of the two types of PSBC lower the heating loads significantly, and the heating loads meet the existing standards in the buildings in the severe cold regions (Table 6). In Dalian, the heating loads of reference buildings are 14.58–16.78 W/m$^2$ with standard constructions, whereas the reference buildings require a 10.28–13.55W/m$^2$ heating load with the two types of PSBC. Compared to the standard heating load in JGJ26-2010, the standard construction fails to meet the standard requirements, whereas the reference buildings reduce the heating load by 2–17% by applying PSBC walls.

Comparing the two types of PSBC, the PSBC (OTC) has advantages in reducing the heating loads of reference buildings, whereas the PSBC (RTC) features maintain similar levels of heating load to those of the PSBC (OTC) with the same internal space as the existing residential buildings. The PSBC (OTC) has 5–8% lower heating load than the PSBC (RTC). Due to the high heating load in the severe cold regions, the advantages of the PSBC (OTC) have a more significant impact on the residential buildings in the regions. In the Region 1C, the heating loads of PSBC (OTC) are 1–1.5 W/m$^2$ lower than those of the reference buildings with PSBC (OTC). In the cold regions, due to the relatively low requirements of thermal insulative properties of walling constructions in the JGJ26-2010, the standard walling thicknesses are between 200–300 mm, which are notably lower than those for the PSBC (OTC). Compared to the two types of PSBC, the heating loads of the PSBC (RTC) are 0.8–1 W/m$^2$ more than those of the reference buildings with the PSBC (OTC). Considering the relatively low thickness of the PSBC (RTC), this type of PSBC would be suitable for further construction of residential buildings in the cold regions.

### 3.2. Heating and Cooling Energy Requirements

The heating and cooling energy demands of the reference buildings across different climatic regions are shown in Figures 6 and 7. Due to the low winter temperatures in the region 1A, the peak energy demands are more than 105 kWh/m$^2$/year in the six-floor reference buildings, and the energy requirements are around 100 kWh/m$^2$/year in the reference buildings in the region. Due to the relatively low cooling energy requirements in the Region 2A, the energy demands of the reference buildings are between 48 and 57 kWh/m$^2$/year, which are the lowest energy demands compared to the ones in all researched climatic regions. The heating and cooling energy demands of the reference buildings are significantly different between the severe cold regions and the cold regions. As the residential periods exclude the daytime (9:00–17:00) in this research, the cooling energy demands exclude the cooling energy requirements to offset the potential overheating periods in the afternoon (12:00–17:00) in the simulation processes. In the severe cold regions, the cooling energy demands contribute less than 5% of the total energy demands and are barely ignorable, whereas the cooling energy demands are much more significant in the cold regions. The features of energy requirements are comparable to the HDD and CDD index in the JGJ26-2010.

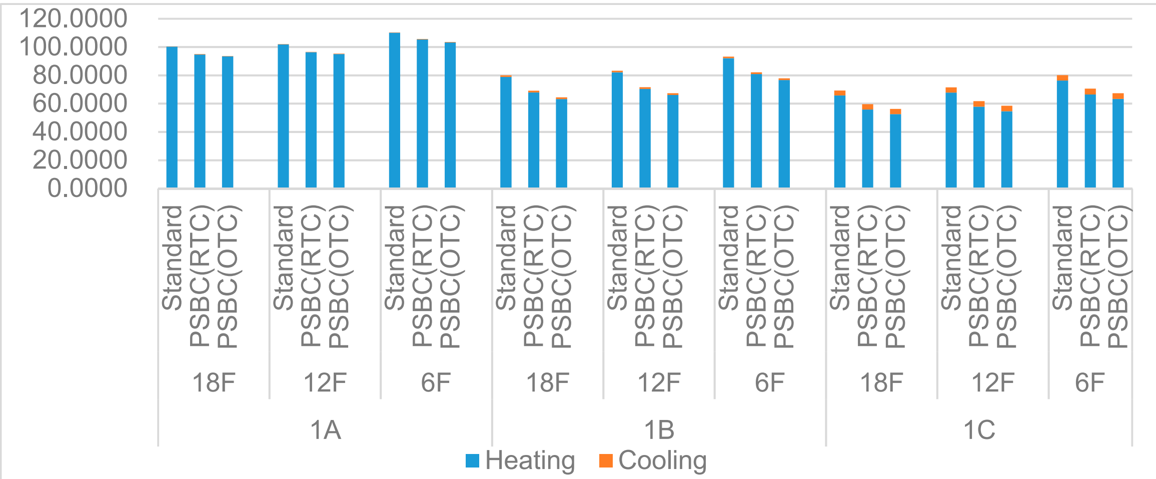


**Figure 6.** Heating and cooling energy demands (kWh/m$^2$/year) of reference buildings in severe cold regions.

In the severe cold regions, due to the high demands of heating energy, the high insulative properties of the two types of PSBC have notable advantages compared to the standard walling constructions in reducing energy demand in reference buildings with different building heights (Figure 6). As high thermal insulative properties of building construction are required in the JGJ26-2010, the advantages of the PSBC are not significant in the region 1A. Reductions of heating and cooling energy demands achieved by the PSBC are between 5 and 10 kWh/m$^2$/year. However, compared to the standard constructions, the two types of PSBC reduce the energy demands by more than 10 kWh/m$^2$/year in the region 1B and the region 1C. Due to the high energy-saving potentials of the PSBC in the regions 1B and 1C, replacing existing walling constructions with the PSBC would achieve a more significant impact on energy efficiency levels of residential buildings in the severe cold regions.

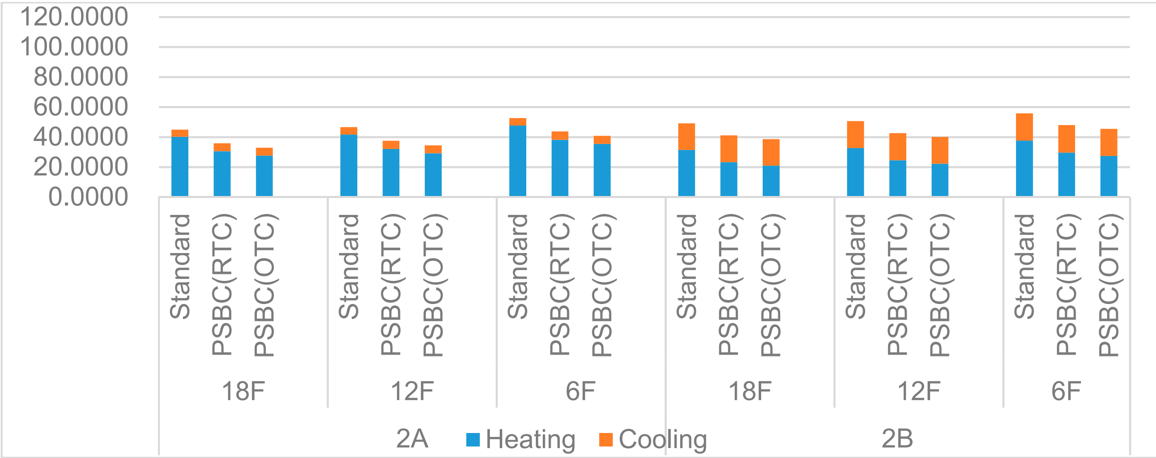


**Figure 7.** Heating and cooling energy demands (kWh/m$^2$/year) of reference buildings in cold regions.

As shown in Figure 7, reductions of cooling energy demands are the major concerns for improving the energy efficiency levels of the reference buildings in the cold regions. Compared to the heating and cooling energy demands of the reference buildings in the cold regions, the reference buildings have higher requirements of heating energy demands in the region 2A than the ones in the region 2B. However, due to the significantly higher cooling energy demands of the reference buildings in the region 2B, the overall energy demands of the reference buildings are 4–6 kWh/m$^2$/year more than those of the reference buildings in the region 2A. In the region 2B, the cooling energy demands are of 33–46% of the total energy demands of the reference buildings with different floor heights. Compared to the energy demands of the standard construction, the PSBC walls have notable advantages in reducing the cooling energy demands of the reference buildings. The cooling energy demands are 17.6–18.3 kWh/m2/year in the reference buildings with different heights in the climatic region. The energy demands of the PSBC (OTC) and the PSBC (RTC) are from 10.4 to 11.1 kWh/m$^2$/year lower than those of the standard constructions, respectively. As a result, the applications of PSBC will lead to lower energy consumptions of residential buildings by reducing both the heating energy demands and the cooling energy demands in the climatic regions.

Table 7 shows the potential energy saving of reference buildings with the two types of PSBC. Due to the higher walling thickness of the PSBC (OTC) than the PSBC (RTC), the thermal properties of the PSBC (OTC) have advantages in preserving heat inside the reference buildings, and lead to energy demands of the buildings that are lower than those of the PSBC (RTC) in the researched regions. Despite the situation in the region 1A, the PSBC (OTC) has 4–6% reductions of heating and cooling energy demands compared to the PSBC (RTC). The features of the PSBC (OTC) would be suitable for residential buildings that have insignificant requirements for walling thickness, including low-rise residential buildings, terrace-houses, and semi-detached houses. Whereas as the reduced walling thickness of the PSBC (RTC) is at a level similar to that of the existing constructions, the PSBC (RTC) would be more suitable for refurbishment of existing buildings and the buildings. The PSBC (RTC) would be suitable for the construction of new residential buildings in the cold regions as well.

The simulation results (Table 7) indicate that the reference buildings would save more heating and cooling energy by applying the PSBC in the higher-floor ones compared to the low-height ones in the researched regions. Comparing the 18 floor reference buildings to the six-floor reference buildings, the reductions of energy are from 2.9% to 4.6% for the PSBC (OTC) and are from 1.8% to 3.5% for the PSBC (RTC) in the researched regions, excluding the region 1A. As more concentrated surface–volume ratios are in the reference buildings with higher floors, heat losses through walling constructions are notably lower than the ones in the low-rise residential buildings. As a result, the greater potential for reduction of energy consumption would be in constructing and retrofitting of the high-rise residential buildings in northern China with the two types of PSBC.

**Table 7.** Reduction of heating and cooling energy consumptions achieved by replacing the standard construction with PSBC.

| Climatic Area | Cities | Reduction of Heating and Cooling Energy Consumptions | | | | | |
|---|---|---|---|---|---|---|---|
| | | PSBC (OTC) | | | PSBC (RTC) | | |
| | | 6F | 12F | 18F | 6F | 12F | 18F |
| Region 1A | Mohe | 6.0% | 6.4% | 6.5% | 4.2% | 5.2% | 5.3% |
| | Hailar | 6.4% | 6.8% | 6.8% | 4.4% | 4.0% | 5.5% |
| | Nenjiang | 6.3% | 6.8% | 6.8% | 4.3% | 5.4% | 5.5% |
| Region 1B | Dunhua | 16.7% | 19.3% | 19.7% | 12.1% | 14.2% | 13.9% |
| | Qiqihar | 16.1% | 18.7% | 19.1% | 11.6% | 13.7% | 13.3% |
| | Harbin | 16.6% | 19.2% | 19.5% | 11.9% | 14.0% | 13.6% |
| Region 1C | Changchun | 15.8% | 17.8% | 18.3% | 11.8% | 13.3% | 13.7% |
| | Shenyang | 16.9% | 19.3% | 19.9% | 12.6% | 14.4% | 14.8% |
| | Wulumuqi | 15.4% | 17.5% | 18.0% | 11.4% | 12.9% | 13.3% |
| Region 2A | Taiyuan | 22.6% | 26.1% | 27.1% | 16.9% | 19.5% | 20.2% |
| | Lanzhou | 22.7% | 26.3% | 27.3% | 16.8% | 19.5% | 20.3% |
| | Dalian | 22.3% | 25.5% | 26.3% | 17.0% | 19.4% | 20.0% |
| Region 2B | Beijing | 19.1% | 21.5% | 22.1% | 14.6% | 16.4% | 16.8% |
| | Shijiazhuang | 18.3% | 20.6% | 21.1% | 13.9% | 15.5% | 15.9% |
| | Ji'nan | 18.4% | 20.5% | 21.1% | 13.9% | 15.5% | 15.9% |

0% ~ 10% 10.1% ~ 20% 20.1% ~30%.

Due to the high thermal insulation demands of walling constructions for the region 1A in the JGJ26-2010, the reductions of energy loads are not significant compared to the ones in other climatic regions. Compared to the standard walling constructions, the heating reductions are 4.2%–6.5% in the reference buildings in the region 1A. The PSBC constructions would be less efficient for replacing the walling constructions in the region compared to applying the PSBC in other climatic regions in northern China.

## 4. Discussion on Applicability of PSBC

### *4.1. Environmental Impact of PSBC*

The low environmental impact of the straw bales is the capital advantage of using PSBC in building industries. There are three stages, including the materialization stage, the operational stage, and the end-of-life stage, to assess the life cycle assessment (LCA) of buildings [60]. Compared to conventional building materials, the materialization of straw bales has much lower carbon emissions and has notably less environmental impact during the end-of-life stage.

The single research relating embodied carbon of straw bale is the Inventory of Carbon Emission (ICE) done in the University of Bath, and the carbon emission of straw bales is estimated to be 0.01 $kgCO_2/kg$ [61]. However, the $CO_2$ emission of straw bales is based on the data from the wheat straw in New Zealand [61]. As the growing process of rice produces methane, the carbon emission of rice straw would be notably higher than the one of wheat straw [62]. Due to the limited research on carbon emissions of rice straw and wheat straw regarding the conditions in China, the overall carbon emissions of PSBC walls may not be assessed in detail. However, considering that the straw is a by-product of agricultural activities, the carbon emissions of straw would be significantly lower than those of other building materials [29].

As a bio-based building material, straw will be degradable after the end of the life of PSBC walls. Compared to conventional fossil-fuel-based building materials, straw has a significantly lower degradation period. With the presence of favorable environments of degradation, straw would degrade within four weeks [63]. Due to the lack of a recycling scheme for building materials, existing research did not evaluate the end-of-life stage in the LCA for building industries [55,64]. The advantage of the low end-of-life impact of straw bales may have an insignificant impact on building projects in the short term.

### 4.2. Hygrothermal Environment and Durability

Due to the high potential of degradation of straw, the designs of controlling hygrothermal environments of straw bales are critical for the durability of PSBC walls. The designs of controlling are subject to the local climatic features of the construction site. Rainscreens have positive impacts on the durability of straw bale walls in the UK [41], whereas similar walling constructions have direct opposite effects on the cases in Japan due to the high temperatures and high humidity in summer months [65]. Existing research on walling constructions of straw bale buildings regarding climatic conditions in the severe cold region of China shows that the lime render maintains enough breathability and favorable hygrothermal conditions for the straw inside straw bale walls [66]. As there is no research on the effects of rainscreens on hygrothermal environment inside straw bale walls regarding the local climatic features, applications of rainscreens on the PSBC walling constructions need further research.

### 4.3. Material Availability

Both rice production and wheat production are vast in both severe cold regions and cold regions. The rice production contributes more than 15% of total domestic rice production in the three provinces (Heilongjiang, Jilin, and Liaoning) of northeast China [67], and the wheat production is more than 50% in the three provinces (Hebei, Shandong, and Henan) in the cold regions [68]. Both the rice production and the wheat production will keep growing in the future [69] and guarantee the availability of the raw materials of the PSBC walling construction. However, as there are no applications of straw bale walls in existing building projects, the issues relating to logistics, quality control, and prices remain uncertain. As a result, despite the vast availability of the raw materials, the application of PSBC walling construction still needs to be developed.

## 5. Conclusions

This research provides potential application methods regarding the standards in China for PSBC in multiple-floor and high-rise residential buildings, following an analysis that evaluates the energy-saving potential of the PSBC in the building types across northern China. Overall, this research has extended the understanding of the feasibility of using PSBC and the energy performance of residential buildings to which PSBC is applied, and which are subject to the climatic features of northern China.

The research results indicate that the energy efficiency levels of residential buildings can be significantly improved by applying PSBC in all climatic regions in northern China. In the residential buildings that apply PSBC, heating energy loads are notably lower than in the residential buildings with existing walling constructions in northern China. Compared to the heating loads in reference buildings with standard constructions, the heating loads can be reduced by 2–4 W/m$^2$ with application of PSBC walling across different cities, and the reductions of heating loads are between 4.8% and 26.1% across different sub-climatic regions in the severe cold and cold regions. The simulation results show that more significant energy saving is achieved by the PSBC by applying the PSBC in high-rise residential buildings rather than the multiple-floor residential buildings. The energy-saving ratios achieved by applying PSBC walling are from 2% to 4% more in the high-rise buildings than in the multiple-floor buildings. Due to the high requirements for thermal insulation properties of existing walling constructions in the existing standards for the region 1A, the advantages of the PSBC are not as significant as the ones in the other climatic regions in northern China. The energy saving achieved by PSBC walling is from 4.2% to 6.5% in the region 1A whereas, the energy reductions are expected to be 11.9% to 27.1% in other regions across the severe cold and cold regions.

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