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Energy Saving and Carbon Reduction in the Operation Stage of Cross Laminated Timber Residential Buildings in China

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Abstract: This paper focused on energy consumption and carbon emission for heating and cooling during a building's operation stage, and examined the energy effects of using Cross Laminated Timber (CLT) as an alternative building material to reinforced concrete (RC) in China's 31 key cities located in different climate zones. The authors designed two seven-story residential buildings, which were constructed with RC framed and CLT systems, separately. This was followed by simulating the energy consumption using commercialized software IES^{TM} under the different climate zones and calculating the carbon emissions. Comparisons were made between RC and CLT systems buildings on the basis of simulation data. The results show that the estimated energy consumption and carbon emission in CLT buildings are much lower than that of RC buildings in all studied cities, which indicates that CLT systems have good potential in reducing carbon emission and saving energy consumption compared to RC. The energy consumptions and carbon emissions in both concrete and CLT buildings are closely related to the climate zones. Buildings in Severe Cold and Cold Regions consumed the most energy and released more carbon. At the national level, the estimated energy consumption at the operation stage, in the studied building with RC frames and CLT system was approximately 465.1 MJ/m^2 and 332.6 MJ/m^2 per annum, respectively. Despite vast differences in China's climate zones, the effects of energy saving and carbon reduction potentials of CLT buildings show little relationship to the climate zone. CLT buildings may result in a weighted 29.4% energy saving, which equals 24.6% carbon reductions, compared with RC buildings at the operation stage at national level, although it may vary in different climate zones.

Keywords: carbon reduction; energy saving; Cross Laminated Timber (CLT); residential building

1. Introduction

1.1. Energy Consumption and Carbon Emissions in the Building Sector

At present, energy consumption and carbon emission in the building sector is attracting increasing attention worldwide. The building sector is already the largest energy consumer. The IPCC reported that, in 2007, 36% of global energy was consumed by buildings and around 50% of greenhouse gas (GHG) emissions were related to buildings [1]. In 2010, buildings accounted for 32% of total global final energy use and 19% of energy-related GHG emissions, which equals 9.18 Gt CO_2 [2]. Buildings were responsible for approximately 40% of total primary energy consumption and 40% of total GHG emission in some developed countries [3]. In the United States, the building sector constituted a major portion of energy use, accounting for one-third of total final energy use and over 70% of electricity being used by buildings [4]. In the UK, the building sector accounted for approximately 50% of total CO_2 emissions (including construction work and the use phase of the building) [5]. In the EU, the building sector dominated nearly 40% of final energy use and was responsible for 36% of total carbon emissions in 2010 [6].

The IEA reported that, in 2010, the 32% of total global energy consumed in buildings can be further divided into 24% for residential buildings (equal to 24.2 PWh) and 8% for commercial ones (equal to 8.2 PWh). Figure 1 presents the energy consumption in residential buildings of different countries, which show significant differences in their types of energy consumption. On the global average, energy consumed in space heating dominated 32% of the total consumption, followed by 29% for cooking, 24% for water heating, 9% for appliances, 4% for lighting, and 2% for cooling [6,7]. The residential building sector is the largest consumer of energy and CO_2 emitter at a global level, especially in the BRICS (Brazil, Russia, India, China and South Africa) countries. Researchers also pointed out that, at the global level, energy consumption in buildings will increase in the following decades. Diana et al. created scenarios based on Kaya models and pointed out that energy consumption in residential heating and cooling was expected to increase approximately 79% by 2050 as compared to 2010. This figure was 84% for commercial heating and cooling [8]. King et al. pointed out that the demand for more energy consumption and social electricity shortages would occur due to an increase in the world's population [9].

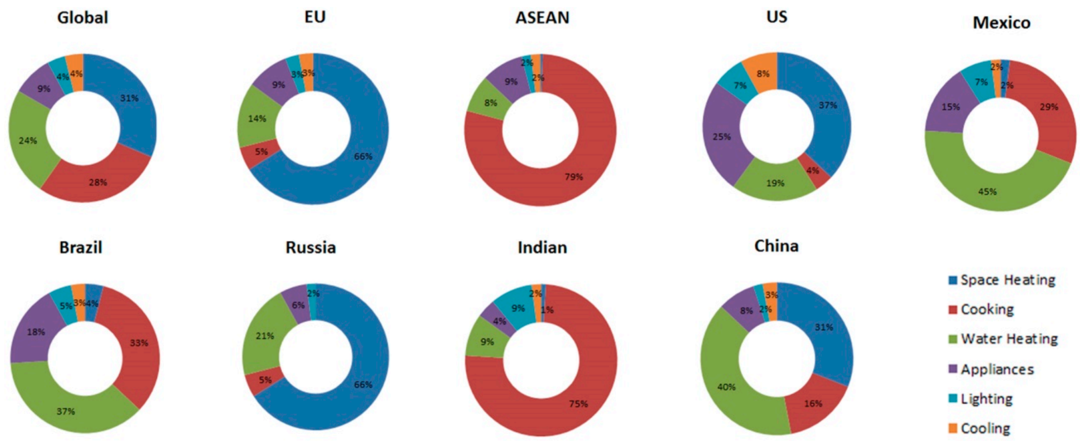

Figure 1. Energy Consumption in Residential Buildings of Selected Countries/Regions (the Figure is drawn by the authors according to the data from [7]). ASEAN is comprised of the ten member states: Brunei, Cambodia, Indonesia, Laos PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam.

China is the country with the largest energy consumption and carbon emission worldwide. In 2010, China consumed 19% in global terms of primary energy supply (TPES), while the United States accounted for roughly 17%. In 2012, the annual carbon emissions of China totaled 8.5 billion tons, accounting for a quarter of all global emissions [10]. Although buildings make an increasing contribution to China's total energy consumption, given the lack of authority's survey data, it is difficult to obtain the accurate amount of energy consumed in buildings from official sources. The IEA pointed out that, in 2007, China's buildings sector consumed 31% of China's total final energy [11], while, in 2010, energy consumption in buildings was dominated by the residential sub-sector, which accounted for 84% of total energy consumption [6]. Hong showed that the building sector was responsible for more than 25% of China's total TPES in 2006, and was expected to increase further to 35% by 2020. Furthermore, 18% of the overall Chinese GHG emission was from the building sector [12]. Chen et al. pointed out that the residential building sector consumed 11% of national TPES [13], while David et al. highlighted that in China the construction phase accounts for approximately 22%, while the operation phase accounts for about 78% of total carbon emissions during the lifetime of a building [14].

However, in China, the energy consumption in building use will increase sharply during the upcoming decades. In 2050, energy consumption will be 15 times higher than in 1970 [3]. The percentage of registered urban residents in the total population of China was 52.6% in 2012, which equaled 19 million people moving from the countryside to urbanized areas annually since 1990 [15]. The Chinese government plans to increase its urbanization level to 60% by 2030, and to 70% in the next 25 years. Increased urbanization results in demands for greater energy. This is mainly due to the demands of higher living standards from the citizens and more energy-intensive sectors moving into urban areas [16]. Annually, there are about two billion square meters of new building floor area in China and the total building floor space increased from 10.2 billion square meters in 1980 to 52.7 billion square meters in 2008. It was estimated by the Chinese Ministry of Construction that 30 billion square meters of new buildings would be built between 2005 and 2020, dominating about half of the world's new construction during this period [17]. It can be predicted that the building sector in China will account for more energy consumption and carbon emission in the subsequent decades. Sustainable building materials and advanced technologies are essential to save energy and lower carbon emissions for the new buildings, while energy retrofitting can help to save more energy for the existing buildings. However, the knowledge to integrate all active components is still scarce [18].

At present, reinforced concrete (RC) frames are the most frequently used structural materials in buildings in China. However, the building envelope insulation performance is 200%–300% less efficient than in developed countries [12]. State-of-the-art literature showed that different structural materials resulted in diverse energy consumptions for buildings. Foraboschi et al. assessed the embodied energy of tall building structures composed of a RC central core and either RC or steel rigid frames. The result showed that the entire structurally embodied energy consumption in a 20-story building with RC frames and RC slabs (full weight), was approximately 2.2 GJ/m^2 of the Net Rentable Area. They also pointed out that floor type was the most critically influential factor for tall building structures and that RC frames buildings consumed less embodied energy than steel frames [19]. Treloar et al. made comparative assessments of a seven-story building consisting of an integral RC band beam and slab floor construction, supported on reinforced concrete columns. The results showed that the entire structurally embodied energy consumption of the building was 11.9 GJ/m^2 of the Gross Floor Area [20]. Trabucco pointed out that the building of 30 St Mary Axe, designed by Foster, was expected to consume 504 MJ/m^2 per annum for building's operation [21]. Liu et al. made comparisons between two seven-story buildings that were constructed by RC and CLT in Severe Cold Region of China. They found that the energy consumptions for heating and cooling were 338 MJ/m^2 and 231.2 MJ/m^2 per annum, respectively [22]. Gustavsson et al. studied the energy use and CO_2 emission of an eight-story wood-framed apartment building. They found that in the operation stage, the end-use energy consumption of the building with a district heating system was 356.6 $MJ/\ m^2$ and the CO_2 emission was 59.3 KG/m^2 per annum [23].

The Chinese government has made a series of documents to encourage the development and use of sustainable materials. The *Technical Assessment Handbook for Ecological Residence of China*, as the first evaluated document of green buildings, was published in 2001. The Ministry of Housing and Urban–Rural Development of China (MOHURD) has already drafted energy saving standards for public and residential buildings and made it a compulsory implementation. In 2015, *Action Plan to Promote Green Building Materials Production and Building Applications* was published by MOHURD, which clearly showed the government's intention to promote the use of timber as a construction material for public buildings in China [24].

1.2. CLT as a Sustainable Building Material

CLT started in Europe in the early 1990s, and in the last two decades it has experienced a double-digit growth rate. CLT is widely used for mid-rise residential and low-rise commercial buildings due to its competitive cost, environmental sustainability and shorter construction time [25]. A growing number of tall CLT buildings have been built worldwide in recent years. Currently, CLT is mainly produced in central Europe, accounting for 80% of the global installed production capacity in 2015 [26]. In China, the CLT market is still on a limited scale.

As shown in Figure 2, Cross-Laminated Timber (CLT) is an integrated building system based on the use of multi-layered wood panels. CLT is commonly composed of an uneven number of layers (usually three, five or seven layers). Each layer is arranged crosswise to each other at an angle of 90° and quasi-rigidly connected by adhesive bonding. The thickness of a single layer is between 20 and 50 mm and the whole panels are available in thicknesses from 60 to 500 mm [27]. The width and length of the panel can be 4.8 m by 20 m. CLT can provide uniform mechanical and physical properties due to its layup configurations. It can be used not only as load bearing panels (walls, floors and roofs) and shear walls, but also partitions and linear structural components in buildings [28]. When CLT is used as a linear structural element, it shows promising resistance against shear in-plane and tension perpendicular to grain [29]. As an integrated system, CLT buildings are much more efficient than reinforced concrete, brick or other mineral based buildings. Due to a high degree of pre-fabrication and assembling of large-sized elements, the on-site erection time of CLT buildings is much shorter than that of mineral based buildings.

Figure 2. Layer figurations of Cross Laminated Timber.

Among the advantages of CLT, is the well accepted fact that using a CLT construction system as an alternative to traditional energy-intensive construction materials is an effective way to lower energy consumption and carbon emission. Research on life cycle analysis (LCA) reveals that during raw material extraction, transportation and the manufacture process, CLT may store more carbon, emit less GHG and use less fossil energy than steel, concrete and brick [30,31]. Malmsheimer et al. showed that the carbon storage rate of wood is approximately 1.10 tons of CO_2 per cubic meter. Even after wood harvesting, much of the carbon was stored in forest products and may not be released for decades [32]. Hammond et al. pointed out that in the UK, the embodied CO_2 in concrete and steel is approximately 1984 tons per cubic meter, while the embodied CO_2 in the CLT system is as much as 727 tons per cubic meter or −2314 tons per cubic meter, if taking sequestration into account [33]. Borjesson et al. indicated that concrete frame buildings result in about 80% higher primary energy use in the materials production stage and about 100%–200% higher net GHG emissions compared with wood framed buildings [34]. Gong et al. made a comparison between concrete and timber as materials for frameworks in Beijing in various scenarios, and showed that concrete frames would consume 30% more energy compared to timber frames [35]. Liu et al. made a building energy simulation in Harbin and Xi'an and demonstrated that using CLT as an alternative material to concrete is a feasible way to improve energy efficiency and reduced carbon emissions [22].

However, existing references are limited in relation to the study of energy saving and carbon reduction effects of CLT in China. China faces complexity in having a number of distinct climate zones. The building codes vary in different climate zones, which make it more difficult to study the integrated effects of sustainable materials by scenarios. The aforementioned context has raised several questions, including: (1) Is using CLT as a sustainable material for construction an efficient way to reduce carbon emission and lower energy consumption in China? (2) Is the effect of energy saving and carbon reduction of CLT buildings affected by China's climate zones? (3) What is the suitable development strategy of CLT under the condition of limited timber production in China? This paper aims to answer these questions by instituting energy scenarios in China's 31 key cities with the official data and buildings codes.

2. Study Scope and Description of Studied Cities

2.1. Study Scope

In this paper, our study focused on energy consumption of cooling, heating and cooling appliances in the operation stage of the buildings, which is supposed to be the majority of the total in the operation phase especially in the Severe Cold and Cold regions.

Life-cycle assessment (LCA, also known as Eco-balance or cradle-to-grave assessment) is a method used to evaluate the environmental effect, energy consumption and sometimes the cost of a production [36]. Life cycle energy analysis is a sub-approach of LCA that accounts for all energy inputs to a building in its life cycle [37]. Figure 3 presents flow-chart of Life-cycle assessment and the explicit study scope of this paper. The whole process of building construction can be divided into three stages: materialization stage, operation stage, and end of life stage. The materialization phase includes material production, transportation and on-site installations. The operation phase includes all activities related to the use of the building over its life span. Above these activities, energy consumed by heating and cooling is significantly related to building materials, while energy used in cooking appliances, water heating and lighting is related more to the habits of the inhabitants. According to the existing references, the operation phase dominates the majority, equal to 78% of the total building's energy consumption in China [38]. Finally, the end of life phase includes destruction of the building and transportation of dismantled materials to landfill sites or recycling plants.

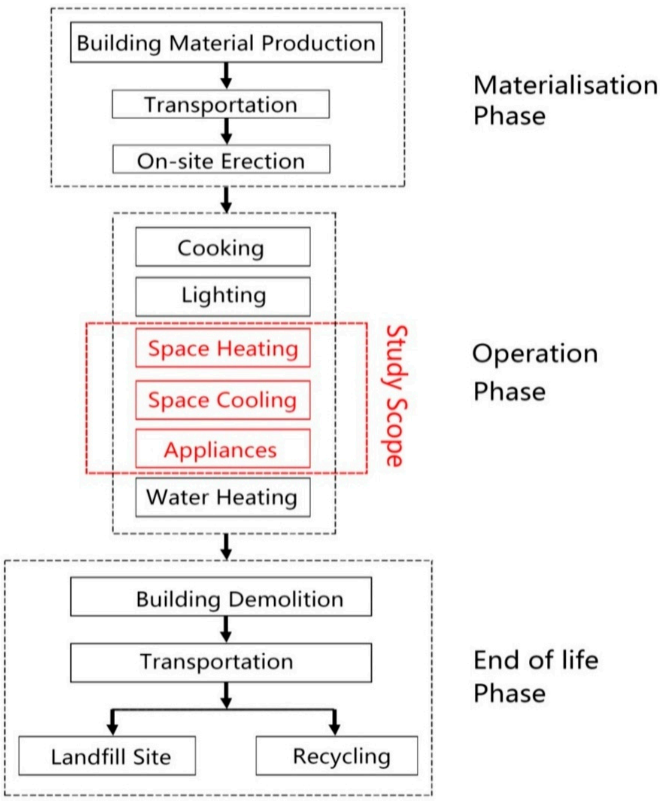

Figure 3. Flow chart of Life-cycle assessment and the study scope.

2.2. Thirty-One Key Cities in China

In this paper, 31 key cities are selected as simulation environments for the concrete and CLT buildings. These cities are either provincial capitals or provincial cities that are highly urbanized, economically developed and population-concentrated. They best represent the implementation of key policy measures in urban and building energy efficiency. As shown in Table 1, these cities have made significant contributions to the GDP and consume huge amounts of primary energy. However, as shown in Figure 4, there are significant diversities as well between these cities in terms of GDP and carbon emissions. Therefore, creating the simulation in these cities may adequately reflect the energy saving and carbon reduction effects of CLT in the entirety of China.

Table 1. Estimated carbon emission and energy consumption of 31 studied cities.

	China	31 Studied Cities	Ratio
Population (Million)	1360.72	256.76	18.87%
GDP (Billion Chinese Yuan)	63,646.3	22,318.3	35.07%
Energy consumption (Billion Tonne Standard Coal)	4.26	1.61	37.79%
Per capita energy consumption	3.13	6.26	200.00%
CO_2 emissions (Gt)	9.2	1.99	21.63%
Per capita CO_2 emissions (Tonne)	6.76	7.76	114.79%

Source: GDP, Population, Energy Consumption is from Statistical Yearbooks 2015 published by authorities; carbon emissions of 31 cities are estimated by authors based on Statistical Yearbooks 2015 published by 31 cities' local authorities; total carbon emission of China is from IEA [39].

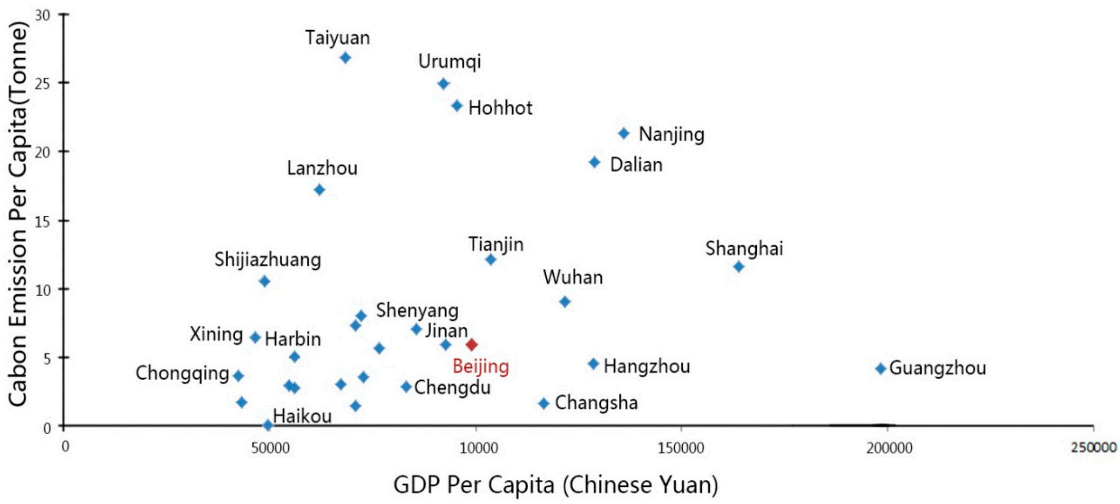

Figure 4. GDP per capita and carbon emissions per capita of 31 Chinese cities in 2014 (Source: Estimated by authors based on Statistical Yearbooks 2015 published by 31 cities' local authorities).

2.3. Climate Zones

Figure 5 presents the climate zones in Mainland China. According to *Code for Design of Civil Buildings* (GB 50352-2005), there are five types of climate zones in China: the Severe Cold Region, Cold Region, Hot-Summer Cold-Winter Region, Hot-Summer Warm-Winter Region, and Temperate Region. The standard further divides these regions into A, B, C and D sub-regions when necessary. The 31 studied cities divided by climate zones are tabulated in Table 2. China has developed a series of residential energy standards and made it compulsory since the 1980s. The Chinese building codes vary in each of the different climate regions for residential and commercial buildings. The designers must follow these building codes such as envelope criteria, insulation levels of opaque constructions, and thermal/optical performance of windows and skylights [12].

Figure 5. Climate Zones in Mainland of China (the Figure is drawn by the authors according to the data from *Code for Design of Civil Buildings* (GB 50352-2005)).

Table 2. Thirty-one Chinese key cities by climate zones.

Climate Zones	Temperature		Cities	
	Coldest	Hottest		
Severe Cold	≤−10 °C	≤25 °C	I B I C	Harbin Changchun, Hohhot, Shenyang, Xining, Urumqi
Cold	−10–0°C	18–28 °C	II (A) II (B)	Dalian, Yinchuan, Taiyuan, Lanzhou Beijing, Tianjin, Xi'an, Shijiazhuang, Jinan, Zhengzhou
Hot Summer Cool Winter	0–10 °C	25–30 °C	III	Nanjing, Hefei, Wuhan, Shanghai, Changsha, Hangzhou, Chengdu, Chongqing, Nanchang
Hot Summer Warm Winter	>10 °C	25–29 °C	IV (A) IV (B)	Fuzhou Nanning, Haikou, Guangzhou
Temperate	0–13 °C	18–25 °C	V	Guiyang, Kunming

3. Methodologies

3.1. The Framework

The purpose of this study is to compare energy consumption and carbon emission performances in the operation stage between RC and CLT buildings in China's 31 key cities. However, due to the lack of authority's survey data and the vast differences of China's local building codes in different climate zones, it is difficult to obtain accurate data for energy consumed in real buildings from official sources. Therefore, creating a scenario is an optimal way to evaluate the energy consumption of buildings. Figure 6 presents the framework of this paper. The study can be divided in to the following steps.

Firstly, we select a real seven-story residential building with RC framed and brick infill walls as studied objects. The comparison CLT building is redesigned on the basis of this concrete building. Nevertheless, the design strategy of the CLT buildings is not simply material replacement but an integrated system build-up. Secondly, we obtain the basic simulation data including the building dimensions, assumed simulation settings and U values according to the case designs and local construction specifications. Some parameters of the concrete and CLT buildings, for example, the thickness of the insulators and walls, are changed in different studied cities according to the building codes in separate climate zones. Thirdly, we make the simulation by the IES and obtain the energy consumption and carbon emission results of the operation stage in the 31 studied cities. Finally, after the comparison and analysis of results, potential suggestions on energy saving and carbon reductions are made for policy makers.

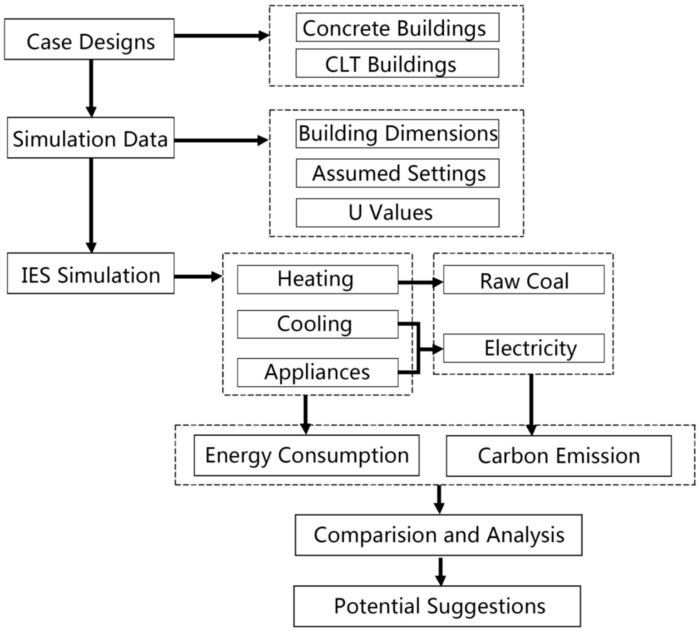

Figure 6. The flow-chart of the study.

3.2. *Designs of Concrete Buildings and CLT Buildings*

3.2.1. Concrete Buildings

In this paper, to examine the energy consumption and carbon emissions of residential RC building in different climate zones, a real seven-story residential building with RC framed, RC slabs (full weight) and brick infill walls was selected as study object. Figure 7 illustrates the floor plan and section plan of the building with dimensions. The building consists of two dwelling units, and there are two flats with staircase in one unit. The total gross internal floor area of the building is 2799.3 m^2. The internal story height of the structure is 2.70 m, which is a representative value for residential buildings in China. This is a typical residential building in China; the envelope design complies with requirements for residential building regulations. In the simulation, the thickness of the constructions and thermal insulators were redesigned to apply to the local building codes, which can be reflected from the changes of U-values.

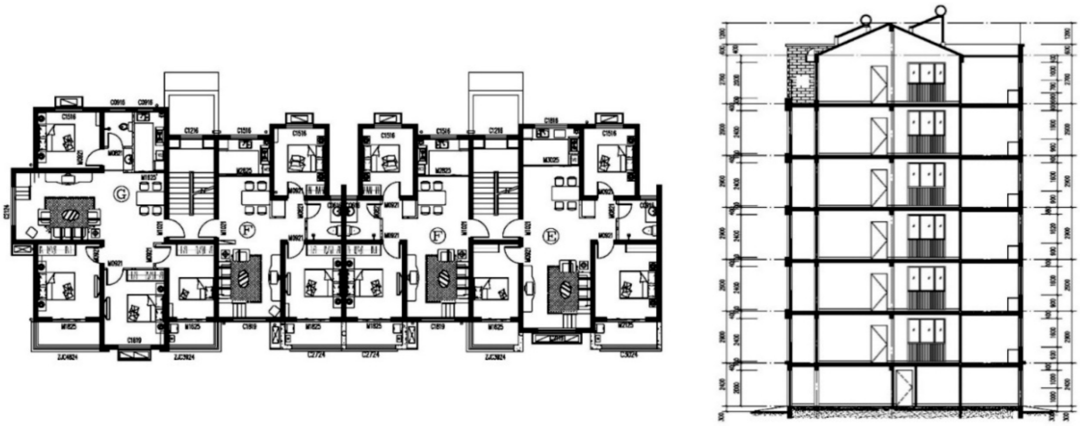

Figure 7. Floor plan and section drawings of selected building (Modified from [22]).

3.2.2. CLT Buildings

As mentioned above, the CLT market is still in its infancy in China at present, so there is no CLT design standard available in China. In this study, we instead adopted Euro code 5 and relevant documents [40,41] to design CLT buildings instead. The design strategy of CLT buildings is not simply material replacement but an integrated system build-up. The dimensions of load bearing structures and partition walls are all redesigned by proper parameters in different studied cities. According to the design code in China, the strength properties of local species are similar to C22 timber specified in British Standard. Load bearing panels (walls, floors and roofs), partition walls and other linear structural components in buildings are assumed to use Grade C22 wood. The foundation of the building is not redesigned in this paper.

The dimensions of the buildings, such as structural height, building orientations, and floor areas, remain the same as for the reference concrete structure. However, the thickness of the insulation layer, wall and roof vary in different climate zones. For example, Figure 8 presents the details for exterior walls and floor for CLT structures according to the building regulations in Harbin. To satisfy the building regulation in the Severe Cold Region, the CLT exterior walls in Harbin consist of 150 mm three-ply CLT panels, one layer of 120 mm thick brick, 100 mm thick insulation and 30 mm plasterboard. In sum, 842.2 m^3 CLT panels are consumed for constructions of the building in Harbin.

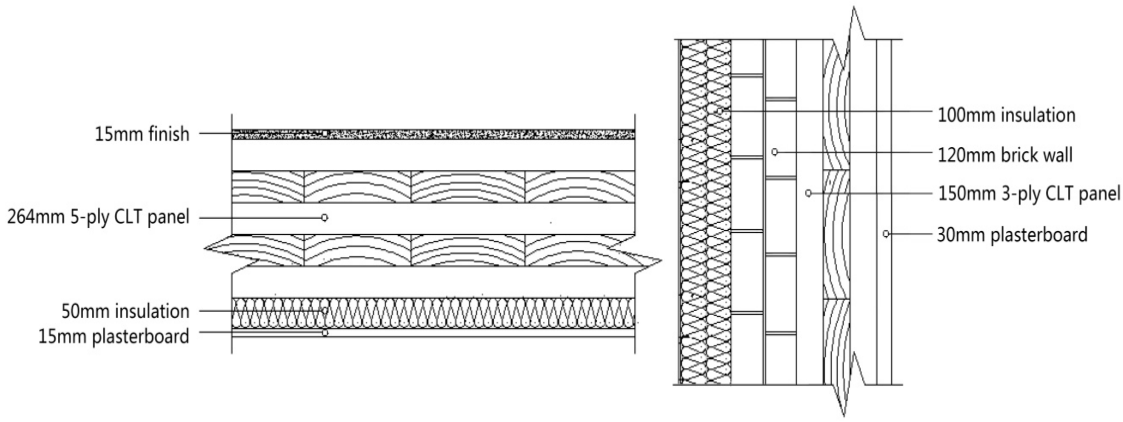

Figure 8. Details for exterior walls and floor for CLT structures in Harbin.

3.3. Energy Consumption during the Operation Stage

In this paper, the energy consumptions of CLT and concrete buildings in 31 of China's key cities were simulated by the commercial program IES^{TM} (Integrated Environmental Solution). Local building regulations of 31 key cities were considered due to the fact that different cities are located in different climate zones. This is reflected in the different U-values tabulated in Table 3. In the simulation, the following assumptions were made:

(1) According to the building grade classification in China, in this paper, the life spans of the residential buildings are assumed to be 50 years.
(2) Only energy used for heating, cooling and cooling appliances are simulated.
(3) The indoor temperature is assumed to be controlled between 18 °C and 26 °C. According to the *Chinese Residential Design Specification*, the minimum temperature in the bedroom, toilet and living room is set to be 18 °C and the comfortable temperature is suggested to be no more than 26 °C. Cooling and heating systems will be operated automatically when the temperature is not in this range.
(4) Electricity is used for cooling and raw coal is used for heating. This is the current practice in China and will be described in detail later.

Table 3. Basic Buildings Information of Studied Cities.

City	Climate Region	U-Value (Regulation)	U-Value (Simulation)
Harbin	I (B)	Roof:0.28 Wall:0.38	Roof:0.25 Wall:0.33
Hohhot	I (C)	Roof:0.35 Wall:0.43	Roof:0.25 Wall:0.40
Changchun	I (C)	Roof:0.35 Wall:0.43	Roof:0.30 Wall:0.44
Shenyang	I (C)	Roof:0.35 Wall:0.43	Roof:0.32 Wall:0.44
Xining	I (C)	Roof:0.35 Wall:0.43	Roof:0.38 Wall:0.44
Yinchuan	I (C)	Roof:0.35 Wall:0.43	Roof:0.47 Wall:0.50
Urumqi	I (C)	Roof:0.35 Wall:0.43	Roof:0.38 Wall:0.47
Dalian	II (A)	Roof:0.45 Wall:0.50	Roof:0.44 Wall:0.46
Taiyuan	II (A)	Roof:0.45 Wall:0.50	Roof:0.44 Wall:0.58
Lanzhou	II (A)	Roof:0.45 Wall:0.50	Roof:0.41 Wall:0.51
Xi'an	II (B)	Roof:0.45 Wall:0.50	Roof:0.47 Wall:0.51
Zhengzhou	II (B)	Roof:0.45 Wall:0.50	Roof:0.44 Wall:0.51
Shijiazhuang	II (B)	Roof:0.45 Wall:0.50	Roof:0.47 Wall:0.50
Jinan	II (B)	Roof:0.45 Wall:0.50	Roof:0.44 Wall:0.51
Beijing	II (B)	Roof:0.45 Wall:0.50	Roof:0.44 Wall:0.55
Tianjin	II (B)	Roof:0.45 Wall:0.50	Roof:0.45 Wall:0.60
Chengdu	III	Roof:0.50 Wall:0.80	Roof:0.47 Wall:0.90
Hefei	III	Roof:0.50 Wall:0.80	Roof:0.47 Wall:0.74
Hangzhou	III	Roof:0.50 Wall:0.80	Roof:0.65 Wall:0.67
Nanchang	III	Roof:0.50 Wall:0.80	Roof:0.59 Wall:0.72
Changsha	III	Roof:0.50 Wall:0.80	Roof:0.47 Wall:0.51
Wuhan	III	Roof:0.50 Wall:0.80	Roof:0.79 Wall:1.03
Shanghai	III	Roof:0.50 Wall:0.80	Roof:0.42 Wall:0.80
Chongqing	III	Roof:0.50 Wall:0.80	Roof:0.68 Wall:0.78
Nanjing	III	Roof:0.50 Wall:0.80	Roof:0.47 Wall:0.66
Fuzhou	IV (A)	Roof:0.80 Wall:1.50	Roof:0.79 Wall:0.85
Nanning	IV (B)	Roof:0.80 Wall:1.50	Roof:0.47 Wall:0.51
Haikou	IV (B)	Roof:0.80 Wall:1.50	Roof:0.71 Wall:2.20
Guangzhou	IV (B)	Roof:0.80 Wall:1.50	Roof:0.71 Wall:1.35
Kunming	V (A)	Roof:0.80 Wall:1.50	Roof:0.59 Wall:2.08
Guiyang	V (A)	Roof:0.80 Wall:1.50	Roof:0.75 Wall:2.10

3.4. Carbon Emissions during the Operation Stage

In this study, the result we obtained from the simulation of the operation stage is the amount of energy rather than carbon discharge. In order to estimate the carbon emissions in both concrete and CLT buildings, we need to convert energy into carbon emissions by multiplying the carbon emission factors. The estimated carbon emissions can be obtained by the following Equation [16]:

$$E_t = \sum Q_{jt} C_j \eta_j \times \frac{11}{3} \quad (1)$$

where E_t is the estimated amount of carbon emissions of the t-th studied city, Q_{jt} is the j-th physical energy consumption of the t-th studied city, C_j is the appropriate Calorific Value of j-th energy, and η_j is the Carbon Emission Factor of the j-th energy source. As mentioned above, in this study, electricity is used for cooling and cooling appliances, while raw coal is used for heating. The values of C_j and η_j are summarized in Table 4 [16,42,43].

Table 4. C_j and η_j of raw coal and electricity.

Fossil Energy Items	C_j	η_j
Raw Coal	20,934 KJ/KG	26.80 (T-C/TJ)
Electricity	3600 KJ/KWH	1.14 (TCO_2/MWh, Northeast China) 1.13 (T-CO_2/MWh, North China) 0.78 (T-CO_2/MWh, East China) 0.81 (T-CO_2/MWh, Northwest China) 0.70 (T-CO_2/MWh, Central China) 0.67 (T-CO_2/MWh, Southern China)

The values of raw coal's η are supposed to be the same nationwide, but the values of electricity's η are strongly related to the energy source used for generating. For example, there will be little carbon emission if the electricity is from hydro, wind and solar. However, in China, the electricity is mainly from coal. In 2014, thermal energy accounted for 75% of electricity generation [44]. Table 5 shows the 31 studied cities by sub-regions of national grids; these cities can be divided into six sub-regions of national grids with diverse values of η.

Table 5. Thirty one studied cities by sub-regions of national grids.

National Grids	Cities
Northeast China	Dalian, Shenyang, Changchun, Harbin
North China	Jinan, Taiyuan, Hohhot, Beijing, Tianjin, Shijiazhuang
East China	Hefei, Fuzhou, Shanghai, Nanjing, Hangzhou
Northwest China	Xi'an, Lanzhou, Xining, Yinchuan, Urumqi
Central China	Zhengzhou, Wuhan, Changsha, Nanchang, Chengdu, Chongqing
Southern China	Guangzhou, Nanning, Kunming, Guiyang, Haikou

3.5. Data Source

This paper includes statistical data of 31 key cities in China. The economic data of coal consumption, electric power capacity and GDP per capita can be obtained directly from local statistical yearbooks published by the authorities. The reliability of the data is considered as high, since it is official. The coefficients in Equation (1), such as C_j and η_j, are taken from relevant scientific references and *China Energy Statistical Yearbooks* published by China Statistics Press [42]. The U values of 31 studied cities are obtained and set on the basis of a series of building codes. In this paper, the building codes we adopt for the simulation are: codes JGJ26-95, JGJ132-2001, and JGJ129-2000 for the Severe Cold and Cold Regions in the north; code JGJ134-2001 for the Hot-Summer Cold-Winter Regions in the central area; and code JGJ75-2003 for the Hot-Summer Warm-Winter Regions in the south.

4. Results and Analysis

Figure 9 presents the estimated results of energy consumption of RC and CLT buildings in 31 studied cities per year. It can be seen that the estimated energy consumption in RC buildings is higher than that of CLT buildings in all studied cities. The energy consumption for heating and cooling in the concrete buildings ranges from 30.7 to 324.7 MJ/m^2 per annum, with the weighted average value of 162.8 MJ/m^2 per annum. In the CLT buildings, the energy consumption for heating and cooling ranges from 18.3 to 241.9 MJ/m^2 per annum, with the weighted average value of 116.4 MJ/m^2 per annum. As mentioned above, on average, cooling and heating energy account for 35% of total energy consumption in China [7], and it can be estimated that at the national level, energy consumption in a story-story building with RC frames and CLT system are approximately 465.1 MJ/m^2 and 332.6 MJ/m^2 per annum, respectively. These results echo those outcomes from existing research [21–23].

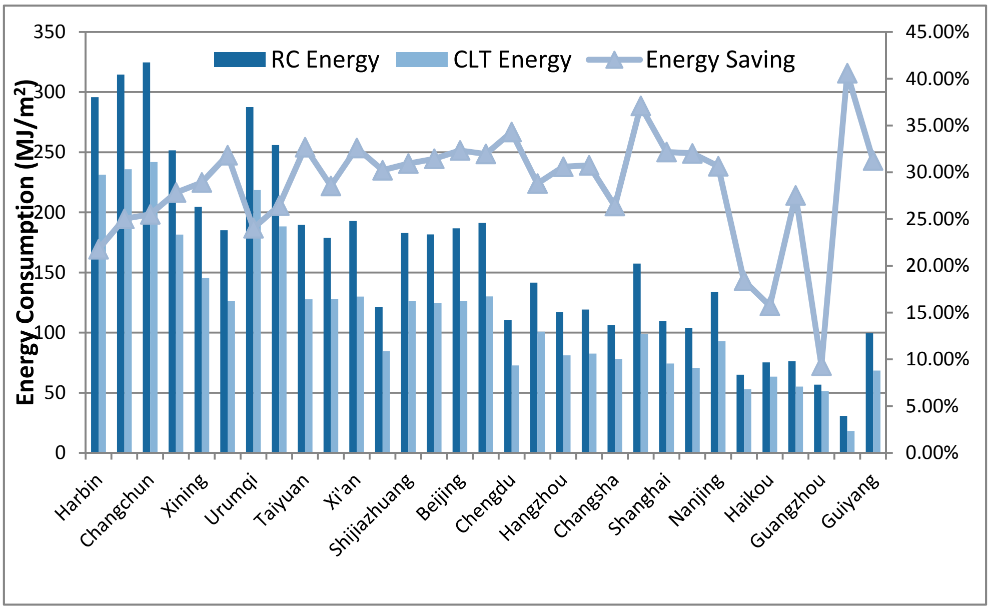

Figure 9. Simulation results of energy consumption for heating and cooling per annum.

However, our research results also present the diversities of 31 key cities in different climate zones. The results indicate that the total energy consumption in both RC and CLT buildings are closely related to the climate zone. Buildings in Severe Cold Region and Cold Region, where heating contributes to the main portion of energy consumption, consumed the most energy, followed by Hot Summer Cool Winter Region, Hot Summer Warm Winter Region, and Temperate Region. Changchun, Hohhot and Harbin are the three cities from the Severe Cold Region with the highest energy consumption. They consumed more than 60% of total energy in heating. In contrast, Nanning, Haikou and Guangzhou, which are located in Hot-Summer Warm-Winter Regions, consume zero energy in heating. However, the energy saving curve indicates that the energy saving effect of using CLT as an alternative to concrete showed little relationship with the climate zone in China. The energy consumptions of the CLT buildings are 25%–35% lower than that of the RC buildings in the operation stage for most cities. The weighted energy saving percentage of 31 key cities is 29.4%.

Figure 10 presents the estimate results of CO_2 emissions of concrete and CLT buildings in the 31 studied cities. Similar phenomena can be found in that the estimated CO_2 emissions in RC buildings are higher than that of CLT buildings in all studied cities.

The CO_2 emission for heating and cooling in the concrete buildings ranges from 3.4 to 34.4 KG/m^2 per annum, with the weighted average value of 19.4 KG/m^2 per annum, while, in the CLT buildings, the energy consumption for heating and cooling ranges from 2.5 to 27.0 KG/m^2 per annum, with the weighted average value of 14.8 KG/m^2 per annum. At the national level, the estimated average values of CO_2 emissions in the operation stage in the RC and CLT buildings are 55.4 KG/m^2 and 42.3 KG/m^2 per annum, respectively. This result is also comparable to the findings from Gustavsson et al. [23].

In addition, the CO_2 emissions from the buildings in the Severe Cold and Cold Regions are higher than those in other regions. Changchun, Hohhot and Harbin are the top three cities with the highest carbon emissions from the Severe Cold Region. The carbon emissions of the CLT building are 20%–30% lower than those of the concrete building in the operation stage for most cities over the period of 50 years. The weighted carbon reduction percentage of 31 key cities is 24.6%.

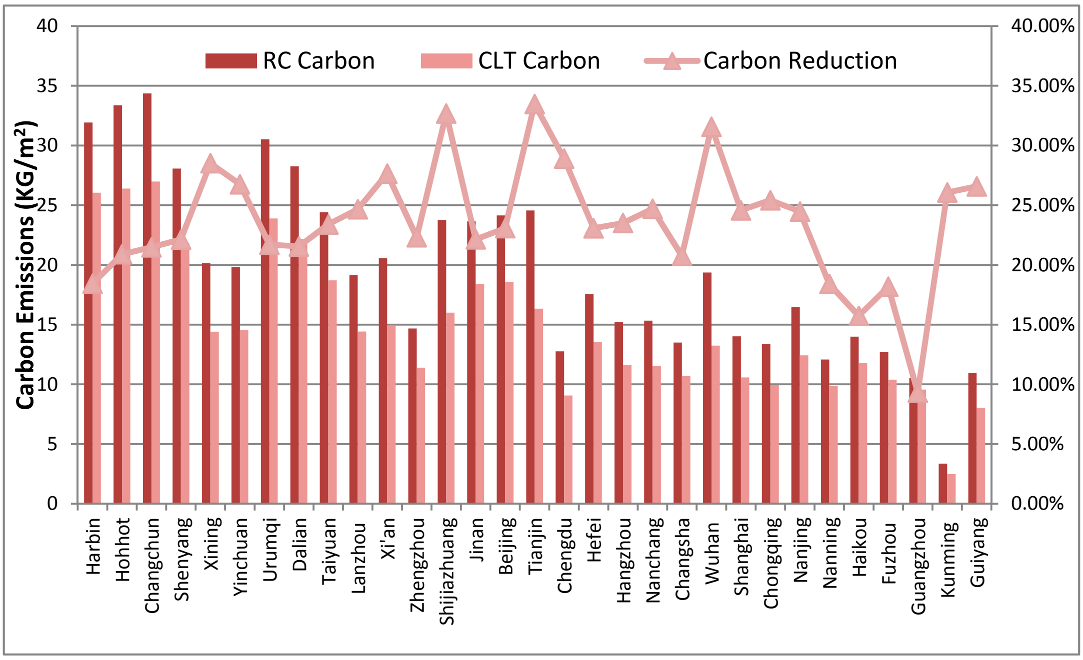

Figure 10. Calculation results of carbon emission from heating and cooling per annum.

Figure 11 presents the comparison effects of energy saving and carbon reduction of using CLT as an alternative to RC. The results show that the percentage of energy saving is greater than that of carbon reduction. Although CLT buildings have better performance on saving heating energy, building overheating may occur in CLT buildings in most cities, which means extra electric power will be consumed for cooling in CLT buildings. The carbon emission factor of electricity is higher than that of coal, especially in cold and severe cold regions. This may result in a lower carbon reduction percentage compared with the energy saving percentage.

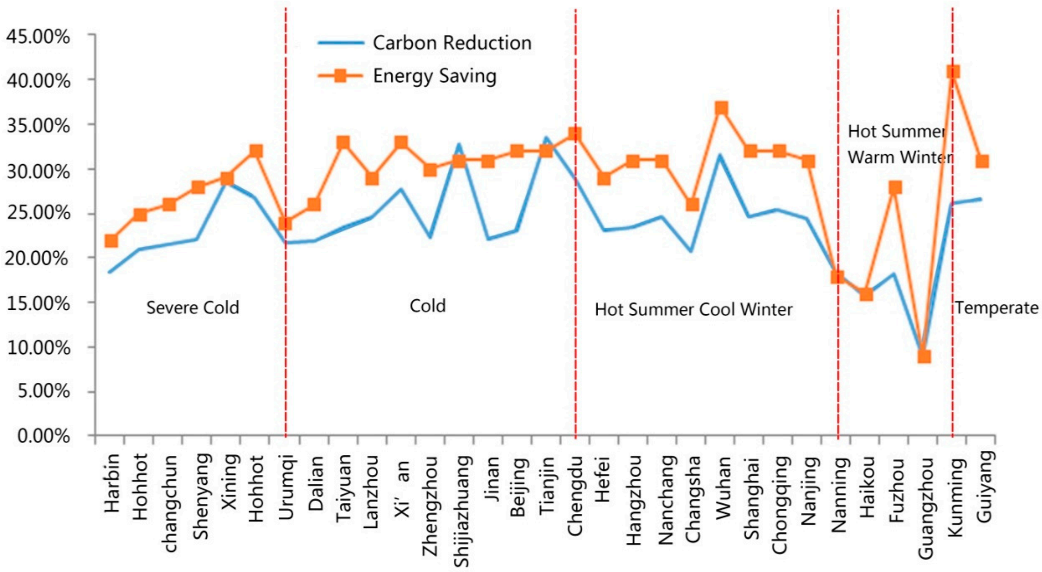

Figure 11. Carbon reduction and energy saving performance of CLT buildings.

5. Discussions

As mentioned above, the energy saving and carbon reduction effects of the CLT systems in the manufacture stage and demolition stage are not considered. According to the existing references, the manufacture stage accounts for 22%, while the operation phase accounts for 78% of the total energy consumption in China [38]. For the demolition stage, the destruction of a building is assumed to be 90% of the energy required in the erection phase [45]. The carbon sequestration of CLT is that one cubic meter of timber would store 1100 kg of CO_2, and the on-site erection of CLT buildings is set to be 20 MJ/m^2 [22,32]. We can put this together on the basis of references above that, taking carbon storage in timber into consideration, the timber would store more carbon in itself than those emitted during the process of materialization and end-of-life stages, and more carbon reductions can be obtained if using CLT systems as an alternative to RC. Darby et al. demonstrated that a CLT solution for a multi-story residential building, in comparison with a more conventional RC solution, may result in approximately 60.6% carbon reductions in view of life-cycle assessment [27]. However, due to the complexity of China's climate zone and local construction standards, the result may vary in different cities, which needs further studies to clarify.

The scenario results show that, despite vast differences in China's climate zones, heating and cooling energy consumption of the CLT building is approximately 25%–35%, equal to 20%–30% of carbon emissions, lower than that of the concrete building in the operation stage for China's 31 key cities. The percentages of energy saving and carbon reduction have shown little relationship to the climate zone, which indicates that CLT as a sustainable material can be developed nationwide in China. Figure 12 shows how much energy of 1 cubic meter CLT can be saved in 31 key cities compared to RC buildings. The trend indicates that more energy savings can be obtained per unit CLT in severe cold and cold regions. Taking the total amount of energy consumption into consideration, the buildings in severe cold and cold regions consume much more energy than those in other regions for heating. For the policy makers in China, under the condition of limited timber production, it is better to develop the CLT system in cold and severe cold regions first.

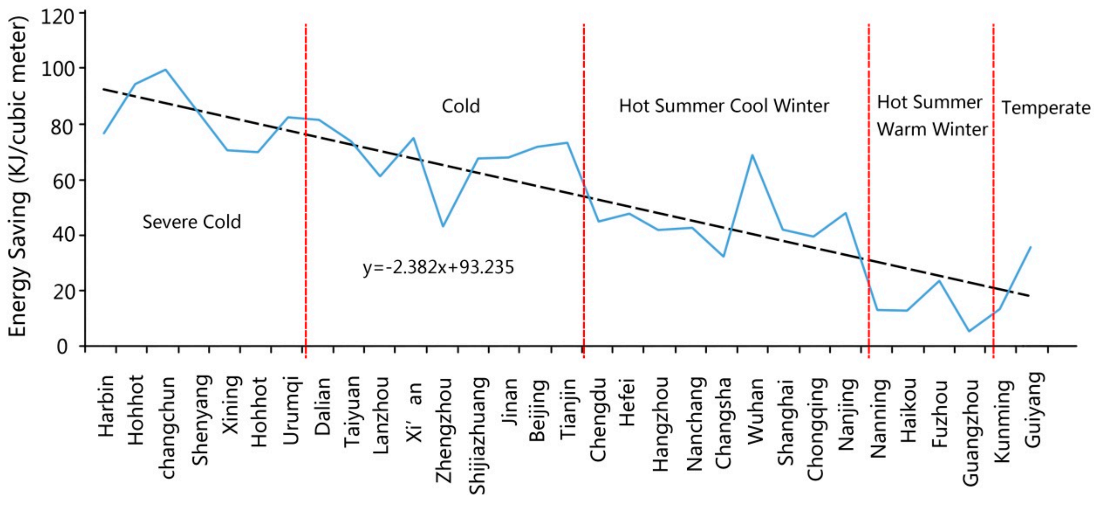

Figure 12. Energy savings of 1 cubic meter CLT in 31 key cities.

Policies in the buildings sector should take into consideration the different buildings energy demands in the various climate regions. In severe cold and cold regions, where heating accounts for the majority of energy consumption, coal is the main energy source. There is great potential to improve the energy efficiency of the heating supply. More efficient solutions, such as solar thermal, heat pump technologies, biomass boilers and micro co-generation units, have the potential to reduce heating energy consumption in buildings [6]. In southern China, where cooling dominates, electricity is the main energy source. A variety of technologies, including highly efficient solar roof top units (RTUs) in commercial areas and high-efficiency heat pumps in residential areas, will play a key role in reducing cooling demand.

At present, reinforced concrete (RC) is the most frequently used material in buildings, while timber as a construction material is still rarely applied in China. The use of timber has not been widely accepted and the timber industry is still on a limited scale. Currently, most timber buildings in China are lightweight frame buildings and the heights of the buildings are limited to three floors. Due to its national strategies to conserve forests and successive efforts at afforestation, the forest coverage of China has increased steadily. In 2008, the forest areas were 195.5 million hectares, which accounts for 20.4% of the national land area with the figure increased to 22.2% by 2015. The country plans to increase the forest area to 16.5 billion cubic meters by 2020, which accounts for 23.04% of the national land area. Existing research points out that the carbon storage rate tended to slow down to minimal approximately 100 years after the trees were planted [46]. Therefore, using timber in construction will be sustainable if responsible harvesting plans are in place. That simply means that we will have some old timbers that have limited capacity to increase carbon storage in the buildings and meanwhile we will have new trees in the forest which will continue contributing to the sequestration of carbon in the atmosphere.

6. Conclusions

This paper makes comparisons between reinforced concrete buildings and CLT buildings in China's 31 key cities to assess the energy consumptions and carbon emissions of residential buildings. The result shows that developing CLT as a sustainable material in China will be a sufficient way to save energy and reduce carbon emission. The main findings are summarized as follows.

(1) The estimated energy consumption and carbon emission in CLT buildings are much lower than those of RC buildings in all studied cities, which indicate that CLT systems have good potentials in reducing carbon emission and saving energy consumption compared to RC. The energy consumption and carbon emissions in both concrete and CLT buildings are closely related to the climate zones. Buildings in Severe Cold and Cold Region, where heating contributes to the main portion of energy consumption, consumed the most energy and released more carbon, followed by the Hot-Summer Cool-Winter Region, Hot-Summer Warm-Winter Region, and Temperate Region. At the national level, the energy consumption at the operation stage in the seven-story building with RC frames and CLT system were approximately 465.1 MJ/m^2 and 332.6 MJ/m^2 per annum, respectively, while the CO_2 emissions were 55.4 KG/m^2 and 42.3 KG/m^2 per annum, respectively.

(2) The effects of energy saving and carbon reduction of CLT buildings have little relationship with the climate zone. Despite the vast differences in China's climate zones, the energy saving and carbon reduction effects of CLT are significant in all studied cities. On the national level, CLT buildings may result in a weighted 29.4% energy saving, which equals 24.6% of carbon reductions, compared with the concrete building in the operation stage.

(3) Although CLT as a sustainable material can be developed nationwide in China, it is better to develop it in Severe Cold and Cold regions first due to the condition of limited timber production.

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