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Comparative Whole Building Life Cycle Assessment of Energy Saving and Carbon Reduction Performance of Reinforced Concrete and Timber Stadiums—A Case Study in China

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Abstract: Many stadiums will be built in China in the next few decades due to increasing public interest in physical exercise and the incentive policies issued by the government under its National Fitness Program. This paper investigates the energy saving and carbon reduction performance of timber stadiums in China in comparison with stadiums constructed using conventional building materials, based on both life cycle energy assessment (LCEA) and life cycle carbon assessment (LCCA). The authors select five representative cities in five climate zones in China as the simulation environment, simulate energy use in the operation phase of stadiums constructed from reinforced concrete (RC) and timber, and compare the RC and timber stadiums in terms of their life cycle energy consumption and carbon emissions. The LCEA results reveal that the energy saving potential afforded by timber stadiums is 11.05%, 12.14%, 8.15%, 4.61% and 4.62% lower than those of RC buildings in "severely cold," "cold," "hot summer, cold winter," "hot summer, warm winter," and "temperate" regions, respectively. The LCCA results demonstrate that the carbon emissions of timber stadiums are 15.85%, 15.86%, 18.88%, 19.22% and 22.47% lower than those of RC buildings for the regions above, respectively. This demonstrates that in China, timber stadiums have better energy conservation and carbon reduction potential than RC stadiums, based on life cycle assessment. Thus, policy makers are advised to encourage the promotion of timber stadiums in China to achieve the goal of sustainable energy development for public buildings.

Keywords: reinforced concrete; timber; energy saving; carbon reduction

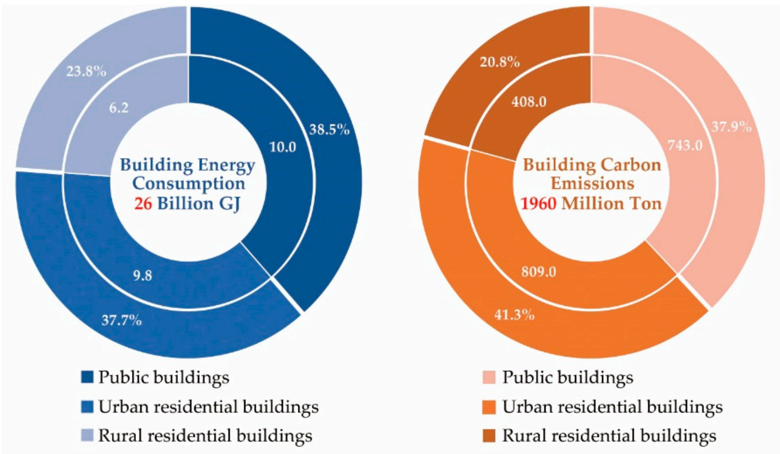
1. Introduction

1.1. Energy Consumption and Carbon Emissions of Public Buildings

Energy is necessary for human development and economic growth [1]. The world's population reached 7.69 billion in mid-2019 and is expected to exceed 9.8 billion by mid-2050 [2]. This massive population growth has had a huge impact on the global environment and natural resources over the last two centuries. Fossil fuels (i.e., coal, gas, and oil) have been the major energy sources for human activities since the 1760s. Burning fossil fuels for energy releases greenhouse gases (GHGs) into the atmosphere [3]. The use of fossil fuels pollutes the environment and emits large amounts of carbon dioxide (CO_2) [4]. The use of fossil fuels is believed to be the main factor leading to global warming [5,6]. Global warming is widely considered to cause glacier retreat and regional climate changes, species extinction, and further uncertain risks [7,8].

Measuring the "greenhouse effect" for mitigation purposes has become a major interest internationally in the last few decades. During the last 50 years, global warming has mainly been caused by excessive GHG emissions due to human activities [9]. International Energy Outlook (2019) reported that the building sector, one of the most important areas of human activities, accounted for 20% of the world's delivered energy consumption in 2018 [10]. This figure will rise to about 22% by 2050 [10]. The *Brown to Green Report* (2019) showed that carbon emissions directly from the building sector accounted for 9% of G20 energy-related CO_2 emissions in 2019 and that 18% of these emissions arose from electricity use in buildings [11].

At the end of 2016, the energy consumption of buildings in China was 26 billion GJ, accounting for 20.6% of the country's total energy consumption. In total, the building industry emitted 1.96 billion tons of CO_2 in this year, accounting for 19.4% of domestic carbon emissions [12]. At the 2015 United Nations Climate Change Conference [13], the Chinese government set the goal of reducing carbon emissions per unit of GDP by 60%–65% by 2030, relative to 2005 levels. Therefore, the annual average rate of decline in carbon intensity between 2005 and 2030 was expected to range from 3.6% to 4.1% [13]. To mitigate the greenhouse effect, it is vital to reduce the energy consumption of the building industry [14]. According to the *Research Report on Building Energy Consumption in China* (2018), public buildings in China accounted for 38.5% of total energy consumption (Figure 1a) and about 41% of carbon emissions in 2016 (Figure 1b) [12]. The report also revealed that the national average carbon emission factor of building sector in China was 2.18 kg CO_2/kgce. Specifically, the carbon emission figures of public buildings and the urban residential buildings was 2.15 kg CO_2/kgce and 2.39 kg CO_2/kgce. The report also highlighted that the carbon emission intensity of public buildings was 64.61 kg CO_2/m^2. The figures of national average and urban residential buildings were 30.88 kg CO_2/m^2 and 29.04 kg CO_2/m^2 respectively (Figure 2). The carbon emissions intensity of public buildings in China was approximately 200% higher than that of the national average in 2016 [12]. These findings demonstrate that public buildings in China contribute significantly to GHG emissions and thus offer great energy saving potential.



(**a**) (**b**)

Figure 1. (**a**) Data on national building energy consumption in China. (**b**) Data on national building carbon emissions in China. Data source: *Research Report on Building Energy Consumption in China* (2018) [12].

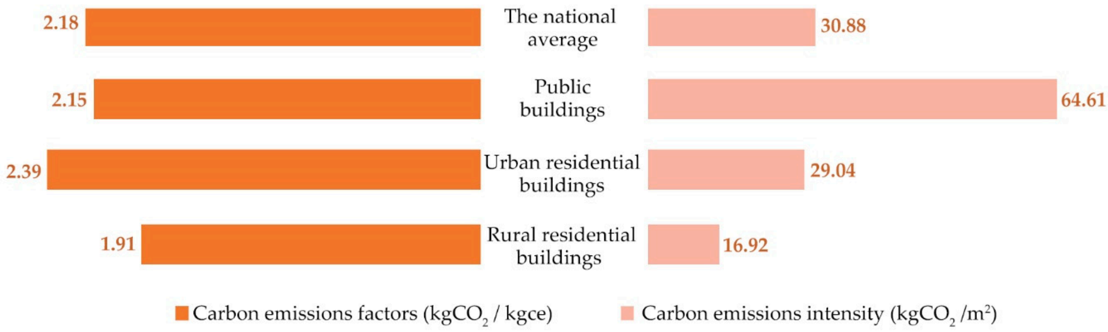


Figure 2. Carbon emissions factors and carbon emissions intensity of building sector in China. Data source: *Research Report on Building Energy Consumption in China* (2018) [12].

1.2. Development Tendency and Current Situation of Gymnasium in China

In the building industry, public and commercial (P&C) buildings can be divided into six types, namely office buildings, commercial lodging buildings, mercantile buildings, educational buildings, health care buildings, and others [15]. The "others" category covered 30% of the total P&C floor area in 2016, including gyms, transportation junctions, and cultural venues [15]. Gymnasiums are long and broad, as they are specially designed to accommodate special events and large audiences. With continuous economic improvement, people are gradually beginning to pay more attention to physical health, so more sports venues are needed. To meet the increasing demand for sports fields, for example, a series of regulations and government documents have been released to promote the development of such venues. According to the *Outline of Building a Strong Sports Country*, released by the State Council of China in 2019, the average area of sports facilities is expected to be 2.5 m^2 per capita in China by 2035 [16]. However, it had only reached nearly 1.46 m^2 per capita by 2016 [17]. To realize the goal, 71.2% more sports venues need to be built in the next 20 years in China [17]. Therefore, gymnasiums, as one of the most important types of sports facilities, have great development potential.

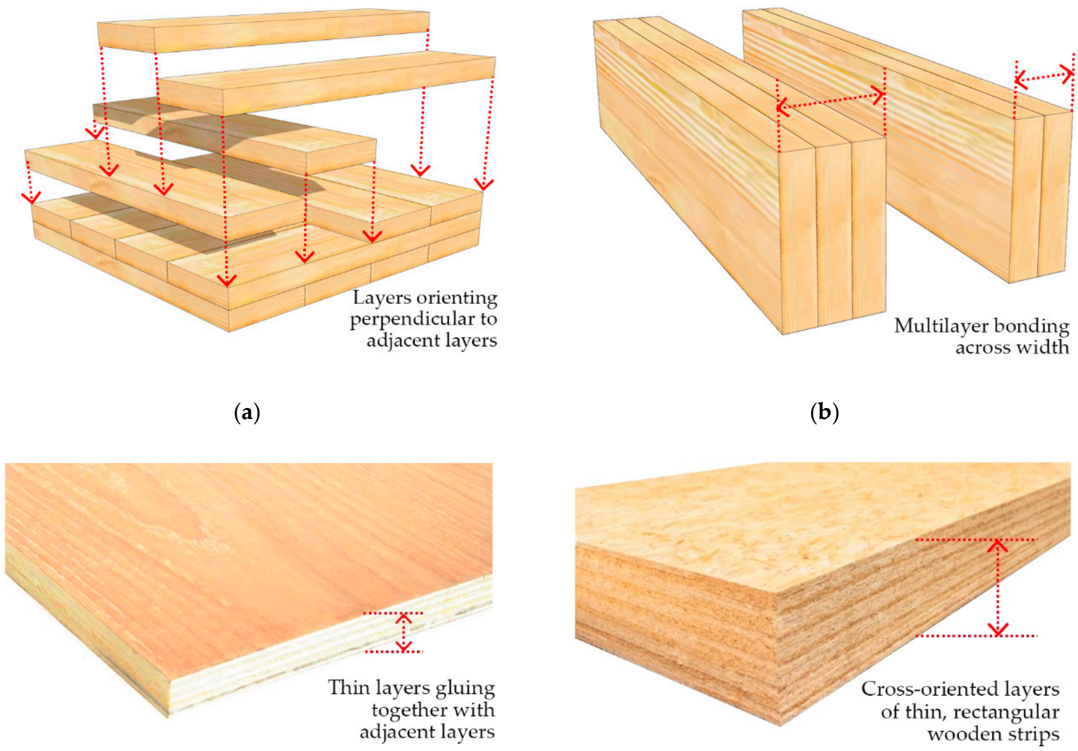
The Chinese government has introduced regulations to increase local residents' access to existing sports facilities, either free of charge or at low prices [16,18]. Gymnasiums in China generally open only in sports competition seasons as competition gymnasiums. The regulations will gradually transform the current operation mode into the new one, under which gymnasiums will open for the whole year, becoming national fitness centers. National fitness centers are expected to open for at least 40 hours a week and 330 days a year [18]. The number of gymnasiums will continually grow, and their opening hours will gradually increase. However, these trends will also exacerbate the existing problem of high energy consumption by gymnasiums, increasing their contribution to GHG emissions in China. Therefore, reducing the energy consumption of gymnasiums will greatly help to mitigate the greenhouse effect.

Some researchers have studied the energy consumption of gymnasiums in their operation phase. For example, Trianti-Stourna et al found that the energy consumption of operational sport halls in Greece is approximately 100 kWh/m^2 per year, and sought to achieve an optimal balance between indoor conditions and energy use [19]. Nishioka et al evaluated the indoor thermal environment and energy consumption of a large domed stadium. The results showed that the annual cooling load of the whole building was about 69.1 Mcal/m^2 and the annual heating load was about 13.2 Mcal/m^2 [20]. Li and Liang studied the cooperative interaction among structure, soil loads and thickness, and energy efficiency when applying the overall roof greening to a large "saddle-shaped" shell [21]. They found that using overall roof greening can save 25.1% of annual air-conditioning energy consumption in Guangzhou, China [21]. However, research on reducing the energy consumption of gymnasiums by replacing traditional materials with sustainable materials is limited.

1.3. Energy Saving and Carbon Emission Reduction Potential of Timber Buildings

Trees and their by-products have been used worldwide for thousands of years [22]. Due to the gradual exhaustion of forest resources, however, wood has been replaced by mineral materials, such as concrete. However, concrete can produce a lot of carbon dioxide during the production process and increase the burden of scarce ecological resources. Recently developed national and international policies and regulations are expected to address the carbon impact and resource scarcity associated with concrete [23].

The sustainability of timber provides a material solution to the problem [23]. With the improvement of timber planting technology, timber can now be recycled without a huge negative impact on natural resources from the planting stage to the harvesting stage. Besides, engineered timber products greatly improve the utilisation efficiency of timber through the advancement of timber industrialisation. At least 52% of the logs brought to wood product manufacturing centers are processed into lumber [24]. Of all engineered timber, the most widely used products include cross laminated timber (CLT), glued laminated timber (GLT), and plywood and oriented strand board (OSB) (Figure 3). Engineered timber products have several advantages. For example, CLT provides great advantages in terms of the speed of construction, minimal waste, and wide-span construction [25]. Furthermore, CLT has negative embodied carbon [25]. These advantages make timber a strong alternative to concrete [26]. Hence, timber has regained its market share from traditional heavyweight materials over the last decade [27].



(a) (b) (c) (d)

Figure 3. (**a**) Cross laminated timber (CLT) panel construction [28]. (**b**). Glued laminated timber (GLT) panel construction. (**c**) Plywood panel. (**d**) Oriented strand board (OSB) panel.

Existing studies have shown that using timber in buildings offers more notable potential reductions in energy use and carbon emission than using concrete and other heavyweight materials. Research on the energy saving of wood-based building is discussed below. Chen compared the energy used for heating, ventilation and air conditioning in concrete and CLT office buildings and pointed out that the operating energy of CLT buildings was 10% lower than that of concrete buildings [29]. Hafner and Schäfer assessed the GHG reduction potential of residential buildings after replacing mineral materials with timber in building construction. The substitute factor (GHG reduction potential) of timber buildings for the construction of single/two-family houses ranged between 0.35 and 0.56, which means that there is a positive GHG reduction potential when using timber [30]. Tettey et al revealed that CLT buildings reduced the total life cycle primary energy use by 20%–37%, compared with the concrete alternative, when space heating came from combined heat and power [31]. Khavari et al simulated a 10-storey multiunit residential CLT building model and found that a timber building model significantly improved heating energy efficiency compared with a light-frame metal construction model [32]. The results showed that using CLT can save 2090 dollars in utility costs annually [32].

There has also been some research on the carbon emissions and environmental benefits of timber buildings. Chiniforush et al found that adopting a steel structure with steel-timber composite floors and shear wall systems resulted in a 107% reduction in embodied carbons, compared with the same building designed with a concrete structure [33]. Pierobon et al evaluated the embodied emissions and energy associated with building materials, manufacturing, and construction for midrise commercial buildings with a hybrid CLT structure [34]. They found that hybrid CLT buildings can save 8% of non-renewable energy (fossil-based) compared with concrete buildings [34]. Pajchrowski et al concluded that the environmental impact of a conventional masonry building is 2.7 times greater than that of a conventional wooden building, and the environmental impact of a passive masonry building is 1.6 times greater than that of a passive wooden building [35]. Dong et al found that the heating energy of CLT office buildings is 11.97% lower than that of RC buildings in Harbin [36]. Balasbaneh and Marsono also found that the GHG emissions associated with using timber prefabricated walls in construction were about 7% lower than those for blockwork systems [37].

Timber is increasingly used as a construction material in buildings worldwide due to the development of engineered timber. Current studies have shown that replacing concrete and other traditional heavyweight materials with timber in buildings has a great energy conservation and carbon reduction potential. With the promotion of sports venues, gymnasiums will consume more and more energy and contribute to GHG emissions enormously in the future. However, timber has not yet been widely used in gymnasiums in China, and studies of the energy saving and carbon reduction potential of timber gymnasiums are limited and unclear.

1.4. Study Objective

Based on the above, the existing research has demonstrated that timber is a kind of environmental-friendly building material capable of reducing building energy. However, limited research has addressed the energy saving and carbon reduction potential of timber gymnasiums in China. This paper evaluates the carbon reduction and energy saving effects of timber gymnasiums through life cycle assessment to determine whether timber offers a feasible new building material for sports facilities in China in terms of energy sustainability.

2. Description of Studied Buildings and Its Environment

2.1. Climate Zones in China

In the Code for Design of Civil Buildings (GB 50352-2005) [38], five major climate zones are distinguished to assess the thermal-technical designs of buildings in China. These regions are "severely cold," "cold," "hot summer, cold winter," "hot summer, warm winter," and "temperate." The climate conditions of these regions vary greatly due to China's vast territory. Where necessary, each of the five climate zones can be further divided into A, B, C, and D, giving 20 sub-regions. In this paper, five major cities, namely Harbin, Beijing, Shanghai, Guangzhou, and Kunming, are selected to represent each climate region (Figure 4). Buildings in each region have to follow local construction regulations, which define structural criteria; the insulation properties of opaque walls, floors, and roofs; and the thermal and optical performance of windows and skylights. Thermal insulation design is one of the most important regulatory areas, and these regulations should be enforced particularly strictly in the severely cold and cold regions due to their frigid climate. The basic information on thermal design in these five cities is presented in Table 1 [38,39].

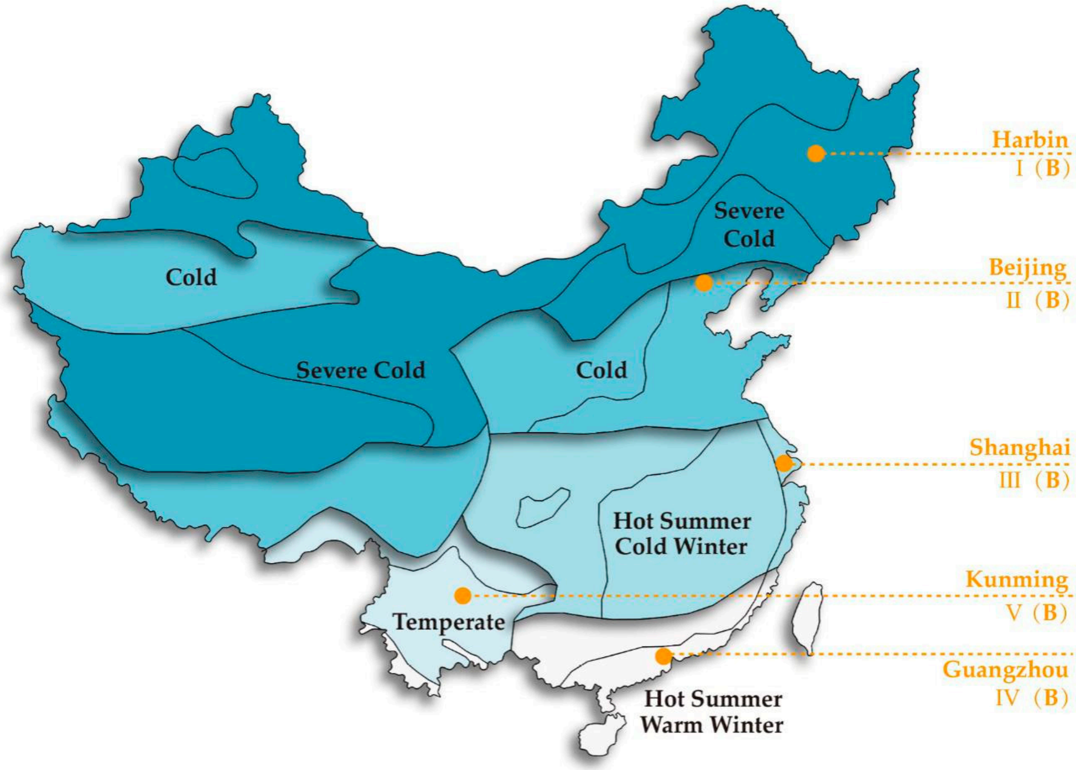


Figure 4. Locations of the five case study cities.

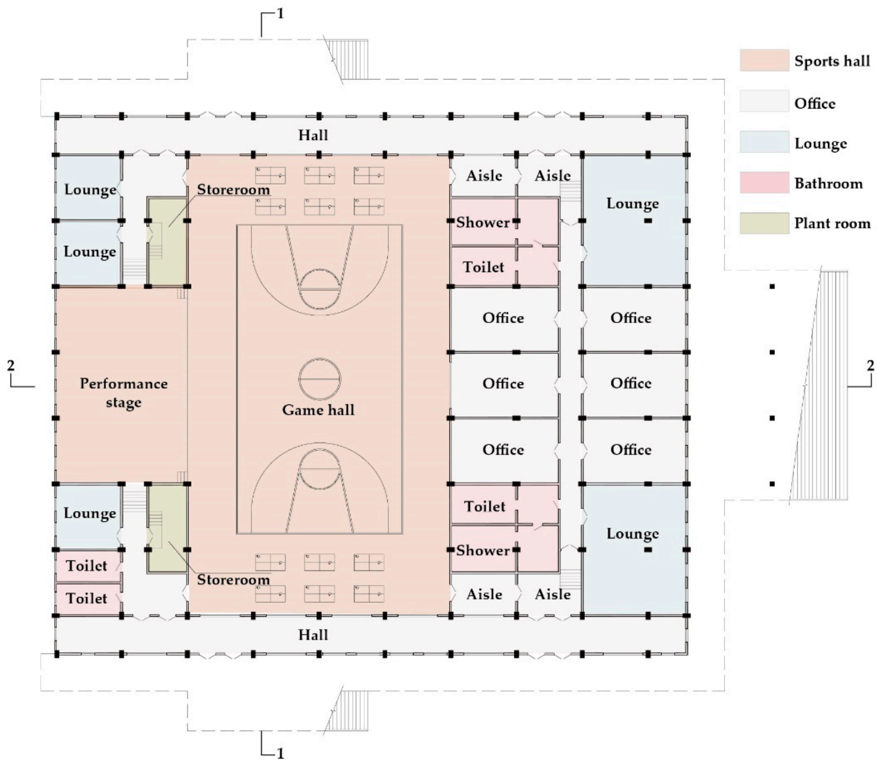
Table 1. Five case study cities by climate regions in China.

Climate Region	Temperature		Sub-Region	Representative City	U-Value (Local Regulations)	R-Value (Local Regulations)
	Hottest	Coldest				
Severely Cold	≤25 °C	≤−10 °C	I (B)	Harbin	Roof: ≤0.28 Wall: ≤0.38 Window: ≤1.3	Ground Floor: ≥1.1
Cold	18 °C~28 °C	−10 °C~0 °C	II (B)	Beijing	Roof: ≤0.45 Wall: ≤0.5 Window: ≤1.5	Ground Floor: ≥0.6
Hot Summer, Cold Winter	25 °C~30 °C	0 °C~10 °C	III (B)	Shanghai	Roof: ≤0.5 Wall: ≤0.8 Window: ≤1.8	—
Hot Summer, Warm Winter	25 °C~29 °C	−10 °C	IV (B)	Guangzhou	Roof: ≤0.8 Wall: ≤1.5 Window: ≤2	—
Temperate	18 °C~25 °C	0 °C~13 °C	V (B)	Kunming	Roof: ≤0.8 Wall: ≤1.5 Window: ≤2	—

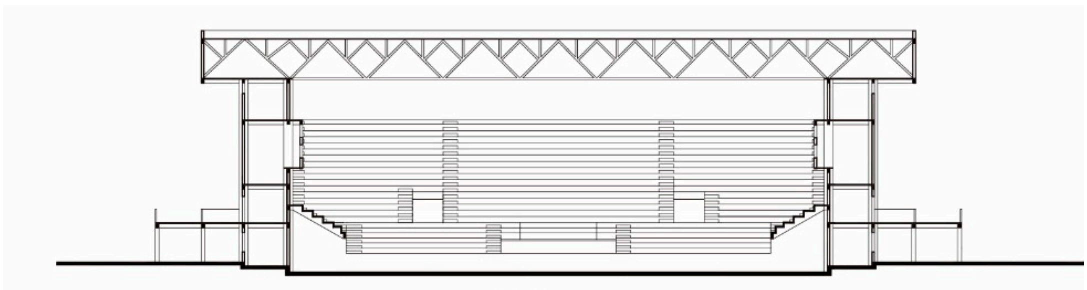
Data Source: Code for Design of Civil Buildings (GB 50352-2005), Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015).

2.2. Details of Simulation Buildings

In this paper, in order to clarify the energy saving and carbon reduction potential of timber stadiums in comparison with stadiums using conventional building materials, a real stadium located in Harbin is selected as a reference building. This is a typical community-scale stadium, which can accommodate 3000 people at most in residential districts. The stadium is normally available to local residents from 09:00 to 17:00, three days a week. The stadium can be divided into five functional areas namely sports hall, office, lounge, bathroom and plant rooms. The basic architectural design information is tabulated in Table 2. Figure 5 presents the floor plan and sections of the stadium. The roof of the original stadium has a plate-like space truss and the external wall is made of reinforced concrete (RC) and steel.



(**a**)



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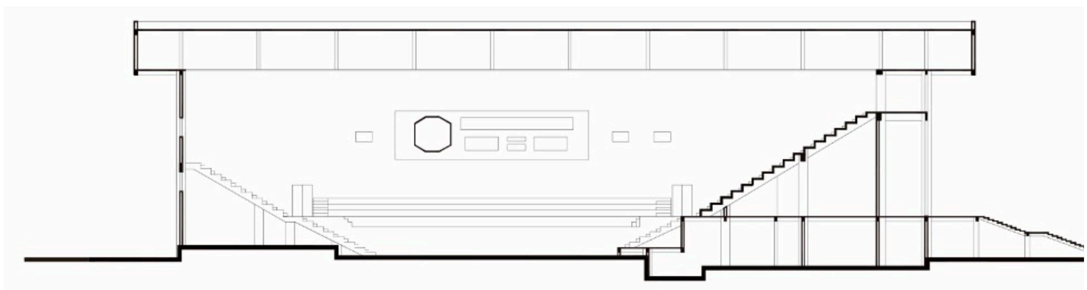


(**c**)

Figure 5. (**a**) First floor plan of the building. (**b**) 1-1 Section of the building. (**c**) 2-2 Section of the building.

Table 2. Stadium information.

Items	Figures	Items	Figures
Total Floor Area (m^2)	5800.00	Plane Size of Performance Stage (m)	18.00 × 12.00
External Wall Area (m^2)	2401.02	Plane Size of Game Hall (m)	24.00 × 42.00
External Opening Area (m^2)	1347.78	Area Index (m^2/per seat)	1.93
Total Volume (m^3)	51420.86	Sports Hall Area (m^2)	2844.13
Total Height (m)	17.60	Office Area (m^2)	947.26
Number of Layers	3.00	Lounge Area (m^2)	1181.95
Number of Seats	3000.00	Bathroom Area (m^2)	426.46
Plane Size (m)	50.20 × 58.20	Plant Room Area (m^2)	400.20

Data Source: Original construction drawings.

The process of designing the simulation buildings is divided into two parts. The building materials and structures are designed according to the different climate zones. In the first stage, four similar buildings located in other climate regions are designed on the basis of the original stadium in Harbin. The stadium's exterior envelope construction and building materials are the same as those of the original stadium, but the thickness of the envelope is adjusted to reflect the actual situation and meet the local building regulations in each climate region. During the second stage, five timber stadiums are designed in five climate regions, respectively, on the basis of the reference RC stadiums. The basic dimensions of the timber buildings, such as floor height, building orientation, ground area, and major functions, are the same as for the reference concrete buildings. However, the load-bearing structure and external envelope are replaced by timber. The related design parameters for the RC and timber stadiums in the five studied cities are presented in Tables 3 and 4.

Table 3. External wall and roof designs of the reinforced concrete (RC) stadiums in the five cities.

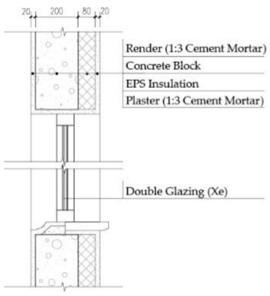
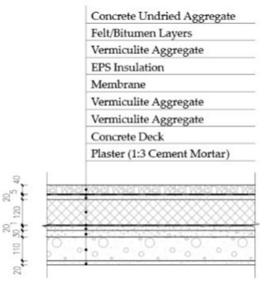
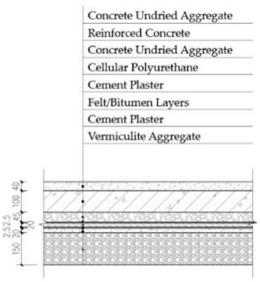
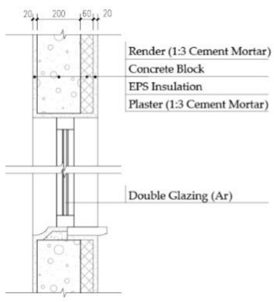
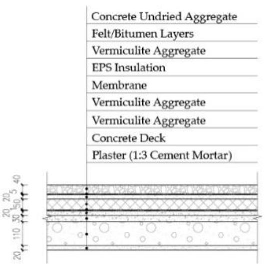
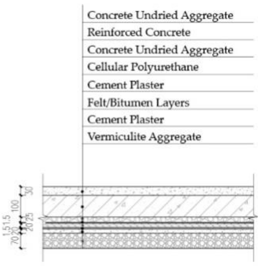
Cities	External Wall and External Window	Roof	Ground Floor
Harbin			
Beijing			

Table 3. *Cont.*

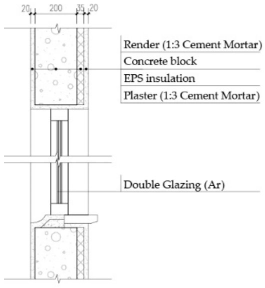
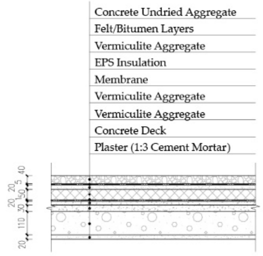
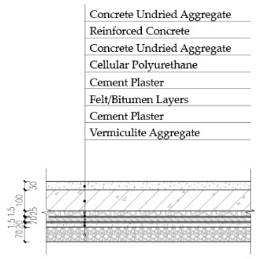
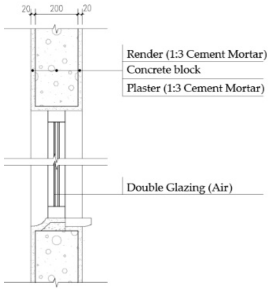
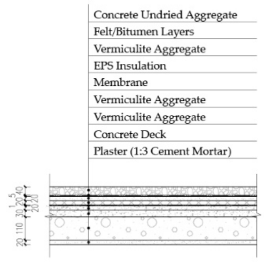
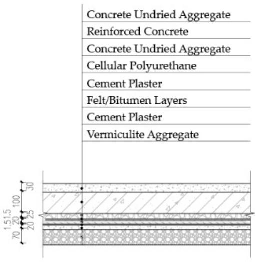
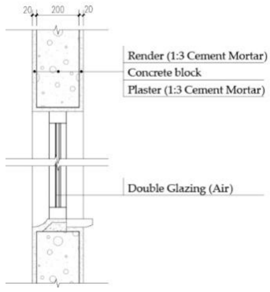
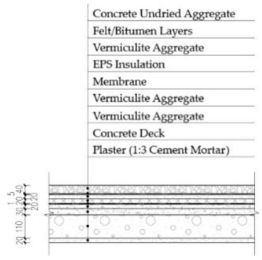
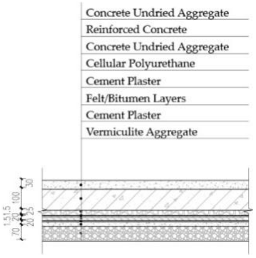
Cities	External Wall and External Window	Roof	Ground Floor
Shanghai			
Guangzhou			
Kunming			

Table 4. External wall and roof designs of the timber stadiums in the five cities.

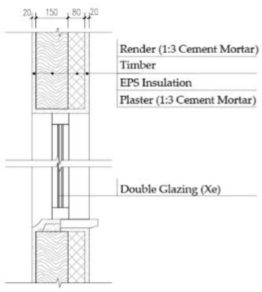
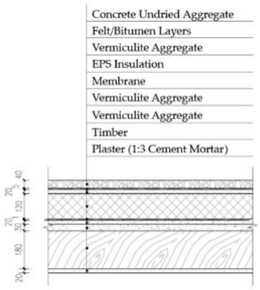
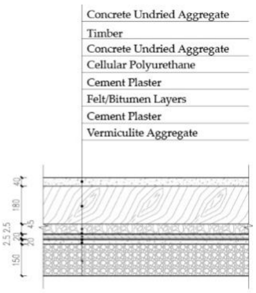
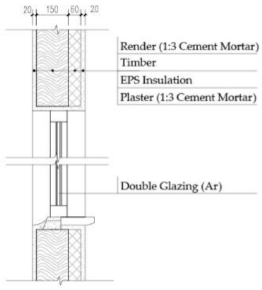
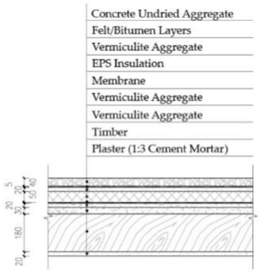
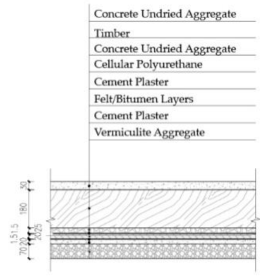
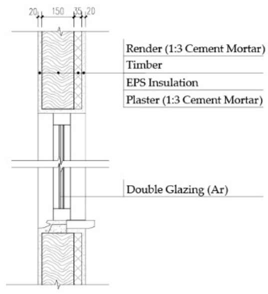
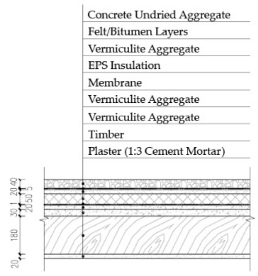
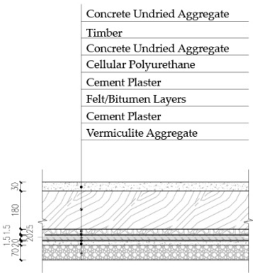
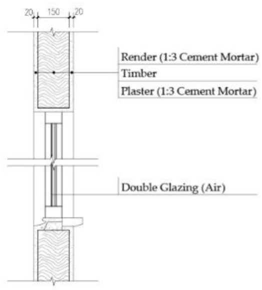
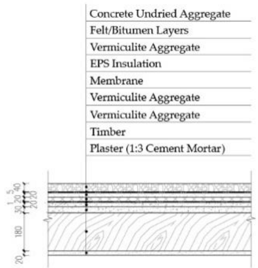
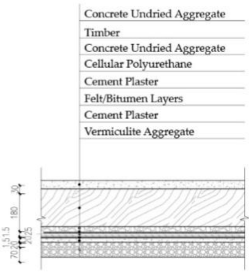
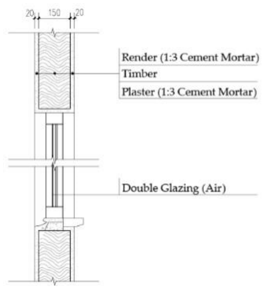
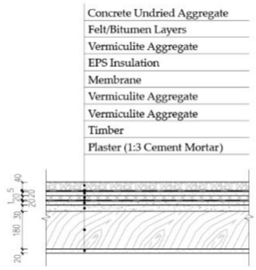
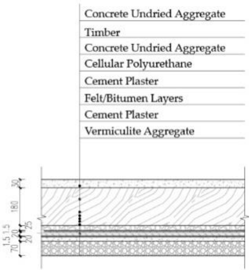
Cities	External Wall and External Window	Roof	Ground Floor
Harbin			

Table 4. *Cont.*

Cities	External Wall and External Window	Roof	Ground Floor
Beijing			
Shanghai			
Guangzhou			
Kunming			

3. Method and Data

3.1. Framework of the Study

Life Cycle Energy Assessment (LCEA) and Life Cycle Carbon Assessment (LCCA)

In relation to building life cycle assessment (LCA), a building's energy consumption and carbon emissions during its lifespan can be divided into three stages, namely materialisation, operation and end of life. In this paper, both energy consumption and carbon emissions during the building's life cycle are taken into account. During the construction phase, energy consumption and carbon emissions can be further divided into building materials, transportation and on-site erection. During the production process, conventional materials such as RC, steel, and cement consume a large amount of energy and release carbon dioxide. In contrast, during the fabrication of wood materials, trees absorb carbon dioxide and consume a small amount of energy. The existing research has demonstrated that 1 cubic meter of wood stores approximately 140–510 kg of C (carbon), which means that it contains about 513–1870 kg of CO_2 [40]. It is well accepted that building energy consumption and carbon emissions are the dominant components during the operation phase. In the context of the building lifespan, two thirds of the total building energy are consumed during this stage [41–43]. In this phase, the energy consumption and carbon emissions of a residential building can be further divided into six categories, namely lighting, space heating, space cooling, ventilation, appliances, and water heating. This study also considers the carbonation and durability of cement and RC. The carbonation of reinforced concrete and cement is one of the causes of corrosion, but it is also a way of sequestering CO_2. The end of life phase comprises the energy consumed and carbon emitted during building demolition, transportation and material disposal. Flowcharts depicting the life cycle energy assessment (LCEA) and life cycle carbon assessment (LCCA) in this study are presented in Figures 6 and 7, respectively.

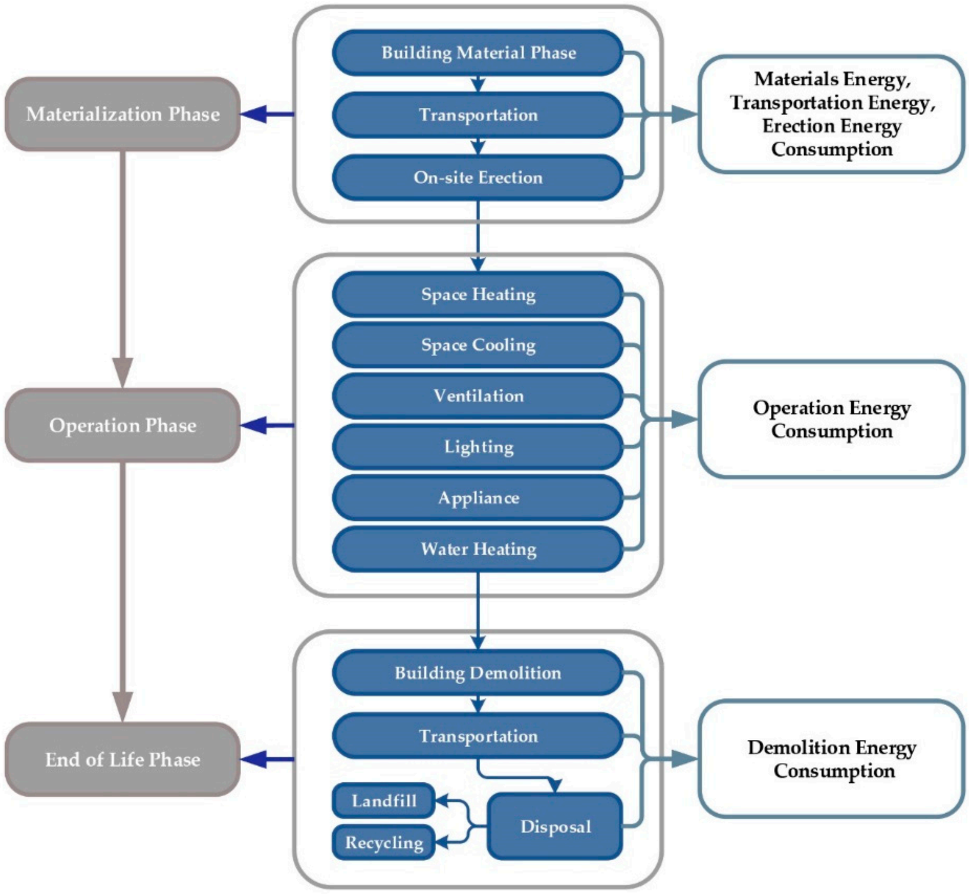


Figure 6. Flowchart of the life cycle energy assessment (LCEA).

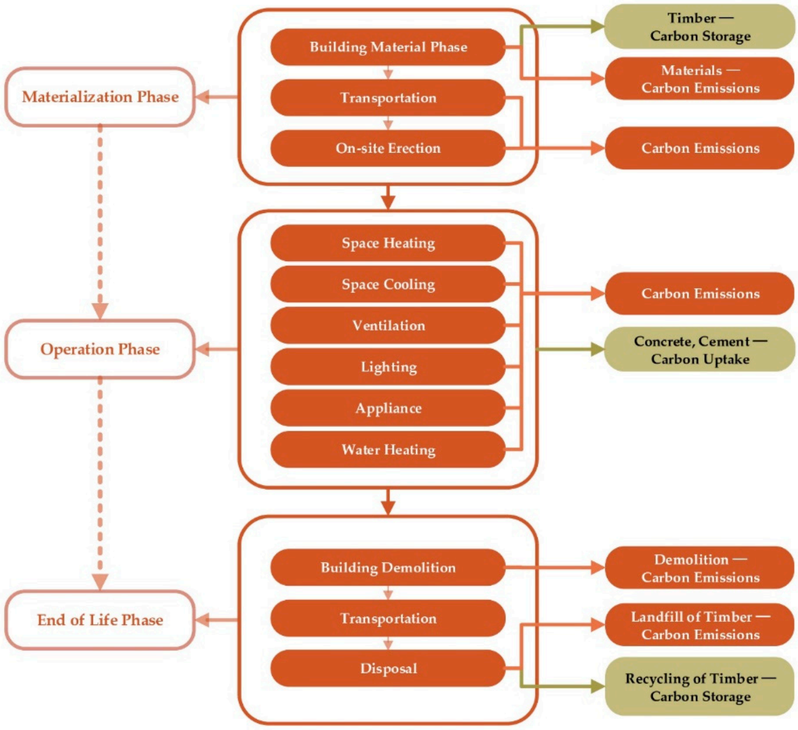


Figure 7. Flowchart of the life cycle carbon assessment (LCCA).

3.2. *Energy Consumption*

3.2.1. Construction Phase

As mentioned above, the materialization stage comprises material production, transportation and on-site erection. Several assumptions are made when carrying out the LCEA and LCCA in the materialization stage.

(1) The energy consumed and carbon emitted during the decoration of concrete buildings are ignored.
(2) Based on existing research, the on-site erection energy consumption of RC and CLT buildings is set at 100 MJ/ m^2 and 20 MJ/m^2, respectively [44].
(3) The boundaries of the materials, including concrete, sand, cement, steel, and brick, start with the extraction of raw materials, whereas the boundary for CLT starts with tree harvesting. The total volume of consumption of building materials for RC and timber stadiums is shown in Table 5. The inventory of data used to calculate the energy consumption of building material production is presented in Table 6.

Table 5. Mass and volume of RC and timber buildings.

Materials	RC Buildings		Timber Buildings	
	Material Volume (m^3)	Material Mass (Tons)	Material Volume (m^3)	Material Mass (Tons)
Concrete	3715.08	4380.53	861.08	1463.84
Sand	584.96	4787.84	420.09	672.14
Cement	194.99	253.48	140.03	182.04
Steel	44.85	349.85	17.33	135.20
EPS (Harbin)	752.64	18.82	752.64	18.82
EPS (Beijing)	435.89	10.90	435.89	10.90
EPS (Shanghai)	328.196	8.205	328.196	8.205
EPS (Guangzhou)	96.08	2.40	96.08	2.40
EPS (Kunming)	96.08	2.40	96.08	2.40
Plasterboard	109.92	76.94	126.50	88.55
Timber	—	—	3186.43	1593.21

Table 6. List of materials used for construction.

Material	Energy Consumption for Material Production		Carbon Emissions during Material Manufacture Process		References
	Unit	Value	Unit	Value	
Concrete	GJ/t	0.764	Kg-CO_2/m^3	352.200	[45]
Sand	GJ/t	0.029	—	—	[44]
Cement	GJ/t	3.186	Kg-CO_2/t	860.000	[44,46]
Steel	GJ/t	19.520	—	—	[47]
EPS Insulation Board	GJ/t	94.000	—	—	[44,48]
Plasterboard	GJ/m^3	2.400	Kg-CO_2/t	213.862	[49]
Timber	GJ/m^3	0.545	—	—	
Transportation (Train)	MJ/t·km	0.220	—	—	[44]
Transportation (Lorry)	MJ/t·km	2.300	—	—	

3.2.2. Operation Phase

This study simulates building energy consumption during the operation stage using the commercial software package Integrated Environmental Solutions—VE (IES-VE). The software is developed by Integrated Environmental Solutions company, which is located in Glasgow, UK. In the software platform, RC and timber stadiums can be established as simulation models (Figure 8). Energy consumption from lighting, space heating, space cooling, appliances, ventilation, and water heating is simulated. Several assumptions are made during the simulation.

(1) According to the building grade classification in China, the life spans of the two stadiums are assumed to be 50 years [50].
(2) The indoor temperature is controlled between 10 °C and 26 °C. In the winter, the temperature of the sports hall is set at 18 °C when occupied. The temperature of the office, lounge and bathroom areas are set at 20 °C. The comfortable temperature in summer is expected to be no more than 26 °C. Cooling is implemented automatically when the temperature exceeds this range. The basic parameters of the thermal conditions are shown in Table 7 [50].
(3) Both natural and infiltrate ventilation are simulated. The basic parameters of ventilation are shown in Table 8 [50].
(4) Electricity is used for cooling, water heating, lighting, appliances, and ventilation, while raw coal is used for heating. This is the current practice in China and is described in detail later.

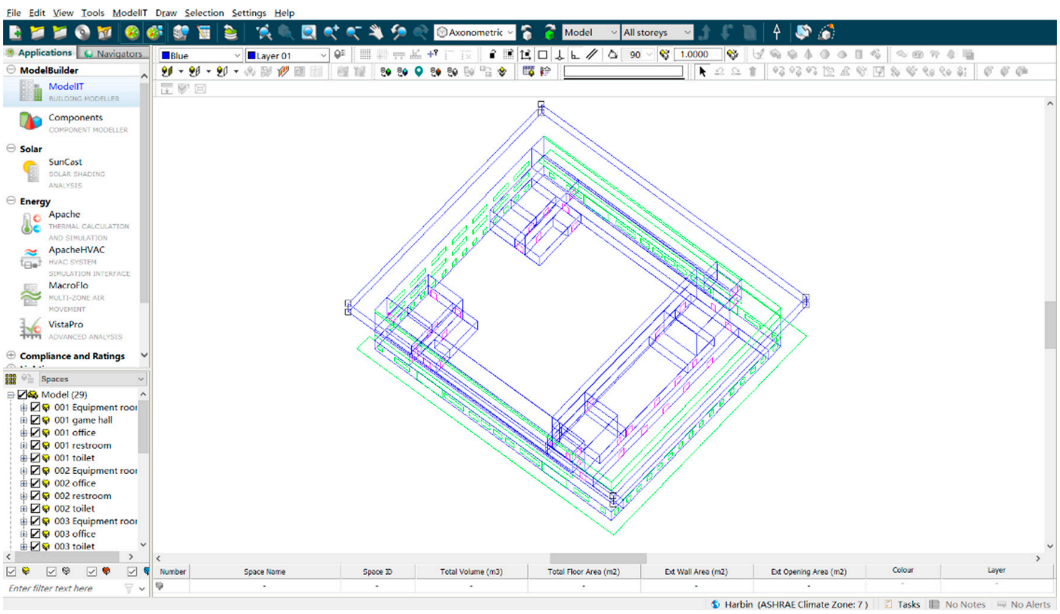


Figure 8. Established model in the Integrated Environmental Solutions software platform.

Table 7. Basic simulation parameters of thermal conditions.

Room	Occupied	Heating Time	Heating Month	Heating Set Point	Cooling Time	Cooling Month	Cooling Set Point
Sports hall	Tuesday, Thursday, Saturday every week 09:00–17:00	24 h	15 October to 15 April (Harbin) 15 November to 15 March (Beijing, Shanghai) No heating (Guangzhou) 15 December to 15 February (Kunming)	18 °C; (When occupied) 10 °C	When Occupied and Room Temp > 26 °C	1 June to 31 August (Harbin) 16 March to 14 November (Beijing, Shanghai, Guangzhou) 16 February to 14 December (Kunming)	26 26 °C
Office				20 °C			26 °C
Lounge				20 °C			26 °C
Bathroom				20 °C			26 °C
Plant Room				10 °C	—	—	—

Table 8. Basic simulation parameters of ventilation.

Room	Infiltrate Ventilation Set Point and Time	Natural Ventilation Set Point	Natural Ventilation Set Time	Auxiliary
Sports Hall	0.25 ach 24 h	—	—	5.56 l/s/person (When Occupied)
Office		1 ach	When occupied and Room Temp is between 18 °C and 26 °C	—
Lounge		3 ach		—
Bathroom		—	—	3 ach (When Occupied)
Plant Room		—	—	—

3.2.3. End of Life

During this phase, the following assumptions are made for calculation.

(1) The energy consumption for demolition of a building is considered to be 90% of the energy consumed during the erection phase as the existing research [51]. The demolition area of RC and CLT buildings is set at 90 MJ/m^2 and 18 MJ/m^2, respectively.

(2) For the concrete buildings, we assume that all of the concrete and steel materials would go into landfill after demolition. This is also the current practice in Northeast China. Due to the relatively small amount of steel used in the stadium, the ignorance of steel recycling may not have significant effect on the total carbon emissions of the building.

(3) For the CLT buildings, a recycling rate of 60% is assumed, with 40% used for biomass energy.

(4) The energy consumed by transportation is ignored.

3.3. Carbon Emissions and Carbon Uptake

3.3.1. Carbon Emissions

During the construction stage, electricity is the main source for the building materials manufacture. During the operation stage, as mentioned above, raw coal and electricity are the two main sources of energy for the operation of stadiums. Electricity is used for cooling, lighting, water heating and appliances, and raw coal is used for heating. During the end of life stage, the energy consumption is assumed to be mainly from the electricity. The energy consumption can be obtained from the simulation and calculation directly. In order to get the carbon emission, the results need to be converted by conversion formulas. The carbon emissions for coal and electricity can be obtained from Equations (1) and (2) [52].

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

$$E_t = \sum Q_{jt}C_j\eta_j \quad (2)$$

where E_t is the estimated amount of carbon emissions of the t-th studied city; Q_{jt} is the energy consumption from the coal and electricity of the t-th studied city; C_j is the appropriate calorific value of the j-th energy source; and η_j is the carbon emission factor of the j-th energy source. The values of C_j and η_j in this study are summarized in Table 9 [52,53].

Table 9. C_j and η_j for coal and electricity.

Fossil Energy Items	C_j	η_j	Studied Cities
Raw Coal	20,934 kJ/kg	26.80 (t-C/TJ)	—
Electricity	3600 kJ/kWh	1.14 (t-CO_2 /MWh, Northeast China) 1.13 (t-CO_2 /MWh, North China) 0.78 (t-CO_2 /MWh, East China) 0.67 (t-CO_2 /MWh, Southern China)	Harbin Beijing Shanghai Guangzhou, Kunming

The values of raw coal's ηj are supposed to be the same nationwide, but the values of electricity's ηj are strongly related to the energy source used for generating. In China, the national power grid is made up of six sub power grids. The CO_2 emissions factors are not the same in each region due to the energy source used for generating. The energy sources of national power grid for electricity generation include coal, nuclear power, hydro, wind and others. Electricity generated from clean energy sources such as hydro and wind has low carbon emissions. While electricity from coal may emit tremendous CO_2. Generally speaking, in China, the electricity is mainly generated from the coal and thermal energy accounted for 70.24% of electricity generation in 2019 [54]. As a result, the average CO_2 emissions factor is much higher than that in other country. In Italy, CO_2 emissions factor in 2017 is approximately 346 g/kWh, while the CO_2 emissions factor is approximately 870 g/kWh in China [53,55]. The 5 studied cities by sub-regions of the national grid and the CO_2 emissions factors of the sub-regions are presented in Figure 9. In northern part of China, where the coal is the dominant resource used for generating the electricity, the CO_2 emissions factors is much higher than that in the other regions. The figures of CO_2 emissions factors range from 0.67–1.14.

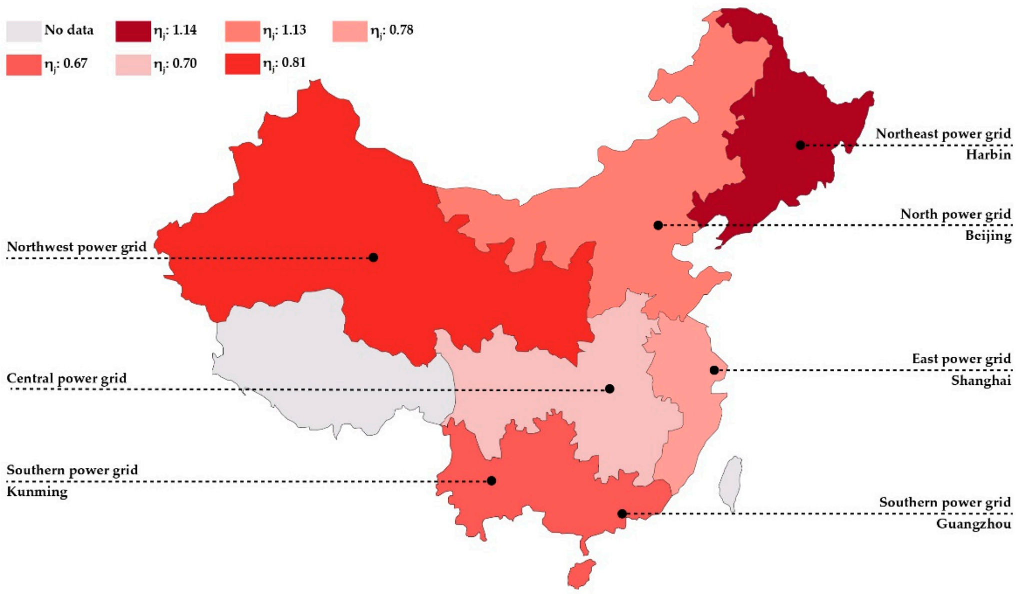


Figure 9. Sub-regions of national power grid and the CO_2 emissions factors (ηj).

3.3.2. CO_2 Uptake of Concrete and Cement during the Operation Stage

In this paper, the cement is mainly used as the opponent of the external rendering and the plaster. The CO_2 uptake of concrete and cement during the operation stage can be obtained by the following steps.

(1) Depth of carbonation. The carbonation of concrete starts at the outer surface and moves progressively inwards. The process is controlled by the diffusion of CO_2 into the concrete. The depth of carbonation as a function of time can be described by Equation 3 [56,57]. The service life of the concrete is estimated to be 50 years (t):

$$d = k \times t^{0.5} \tag{3}$$

where k is a rate constant, presented in Table 11; t is the carbonation time; and d is the depth of carbonation. The K values in this study are shown in Table 11 [58].

(2) Volume of carbonated concrete. The volume of carbonated concrete can be obtained from Equation (4) [57]:

$$Carbonation\ \frac{Concrete}{Cement(m^3)} = \sum (A_{slabs} \times d) + (A_{walls} \times d) + \left(A_{foundations} \times d\right) \tag{4}$$

where A is a rate constant, as presented in Table 10, and d is the depth of carbonation, which can be obtained from Equation (3).

(3) Amount of CO_2 absorbed per volume. The amount of CO_2 absorbed per volume can be calculated using Equation (5) [57]:

$$\text{Carbon } Uptake\left(kg\ CO_2/m^3\ concrete/cement\right) = 0.75 \times C \times CaO \times \frac{M_{CO_2}}{M_{CaO}} \tag{5}$$

where C is the mass of Portland cement clinker per m^3 concrete/cement, assumed to be 1300 kg for cement and 240 kg for concrete respectively [58]; CaO is the average CaO content, which is assumed to be 65% [57,59]; and M is the molar mass of CO_2 and CaO.

(4) Amount of CO_2 uptake. Finally, the total carbon uptake can be obtained by Equation (6).

$$\text{Total Carbon Uptake (kg)} = \text{Equation } 4 \times \text{Equation } 5 \tag{6}$$

Table 10. Surface area (A) for cement and concrete.

	Exposure Condition	Concrete		Cement	
		RC Building	Timber Building	RC Building	Timber Building
A_{slabs}	Indoors	15,945.45	—	—	—
A_{roof}	Indoors	3612.00	—	903.00	903.00
A_{walls} (External Surface)	Exposed	2401.02	—	600.26	600.26
A_{walls} (Internal Surface)	Indoors	9189.59	—	2297.40	2297.40
$A_{columns\ and\ beams}$	Indoors	4780.02	—	1195.01	1195.01
$A_{ground\ floor}$	Indoors	2817.50	2817.50	—	—

Table 11. K (carbonation rate constant) values.

Exposure Condition	Compressive Strength	
	15 Mpa (mm/(year) $^{0.5}$)	23–35 Mpa (mm/(year) $^{0.5}$)
Exposed	5.00	1.50
Indoors	15.00	6.00

3.4. Quality of Data

In this paper, the data that used for assessment of energy consumption and carbon emissions can be summarized as three aspects. (1) The simulation parameters, such as the heating and cooling time, indoor temperature settings and ventilation rate all strictly follow the national building standards that issued by the Chinese government. The data is reliable since it is official. (2) The equations, calculation coefficients, and some parameters such as the C_j and η_j in the Equation (1) and Equation (2) are summarized from the relevant scientific research. (3) The parameters of the buildings, such as the functions, dimensions and thermal designs of the buildings are obtained directly from construction drawings. The reliability of the figures is considered as high, since it is from the original design.

4. Results and Analysis

Table 12, Table 13 and Figure 10 present the results of LCEA and operation phase for RC and timber stadiums in the five cities under study, which are located in different climate zones. The estimated energy consumption in RC stadiums is higher than that of timber buildings in all studied cities. The results demonstrate that timber is an energy efficient building material capable of saving energy and a suitable alternative to conventional building materials. The energy saving potential of timber is closely related to the climate region. The energy consumption during operation phase accounts for the majority of the total life cycle energy consumption. During operation phase, energy consumed for heating in "severely cold" and "cold" regions is much higher than that in other climate regions. Therefore, the total energy consumption of the studied buildings in "severely cold" and "cold" regions, where heating is the dominant energy-consuming activity, is significantly higher than that in other climate regions. Building energy consumption in Harbin is approximately two times greater than that in Kunming. In terms of operation stage, the energy consumption of RC buildings during the operation phase ranges from 343.44 MJ/m^2 to 779.95 MJ/m^2 per annum, while that of timber building ranges from 349.49 MJ/m^2 to 712.24 MJ/m^2 per annum. The results also echo the figures of existing references. Ma et al counted energy consumption of public buildings in North China and pointed out that the average energy consumption of office, hospital and school buildings are 678.11 MJ/m^2, 711.52 MJ/m^2 and 371.77 MJ/m^2 per annum, respectively [60]. Jiang and Tovey revealed that commercial buildings in Beijing and Shanghai consumed 622.8 MJ/m^2 and 475.2 MJ/m^2 per annum [61].

Table 12. Estimated LCEA results for the reference buildings (50 years).

Cities	Buildings	Energy Consumed (MJ/m^2)			
		Construction	Operation	End of Life	Total
Harbin	RC Building	2388.80	38,997.64	90.00	41,476.44
	Timber Building	1262.47	35,611.97	18.00	36,892.44
Beijing	RC Building	2260.46	30,923.55	90.00	33,274.01
	Timber Building	1134.14	28,081.42	18.00	29,233.56
Shanghai	RC Building	2216.83	25,106.60	90.00	27,413.43
	Timber Building	1090.50	24,071.97	18.00	25,180.47
Guangzhou	RC Building	2122.78	22,388.93	90.00	24,601.71
	Timber Building	996.45	22,453.54	18.00	23,467.99
Kunming	RC Building	2122.78	17,171.96	90.00	19,384.74
	Timber Building	996.45	17,474.47	18.00	18,488.92

Table 13. Energy consumed during operation phase for the reference buildings (50 years).

Cities	Buildings	Energy Consumed During Operation Phase (MJ/m^2)					
		Heating	Cooling	Lighting	Appliance	Water Heating	Total
Harbin	RC Building	20,627.87	5163.77	3258.05	7585.71	2362.24	38,997.64
	Timber Building	17,089.68	5316.28	3258.05	7585.71	2362.24	35,611.97
Beijing	RC Building	10,584.65	7132.90	3258.05	7585.71	2362.24	30,923.55
	Timber Building	7511.78	7363.64	3258.05	7585.71	2362.24	28,081.42
Shanghai	RC Building	4452.49	7448.11	3258.05	7585.71	2362.24	25,106.60
	Timber Building	3332.19	7533.78	3258.05	7585.71	2362.24	24,071.97
Guangzhou	RC Building	0.00	9182.92	3258.05	7585.71	2362.24	22,388.93
	Timber Building	0.00	9247.53	3258.05	7585.71	2362.24	22,453.54
Kunming	RC Building	410.06	3555.90	3258.05	7585.71	2362.24	17,171.96
	Timber Building	253.06	4015.40	3258.05	7585.71	2362.24	17,474.47

Figure 10. Estimated life cycle energy assessment (LCEA) results for the reference buildings (50 years).

Table 14, Table 15 and Figure 11 present the estimated results of LCCA and operation phase for RC and timber stadiums in the five cities under study, which are located in different climate zones. Similar to the LCEA, building CO_2 emissions are higher in "severely cold" and "cold" regions than in other regions. The carbon emission values of RC stadiums during the operation stage range from 156.88 kg/m^2 in Harbin to 63.20 kg/m^2 in Kunming per annum. In contrast, the carbon emissions of timber stadiums during the operation stage range from 156.50 kg/m^2 in Harbin to 64.60 kg/m^2 in Kunming per annum. The calculation results also echo the outcomes of the existing scientific research. Jiang and Tovey revealed that a commercial building in Beijing and Shanghai emitted 178 kg CO_2/m^2 and 119 kg CO_2/m^2 per annum [61]. Jing et al evaluated 30 office buildings in Hongkong, and pointed out that the office building emitted 190 kg CO_2/m^2 per annum on average [62]. Garg et al calculated the carbon emissions of 197 commercial buildings in Gujarat, India. The results showed that carbon emissions of commercial buildings ranged from 96 kg CO_2/m^2 to 177 kg CO_2/m^2 per annum [63]. The carbon reduction effects of timber buildings during the operation stage are notable in comparison with those of RC stadiums in "cold," "severely cold," and "hot summer, cold winter" regions. However, in "hot summer, warm winter" regions and "temperate" regions, the carbon reduction effects of timber buildings during the operation stage are less notable.

Table 14. Carbon emissions and uptake of the reference buildings (50 years).

Cities	Buildings	Carbon Emissions (kg/m^2)			Carbon Storage and Uptake (kg/m^2)		
		Construction	Operation	End of Life	Timber	Concrete	Cement
Harbin	RC	1380.38	1380.38	28.50	—	24.34	8.37
	Timber	7844.13	7844.13	5.70	263.70	1.86	8.37
Beijing	RC	482.33	482.33	28.25	—	24.34	8.37
	Timber	7824.81	7824.81	5.65	263.70	1.86	8.37
Shanghai	RC	1333.46	1333.46	19.50	—	24.34	8.37
	Timber	7424.27	7424.27	3.90	263.70	1.86	8.37
Guangzhou	RC	438.54	438.54	16.75	—	24.34	8.37
	Timber	7194.74	7194.74	3.35	263.70	1.86	8.37
Kunming	RC	1104.24	1104.24	16.75	—	24.34	8.37
	Timber	4912.59	4912.59	3.35	263.70	1.86	8.37

Table 15. Carbon emissions during operation phase for the reference buildings (50 years).

Cities	Buildings	Carbon Emissions During Operation Phase (kg/m^2)					
		Heating	Cooling	Lighting	Appliance	Water Heating	Total
Harbin	RC Building	2027.03	1635.19	1031.72	2402.14	748.04	7844.13
	Timber Building	1679.35	1683.49	1031.72	2402.14	748.04	7544.74
Beijing	RC Building	1040.12	2238.94	1022.67	2381.07	741.48	7424.27
	Timber Building	738.16	2311.36	1022.67	2381.07	741.48	7194.74
Shanghai	RC Building	437.53	1613.76	705.91	1643.57	511.82	4912.59
	Timber Building	327.44	1632.32	705.91	1643.57	511.82	4821.06
Guangzhou	RC Building	0.00	1709.04	606.36	1411.79	439.64	4166.83
	Timber Building	0.00	1721.07	606.36	1411.79	439.64	4178.85
Kunming	RC Building	40.30	661.79	606.36	1411.79	439.64	3159.87
	Timber Building	24.87	747.31	606.35	1411.79	439.64	3229.95

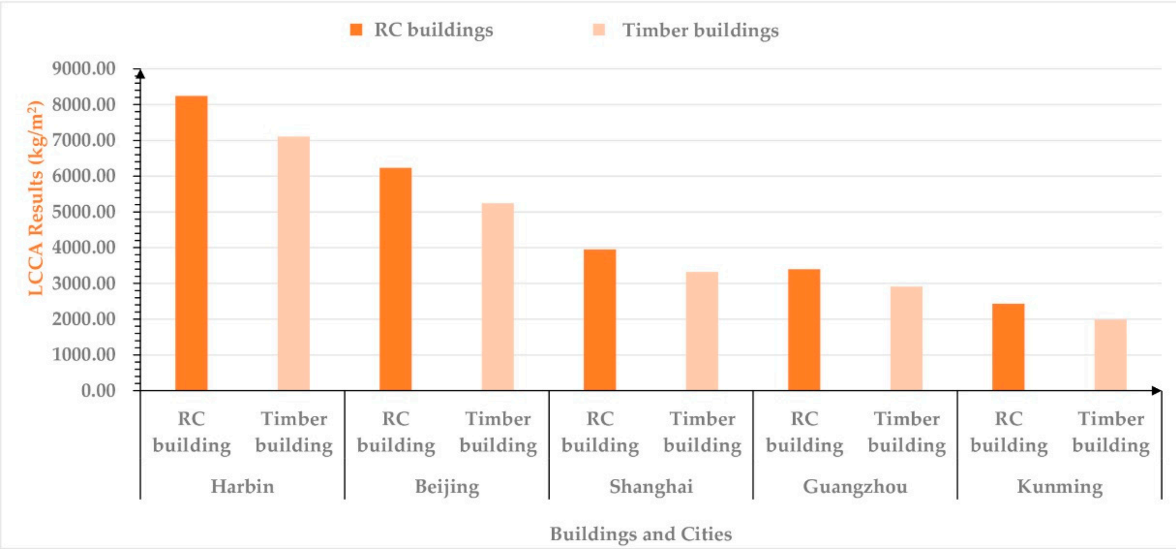


Figure 11. Estimated life cycle carbon assessment (LCCA) results for the reference buildings (50 years).

5. Discussion

5.1. Energy Consumption and Carbon Emissions in Different Climatic Regions

The simulation results demonstrate that timber is a more sustainable building material than RC in all climate regions. As shown in Table 16, the energy saving and carbon reduction potential is greatest in "cold" regions, followed by "severely cold," "hot summer, cold winter," "hot summer, warm winter" and "temperate" regions. However, as a building material, timber lacks effectiveness in regions without considerable space heating in the winter. Although CLT as a sustainable material can be developed nationwide in China, it would be best to develop it in "severely cold" and "cold" regions first due to limitations on timber production. Thus, policy makers are advised to promote the construction of timber public buildings in northern China as an effective way to reduce energy consumption and carbon emissions.

Table 16. Energy saving and carbon reduction potential of timber and RC buildings.

Cities	Energy Saving Potential		Carbon Reduction Potential	
	LCEA	Operation Phase	LCCA	Operation Phase
Harbin	11.05%	8.68%	15.85%	3.82%
Beijing	12.14%	9.19%	15.86%	3.09%
Shanghai	8.15%	4.12%	18.88%	1.86%
Guangzhou	4.61%	–0.29%	19.22%	–0.29%
Kunming	4.62%	–1.76%	22.47%	–2.22%

5.2. Stadium Operation Mode

The results indicate that energy consumption and carbon emissions during the operation phase are dominant throughout the building lifespan. The operation mode of public buildings has a significant influence on their energy consumption and carbon emissions. Stadiums operate for eight hours per day, three days a week. Taking the stadiums in Harbin as an example, energy consumption and carbon emissions seem to vary with the operational time (Figure 12). Although the total operation time remains the same, the current operation mode may result in energy savings of 3.90% and 5.55%, respectively, in comparison with the operational mode of four days a week and six days a week for concrete. Thus, the reasonable arrangement of operation time offers an effective way to reduce the energy of a stadium.

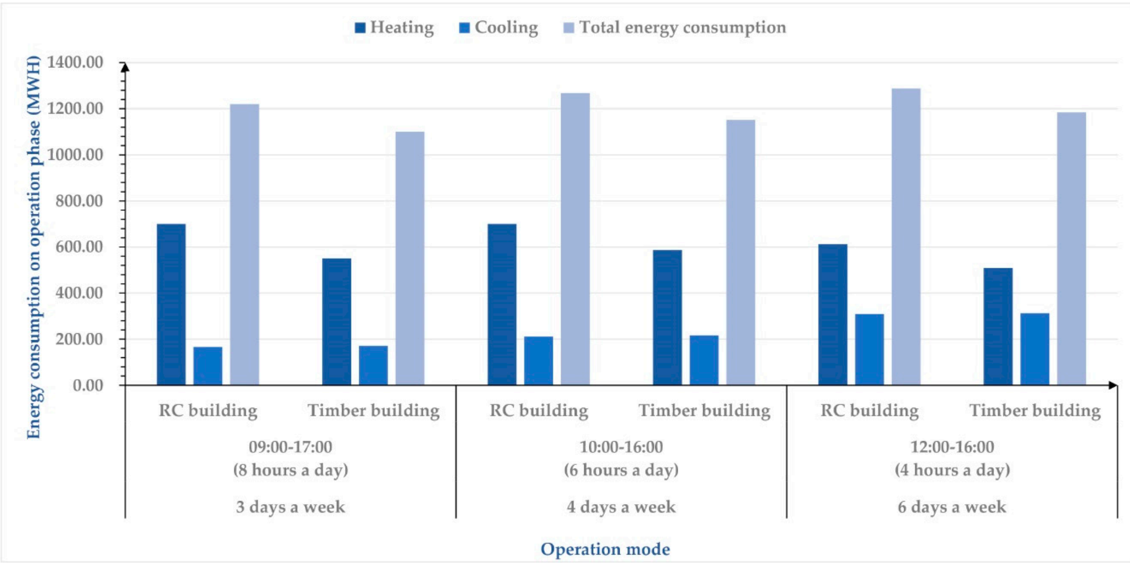


Figure 12. Energy consumption by operation mode in Harbin.

5.3. CO_2 Uptake of Concrete and Cement

In this study, the CO_2 uptake of concrete and cement is taken into consideration. The carbonation of cement and RC is one of the causes of corrosion, but it is also an effective way to sequester CO_2. The calculation results indicate that one cubic meter of cement may absorb 497.95 kg of carbon dioxide during the carbonation process, and the equivalent figure for the concrete is 91.93 kg. Meanwhile, one cubic meter of timber may absorb 800 kg CO_2 during its growth [40]. When the amount of cement in the concrete increases, both the carbonation depth and the amount of CO_2 absorbed decrease, primarily due to the decrease in porosity. Although the total CO_2 uptake from concrete and cement is much less than that of timber, due to the limited volume of carbonation, the carbonation process and ability to sequester CO_2 of cement and concrete should not be neglected.

6. Conclusions

This paper compares the energy consumption and carbon emissions of reinforced concrete and timber stadiums in five climate regions of China. The main findings for timber as a sustainable material are summarized below.

(1) The estimated energy consumption and carbon emissions of CLT buildings are much lower than those of RC buildings in all of the studied cities, which indicates that CLT systems have greater potential than RC systems to reduce carbon emissions and energy consumption.
(2) The energy consumption and carbon emissions of both concrete and CLT buildings are closely related to the climate zones. Buildings in "severely cold" and "cold" regions of China, in which heating is responsible for the majority of energy consumption, consume the most energy and release the most carbon, followed by "hot summer, cold winter" regions, "hot summer, warm winter" regions, and "temperate" regions. Therefore, timber is best suited to regions with considerable space heating in the winter. Although CLT as a sustainable material can be developed nationwide in China, it is better to develop it in severely cold and cold regions first due to limitations on timber production.
(3) Different building operation modes have a great impact on energy consumption and carbon emissions. The reasonable arrangement of operation time is an effective way to reduce the energy consumed by stadiums.
(4) Although the total carbon uptake of concrete and cement is much less than that of timber, the carbonation process and ability to sequester CO_2 of cement and concrete should not be neglected.

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