

Impact of climate change on the life cycle greenhouse gas emissions of cross-laminated timber and reinforced concrete buildings in China

Abstract: With the urgency of addressing climate change, cross-laminated timber (CLT) has become a sustainable material to substitute reinforced concrete (RC) in building applications. There is a growing number of studies on the life cycle assessment of CLT buildings worldwide, mainly based on historical weather files. This study integrates climate change on life cycle greenhouse gas emissions (LCGHGE) in CLT and RC buildings in five climate zones, including the product and construction (P&C), operational and End-of-Life (EoL) stages. The CCWorldWeatherGen tool is used to generate future weather data (i.e., the 2020s, 2050s and 2080s) for the A2 emissions scenario. The simulation results show heating demands will decline significantly and cooling demands will rise in all cases. By the 2080s, global warming will result in an average LCGHGE of 33.09% and 38.90% higher than the baseline scenario for RC and CLT buildings, respectively. Strategies to reduce space cooling demand and decarbonize electricity will become increasingly important in the future. The average LCGHGE of CLT buildings is 27.53%, 26.22%, 24.67% and 22.19% lower than those of RC alternatives in the baseline, the 2020s, 2050s and 2080s, respectively. The study demonstrates that the lower greenhouse gas (GHG) emissions and the greater benefits from EoL from CLT buildings outweigh the operational GHG savings benefits from the thermal mass of RC buildings, even when climate impact is taken into account. Therefore, CLT buildings are a feasible way to reduce GHG emissions from buildings in China.

Keywords: Climate change; Greenhouse gas emissions; Cross-laminated timber buildings; Reinforced concrete buildings; Heating; Cooling

1. Introduction

The Paris Agreement reinforced the targets for reducing greenhouse gas (GHG) emissions to limit the global average temperature rise to 1.5 degrees Celsius above preindustrial levels [1]. According to the Emissions Gap Report 2019 by the United Nations Environment Programme, GHG emissions have climbed every year since 2009 [2]. Rapid urbanization and industrialization have resulted in a significant increase in GHG emissions worldwide. The building sector has become a prominent target for environmental impact reduction, as it accounts for 30-40% of the world's energy use and 40-50% of GHG emissions [3].

China has become one of the world's largest energy-consuming and GHG-emitting economies, with overall energy consumption and electricity consumption in China’s building sector expanding dramatically since 2001 [4]. China's building sector accounted for 46.5% of total energy consumption and 51.3% of the country's carbon emissions in 2018 [5]. As the urbanization rate in China is expected to increase to 70% by 2030 [6], urbanization will inevitably lead to a sharp increase in the number of residential buildings and related energy demand and GHG emissions [7]. Therefore, China plays a critical role in reducing building GHG emissions to mitigate climate change.

Recently, attention has shifted to construction materials to reduce the environmental impact of the building sector [8]. Cross-laminated timber (CLT) has become a sustainable alternative to reinforced concrete (RC) and steel in architectural design and building applications [9], due to its excellent structural rigidity, high degree of prefabrication and environmental benefits [10]. With the advent of CLT, several studies from various countries have developed life cycle assessment (LCA) to assess the environmental impact of CLT buildings in recent decades [11-35]. The current research focuses on the comparison of the environmental impact of entire CLT buildings with alternative constructions such as RC, steel, and light wood frames, with most of these studies focusing on cradle-to-grave [11-27] and cradle-to-gate analyses [28-33]. For instance, Pierobon et al. [28] focused on the cradle-to-gate analysis of two hybrid CLT designs with RC buildings, revealing that the CLT design reduced carbon emissions by an average of 26.5% compared with RC buildings in the U.S. For cradle-to-grave studies, Liu et al. [22] conducted a cradle-to-grave LCA on 7-storey RC and CLT buildings in China, revealing that CLT buildings reduced CO_2 emissions by more than 40%. Jayalath et al. [27] developed LCA to evaluate the cradle-to-grave analysis of RC and CLT buildings in three Australian cities. Dodoo et al. [13] calculated the life cycle carbon footprint of conventional and low-energy CLT, beam and column, and light frame module timber buildings in Sweden, indicating that the low-energy CLT building had the lowest carbon emissions. According to a review of LCA for CLT buildings by Younis et al. [36], the use of CLT instead of conventional building materials can lower the carbon footprint by 40%. Studies also stated that mass timber buildings have higher operational energy demands and GHG emissions than concrete buildings owing to the thermal mass effect [37, 38]. The lower production GHG emissions and greater biomass recovery from mass timber buildings offset the additional operational environmental impact compared to RC buildings.

The operational stage often dominates the life cycle impact of conventional buildings [39, 40], mainly due to the energy demand for HVAC systems [41]. Climate change will lead to changes in the annual energy demand of buildings in the future since climate-related parameters affect the thermal performance of buildings [42, 43]. Recently, various scientific studies have been carried out to investigate the impact of climate change on heating and cooling energy demand in buildings in different geographical areas, including Europe [17, 43-47], South America [48], North America [49-53], and Asia [54-58]. The present research mainly focuses on two aspects: 1) creating future weather files for diverse future climate scenarios and locations, and 2) changes in operational energy demand due to climate impact.

For the first part, Guan [59] reviewed the four methods to generate future weather data. The imposed offset method and extrapolating statistic method are modified based on the observed weather data. The global climate model (GCM) and the stochastic weather model are based on physical models calibrated by historically observed weather data. Shen [52] integrated GCM into typical meteorological year weather files, utilizing a morphing methodology to explore the energy demand of buildings in four representative cities in the U.S. Zhai et al. [51] identified four distinct climate models covering 56 model scenarios for seven climate zones in the U.S. to examine the impact of climate change on the energy analysis of campus building stock. Berardi et al. [50] generated future weather files using statistical and dynamic downscaling methods and analyzed the energy demand of 16 building prototypes accordingly.

Regarding the second aspect, Ciancio et al. [46] compared the impact of global warming on energy demand of residential buildings in 19 European cities. Invidiata et al. [48] investigated the climate effects on the heating and cooling energy demand on residential buildings in three Brazilian cities, showing that the annual energy demand rise varied from 19-65% in 2020, 56-112% in 2050, and 112-185% in 2080. Wan et al. [55] analyzed the energy consumption of office buildings in five Chinese climate zones under future climate scenarios, stating that the cooling energy demand increased by 11.4-24.2% while the heating energy demand decreased by 13.8-55.7% among the five cities. Invidiata et al. [17] explored the impact of climate change on energy demand, CO_2 emissions, and life cycle cost of a multi-family social building in Italy. Some studies have paid attention to a variety of climate variables and different building types to study the impact of climate change [43]. Wang et al. [49] examined the climate impacts of three CO_2 emission scenarios for various types of residential and commercial buildings in all seven U.S. climate zones and found that energy consumption in climate zones 1-4 would increase by the 2080s, while energy consumption in climate zones 6-7 would decrease in the United States. Huang et al. [53] studied the variation of climate change impact on building energy consumption for 2 residential and 15 commercial building types at 925 sites in the U.S., reporting a 39% increase in energy consumption in August for high school buildings and a more than 100% increase for warehouse buildings during some parts of the summer. Tettey et al. [45] investigated the energy use of Swedish multi-storey residential buildings under different future climate scenarios, including the Representative Concentration Pathway (RCP) scenarios RCP2.6, RCP4.5 and RCP8.5, and compared them with the reference climate of Växjö 2013. Previous studies on the impact of climate change on buildings have mainly focused on the operational heating and cooling energy demand. Manufacturing, construction, and recycling are becoming increasingly important as buildings around the world become more energy-efficient [40, 60]. A comprehensive analysis of the impact of climate change on buildings needs to include the various building life cycle activities.

With the advent of CLT and the urgency of limiting GHG emissions to mitigate global warming, research on the LCA of CLT buildings and the impact of climate change on energy consumption is increasing every year. Studies conducted on the LCA of CLT buildings are often based on historical weather files, which only represent past weather conditions, not present or future weather conditions [57]. CLT buildings have advantages in the product and construction (P&C) and End-of-Life (EoL) stages but disadvantages over RC buildings in the operational stage. The operational environmental impact dominates the life cycle impacts, strongly influenced by long-term changes in outdoor climatic conditions. Therefore, it is necessary to integrate climate change into the LCA of CLT buildings.

First, the study aims to explore the impact of climate change on the life cycle greenhouse gas emissions (LCGHGE) of CLT buildings compared to RC buildings and to examine whether climate impact will make the additional operational GHG emissions of CLT buildings surpass the GHG savings in the P&C and EoL stages. Second, this research evaluates the LCGHGE of buildings in five climate zones for four scenarios (i.e., baseline, the 2020s, 2050s and 2080s) in China to systematically explore whether CLT buildings will be a practical way to fight climate change in China. The results of this study can provide useful information for decision-making on CLT buildings in China.

2. Materials

2.1. Case study description

An existing 11-storey residential RC building was selected and simplified as the prototype of this study. The building is constructed of an RC framed structure, RC slabs, and infill walls, whereas CLT buildings replace the concrete with CLT boards (Fig. 1). The RC and CLT buildings have the same functions, layout, height, and size as the RC buildings.

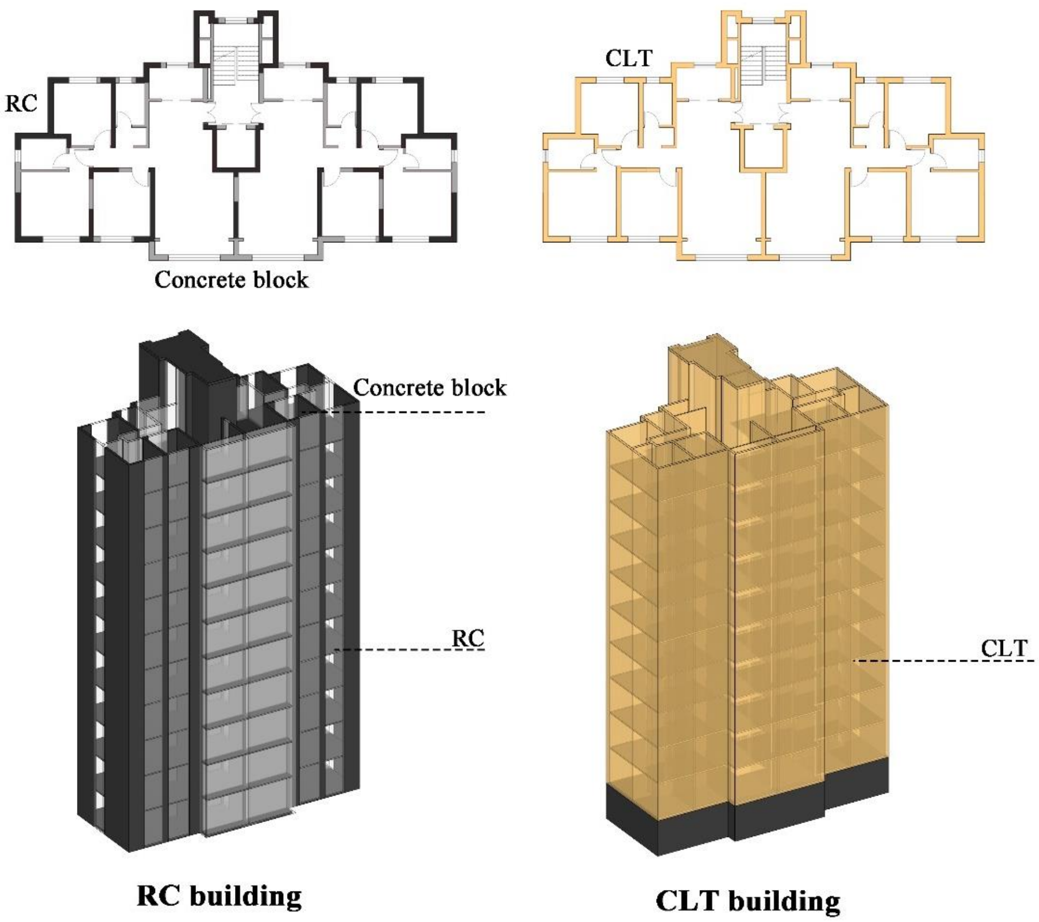

Fig. 1. 3D model and floor plan of 11-storey RC and CLT buildings

As the third-largest country in the world, China has a varied geography, ranging from mountainous areas to flat plains, leading to many different regions with distinct climatic features [56]. According to the thermal design of buildings established based on meteorological data between 1951 and 1980 [54, 61], the most generally used climate is categorized into five categories. Five major metropolitan cities in five climate zones (Fig. 2) across China were selected: Harbin in the severe cold region; Beijing in the cold region; Shanghai in the hot summer and cold winter region; Guangzhou in the hot summer and warm winter region; and Kunming in the mild region, with latitude spanning 22° 26′−46° 40′ N and longitude 102° 10′−130° 10' E.

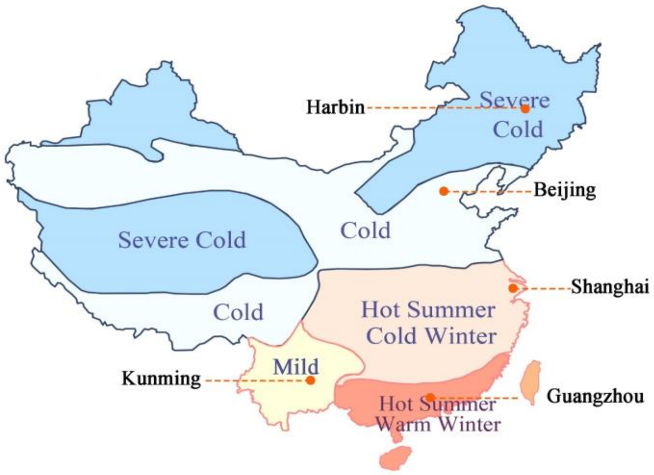

Fig. 2. Overall view of the five climates and geographical distribution of five cities [62]

The details of CLT buildings are based on dataholz.eu, an engineered wood products database [63]. The redesign of the buildings in five cities referred to the requirements for national design standards for the energy efficiency of residential buildings in five climate zones [64-67]. The insulation thicknesses of the RC and CLT buildings were set to meet the same U-value for the envelope in the same climate zone (Table 1), thereby making the CLT and RC buildings functionally equivalent.

Table 1
Thermal characteristics of RC and CLT building components in five cities in China

Buildings	**Climate zones**	**Cities**	**Wall (W/m² K)**	**Floor (W/m² K)**	**Roof (W/m² K)**	**Windows (W/m² K)**
RC/CLT	Severe cold	Harbin	0.289	0.505	0.138	1.600
	Cold	Beijing	0.396	0.505	0.287	2.000
	Hot summer and cold winter	Shanghai	0.526	0.702	0.350	2.200
	Hot summer and warm winter	Guangzhou	0.526	0.702	0.393	4.000
	Mild	Kunming	0.526	0.702	0.770	3.200

2.2. Climate data and scenarios

The original climate data files for the five cities were obtained from EnergyPlus. The future climate data was developed based on an Excel-based tool: Climate Change World Weather File Generator

(CCWorldWeatherGen) [68], which employed the weather data morphing method to transform the original EnergyPlus weather files into climate change weather files [69, 70]. The tool is based on the Hadley Centre Coupled Model 3 (HadCM3) general circulation model (GCM), and the weather parameters in HadCM3 files include outdoor temperature, total incident solar radiation, total downward surface shortwave flux, etc. [46]. Jentsch et al. [69] reviewed 6 GCMs in the third assessment and 23 GCMs in the fourth assessment report of the IPCC, focusing on the available data for the B1, B2, A2, and A1FI emission scenarios. It was found that the HadCM3 A2 model was the most suitable GCM for applying the morphing approach. Additionally, the special report on emissions scenarios stated that the A2 emissions scenario was one of the "marker" scenarios [71], which represented a "business as usual" case where economic development was largely regionally oriented and the global population was continuously increasing. Therefore, it is considered a possible future development path and is chosen for this study.

In this research, to generate the future weather file for each of the five cities, the EPW weather files from EnergyPlus were uploaded to CCWorldWeatherGen. Then the HadCM A2 emissions scenario was selected to generate for the three time slices: the 2020s, 2050s and 2080s, based on the present meteorological data. The future weather files would be used for the simulation of heating and cooling energy demand for RC and CLT buildings in five cities.

3. Method

This study employed a process-based method to evaluate the LCA of CLT and RC buildings, complying with the guidelines of EN 15978 and ISO 14044 [72, 73]. The system boundary includes the product and construction (P&C), operational and End-of-Life (EoL) stages (Fig. 3). The functional unit of this study is 1 m^2 of total floor area for 50 years.

Product and construction stage					Use stage							End-of-Life stage				Benefits and loads
Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
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Fig. 3. LCA modules for whole building analysis from cradle-to-grave according to EN 15978 [73]

The P&C stage comprises the product stage (A1-A3) and the construction stage (A4-A5). The RC and CLT buildings are modeled in Revit, and the bill of quantities is exported from Revit. The life cycle inventory (LCI) data for building materials was retrieved from the Chinese Life Cycle Database (CLCD) [74] and other general databases such as Ecoinvent and ÖKOBAUDAT [75, 76]. CLT was imported from Quebec, Canada, since mass timber in China is in its infancy. The LCI data for the CLT was based on the Athena Sustainable Materials Institute [77].

The construction stage consists of transportation and on-site erection. The transportation distance of common building materials, such as concrete, was set at 40 km, while that of other building materials was 500 km, according to the Standard for Building Carbon Emission Calculation in China [78]. The CLT was assumed to be transported 65 km by truck from the manufacturer to the Port of Cap-Chat according to Google Maps, and 21131 km by sea based on the software NETPAS DISTANCE from the Port of Cap-Chat to the Port of Shanghai. Then, the CLT was transported to five cities using diesel trucks. The GHG emissions related to the on-site erection were calculated based on various construction equipment and machinery used. The A5 module of RC was based on the machines used in the real building construction process, while the A5 module of CLT buildings was identified based on the assumption that CLT buildings took 30% less construction time than RC buildings, according to a study by Jayalath et al. [27].

The operational stage begins with the completion of construction and ends at the deconstruction stage. The heating and cooling energy demands over a 50-year life span were considered in this study since they are highly related to the thermal performance of the envelope and the climate conditions. Space heating was provided by natural gas-fired boiler plants in the severe cold and cold regions (Harbin and Beijing), with an overall efficiency of 85% based on the study conducted by Wan et al. [55]. The emissions factor for natural gas was derived (0.25 kg CO_2-eq/kWh) from Ecoinvent, which is similar to previous studies (0.18-0.19 kg CO_2-eq/kWh) [44, 79]. In other climate zones, heating was powered by electricity. The GHG emission factors for the grid of different cities were obtained from the CLCD database. The energy demand was obtained from the simulation software DesignBuilder under different climate files (i.e., baseline, the 2020s, 2050s and 2080s). The key parameter settings for DesignBuilder are shown in Table 2.

Table 2

Key parameter settings of the buildings

Parameter	Value
Building area	2347.5 m^2
Life span of the buildings	50 years
Infiltration rate	0.3 (l/s m2@ 50 Pa)
Heat recovery efficiency	70%
Natural ventilation	5 ac/h
Heating set point	18 °C (kitchen 15 °C)
Cooling set point	26 °C (kitchen 30 °C)
Seasonal coefficient of performance (CoP)	4.5
Heating and cooling areas	Living room, kitchen, bedroom, toilet

For the EoL scenario, the demolition phase remains a procedure that has not yet occurred and can only be estimated based on assumptions. Demolition GHG emissions are estimated based on the mass of each material to be demolished and the energy per unit mass of energy consumed [80]. The energy used for demolishing RC, concrete, cement mortar and gypsum plaster was 0.0612, 0.0437, 0.0437 and 0.0359 MJ/kg, respectively [81]. The values of CLT, particle board and concrete blocks are assumed to be the same as those of gypsum board. The materials were transported to a recycling site or landfill within 15 km by diesel trucks.

The recyclable materials comprise concrete, steel, and wood products [80], with a mass loss of 10% [15, 19]. Steel scrap is considered for smelting and reformation for new steel production. Concrete is often considered downcycled [82], which is frequently crushed into aggregates to substitute natural gravel in concrete manufacturing or to fulfill other purposes, such as road construction [12, 83]. The concrete is recycled, with 71% for subsequent material and 29% for landfilling [80]. Carbonation of crushed concrete has also been studied, assuming that it is crushed to increase the surface area for CO_2 absorption and exposed to the environment for 4 months to enhance carbonation [84]. The uptake of CO_2 was modeled using the approach proposed by Pade et al. [85].

Various methods are available for the EoL of mass timber, including reuse as lumber, reprocessing into particleboard, incineration for biomass recovery, landfilling and landfill gases [82, 86-90]. Santos et al. [91] suggested that incineration with energy recovery was the best option at present, as wood degradation in landfills remained uncertain. Therefore, the wood was assumed to be entirely incinerated to replace fossil fuel with recovered biofuel in the baseline scenario. Younis et al. [36] claimed that reusing CLT was shown to be the most environmentally friendly alternative. It promotes a circular model that supports a cradle-to-cradle analysis approach and extends the life span of wood materials, resulting in a lower climate effect when the timing of emissions and biogenic forest carbon are considered [28]. In such a future scenario, the optimization of the reuse of wood material will gain additional value before it is incinerated for biomass recovery [88]. Therefore, the EoL scenario of mass timber will be 75% incineration and 25% reuse in the 2020s, 50% incineration and reuse in the 2050s, and 25% incineration and 75% reuse in the 2080s. The avoided GHG emissions of incinerating wood products to replace fossil fuels with recovered biofuel were based on the approach proposed by Sathre et al. [92]. In terms of reusing CLT, the recovered wood is used for construction, with the forest being harvested at year 0 and used as biofuel [93].

4. Results and discussion

This section analyzes the impact of climate change on GHG emissions in CLT and RC buildings in five climate zones and compares the P&C, operational, and EoL stages of the buildings.

4.1. Product and construction stage

A breakdown of the GHG emissions related to the P&C stage of the RC and CLT buildings in the five climate zones is provided in Table 3. The P&C stage comprises raw material extraction (A1-A3), transport (A4), and on-site construction (A5). The average embodied GHG emissions of CLT buildings (450.25 kg CO_2-eq/m^2) were an average of 34.86% lower than those of RC alternatives (691.15 kg CO_2-eq/m^2). The tendency is consistent with previous studies [27, 28]. Jayalath et al. [27] showed that average CLT buildings have 50.11% lower embodied GHG emissions than RC buildings in three cities in Australia. Pierobon et al. [28] indicated that an average embodied carbon emissions reduction of 26.5% is shown in CLT buildings compared to the concrete alternative (foundations excluded). The discrepancies lie in multiple elements, including building type, databases, system boundary and impact assessment method [94].

For the product stage, CLT buildings (346.63 kg CO_2-eq/m^2) had 46.98% lower average GHG emissions than RC buildings (653.73 kg CO_2-eq/m^2) in five cities. The GHG emissions of the building materials accounted for an average of 94.59% of the P&C stage in RC buildings throughout the five climate zones, while transportation and on-site construction contributed 2.26% and 3.15%, respectively. The figures for CLT buildings were 76.99%, 19.62% and 3.39%, respectively. The environmental impact of the transportation of CLT buildings is approximately 3-7 times greater than that of RC buildings since CLT is imported from Canada rather than produced locally, resulting in a surge in transportation GHG emissions. The development of locally engineered wood products can lessen the negative environmental impact of transportation in CLT buildings [95].

Table 3

Embodied GHG emissions (kg CO_2-eq/m^2) of CLT and RC buildings in five cities in China

Buildings	Product (A1-A3)	Transport (A4)	Construction (A5)	Embodied GHG emissions (A1-A5)
Harbin RC	658.40	15.69	26.53	700.61
Harbin CLT	360.93	107.84	18.57	487.34
Beijing RC	655.14	15.64	25.48	696.26
Beijing CLT	352.44	83.04	17.84	453.32
Shanghai RC	651.89	15.60	21.45	688.94
Shanghai CLT	342.93	57.93	15.02	415.88
Guangzhou RC	651.80	15.60	17.76	685.16
Guangzhou CLT	338.91	87.43	12.43	438.77
Kunming RC	651.44	15.59	17.76	684.80
Kunming CLT	337.95	105.54	12.43	455.93

Table 4 lists the representative building materials of RC and CLT buildings in Harbin, as the GHG emissions of building materials show minimal differences in the five cities (primarily in the quantity of insulation materials). RC provided the greatest GHG emissions in both buildings, contributing to 77.78% and 63.56% of the environmental impact in RC and CLT buildings, respectively. This is predominant due to the large amount of RC used in the foundation and first floor of CLT buildings. The structural element (CLT) accounted for 7.50% of the overall GHG emissions of CLT building materials. Furthermore, the RC building weighed 40.32% more than the CLT building. RC dominated the quantity of the building materials and contributed 84.54% and 64.67% of the total mass in RC and CLT buildings, respectively, while CLT represented just 16.61% of the entire mass.

Table 4

GHG emissions and quantities of construction materials in RC and CLT buildings in Harbin

Building materials	Quantity RC (kg)	RC GHG emissions (kg CO_2-eq/m^2)	Quantity CLT (kg)	CLT GHG emissions (kg CO_2-eq/m^2)
Elastic bonded fill	0.00	0.00	45.42	8.85
Cement mortar	101.17	13.36	0.00	1.45
Outdoor plaster	22.71	2.60	22.89	2.62
Particle board	8.65	8.03	8.65	8.03
Gypsum board	200.24	35.14	200.49	35.18
Concrete Block	225.18	46.10	83.64	17.12
Reinforced concrete	3386.21	512.08	1545.73	229.40
Concrete 20	21.06	1.26	23.35	1.40
Mineral wool	0.00	0.00	39.67	19.28
EPS insulation	8.79	17.10	0.00	0.00
Waterproof material	0.92	1.87	2.03	4.14
Sound insulation plasterboard	6.91	1.21	6.91	1.21
polyvinyl chloride (PVC)	12.25	14.50	0.00	0.00
Low-e glass	11.17	5.14	11.17	5.14
Wood	0.00	0.00	3.20	0.03
CLT	0.00	0.00	397.09	27.06
Total	4005.25	658.40	2390.23	360.93

Note: The table only shows the material usage of RC and CLT buildings in Harbin because the material usage of RC or CLT buildings in five cities does not differ greatly (primarily in the quantity of insulation materials).

4.2. Operational stage

4.2.1. Climatic data analysis

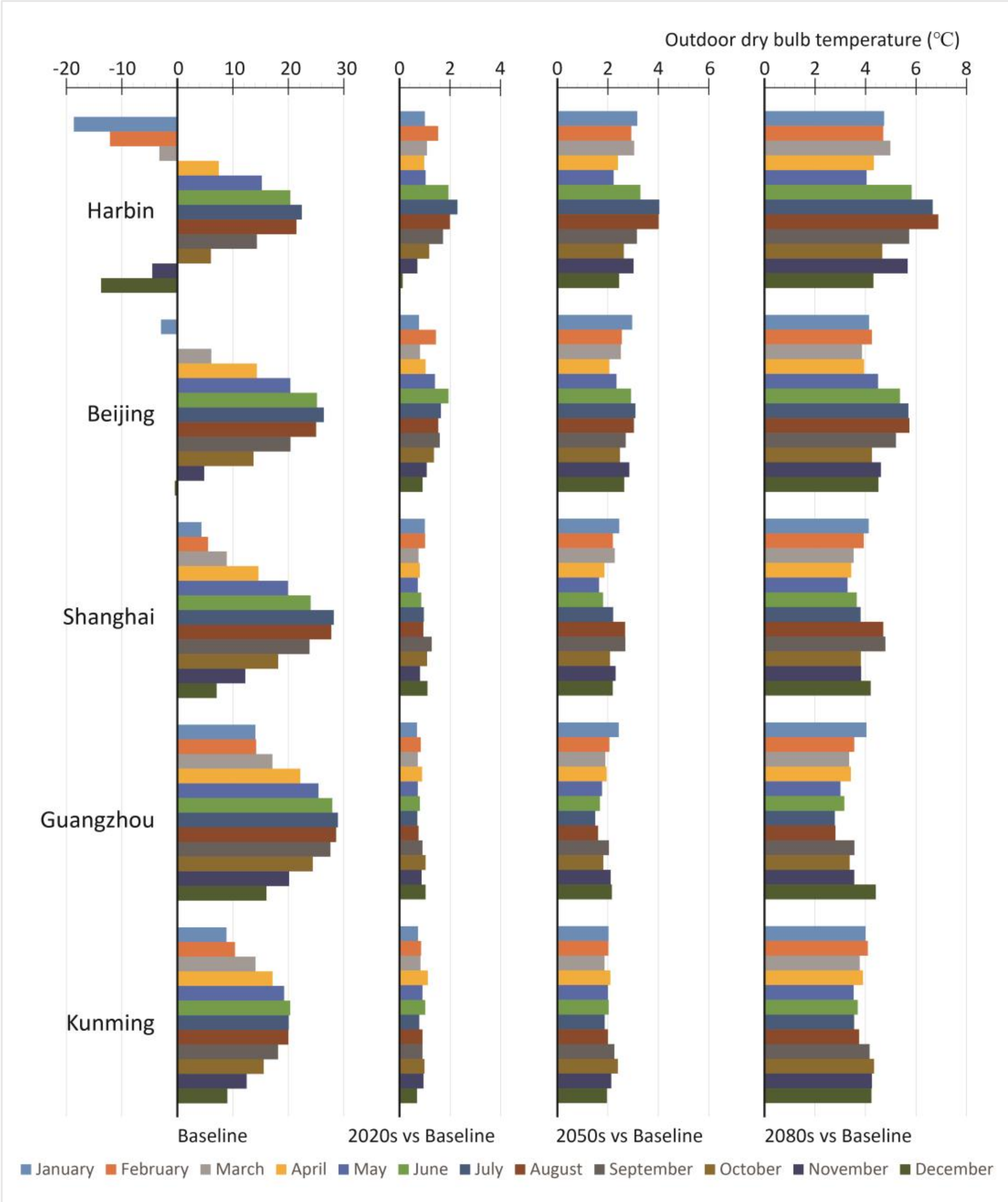

Fig. 4. Monthly mean outdoor air temperature in five cities.

Fig. 4 presents the outdoor dry bulb temperature in five cities and the change in temperature compared to the baseline. There is a clear trend that the outdoor temperature in all five cities will grow in the future. For temperature differences, temperatures in five cities will climb by 0-2 °C in the 2020s, 1-5 °C in the 2050s, and 3-7 °C in the 2080s. Specifically, by the 2080s, the average temperatures in

Harbin, Beijing, Shanghai, Guangzhou, and Kunming will climb by 5.21, 4.67, 3.92, 3.42, and 3.94°C, respectively, above the baseline scenario. The trend is consistent with prior findings [17, 46, 48]. Invidiata et al. [48]. identified that the mean outdoor air temperature would rise by 5.1, 3.6 and 4.6 °C in Belém, Florianópolis and Curitiba in Brazil by 2080, respectively. It can be observed that the temperature increments in Kunming in the future weather data are almost uniform throughout the year. However, in the cities of Harbin, Beijing and Shanghai, temperature increments are highest from June to September in the 2080s, while Guangzhou has the highest value of temperature difference in December and January.

Additionally, to assess the dependability of the weather data, we compared the 2020s data to the real statistics of temperature in the China Statistical Yearbook. The average temperatures in the 2020s are 4.58, 12.74, 16.21, 22.22 and 15.44°C in Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively, which are quite similar to the real average temperatures in the five metropolises (5.39, 13.78, 17.83, 22.68 and 16.47°C, respectively). Therefore, it is assumed that the data for the 2020s, 2050s and 2080s can reflect future climate scenarios to some extent.

4.2.1. Effect of climate change on energy demand and GHG emissions

Fig. 5 shows the annual operational energy demand of the RC and CLT buildings in five cities based on different climate data. The heating demand will decline and the cooling demand will increase in all cases owing to global warming. The tendency is consistent with previous studies [17, 45-58]. For instance, Berardi et al. [50] studied the impact of climate change on energy demand in 16 ASHRAE prototype building models in Toronto and reported a 27% reduction in heating demand and a 44% increase in cooling demand for future high-rise apartments. Invidiata et al. [17] showed that cooling energy demand would increase by 53% and heating energy demand would decrease by 49% in 2080 compared to 2017. The differences in variability are closely related to location, future climate scenarios, building type and the thermal performance of the envelope.

It is worth noting that there will be a net total energy demand reduction in Harbin and Beijing in future years, while the net total energy loads will increase in three other cities. Although a decreased energy demand is observed in Harbin and Beijing, GHG emissions from the operational stage will rise in all 5 cities under future climate conditions. The increasing trend is consistent with the study conducted by Wan et al. [55], in which it was predicted that carbon emissions would rise for five cities in China, ranging from 0.5% in Harbin to 4.3% in Hong Kong. However, the study assumed the same carbon emission factors for electricity in different cities, which would lead to inaccurate results as the emission factors for electricity vary significantly from city to city [50].

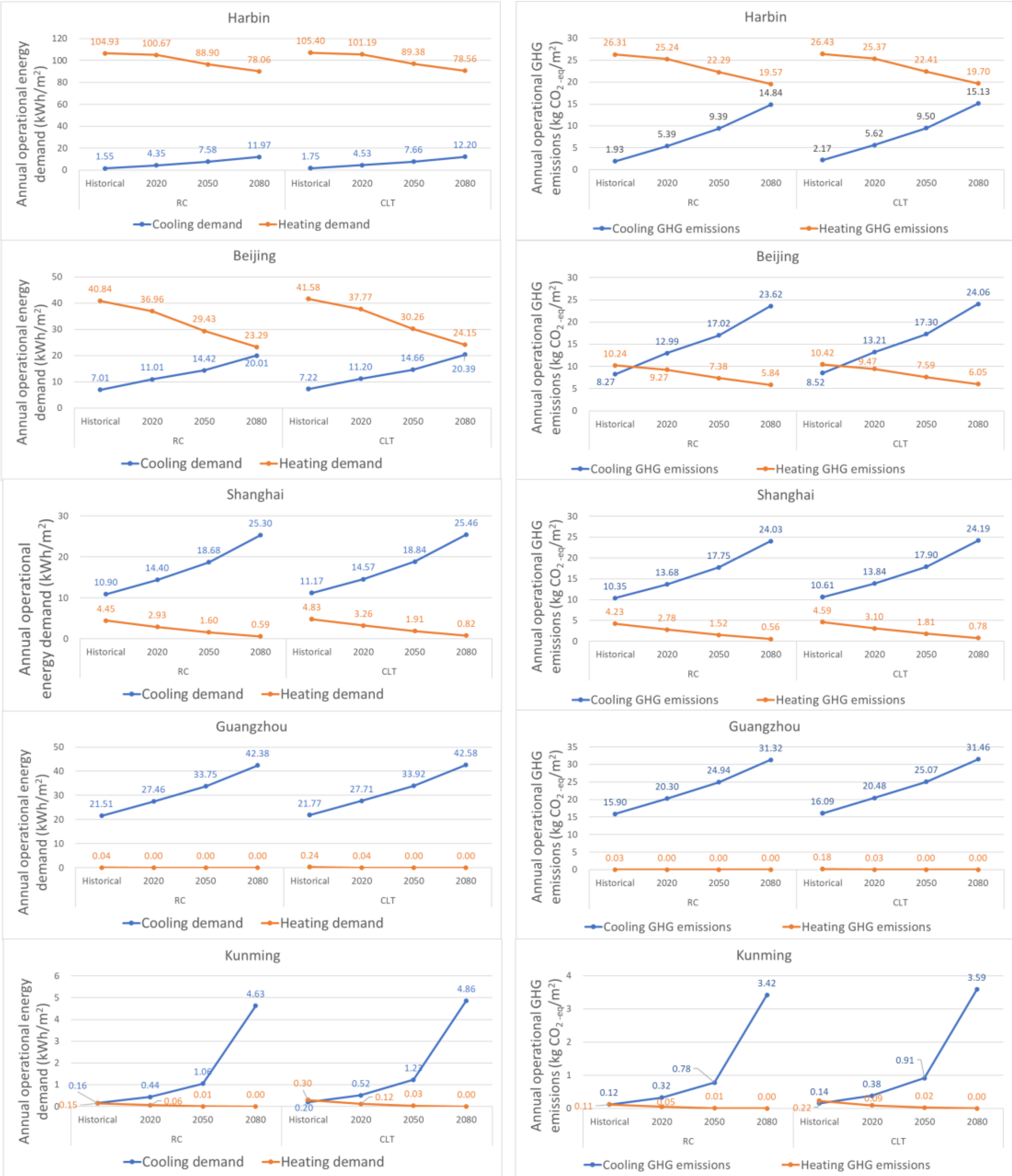

Fig. 5. Annual operational energy demand and GHG emissions of CLT and RC buildings in five cities

The operational energy demand of the CLT building is somewhat greater than that of the RC building in all cases. In the baseline scenario, CLT buildings have an average of 0.58 kWh/m^2/year higher energy demand than RC buildings in five cities, which aligns with previous work [37, 38]. Dodoo et al. [37] verified that the energy consumption of timber buildings is 0.3-0.7 kWh/m^2/year higher than that of RC buildings. Conventional materials such as concrete have the advantage over low thermal mass timber products. In the 2080s, the operational energy demand of CLT buildings will be 0.56 kWh/m^2/year greater than that of RC alternatives. As for the impact of thermal mass on GHG emissions, the operational GHG emissions of CLT buildings are on average 0.38 and 0.35 kg CO_2-eq/m^2/year higher than those of RC buildings in the baseline and 2080s, respectively. Climate change has been demonstrated to have little effect on the thermal mass effect, and CLT buildings will have a slightly higher environmental impact than RC buildings during the operational phase.

In the severe cold climate zone, Harbin has witnessed that the total energy demand will decline from 106.49 kWh/m^2/year in the baseline climate to 90.03 kWh/m^2/year in the 2080s in RC buildings, while the values will decrease from 107.15 kWh/m^2/year to 90.76 kWh/m^2/year in CLT buildings. In a prior analysis by Invidiata et al. [48], the total heating and cooling demand of Brazilian houses would increase by 19-65% in the 2020s, 56-112% in 2050, and 112-185% in 2080. This is mainly because, in the studied Brazilian cities, cooling dominated the energy demand, while heating accounted for less than 5% of the total energy demand. In Harbin, the heating demand decrease will outweigh the increase in cooling in the future scenario. By the end of the century, the cooling energy demand will be approximately 12.20 kWh/m^2/year in CLT buildings, accounting for 13.44% of the total energy, in comparison to 1.63% in the baseline climate. In terms of operational GHG emissions, CLT buildings emit 8.37%, 11.58%, and 21.77% more than the baseline scenario in the 2020s, 2050s, and 2080s, respectively. Space cooling (15.13 kg CO_2-eq/m^2/year) will amount to 43.12% of the total operational GHG emissions (34.82 kg CO_2-eq/m^2/year) in CLT buildings in the 2080s, although it will only account for a small part of the total energy demand (13.44%).

In the cold climate zone, operational heating energy for CLT buildings in the 2080s would show a 41.93% reduction in heating load (-17.43 kWh/m^2/year) and a 182.27% increase in cooling demand (13.17 kWh/m^2/year), for an 8.74% reduction in overall energy demand, compared to the baseline. This trend is similar to the results in the Tettey et al. study [45] for the RCP8.5 scenario, showing that cooling demand would increase by 159%, while heating demand would decrease by 40% in RCP8.5, compared to the reference climate. Climate change will lead to a 58.93% increase in GHG emissions compared to the baseline climate. This is predominant due to the higher carbon intensity for electricity for space cooling than the heating boiler for space heating. The decarbonization of electricity is an important step in mitigating GHG emissions from buildings under climate impact [44]. In the historical climate, GHG emissions from cooling were lower than those from heating, but in the 2020s, 2050s and 2080s, they will exceed the GHG emissions from heating. It is shown that the cooling GHG emissions will dominate the operational environmental impacts in the 2080s, accounting for 79.90% of the operational GHG emissions. Furthermore, although heating energy demand will be higher than cooling energy demand by the end of the century, they will be very close.

Regarding the hot summer and cold winter climate zone, operational energy demand will increase in the future scenario, which is contrary to the trend of decreased energy demand in severe cold and cold climate zones. Compared to the baseline, the operational energy demand of CLT buildings will increase by 64.26% in the 2080s. In addition, the cooling energy demand of CLT buildings will dominate the operational energy consumption, accounting for 69.82% and 96.90% in the baseline and 2080s, respectively. The change in cooling energy is more significant than the change in heating energy in Shanghai. One possible reason is that increased outdoor temperatures will decrease the CoP of cooling equipment. Wang et al. [49] stated that global warming would not only increase the cooling load but also would increase the cooling energy use by decreasing the CoP. For CLT buildings, the annual space cooling energy demand will climb by 14.29 kWh/m^2 from the baseline (11.17 kWh/m^2) to the 2080s (25.46 kWh/m^2). The annual heating energy demand will fall from 4.83 kWh/m^2 to 0.82 kWh/m^2. A similar trend is found in the GHG emissions of space heating and cooling. Heating energy for Shanghai buildings will become insignificant in comparison to cooling energy in the future. This is similar to the results of the Shen [52] study on building energy changes in Phoenix, where climate change made the winter weather hotter with little need for residential building heating. Due to the thermal mass effect, CLT buildings have 4.25%, 2.88%, 2.31%, and 1.50% higher operational energy than RC buildings in the baseline, the 2020s, 2050s, and 2080s, respectively.

In terms of the hot summer and warm winter climate zone, the cooling energy demand will increase in both CLT and RC buildings significantly higher than in other climate zones. The heating energy demand in Guangzhou will be maintained at 0 kWh/m^2 under all scenarios. The annual cooling energy demand for CLT buildings will increase by 5.94, 12.15 and 20.81 kWh/m^2 over the baseline scenario in the 2020s, 2050s and 2080s, respectively. The GHG emissions from CLT buildings are higher than those from RC buildings by 1.18% (baseline), 0.88% (the 2020s), 0.50% (the 2050s), and 0.47% (the 2080s), resulting from the thermal mass effect. The overall energy consumption of CLT buildings in the 2080s will be 42.58 kWh/m^2/year and they will emit 31.46 kg CO_2-eq/m^2/year GHG, slightly lower than the highest GHG emissions of 34.82 kg CO_2-eq/m^2/year (the CLT building in Harbin in the 2080s). Global warming will result in a greater increase in cooling demand in hot summer and warm winter climate zone than in other climate zones, which should be taken into account in future building designs. Buildings equipped with higher levels of insulation, lower infiltration rates and smaller window-to-wall ratios are more isolated from the outdoor environment and therefore less affected by climate change [49]. Buildings in warmer climate cities (Guangzhou) typically have higher envelope U-value than those in the cold and severe cold regions (Harbin and Beijing) [53]. Therefore, buildings in Guangzhou are more susceptible to increased external temperatures and will have a higher space cooling energy demand. The surge in cooling energy demand may be mitigated by increasing airing and solar shading [43].

For the mild climate zone, the trend in heating and cooling energy demand change is the same as in the other climate zones. The buildings in Kunming have the lowest energy demand and GHG emissions, whereas the buildings in Harbin have the highest energy consumption and carbon emissions. The annual energy demand for RC and CLT buildings is 0.31 and 0.50 kWh/m^2 in the baseline scenario, contributing to 0.23 and 0.37 kg CO_2-eq/m^2 each year. The cooling energy demand of the RC and CLT buildings will decline to 0 kWh/m^2/year in the 2050s and 2080s, comparable to the change in Guangzhou. Although the cooling demand in the 2080s indicates a significant increase over the baseline scenario, the figures (4.63-4.86 kWh/m^2/year) are fairly small compared to the energy demand in other climate zones.

To sum up, in regions where heating loads predominate, such as severe cold and cold climate zones, space heating demand will decline significantly in the 21st century. There will be a very small drop in the total operational demand for buildings in these two climate zones (Harbin and Beijing). However, for buildings in Shanghai, Guangzhou and Kunming, the total energy loads are expected to increase. The cooling energy demand is expected to rise tremendously in hot summer and cold winter climate zone as well as in hot summer and warm winter climate zone. The cooling demand will also increase in mild climate zones, but it is still fairly minimal when compared with others. The cold energy demands of Kunming and Guangzhou will be maintained at 0 kWh/m^2 in the 2080s. The energy savings due to thermal mass are small and less related to climate change. Thermal mass effects result in an average increase of 0.35 kWh/m^2/year in cooling demand and a 0.19 kWh/m^2/year heating load increase for CLT buildings compared to RC buildings. In terms of annual operational GHG emissions, the operational environmental impact will increase in all cases in the future scenario, by 6.33 kg CO_2-eq/m^2 in Harbin, 11.17 kg CO_2-eq/m^2 in Beijing, 9.77 kg CO_2-eq/m^2 in Shanghai, 15.20 kg CO_2-eq/m^2 in Guangzhou and 3.22 kg CO_2-eq/m^2 in Kunming from the baseline to the 2080s. The operational GHG emissions in Guangzhou will increase tremendously due to the surge in cooling energy demand in buildings in Guangzhou. Although the total energy demand in Harbin will decrease in the 21st century, buildings will still have the highest operational GHG emissions.

4.3. End-of-Life stage

Fig. 6 presents the GHG emissions at the EoL stage of RC and CLT buildings. In the baseline scenario, CLT buildings (-165.19 kg CO_2-eq/m^2) have on average 83.17% more EoL GHG benefits avoided than the RC alternatives (-90.18 kg CO_2-eq/m^2). This is mainly due to the greater biomass recovery of mass timber, as evidenced by Tettey et al. [14]. In the 2080s, CLT buildings (-201.24 kg CO_2-eq/m^2) will present 118.69% greater EoL GHG benefits than RC alternatives (-92.02 kg CO_2-eq/m^2). For the benefit of recycling steel, the value for RC buildings is -86.67 kg CO_2-eq/m^2, 127.40% higher than that of CLT buildings (-38.11 kg CO_2-eq/m^2), which is due to the large amount of steel used in the structure. In the baseline, concrete recycling accounted for 17.81% and 4.49% of the EoL stage in RC and CLT buildings, respectively.

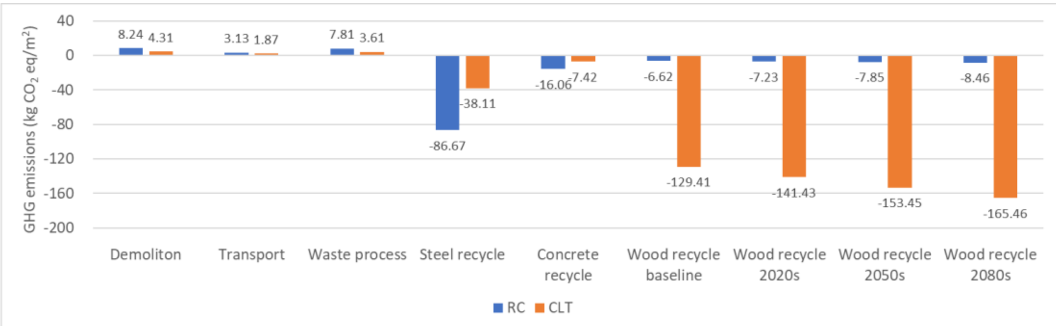

Fig. 6. GHG emissions breakdown at the EoL stage of RC and CLT buildings

The avoided GHG emissions from biomass residues in CLT buildings are -129.41 kg CO_2-eq/m^2, whereas the value for RC buildings is -6.62 kg CO_2-eq/m^2 in the baseline scenario. In such a future scenario, the optimization of the reuse of wood material will gain additional value before it is incinerated for biomass recovery. For example, the avoided GHG emissions from the EoL of wood products will be

165.46 kg CO_2-eq/m^2 for CLT buildings and 8.46 kg CO_2-eq/m^2 for RC buildings in the 2080s. In the 2020s, 2050s, and 2080s, RC buildings will avoid 0.68%, 1.36%, and 2.04% more GHG emissions than the baseline scenario, respectively, while the figures for CLT buildings will be 7.27%, 14.55%, and 21.82%. This is primarily because of the much greater benefit from the reuse of CLT before it is burned for energy recovery. This is consistent with the results obtained by Darby et al. [96], who compared the different EoL scenarios of a CLT building and found that the reuse of mass timber provided a carbon footprint of -1021 tCO_2, while the values for recycling, incineration, incineration with energy recovery and landfill were -999, 126, -502 and -53 tCO_2, respectively. In addition, the design for the disassembly of buildings will facilitate the future reuse of CLT, which will extend the period of time that GHG is stored in mass timber, delaying its contribution to global warming [97].

4.4. Life cycle GHG emissions

Table 5 provides the LCGHGE of the RC and CLT buildings in five climate zones. Positive numbers indicate that GHG emissions are released into the atmosphere, whereas negative numbers imply that GHG emissions are decreased or avoided. The average CLT buildings give 13.21%, 17.24%, 22.16%, 18.67% and 48.02% less LCGHGE than RC buildings in Harbin, Beijing, Shanghai, Guangzhou and Kunming, respectively. The lower GHG emissions in the P&C stage and greater EoL benefits of the CLT buildings offset their additional operational GHG emissions compared to RC alternatives, indicating that CLT buildings generally have lower global warming potential than RC buildings. This is consistent with the findings in references [22, 23, 25, 35]. For instance, Liu et al. [22] found that CLT buildings had a greater than 40% LCGHGE reduction compared to RC buildings in China. In the study, the two buildings were set with the same insulation thickness, making the U-value of the CLT building envelope smaller than that of the RC building. This makes a huge difference in the energy consumption of the two buildings during the operational stage, making the two buildings not functionally equivalent.

The average LCGHGE of CLT buildings is 27.53%, 26.22%, 24.67%, and 22.19% lower than that of RC buildings in the baseline, the 2020s, 2050s and 2080s, respectively. Though climate change will lead to increased GHG emissions in the operational phase, undermining the advantages of CLT buildings in the P&C and EoL phases. CLT buildings still have a lower LCGHGE than RC buildings and will be an effective means of decreasing GHG emissions in the built environment, even if climate change is taken into account.

Table 5

LCGHGE (kg CO_2-eq/m^2) for RC and CLT buildings in five cities for a life span of 50 years.

	Harbin		Beijing		Shanghai		Guangzhou		Kunming	
	RC	CLT	RC	CLT	RC	CLT	RC	CLT	RC	CLT
Product and construction										
Product	658.40	360.93	655.14	352.44	651.89	342.93	651.80	338.91	651.44	337.95
Transport	15.69	107.84	15.64	83.04	15.60	57.93	15.60	87.43	15.59	105.54
On-site construction	26.53	18.57	25.48	17.84	21.45	15.02	17.76	12.43	17.76	12.43
P&C Total	700.61	487.34	696.26	453.32	688.94	415.88	685.16	438.77	684.80	455.93
Operational										
Baseline	1411.78	1429.82	925.52	947.42	729.05	760.00	796.48	813.39	11.60	18.47
The 2020s	1531.79	1549.50	1112.86	1134.23	823.27	846.98	1015.00	1025.15	18.50	23.54
The 2050s	1584.22	1595.41	1219.66	1244.52	963.42	985.66	1247.20	1253.63	39.37	46.81
The 2080s	1720.84	1741.15	1472.71	1505.72	1229.84	1248.34	1565.85	1573.23	170.93	179.47
End-of-Life										
Demolition	8.24	4.31	8.24	4.31	8.24	4.31	8.24	4.31	8.24	4.31
Transport	3.13	1.87	3.13	1.86	3.12	1.83	3.12	1.83	3.12	1.82
Waste process	7.81	3.61	7.81	3.61	7.81	3.61	7.81	3.61	7.81	3.61
Recycle baseline	-109.35	-174.95	-109.35	-174.95	-109.35	-174.95	-109.35	-174.95	-109.35	-174.95
Recycle 2020	-109.97	-186.97	-109.97	-186.97	-109.97	-186.97	-109.97	-186.97	-109.97	-186.97
Recycle 2050	-110.58	-198.98	-110.58	-198.98	-110.58	-198.98	-110.58	-198.98	-110.58	-198.98
Recycle 2080	-111.19	-211.00	-111.19	-211.00	-111.19	-211.00	-111.19	-211.00	-111.19	-211.00
LCGHGE										
Baseline	2022.21	1752.01	1531.60	1235.56	1327.81	1010.67	1391.46	1086.95	606.21	309.19
The 2020s	2141.62	1859.67	1718.32	1410.36	1421.42	1085.64	1609.36	1286.70	612.50	302.24
The 2050s	2174.25	1883.77	1805.35	1498.85	1541.78	1202.56	1821.78	1493.42	613.59	303.76
The 2080s	2329.44	2027.29	2076.95	1757.81	1826.76	1462.96	2158.99	1810.75	763.71	434.14

The RC building in Harbin in the 2080s had the highest GHG emissions (2329.44 kg CO_2-eq/m^2) over a 50-year life cycle, while the CLT building in the baseline in Kunming (309.19 kg CO_2-eq/m^2) had the lowest carbon footprint. This is mainly due to the huge variation in operational energy consumption between the two regions. The buildings in the mild climate zone need less energy for space cooling and heating, whereas the buildings in the severe cold region require a large amount of heating energy. The average LCGHGE of RC buildings in five cities in the 2080s (1831.17 kg CO_2-eq/m^2) will be 33.09% higher than the baseline scenario (1375.86 kg CO_2-eq/m^2), while the average figure for CLT buildings by the end of the century (1498.59 kg CO_2-eq/m^2) will be 38.90% greater than the baseline scenario (1078.88 kg CO_2-eq/m^2).

The operational stage varied greatly in five cities, accounting for 1.91-86.88% of the overall environmental impact. Operational energy use is highly influenced by geographic location, climatic conditions and building efficiency [43, 49, 98]. For the baseline scenario, operational environmental impact dominated the LCGHGE in Harbin, Beijing, Shanghai and Guangzhou, accounting for 54-82% of the carbon footprint. However, operational GHG emissions only contributed to 2-6% of the LCGHGE in Kunming, while the P&C stage dominated the LCGHGE in both RC and CLT buildings. In terms of the 2080 scenario, the proportions of the operational stage climb up to 67-86% for four metropolises (Harbin, Beijing, Shanghai and Guangzhou). This is because global warming increases the cooling energy demand of buildings. For buildings in Kunming, the operational GHG emissions will contribute to 22-42% of the LCGHGE in the 2080s.

For GHG emissions in the baseline scenario, the EoL stage saves 4-15% of the LCGHGE in RC buildings (average 90.18 kg CO_2-eq/m^2). The values for CLT buildings are 9-54% (165.19 kg CO_2-eq/m^2). In the 2080s, the figures will be 3-13% and 9-47% for RC (average 92.02 kg CO_2-eq/m^2) and CLT buildings (average 201.24 kg CO_2-eq/m^2), respectively. The reuse of CLT exhibits greater carbon benefits in the recycling phase and will amplify the benefits of CLT buildings in LCGHGE [36].

5. Conclusion

This paper explored the impact of climate change on the LCGHGE of CLT buildings compared to RC buildings in five climate zones in China since prior studies conducted on the LCAs of CLT buildings are often based on historical weather files, which only represent past weather conditions.

The LCGHGE of the buildings encompasses the environmental impact of the P&C, operational and EoL stages over a 50-year life span. For the embodied GHG emissions in the P&C stage, CLT buildings (450.25 kg CO_2-eq/m^2 reduce GHG emissions by an average of 34.86% compared to RC alternatives (691.15 kg CO_2-eq/m^2). Regarding the operational stage, there is a clear trend that heating energy loads will decline significantly and the cooling energy demand will rise for all buildings in future climate scenarios. It is reported that RC buildings have slightly lower operational energy demand and GHG emissions than CLT alternatives. CLT buildings have an average increase of 0.58 kWh/m^2/year and 0.56 kWh/m^2/year in energy demand compared to RC buildings in the baseline and 2080s, respectively, due to the thermal mass effect. The results show that the energy savings from the thermal mass are small and are less affected by climate change. The overall building energy demand in Harbin and Beijing will decrease slightly in the future, while the overall energy demand in Shanghai, Guangzhou and Kunming is expected to increase. For GHG emissions, it is obvious that operational GHG emissions will rise in all cases in the future. In the 2080s, annual operational GHG emissions in Harbin, Beijing, Shanghai, Guangzhou, and Kunming will be 6.33, 11.17, 9.77, 15.20 and 3.22 kg CO_2-eq/m^2, respectively, higher than the baseline. The heating GHG emissions will still dominate the operational GHG emissions in Harbin, whereas the cooling GHG emissions will become the majority of the operational environmental impact in four other metropolises. For the EoL stage, the research demonstrates that CLT buildings (-165.19 kg CO_2-eq/m^2) benefit much more from the GHG emissions in EoL than the RC alternatives (-90.18 kg CO_2-eq/m^2) in the baseline. However, in the 2080s, the values will be -201.24 and -92.02 kg CO_2-eq/m^2 for CLT and RC buildings, respectively. Therefore, reusing wood will gain additional value before it is incinerated for biomass recovery in the future, strengthening the advantages of CLT buildings.

This study explored how climate change influenced the LCGHGE of functionally equivalent RC and CLT buildings in five climatic zones of China. The average 50-year LCGHGE of CLT buildings was 27.53%, 26.22%, 24.67% and 22.19% lower than those of RC alternatives in the baseline, the 2020s, 2050s and 2080s, respectively. The study demonstrated that the lower GHG emissions and the greater benefits from EoL from CLT buildings outweighed the operational GHG savings benefits from the thermal mass of RC buildings, even considering climate impact. The increase in GHG emissions during the operational phase due to global warming will result in an average LCGHGE of 33.09% and 38.90% higher than the baseline scenario for RC and CLT buildings by the 2080s. CLT buildings reduced LCGHGE by 13.21%, 17.24%, 22.16%, 18.67% and 48.02% on average than RC buildings in Harbin, Beijing, Shanghai, Guangzhou and Kunming, respectively, indicating that CLT buildings are a feasible way to reduce GHG emissions from buildings in China. Global warming has led to an increase in LCGHGE for CLT and RC buildings in all five climate zones. Strategies to reduce space cooling demand and decarbonize electricity will become increasingly important in fighting climate change in the future. Although this study was undertaken for RC and CLT buildings in five climatic zones in China, it is anticipated that the approach may be extended elsewhere, and the findings of the impact analysis reported in this work could serve as a foundation for future research on building responses to climate change.

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