Embodied energy and carbon emissions of building materials in China

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Abstract

Increasing building constructions have become one of the fastest-growing drivers of carbon emissions. Energy conservation and carbon reduction in buildings have become increasingly crucial in the context of global carbon neutrality. This paper assesses the annual total energy and carbon embodied in the ten most intensively used building materials in China, aiming to find potential CO_2 reduction opportunities in the construction industry from a macroscopic perspective. The results show that: (1) the embodied energy and carbon of cement, steel, and brick account for more than 70% of the total embodied energy and carbon of all building materials; (2) the embodied energy and carbon between steel-concrete buildings and brick-concrete buildings are not distinct; (3) disparities in embodied energy and carbon of building materials between different regions are significant. The eastern and south-eastern regions consume excessive building materials and embody significantly higher energy and carbon than other regions. Several strategies are provided for China's building sector in energy and carbon reduction.

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1. Introduction

With rapid economic growth and housing marketization, China's building industry thrived after 1978 [1]. The average living space per capita in urban China has increased from 6.7 m^2 in 1978 to 39 m^2 in 2018 [2]. Since 2013, the annual newly constructed floor space has surpassed 4 billion m^2 [3]. The booming building industry has been identified as a vital driver for China's economic development [4, 5] and also for the increasing demand for building materials [1]. For instance, China consumed 835.0 million tonnes of finished steel products (48.8% of the world's total) in 2018, of which 46.5% can be attributed to the building sector (388 million tonnes) [6].

Along with the processes of manufacturing and transporting building materials, the consumption of energy is essential. The high demand for building materials propels the rise of energy consumption. In 2018, China consumed 3273.5 Mtoe of primary energy, which accounted for 23.6% of the world's total [7]. The steel industry alone accounted for 11% of the total energy consumed in China [8]. Since the majority of energy sources in China are dominated by fossil fuels [9], the energy consumption boosted by increasing building materials will prompt the rapid growth of carbon emissions. If new buildings continue to increase at high speed, the extensive use of building materials will bring enormous carbon emissions and toxic pollutions to the environment [10]. Meanwhile, vast natural resource extractions will lead to a shortage of natural resource supply [10].

To achieve carbon neutrality before 2060, China is under tremendous pressure to reduce carbon emissions [11]. Cutting down carbon emissions in building materials has become a significant path. Efforts focused on reducing energy use and carbon emissions associated with the production of building materials need quantification. Embodied energy (EE) and embodied carbon (EC) of building materials indicate all the energy expended and all carbon emitted in producing final building materials, from the extract of natural resources to manufacturing processes and transport [12]. An extensive number of studies have adopted different methods to evaluate the embodied energy and embodied carbon of a wide range of building materials in different countries. Several studies [13, 14] recommend process analysis systematically examining direct and indirect energy inputted in a process. Lenzen and Dey [15] point out that process analysis suffers from truncation error, namely lacking the involvement of higher order energy. Some other studies [16, 17] suggested input-output analysis to comprehensively include all processes of producing building materials from upstream to downstream. But this method lacks clarity on main process energy, and the result may be unreliable as it may be under or over-estimated [18]. Given the limitations of process analysis and input-output analysis, Treloar, Love [19] suggest a hybrid method, which combines process analysis and input-output analysis to include both direct energy and higher order energy. The hybrid analysis allows the avoidance of both the incompleteness of process analysis and the unreliability of input-output analysis.

Different factors like the system boundary, the assessment method, the energy types, the age of data sources, the manufacturing process, and the geographic location cause discrepancies in values of embodied energy and carbon [12, 14, 20, 21]. A number of studies [22-24] try to compile EE or EC data within a certain boundary. EE and EC datasets allow more studies to be conducted. Several studies compared EE and EC of different building types. Reddy and Jagadish [25] found the energy embodied in soil-cement buildings were 45% lower than brickwork buildings. Lenzen and Treloar [26] concluded that concrete-framed buildings caused higher carbon emissions than wood-framed buildings. However, Nässén, Holmberg [27] found no strong correlation between the EE value and building structures.

Previous literature has provided insightful knowledge and various methods to assess the embodied energy and carbon of buildings. Most studies explored the embodied energy and carbon of specific building materials or a type of buildings, which were from relatively micro perspectives. There is a lack of macro assessment of the total embodied energy and carbon of building materials in China. Besides, although several studies [26, 27] have explored the relationship between embodied energy or carbon and building structures, studies that compared the most common steel-concrete and brick-concrete structures in China are rare. In addition, China is a geographically vast country with a lot of internal differences. Nevertheless, in assessing the embodied energy and embodied carbon of building materials, few studies have addressed the regional disparity and the corresponding strategies to reduce the embodied energy and carbon. By macroscopically assessing the annual total embodied energy and carbon of building materials and concerning two main building structures, this paper attempts to bridge these gaps to identify opportunities and find strategies to reduce the environmental impacts of building materials.

2. Methodology

2.1. Research objects and system boundary

All newly built buildings in China from 2000 to 2018 have been chosen as the research object in this study. The ten most predominant building materials used for fundamental constructions in China are chosen: steel, wood, cement, brick, sand, gravel, lime, glass, linoleum, and asphalt. Although embodied energy and carbon values of building materials vary due to numerous factors like geographic locations, manufacturing technologies, and energy mix [12, 21], the production technology and the fuel used in production and transportation are similar in different regions within China. The same material tends to hold embodied energy and carbon values within a small range. Therefore, the national standards' embodied energy and carbon coefficients of the most commonly used materials are employed to calculate the total embodied energy and carbon of building materials in China.

The energy consumption and carbon emissions that occur in buildings' lifecycle can be classified into five phases, including the extraction of raw materials, the production of materials, on-site assembly and construction, operation, and end-of-life [28]. Between every site, transportation is needed, which also involves considerable carbon emissions [28]. As shown in Fig.1, the computation of embodied energy and carbon of building materials is defined within the boundary of "cradle to site", including the extraction of raw materials, the transportation of raw materials to manufacturing sites, the material manufacture process, and the transportation of materials from manufacturers to construction sites.

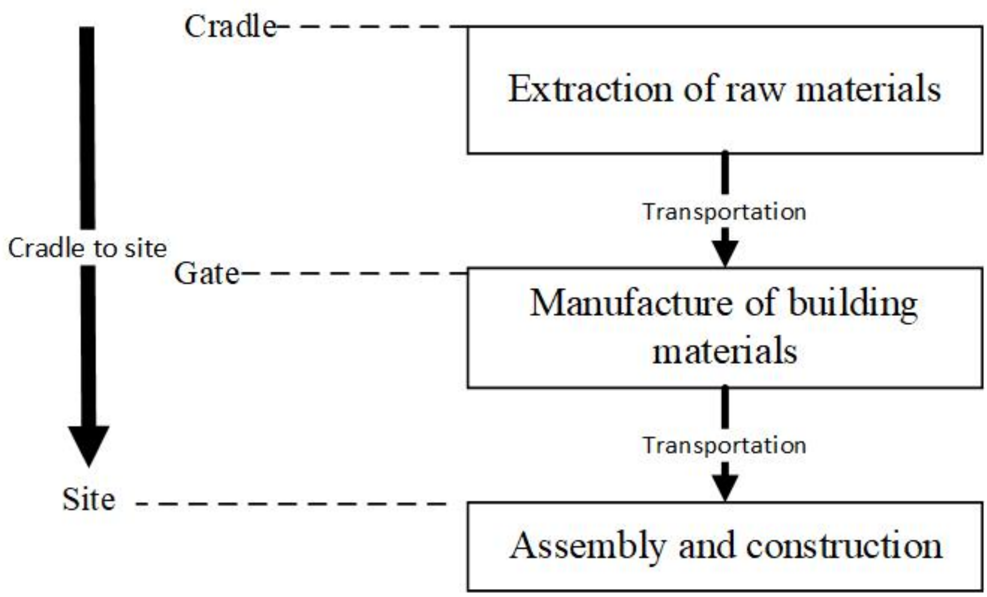


Fig. 1. "Cradle to site" boundary.

2.2. Research framework

Maintaining the feasibility and reliability, a research framework that involves all the research processes is illustrated in Fig. 2. First, buildings are grouped into six types according to their structures and functions. Then, the annual total consumption and the embodied energy and carbon of ten building materials are calculated. Afterwards, the disparities in material consumption and the embodied energy and carbon between two primary building structures and among 31 provinces are compared. In the discussion section, findings are discussed and analysed, and strategies are suggested.

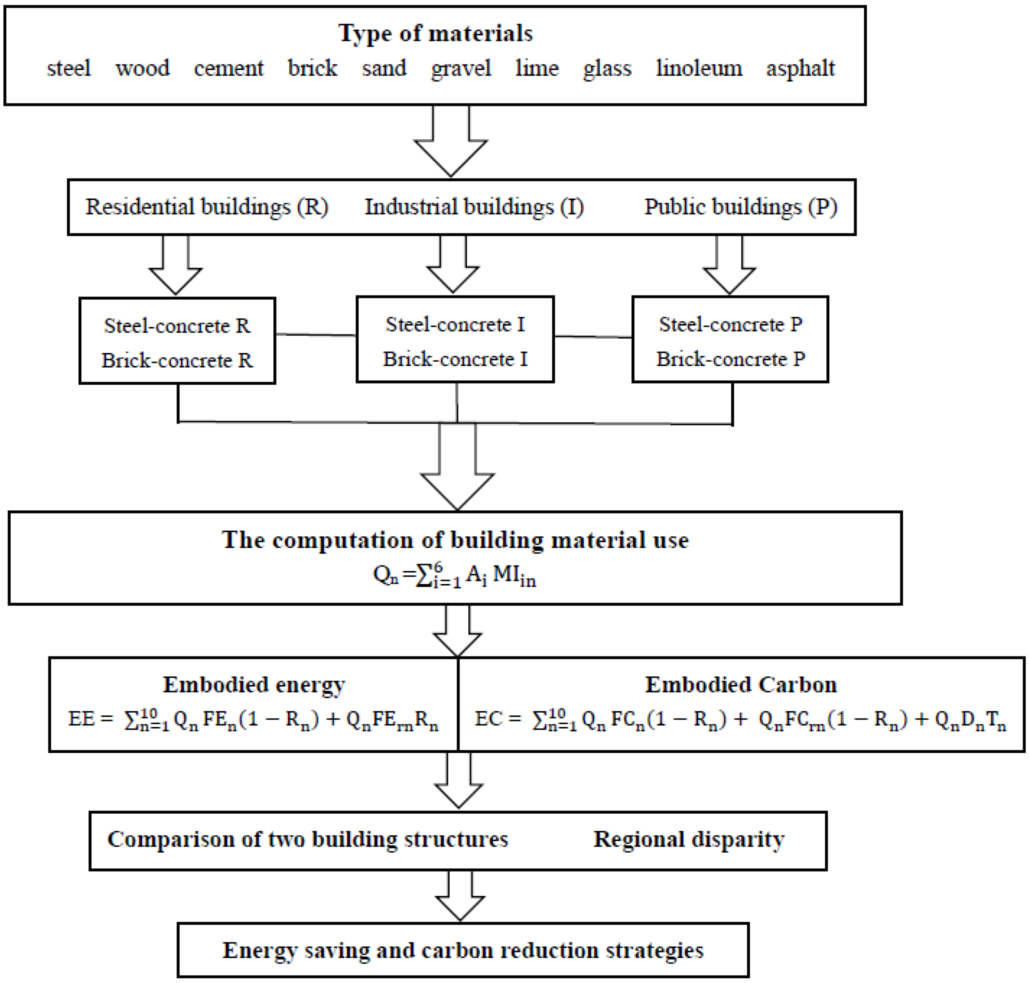


Fig. 2. The research framework.

2.3. Material consumption and embodied energy and carbon calculation

In this study, buildings in China are categorized into six types according to different functions and structures, including steel-concrete residential buildings (S-C R), brick-concrete residential buildings (B-C R), steel-concrete industrial buildings (S-C I), brick-concrete industrial buildings (B-C I), steel-concrete public buildings (S-C P), and brick-concrete public buildings (B-C P). The annual consumption of an individual material in each building type is obtained by multiplying the newly constructed floor area of each building type and the material intensity (MI) of the material in this type. Material intensity denotes the quantity of a certain material used per unit of floor areas [29]. Then by summing up the quantities of the material in six building types, the annual total consumption of each material (Q_n) is obtained, as described in Formula (1):

$$Q_n = \sum_{i=1}^{6} A_i \, MI_{in} \tag{1}$$

Here, n is one of the ten building materials, i is one of the six building types, A_i is the annual newly built floor area of the i^{th} type of buildings, MI_{in} is the material intensity of the n^{th} material in the i^{th} type of buildings.

The embodied energy of a material is obtained by multiplying the quantity of the material and its embodied energy coefficient. Embodied energy coefficient indicates the sum of all the energy consumed from cradle to site in producing and transporting per unit building material. The annual total embodied energy of building materials (EE) is developed by summing up embodied energy of all ten materials, as presented in Formula (2):

$$EE = \sum_{n=1}^{10} Q_n \, FE_n (1 - R_n) + Q_n FE_{rn} R_n \tag{2}$$

Here, n is one of the ten building materials, Q_n represents the consumption of the n^{th} building material, R_n is the proportion of recycled building materials, FE_n is the embodied energy coefficient of the n^{th} completely new building material, and FE_{rn} is the embodied energy coefficient of the n^{th} recycled building material.

The production carbon of a material is obtained by multiplying the quantity of the material and its carbon coefficient. Carbon generated in transporting material is calculated by multiplying the amount of the material, the mean transportation distance, and the carbon coefficient of the transportation mode. Then by summing up the carbon both in the production and transportation process, the embodied carbon of a material is obtained. The whole calculation process is presented in Formula (3):

$$EC = \sum_{n=1}^{10} Q_n\, FC_n(1 - R_n) + Q_n FC_{rn}(1 - R_n) + Q_n D_n T_n \qquad (3)$$

Where n represents one of the ten building materials, Q_n is the quantity of the material, R_n is the proportion of recycled building materials, FC_n is the carbon coefficient of the n^{th} new building material, FC_{rn} is the carbon coefficient of the n^{th} recycled building material, D_n is the mean distance for transporting the n^{th} material, and T_n indicates the transportation carbon coefficient of material n.

2.4. Data collection and assumptions

This study collects the annual newly constructed floor areas of residential buildings, industrial buildings, and public buildings from the China Statistical Yearbook on Construction from the National Bureau of Statistics of China (NBSC, 2001-2019). The proportions of steel-concrete and brick-concrete structures are assumed according to a trend chart drawn by Huang, Shi [30], where the ratio of brick-concrete was at around 58% in 2000 and decreased approximately one per cent a year. The descending rate was assumed to be the same in residential, industrial, and public buildings. The building material intensities of the ten materials are selected from the MI database built by Yang, Guo [31]. Though building material intensities vary over time with the changes in construction technologies and construction standards, buildings constructed in the same period tend to have similar material intensities [31]. As targeted years of this study are between 2000 to 2018, material intensities in the group 2000-2015 are chosen.

Most embodied energy coefficients are collected from the Assessment System for Green Building of Beijing Olympic [32]. Under current technology, the range of embodied energy variation of materials like linoleum is small in different countries. Since there is limited data on embodied energy coefficient specific in China, a commonly accepted value within the range of embodied energy coefficient of linoleum is extracted [33]. In general, obtaining a single embodied energy value for material is unpractical since the embodied energy value is affected by a variety of factors, like the fuel type used in manufacturing, the energy efficiency, and the transportation distance [34]. Though embodied energy coefficients adopted in this study are general figures, the importance is to provide an overall guideline and try to identify materials that could have lower embodied energy [34]. When considering the embodied energy of building materials, several recyclable materials also need to be considered. The recycling of these building materials also requires the input of energy and therefore emits carbons. According to GOB [32], the embodied energy of recycled steel is 20% to 50% of the embodied energy of virgin steel, and the proportion of the quantity of recycled steel is around 50%. The energy coefficients of recycled steel are assigned to be 40%, that is, 11.6 GJ/t. Glass and wood can also be partially recycled, but recycled wood and glass generally will not be used in building constructions. Therefore, recycled glass and wood are not taken into account in this study. Gravel and sand can be substituted by crushed waste concrete, and concrete with up to 30% of aggregate replaced by recycled aggregate is acceptable [35]; thereby the proportions of recycled gravel and sand are assumed to be 30%. Since energy is required to crush the waste concrete, the energy use of recycled gravel and sand is 5% higher than virgin materials [36]. The EE coefficients of the ten building materials are presented in Table 1.

Table 1

Parameters for embodied energy calculation.

Building materials	Embodied energy coefficient (GJ/t)	Embodied energy coefficient (Recycled) (GJ/t)	Rate of recycled materials (%)
Steel	29.0	11.6	50%
Wood	1.8		
Cement	5.5		
Brick	2.0		
Sand	0.06	0.063	30%
Gravel	0.08	0.084	30%
Lime	5.3		
Glass	16		
Linoleum	77.2		
Asphalt	3		

The production carbon coefficients and transportation carbon coefficients of the ten materials are acquired from the Building carbon emission calculation standard of China [37]. The rates of recycled materials are the same as in Table 1. The carbon coefficients of recycled materials are assumed to comply with their embodied energy in Table 1. Therefore, the production carbon coefficient of recycled steel is 40% of new steel, and the production carbon coefficients of recycled sand and gravel are 5% higher than new sand and gravel. The mean distance of each material and transportation carbon coefficients are also collected from China's Building carbon emission calculation standard [37]. These materials are assumed to be transported mainly by medium diesel trucks or heavy diesel trucks.

Table 2

Parameters for embodied carbon calculation.

Material type	Carbon coefficient (kg CO_2 /t)	Carbon coefficient (Recycled) (GJ/t)	Rate of recycled materials (%)	Distance (km)	Transportation carbon coefficient (kg CO_2 /t*km)
Steel	2380.00	1190	50%	500	0.057
Wood	200.00			500	0.057
Cement	735.00			500	0.057
Brick	292.00			40	0.179
Sand	2.51	2.59	30%	40	0.057
Gravel	2.18	2.29	30%	40	0.057
Lime	1190.00			500	0.129
Glass	1130.00			500	0.129
Linoleum	7300.00			500	0.179
Asphalt	162.00			500	0.179

3. Results

3.1. Annual building material consumption

The annual total consumptions of building materials are presented in Fig. 3. It shows the annual building material consumption has significantly increased from 1289.6 million tonnes in 2000 to 6357.6 million tonnes in 2018, with an average annual growth rate of 21.8%. Building construction booms in China during these years, and more raw materials were consumed by buildings [1]. The annual total building materials stopped climbing up after 2014, which may ascribe to the issue of the GB50096-2011 Design code for residential buildings by MOHURD [42]. The code restricts that from August 2012, building construction projects need to comply with the new version of the design code. The new code requires building design to improve to meet higher performance in many aspects like safety, health, environment, and energy saving, but no change has been made in the construction technology. Since numerous building projects failed to meet new requirements promptly, the annual newly constructed floor areas stayed flat. However, the annual material consumption attributable to building constructions remains high. A large number of building materials accelerated the depletion of natural resources. According to Torgal and Jalali [38], around half of the raw materials extracted from the earth's surface were turned into building materials. It shows that sand, gravel, brick, and cement respectively accounted for 35%, 24.4%, 19.9%, and 12.3% of the total building material consumption in 2018. These four materials took up about 91.7% of all the building materials consumed in constructing buildings, while the remaining six materials only accounted for 8.3%.

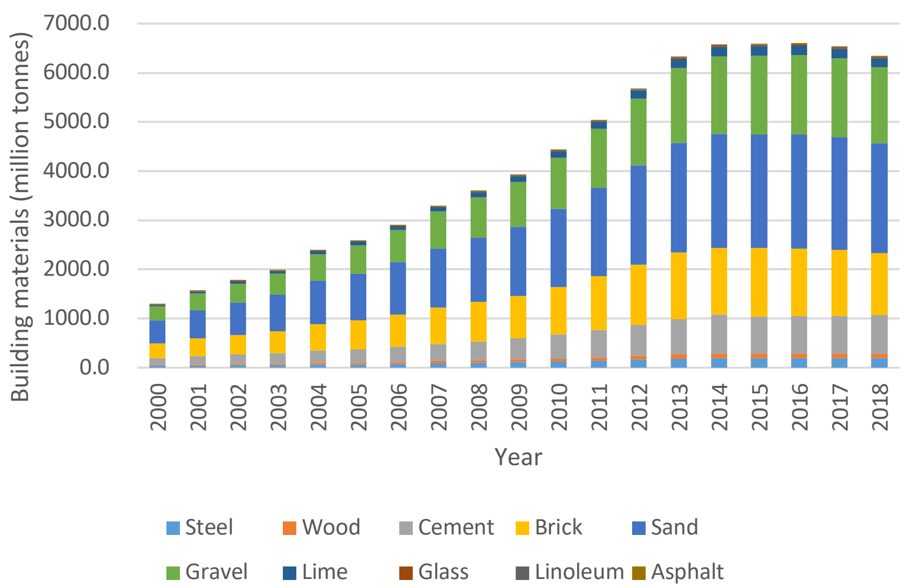


Fig. 3. Annual consumption of building materials.

3.2. Annual embodied energy

The annual embodied energy of building materials is shown in Fig. 4. The total embodied energy was estimated at 13345 million GJ in 2018, approximately 5.2 times as much as the embodied energy in 2000. The trend of embodied energy showed a similar tendency with the annual building material consumption. According to Chen, Liu [1], the fast development of the building construction industry in China propelled the rise of building materials use, thereby consuming increasing energy. Cement, steel, brick, lime, and linoleum respectively accounted for 32.2%, 29.8%, 19.0%, 7.5%, and 4.7% of the total embodied energy in 2018. It is noticeable that steel accounted for a small share in the total building material use but was the second-largest energy consumer. Cement and brick were another two materials that embodied high energy despite their weights being much lower than sand and gravel. In producing sand and gravel productions, energy is consumed in gathering, filtering, crushing, and transporting the materials. There is no energy-intensive hyperthermal smelting process in producing sand and gravel. In contrast, the production of steel, cement, and brick all need the high-temperature forging process, which is energy-intensive and leads to high embodied energy. Similarly, linoleum accounted for the least share of 0.13% of the total building material consumed in 2018, whereas it ranked 5th in energy consumption (about 4.7% of the total embodied energy).

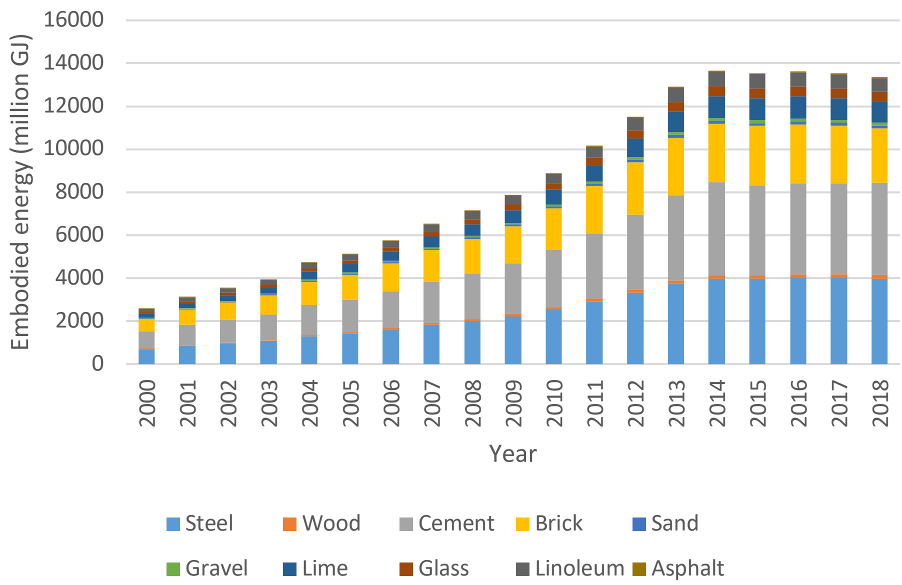


Fig. 4. Annual embodied energy of building materials (2000-2018).

3.3. Embodied carbon emissions

The annual embodied carbon of building materials within the cradle to site boundary is illustrated in Fig. 5. The annual embodied carbon grew from 346.2 million tonnes in 2000 to 1757.5 million tonnes in 2018, which has increased by 407.7% in 19 years. Cement, steel, brick, lime, and linoleum respectively representing 34.0%, 20.2%, 24.7%, 13.4%, and 3.4% of the total embodied energy in 2018. These five building materials constituted more than 95% of the total embodied carbon, while sand, gravel, glass, wood, and asphalt only accounted for less than 5% of the total. Similar to the embodied energy results, the contributions of steel and linoleum to embodied carbon were high though these two materials were among the five least consumed materials. In contrast, sand and gravel shared minor proportions in generating carbon emissions though they were the top two in material consumption. Under the current situation that fossil fuels still dominate in China's energy supply and electricity, the embodied carbon emissions of building materials are highly related to the embodied energy. The high thermal energy needed in manufacturing materials like steel and cement is mainly generated by combusting a large amount of fossil fuel, thereby emitting vast amounts of carbon. Sand and gravel generate much less carbon in production, but the carbon generated in transporting sand or gravel takes up nearly half of the total embodied carbon.

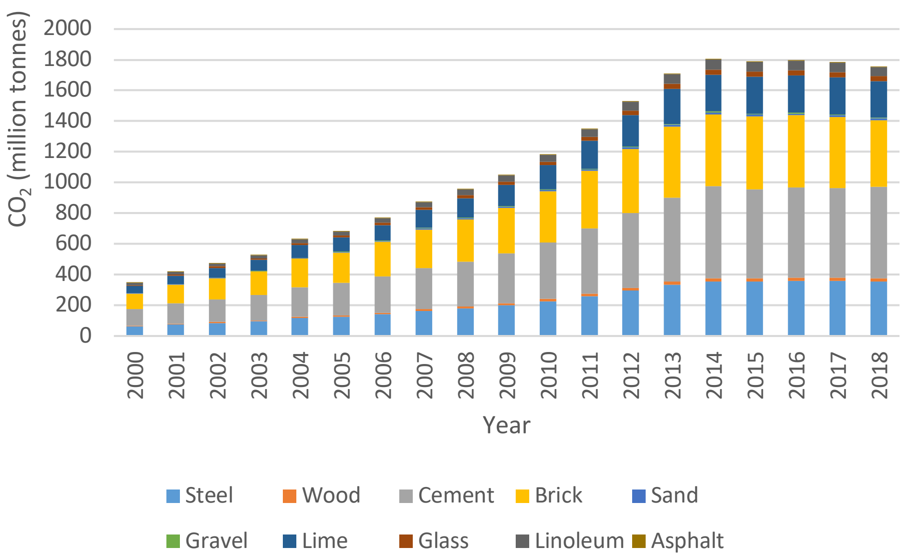


Fig. 5. Annual embodied carbon of building materials (2000-2018).

3.4. The comparison of two building structures

Fig. 6 presents material intensities of two building structures, steel-concrete (S-C) buildings, and brick-concrete (B-C) buildings. In the 1950s, the material intensity of S-C far outweighed B-C in residential buildings and public buildings. With years of improvement, the material intensity of steel-concrete residential buildings declined and was significantly lower than the material intensity of brick-concrete residential buildings since the 1970s. Compared with the 1950s, the material intensity of steel-concrete residential buildings in 2000-2015 has been reduced by around 51% (267.26 to 130.77 t/100 m^2). This may result from the significant reduction of the weight of bricks, which is partly ascribed to the substitution of traditional solid clay bricks to hollow bricks [39]. Solid clay brick is a conventional masonry material that was largely used in the past. In recent years, bricks have been developed from solid to porous or hollow ones. Voids inside hollow bricks can decrease the use of natural resources without reducing the performance. Hollow brick is light in weight, high in strength, and has good performance in heat preservation and sound insulation [39]. Besides, industrial wastes such as coal gangue and fly ash were utilized to produce bricks. New versions of bricks can benefit the environment since they require fewer natural resources like clays and less energy for production and transportation [39]. According to Yang, Kohler [40], the production of clay bricks has been banned by the Chinese government because the extensive use of clay in manufacturing bricks has led to a severe loss of arable land. With regard to the brick-concrete structure, the material intensity fluctuated, and the material saving was not significant over the past few decades.

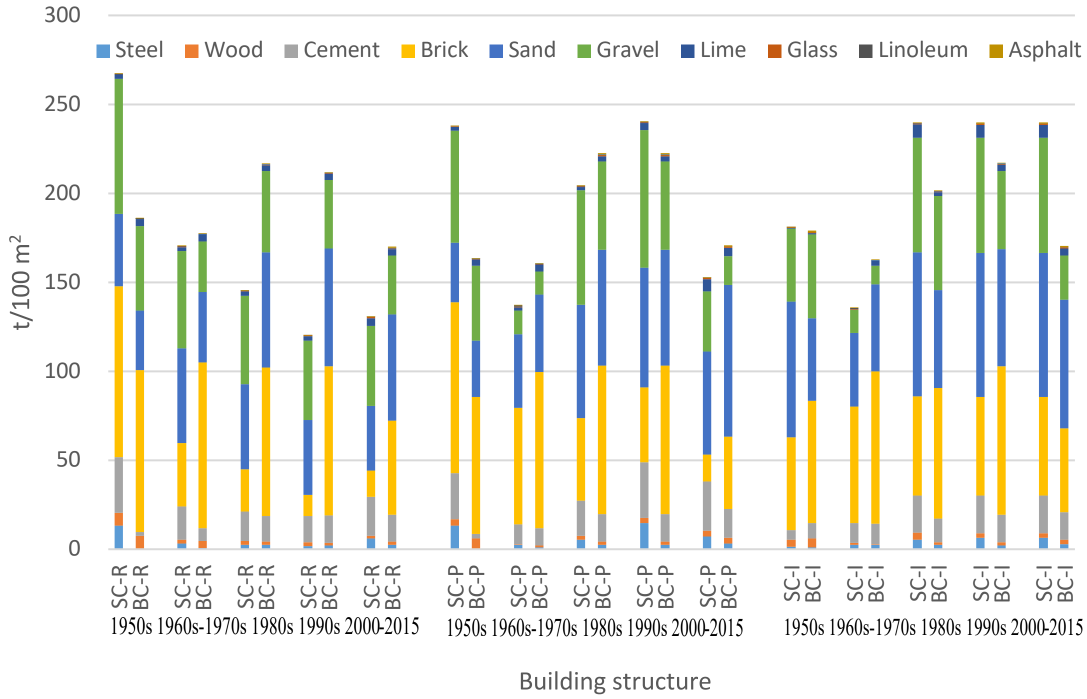


Fig. 6. The comparison of material intensities between steel-concrete and brick-concrete buildings.

Fig. 7 compares the embodied energy and embodied carbon between two building structures. The embodied energy of building materials in steel-concrete residential (S-C R) buildings is slightly higher than brick-concrete residential (B-C R) buildings, whereas the above result reveals the materials used by steel-concrete residential buildings is lower than brick-concrete residential buildings. However, the embodied carbon of building materials in steel-concrete residential buildings are slightly lower than brick-concrete residential buildings. In public and industrial buildings, the embodied energy and carbon of the steel-concrete structure are much higher than the brick-concrete structure. The embodied energy and carbon of steel in the steel-concrete structure is significantly higher than brick-concrete structure, which should be responsible for the high embodied energy of the steel-concrete structure. In general, given the differences in the embodied energy and carbon between these two structures, cutting down the energy use in steel turns to be crucial for steel-concrete buildings to gain better environmental performance than brick-concrete buildings.

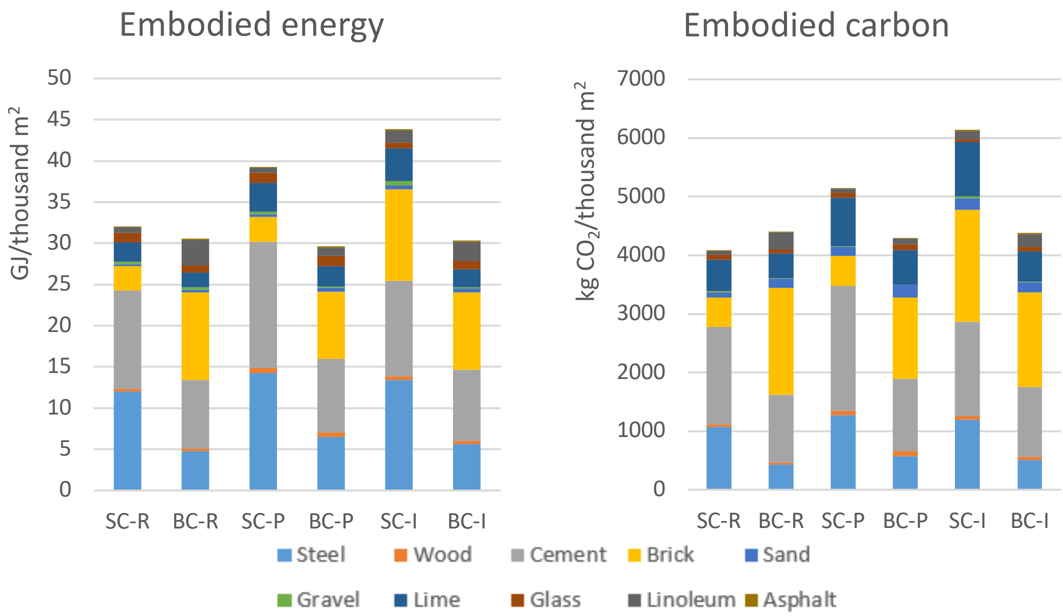


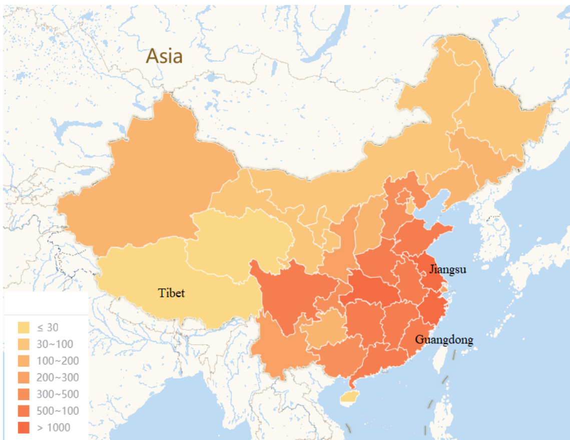
Fig. 7. The comparison of embodied energy and carbon between steel-concrete and brick-concrete buildings (2018).

3.5. Regional disparities

China has an extensive national territorial area and numerous regions, and the economic developments are imbalanced among regions [41]. In that case, regional disparities may exist in building material consumption and the associated embodied energy and carbon. As most of the buildings are built in strict accordance with national construction standards by mega construction enterprises, construction technologies are similar in different regions. Therefore, we mainly focus on the disparities in buildings area, population, and economic level among different regions. The consumptions of building materials, as well as the associated embodied energy and carbon in 31 provinces of China in 2018, are presented in Fig. 8. It shows that building construction activities occurred in the eastern and south-eastern regions, particularly in Jiangsu and Zhejiang provinces. Building material consumptions in these regions were significantly higher than in the western and northern districts. Accordingly, the embodied energy and carbon in the eastern and south-eastern regions were higher. In 2018, Jiangsu consumed 1288.9 million tonnes of building materials, while Tibet only consumed 3.1 million tonnes. 2964.3 million GJ of embodied energy was consumed by building materials in Jiangsu, whereas only 7.7 million GJ was consumed by Tibet. About 353.0 million tonnes of carbon were embodied in building materials consumed in Jiangsu, while only 0.9 million tonnes of embodied carbon were generated in Tibet. The disparities regarding the embodied carbon of building materials between the two regions are distinct, which have reached 383.1 times. In contrast, the population was 80.5 million in Jiangsu province and 3.4 million in Tibet. The population gap between these two regions was only 22.4 times, which was much lower than the embodied carbon gap.

a. Building materials consumption (million tonnes)

b. Embodied energy (million GJ)



c. Embodied carbon emissions (million tonnes)

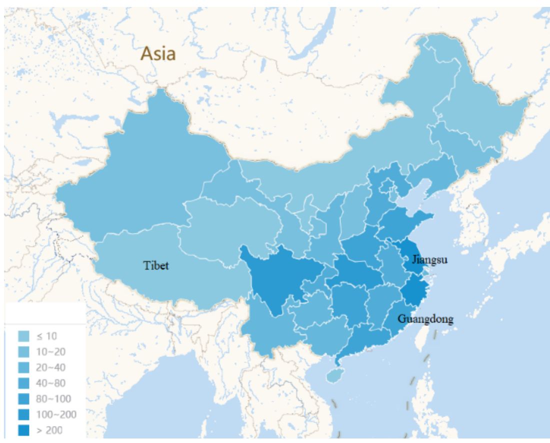


Fig. 8. Regional disparities (2018).

As shown in Fig. 9, the gross domestic product (GDP) of Jiangsu province and Guangdong province far outweighed Tibet during past years. In 2018, the GDP of Jiangsu was 9259.5 billion CNY, whereas the GDP of Tibet was 147.8 billion CNY [53]. The gap between these two regions in terms of the GDP was about 63 times, which is far lower than the gap of embodied energy and carbon of building materials (more than 350 times). More advanced regions like Guangdong province possessed the highest regional GDP (9727.8 billion Chinese Yuan) and the highest population (113.5 million) in China [53], but it only consumed 293.2 million tonnes of building materials in 2018, which was merely 23.4% of building materials consumed in Jiangsu. The embodied carbon was 84.5 million tonnes in Guangdong province, which accounted for only 23.9% of embodied carbon in Jiangsu province. The excessive building materials consumed by Jiangsu province and the associated higher energy and carbon than other regions should not be largely attributed to economic and population gaps. Jiangsu province indeed has consumed excessive building materials beyond its development need.

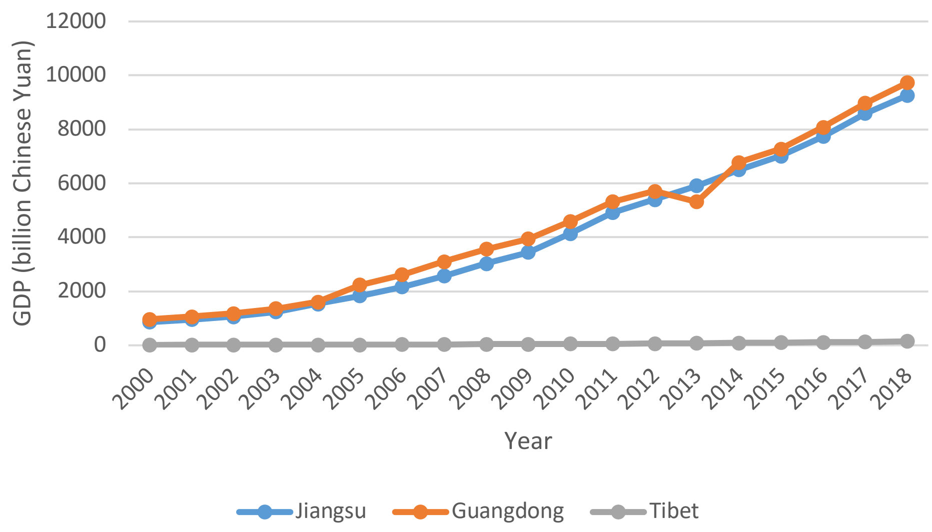


Fig. 9. Regional GDP.

4. Discussions

As the results present, sand was the most used material among the ten building materials in China. Due to a large amount of sand consumption, the world faces sand scarcity [42]. Sverdrup, Koca [43] projected that the increasing demand for sand would outstrip available sand in a few years. The situation for gravel is also not optimistic. Bendixen, Best [42] indicated that the extraction speed of gravel was faster than the growth of alternative materials. Reusing or recycling these two materials has become an essential way to solve the sand and gravel scarcity problem. However, the recycling of sand and gravel may increase the energy use in the reproduction process. Since the transportation process takes almost half of the embodied carbon of sand or gravel, cutting down the fossil fuel use in transporting these two materials become significant. Two strategies can be employed to realize the carbon reduction in transporting sand and gravel. The first way is to develop the local recycling industry for sand and gravel and require building construction companies to first use local recycled sand and gravel. The second strategy is to develop electric trucks. In regions like Sichuan province, where the ratio of clean energy sources is high, the use of electric trucks will effectively remove large amounts of sand and gravel's embodied carbon.

Compared with sand, gravel, brick, and cement, steel occupied a small share (3.1%) in total building material use. However, the building construction sector accounts for a high share of steel consumption in China. In 2018, around 196.0 million tonnes of steel was used in constructing buildings, which took up about 23.5% of the total finished steel products consumed (835.0 million tonnes) in China [44]. Meanwhile, the establishment of higher requirements for building qualities will result in more steel consumption. In April 2019, the Unified Standard for Reliability Design of Building Structures was officially implemented [45]. According to this new standard, the constant load component coefficient was adjusted from 1.2 to 1.3, and the live load component coefficient was adjusted from 1.4 to 1.5. It was estimated that the steel used in the underground part and the above-ground part would respectively increase around 10% and 5%. The pull of the new standard on steel demand is very significant [45]. Besides, since the results show that the embodied energy and carbon of recycled steel are much lower than new steel, a higher proportion of recycled steel need to be used in building constructions to alleviate the pressure on steel consumption and reduce carbon.

It is noticeable that steel accounted for a small share in the total building material consumption but was the top energy consumer and carbon emitter. As the result shows, most energy consumed and carbon emitted by steel ascribe to the high thermal energy needed in the manufacturing process. Since the energy consumed by recycled steel can be 50% lower than virgin steel, recycling steel has become particularly important. The current recycling rate of steel is high in China; thereby, the energy-saving and decarbonization in producing steel, especially recycled steel, become the priority. By transforming the currently dominated Basic Oxygen Furnace (BOF) to Electric Arc Furnace (EAF), significant carbon reductions in steel production can be achieved. In the BOF route, approximately 89% of energy is provided by coal, and 3% of energy is provided by natural gas. In contrast, in the EAF route, electricity accounts for over 50% of energy supply, while coal and natural gas inputted respectively account for only 11% and 38% [46]. By substituting BOF with EAF, 220 kWh could be saved per tonne of steel [53]. The proportion of Electric Arc Furnaces in China was extremely low (10%), compared with around 61% in the US and 42% in European countries [47]. However, transforming the technology may face several obstacles. The steel industry has to consider the high transformation cost and the technical support. Subsidies could be given to steel manufacturers who use Electric Arc Furnace based on the amount of carbon they reduce.

The result shows that disparities in the embodied energy and carbon between brick-concrete buildings and steel-concrete buildings are not significant. Nevertheless, steel-concrete buildings have higher compressive strength, longer durability, and better fire resistance [48]. With the rapid urbanization, the explosive growth of population, and increasing land prices, more high-rise buildings are needed to accommodate more residents [30]. The brick-concrete structure was not solid enough to support the increasing higher buildings. Therefore, the transformation from the brick-concrete structure to the steel-concrete structure is worth continuing. Building design codes should put more emphasis on the carbon reduction and energy-saving standard of steel-concrete buildings. More policy incentives such as tax abatements can be provided to construction companies that use low-carbon materials in steel-concrete buildings. A new technology—Hydrogen Breakthrough Ironmaking Technology, which can remove fossil fuels in iron and steel production [49], can be further developed to reduce the carbon embodied in steel-concrete buildings.

The regional disparity analysis reveals that the eastern and south-eastern regions consumed much more building materials and embodied more energy and carbon than the western and northern regions. Jiangsu province seems to build excessive buildings when compared to Guangdong province. Measures need to be taken to restrain the excessive energy use and carbon emission embodied in the building construction sector of provinces like Jiangsu. First, the government could impose restrictions on the number of buildings. A reasonable number of newly constructed buildings should be set based on the guarantee of local development. Those regions that construct extra buildings should be levied higher taxes. Second, in the economically advanced regions of China, numerous people own more than one property, leaving these spaces empty. Policies can be made to incentivize the mobilization of vacant building spaces. Companies could be set to decorate and manage these vacant rooms uniformly and rent them to people in need. Property owners who lend their rooms to the companies could also benefit via receiving part of the rental fee and free decoration. Thirdly, since building renovation is prevalent in big cities, waste building materials are continuously generated. Motivations should be given to those companies who recycle waste building materials and remanufacture them. Carbon reduction concessions could be provided to those companies who reduce the embodied carbon of recycled building materials.

5. Concluding remarks

Assessment of the total embodied energy and carbon of building materials that are extensively used in China is needed to facilitate decision-makers to make building construction planning with consideration on the environmental cost of new buildings. Controlling the carbon emissions in the construction sector will be helpful for achieving the goal of carbon neutrality in 2060. Although there have been studies assessing the embodied energy and carbon of several material types or certain building types, no existing literature compares the total embodied energy and carbon of building materials in different regions in China. This study has identified ten primary building materials in China and assessed their embodied energy and carbon. The results illustrate that sand, gravel, brick, and cement constitute the majority of building material consumption. Cumulatively, they were responsible for over 91.7% of the materials used in constructing buildings in 2018. Cement, steel, brick, lime, and linoleum were five major materials with high embodied energy and carbon. Approximately 93.1% of the total embodied energy and about 95.7% of the total embodied carbon were associated with the five materials. A noticeable finding was that whereas steel and linoleum were among the least used building materials, they were the heaviest energy consumers and prime carbon emitters. In contrast, the consumption of sand and gravel was high, but their embodied energy and carbon were among the least. The results also show no apparent differences in the total embodied energy and carbon between steel-concrete buildings and brick-concrete buildings. The regional disparity analysis illustrates that eastern and south-eastern regions consumed most building materials and embodied significantly higher energy and carbon.

Our quantitative assessment provides implications for reducing carbon emissions in the building industry. The results inform that local recycling and low-carbon transportation should be promoted to reduce the high consumed building materials such as sand and gravel. As for energy-intensive building materials like steel, improving steel recycling and using low carbon energy sources and technologies in manufacturing are effective strategies. In regions with excessive building material consumption and high embodied energy & carbon, setting a reasonable number of new buildings, promoting the mobilization of vacant building spaces, and recycling waste building materials may be effective approaches. This study can offer implications for practitioners and policymakers when assessing green building materials, evaluating carbon burdens on the building sector, and promoting low carbon production of building materials.

One of the limitations of this study is the simplification of data and assumptions. The first is the simplified classification of building structures into two common structures. In practice, structures like brick-wood and steel structures still exist in China, even if their quantities are few. Second, only materials used in the main body of the building are considered; other components like aluminium alloy for windows and copper for electric wire are excluded from the estimation. Last, this study adopts embodied energy coefficients and embodied carbon coefficients of the most common used material type, while disparities in various material models have not been considered.

We suggest several directions for future studies. Since there was no consolidated methodology available to calculate embodied energy accurately and consistently [50], the calculation of embodied energy was complicated [51]. Few studies offered reliable data and coefficients to assist in assessing the embodied energy and carbon [52]; thereby measuring the embodied energy and carbon is challenging. This study is a preliminary attempt in assessing the embodied energy and carbon of building materials in China as an application of embodied energy coefficients and embodied carbon coefficients. Future research could build a more detailed list of broader building materials to improve the available data on embodied energy and carbon coefficients. This will be beneficial for more assessments of the embodied energy and carbon of building materials, thereby providing accurate references to practitioners and policymakers to reduce the negative impacts of buildings on the environment.

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