buildings

Article

Embodied Carbon Emissions in China's Building Sector: Historical Track from 2005 to 2020

Chen Zhu [1], Zhihan Yang [1], Boyu Huang [2] and Xiaodong Li [1,*]

[1] Department of Construction Management, Tsinghua University, Beijing 100084, China
[2] Department of Building and Real Estate, Faculty of Construction and Environment, Hong Kong Polytechnic University, Hong Kong 999077, China
* Correspondence: eastdawn@tsinghua.edu.cn

Abstract: China's large-scale construction has led to massive energy consumption and carbon emissions. The embodied carbon emissions (ECs) of China's building sector play a key role in realizing national emission reduction targets. Currently, the understanding of the status quo of ECs is vague and inconsistent, and the existing accounting models still have several limitations. Therefore, this study develops two improved models (i.e., the process-based and the input-output-based life cycle assessment models) and dynamic accounting datasets to reveal historical trends and emission characteristics of ECs from 2005 to 2020. The results show that the total ECs in 2020 were as high as 2.28 billion tCO_2, accounting for 25.2% of China's total energy-related carbon emissions. The indirect ECs are the largest contributor, representing 95.9% of the total building ECs. The ECs increased quickly at first and entered a plateau, stable at about 2.2 billion tCO_2 after 2015. From 2005 to 2020, the total building ECs contributed 38.7% to the national carbon emission growth, while the intensity of ECs showed a downward trend, indicating that the increase in China's building ECs is scale-driven. This study provides sound methodological, and data support for emission tracing and the low-carbon development of China's building sector.

Keywords: building sector; embodied carbon emissions; emission accounting; historical trend; emission status

check for updates

Citation: Zhu, C.; Yang, Z.; Huang, B.; Li, X. Embodied Carbon Emissions in China's Building Sector: Historical Track from 2005 to 2020. *Buildings* **2023**, *13*, 211. https://doi.org/10.3390/buildings13010211

Academic Editor: Luigi Di Sarno

Received: 4 December 2022
Revised: 1 January 2023
Accepted: 9 January 2023
Published: 12 January 2023

1. Introduction

Climate change is the defining crisis of our time. China, the world's top emitter, committed to peaking its carbon dioxide emissions (CEs) by 2030 and reaching carbon neutrality by 2060 at the General Debate of the 75th session of the United Nations General Assembly. The building sector plays a vital role in realizing the national emission goals since its CEs account for a large proportion of China's total emissions, and suggest a growing trend in the coming years with the continuous urbanization process and the improvement of people's living standards [1]. Furthermore, the building sector also has great potential for emission reduction, and the mitigation costs are relatively low compared to other sectors [2]. The Chinese government attaches great importance to low-carbon development of the building sector and has issued a series of action plans to guide building emission abatements, such as the *Action Plan for Peaking Carbon Dioxide Emissions in Urban-Rural Development* and *the 14th Five-Year Building Energy Efficiency and Green Building Development Plan*. Compiling a clear and reliable CEs accounting of China's building sector and analyzing the emission evolution laws are foundations for developing scientific and effective mitigation strategies.

The building-related CEs include two parts: operational CEs (OCs) and embodied CEs (ECs) [3]. Generally, it is believed that the OCs are more prominent due to the huge building stock and the long usage time. Thus, the building operational energy consumption and CEs have become a wide concern for the industry and academia. Previous studies have proposed various building OC accounting models, which can be grouped into two categories, i.e., top-down models (e.g., the China Building Energy Model [4,5], the

World Energy Model by the International Energy Agency) and bottom-up models (e.g., the Statistical Yearbook-Energy Balance Sheet based splitting method [6], Building Operational Carbon Emissions Accounting Model [7]). In general, the accounting models of building OCs have been well developed, and related research results are regularly published by academic institutes, such as the China Association of Building Energy Efficiency [8] and the Building Energy Research Center of Tsinghua University [4], which provides sound method and data for a holistic understanding of China's building OCs and further analysis.

For building ECs, from the annual cross-sectional perspective, the emission share in countries at different stages of socioeconomic development varies significantly. The United States, as a typical developed country, has a small scale of annual new buildings, and building operational energy consumption and emissions predominate nowadays (roughly 90% [9,10]). However, China is still a developing country, and with continuous urbanization and the increasing demand for high-quality construction, China has the world's largest scale of new building construction at present. Since 2013, annual new buildings have exceeded 3.5 billion m^2, nearly half of the world's total new increments [1]. In addition, the emergence of a variety of high-performance buildings also brings higher building ECs [11,12]. China's building ECs are becoming increasingly significant and play an essential role in emission reduction. Hence, it is vital to assess the status quo and grasp the emission characteristics of ECs to better guide the low-carbon development of the building sector and support China in achieving the overall emission goal.

Research on China's building ECs accounting at the macro level has gained increasing attention in recent years, as shown in Table 1. However, these studies still need further development and improvement in accounting scope, methodologies, and empirical analysis. Specifically, the main points are as follows.

Table 1. Research on embodied carbon emissions at the macro level.

Year	Author	Object	Accounting Boundary	Time	Method	Reference
2022	Chen et al.	China's building sector	Building materials ECs only	2000–2018	P-LCA [1]	[13]
2021	Bai and Qu	China's building sector	Building materials ECs only	1997–2016	P-LCA	[14]
2020	Zhu et al.	China's building sector	Initial, recurrent, and demolition ECs	2015	P-LCA & IO-LCA [2]	[15]
2019	Chen et al.	The construction industry in China and the US	ECs from the entire production supply chain	1995–2009	IO-LCA	[16]
2019	Zhang et al.	China's building sector	ECs from building material extraction, manufacturing, transportation, and on-site construction	2000–2016	P-LCA	[17]
2018	Huang et al.	The construction industry in 40 countries around the world	ECs from the entire production supply chain	2009	IO-LCA	[18]
2017	Shi et al.	China's construction industry	ECs from the entire production supply chain	1995–2009	IO-LCA	[19]
2016	Guan et al.	China's construction industry	ECs from the entire production supply chain	2010	H-LCA [3]	[20]
2016	Zhang and Wang	China's construction industry	ECs from the entire production supply chain	1997–2012	H-LCA	[21]
2016	Zhang and Wang	China's construction industry	ECs from building material manufacturing, transportation, construction, demolition, and waste disposal	2005–2012	P-LCA	[22]
2016	Chang et al.	China's building sector	ECs from the entire production supply chain	2007	IO-LCA	[23]

[1] Process-based life cycle assessment (P-LCA) method. [2] Input-output-based life cycle assessment (IO-LCA) method. [3] Hybrid life cycle assessment (H-LCA) method.

First, the accounting boundary of building ECs at the macro level varies, which has not yet reached a consensus and needs to be clarified. Unlike the unambiguous definition of OCs, ECs involve numerous and scattered stages of the building life cycle and have different explanations in various studies. Moreover, the definition of direct and indirect ECs is vague, and there is no definite classification principle yet. For example, the building ECs calculated by Bai and Qu [14] only include the material ECs, while the ECs assessed by Zhang et al. [17] involve four building pre-use stages (i.e., material extraction, manufacturing, transportation, and on-site construction). Peng et al. [24] classify emissions from fossil fuel combustion for all activities involved as direct ECs, whereas Onat et al. [9] and Zhang and Wang [21] group only emissions from the combustion of fossil fuels within the physical boundaries of the building as direct ECs.

Second, the annual ECs accounting model for the building sector remains to be further developed, and the accounting data quality needs to be improved. Due to the industrial aggregation of statistical data (e.g., input-output tables and industrial energy and material consumption data), most of the existing ECs accounting studies are for the construction industry (including buildings and infrastructure), while the ECs accounting research on the building sector is sporadic. Some studies [21,25] even have a mismatch between accounting data and scope; that is, the scope definition is expressed as the building sector, but the accounting data used are statistics of the construction industry, without data splitting and extracting. In addition, the timeliness, consistency, and representativeness of the underlying accounting data need to be improved to enhance the reliability and accuracy of the accounting results. When calculating the ECs for several years, most existing studies adopt fixed emission factors from different sources [13,22,26], ignoring the dynamic changes in data brought about by technological advances, energy mix adjustments, etc.

Third, there is still a lack of clear and consistent understanding of the status quo and the evolution of China's building ECs. On the one hand, as mentioned above, relevant studies calculating ECs in China's building sector are scattered and mostly single-year accounting [15], which can hardly reflect the historical emission development. On the other hand, the building ECs estimated by scholars exhibit significant discrepancies affected by the accounting boundary, approaches, and data. According to the accounting of Zhu et al. [15], China's building ECs in 2015 were approximately 1.5 billion tons, while Wu's research [26] indicates that ECs in China's building sector were about 2.7 billion tons, in 2015. Zhang and Wang's study [21] shows that the building ECs exceeded 4 billion tons in 2012. Such varied results can hardly support a scientific and objective grasp of the annual ECs status in China's building sector.

To remedy these research deficiencies, this study aims to investigate the historical trend and emission characteristics of China's building ECs during 2005–2020 through improved models and dynamic data. Specifically, the primary contributions of this study are presented as follows. On the one hand, a bottom-up process-based method and a top-down input-output-based method are tailored to estimate the annual ECs of China's building sector from a macro perspective. The models fully consider the dynamic characteristics of underlying data and have the advantages of easy data acquisition, authoritative data source, and transparent and repeatable calculation process, which can provide strong methodological support for emission data tracing. On the other hand, the accounting results show a clear and integrated image of China's building ECs and unfold the evolution laws of total emission, emission intensity, and composition, which help identify priorities for reducing emissions in the building sector.

2. Research Framework

Figure 1 illustrates the research framework, and the main steps are as follows:

- Scope definition. Detail the key definitions and accounting scope, including the macro- and micro-level building ECs and direct and indirect emissions.

- Establishment of accounting models. The top-down input-output-based and bottom-up process-based methods are adopted to develop the annual total ECs accounting model for China's building sector.
- Data collection and process. Build the dynamic accounting datasets for each model, including emission factors and activity data.
- Accounting results and discussion. Analyze the historical trend and emission characteristics of the building ECs and conduct comparative analyses, including two model results, as well as the OCs and ECs of China's building sector.

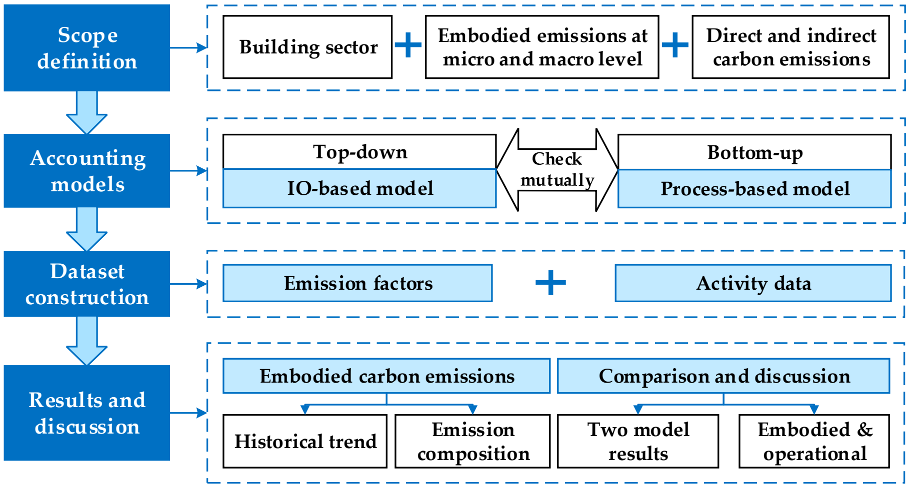

Figure 1. Research framework.

3. Methodology and Data

3.1. Definition and Scope

The key definitions and scopes in this study are described below.

- Building sector: to support the comparison between OCs and ECs, the building sector in this study includes the totality of buildings within a given year and region scope, which is distinguished from the construction industry. Infrastructure projects such as roads and bridges are outside the study scope.
- Embodied carbon emissions: for a single building, the ECs generally refer to emissions associated with material manufacturing, transportation, building construction, maintenance, and demolition processes throughout the whole life cycle of a building [27], which is the longitudinal perspective. While for the building sector in this study, the ECs are a macro-level concept, referring to the aggregated emissions from the production and transportation of the primary building materials consumed, building construction, maintenance, and demolition throughout the entire year at the national level, which is the cross-sectional perspective [28]. Figure 2 illustrates the differences between ECs at the micro and macro levels.
- Direct and indirect emissions: this study also unifies the classification rules for direct and indirect emissions for both OCs and ECs. Emissions from the direct combustion of fossil fuels by activities within the physical boundary of buildings are classified as direct emissions, while emissions caused by construction activities but from emission sources controlled by other sectors are classified as indirect emissions, as shown in Figure 3.

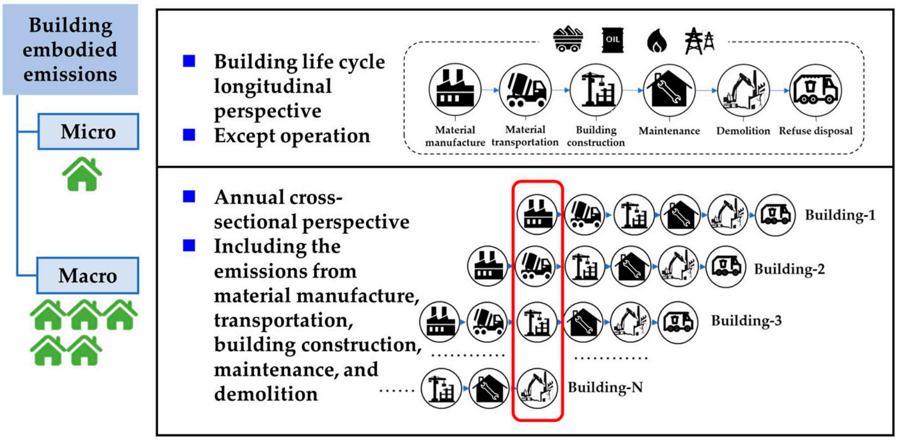

Figure 2. The comparison of building embodied emissions at the micro and macro levels.

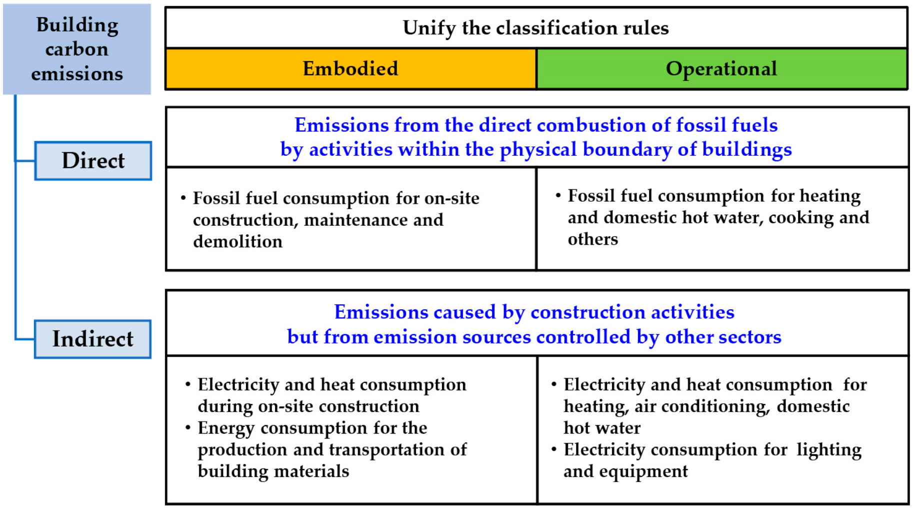

Figure 3. Classification of building direct and indirect emissions.

3.2. Embodied Carbon Emission Accounting Models

3.2.1. Comparison and Selection of Accounting Methods

There are three major types of accounting methods for macro-level ECs, that is, the bottom-up process-based life cycle assessment (P-LCA), the top-down input-output-based life cycle assessment (IO-LCA), and the hybrid life cycle assessment (H-LCA). The method comparison is shown in Table 2.

Table 2. Comparison of accounting methods for embodied carbon emissions.

Methods	P-LCA	IO-LCA	H-LCA
Data requirement	Relatively flexible	Highly dependent on input-output tables	High demand and not easily accessible
System boundary	Incomplete	Complete	P-HLCA, incomplete IO-HLCA, complete
Calculation complexity	Relatively easy	Relatively easy	Complex
Time-series accounting results	Easy to get	Hard to get	Hard to get
Comparability of results	Medium	Strong	Weak

The P-LCA method classifies the buildings within the study scope according to their life cycle stages (e.g., new construction buildings and demolished buildings), quantifies the inputs and emissions of each stage, and summarizes each stage's accounting results to obtain the total emissions. This method has the advantages of conciseness, clarity, and simple calculation, but there are horizontal and vertical truncation errors in the accounting results [20,29]. Moreover, the reproducibility of the accounting process and comparability of the results are weak in existing research due to the subjectivity of defining the scope and selecting data sources. The clear definition of the accounting scope and the scientific and reasonable construction of the underlying dataset at each stage are the research focuses of applying this method to accounting building ECs.

The IO-LCA method is an extension of the input-output (IO) model. The IO model, proposed in 1936 by the American economist Leontief, describes the complex dependence, constraint, and correlation between the production input and output of various sectors. In 1970, Leontief [30] extended the model to environmental research, correlating environmental data with sectoral economic data to measure direct and indirect environmental impacts along the entire production supply chain. This method has the advantages of authoritative data sources, a clear and consistent accounting framework, a repeatable process, strong comparability of accounting results, and a complete system boundary. However, sectoral aggregation and homogeneity assumption lead to the model results only reflecting the average emissions of the industries listed in the IO table. The disaggregation of sectors is the challenge of the model application. Furthermore, limited by the availability of IO tables, the method makes it hard to perform continuous time-series accounting.

The H-LCA method combines the P-LCA and IO-LCA methods to improve the weaknesses of using one method alone. According to the accounting framework and data that are mainly dependent on it, hybrid methods can be further grouped into the process-based hybrid method (P-HLCA) and IO-based hybrid method (IO-HLCA) [29]. Although this method can achieve complementary advantages, there are still many limitations, such as complex calculation, high data requirements, weak comparability and replicability of accounting results, etc.

In this study, the top-down IO-LCA and the bottom-up P-LCA methods are selected to develop the total building ECs accounting model, considering the availability of data, the reliability, feasibility, and convenience of methods, and the comparability of results. These two methods can complement each other regarding the continuity of accounting data and the integrity of system boundaries, as well as both being able to assess direct and indirect emissions. Simultaneously using the two methods allows for cross-checking to improve the reliability of accounting results.

In addition, to fully understand the total CEs of China's building sector and the relative quantitative relationship between ECs and OCs, this study established the integrated accounting model for the total annual building CEs, as shown in Figure 4. Regarding the building OCs, the model proposed by the China Association of Building Energy Efficiency has been adopted [6]. The improved building ECs accounting models are detailed as follows.

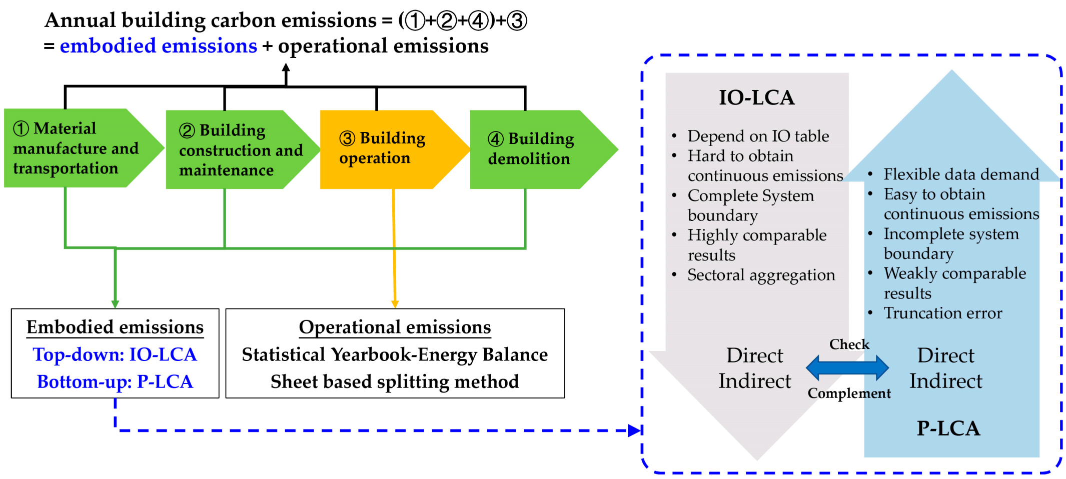

Figure 4. Annual total carbon emission accounting model for China's building sector.

3.2.2. The P-LCA Model

Figure 5 shows the framework of the P-LCA ECs accounting model. According to the scope definition, the ECs of the building sector can be further divided into three parts:

- The on-site direct ECs (DEC) refer to the CEs from fossil energy directly consumed by on-site construction during the building construction, maintenance, and demolition phases.
- The on-site indirect ECs (IEC1) refer to the CEs from secondary energy (electricity and heat) directly consumed by on-site construction, while the CEs physically occur in the electricity and heat production and supply sectors.
- The off-site indirect ECs (IEC2) refer to the CEs from the manufacturing and transporting of the building materials consumed.

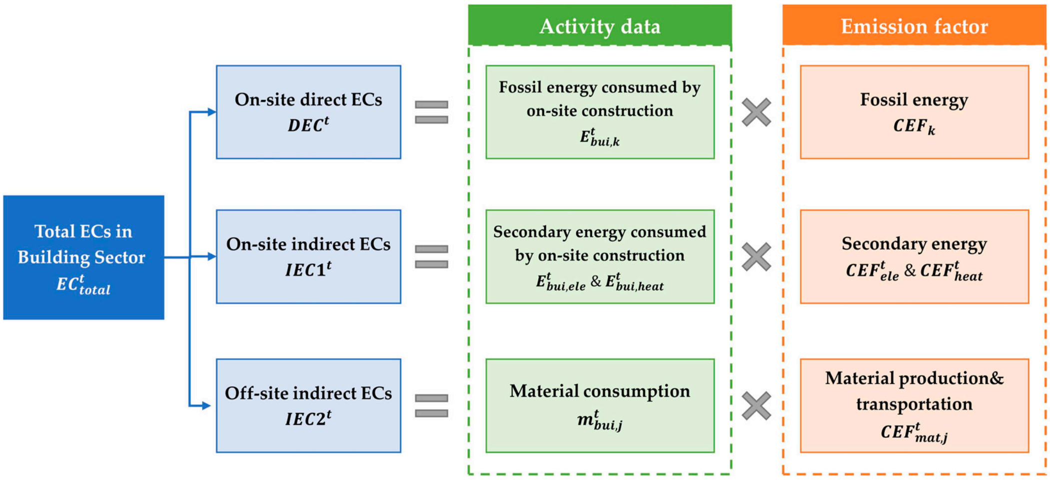

Figure 5. The framework of the P-LCA accounting model.

Thus, the total annual ECs of the building sector can be calculated by summing the DEC, IEC1, and IEC2, see Equation (1):

$$EC^t_{total} = DEC^t + IEC1^t + IEC2^t = DEC^t + IEC^t \tag{1}$$

where EC^t_{total}, DEC^t, $IEC1^t$, and $IEC2^t$ denote the total ECs, DEC, IEC1, and IEC2 of the building sector in year t; DEC^t and IEC^t denote the building sector's direct ECs and indirect Ecs in year t.

According to the emission-factor approach in the Intergovernmental Panel on Climate Change (IPCC) guidelines [31], DEC^t, $IEC1^t$, and $IEC2^t$ can be calculated by the following Equations (2)–(4), respectively.

$$DEC^t = \sum\nolimits_1^k \left(E^t_{bui,k} \times CEF_k\right) \tag{2}$$

where $k = 1, 2, \ldots, K$, denotes the types of fossil energy; $E^t_{bui,k}$ denotes the consumption of the k-th type of fossil energy in the building sector in year t; and CEF_k denotes the CO_2 emission factor (CEF) of the k-th type of fossil energy.

$$IEC1^t = EC^t_{bui,ele} + EC^t_{bui,heat} = E^t_{bui,ele} \times CEF^t_{ele} + E^t_{bui,heat} \times CEF^t_{heat} \tag{3}$$

where $EC^t_{bui,ele}$ and $EC^t_{bui,heat}$ denote the indirect CEs from electricity and heat directly consumed by building on-site construction in year t, respectively; $E^t_{bui,ele}$ and $E^t_{bui,heat}$ denote the electricity and heat consumption during building on-site construction in year

t, respectively; and CEF_{ele}^{t} and CEF_{heat}^{t} denote the CEFs for electricity and heat in year t, respectively.

$$IEC2^t = \sum_1^j \left(m_{bui,j}^t \times CEF_{mat,j}^t \right) \tag{4}$$

where j denotes the types of building materials; $m_{bui,j}^t$ denotes the consumption of material j in the building sector in year t; and $CEF_{mat,j}^t$ denotes the CEF of material j in year t, including material manufacturing and transportation.

3.2.3. The IO-LCA Model

The IO-LCA accounting model measures the sectoral direct and indirect ECs along the supply chain by correlating sectoral environmental data with IO economic data. Figure 6 illustrates a simplified environmental extended IO table for an economic system consisting of n sectors. The horizontal dimension of the IO table mainly describes where the sectoral production outputs are used, while the vertical dimension describes the sources of the sectoral production inputs and the value formation process [32,33].

Input \ Output		Intermediate use				Final use	Total output
		Sector 2	Sector 2	...	Sector n		
Intermediate input	Sector 1	z_{11}	z_{12}	...	z_{1n}	y_1	x_1
	Sector 2	z_{21}	z_{22}	...	z_{2n}	y_2	x_2
	...	...	...	...	...	...	...
	Sector n	z_{n1}	z_{n2}	...	z_{nn}	y_n	x_n
Primary input		v_1	v_2	...	v_n		
Total input		x_1	x_2	...	x_n		
Environmental emissions		e_1	e_2	...	e_n		

Figure 6. A simplified environmental extended input-output table.

For each row in the IO table, there are the following balancing equations:

$$x_i = \sum_{j=1}^{n} z_{ij} + y_i \tag{5}$$

where x_i denotes the total output of the sector i; z_{ij} denotes the input from the sector i to sector j; and y_i denotes the final demand of sector i.

Define the direct consumption coefficient as follows.

$$a_{ij} = z_{ij} / x_j \tag{6}$$

where a_{ij} denotes the direct consumption coefficient of sector j to sector i and x_j denotes the total input of the sector j.

Substitute Equation (6) into Equation (5), and we can get:

$$x_i = \sum_{j=1}^{n} a_{ij} x_j + y_i \tag{7}$$

Its matrix is expressed as follows.

$$\boldsymbol{X} = \boldsymbol{AX} + \boldsymbol{Y} \tag{8}$$

Transforming Equation (8) by matrix, we can get:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} = \boldsymbol{LY} \tag{9}$$

where $\boldsymbol{X}$ denotes an $n \times 1$ total output vector; $\boldsymbol{A}$ denotes the $n \times n$ technical coefficient matrix, consisting of direct consumption coefficient a_{ij}; Y denotes an $n \times 1$ final demand vector; $\boldsymbol{I}$ denotes an $n \times n$ identity matrix; and $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} = [L_{ij}]_{n \times n}$ denotes the Leontief inverse matrix. The element of the Leontief inverse matrix is called the complete consumption coefficient L_{ij}, which refers to the product quantity of sector i, directly and indirectly consumed by sector j, when sector j provides per unit final product.

Further correlate economic output with environmental emissions and define the direct emission intensity ε_j, as shown in Equation (10).

$$\varepsilon_j = e_j / x_j = \sum_1^k \left(E_{j,k}^t \times CEF_k\right) / x_j \tag{10}$$

where ε_j denotes the direct CEs intensity of sector j; e_j denotes the total direct CEs of the sector j; x_j denotes the total output of the sector j; $k = 1, 2, \ldots$, K, denotes the types of fossil energy; $E_{j,k}^t$ denotes the consumption of the k-th type of fossil energy in the sector j in year t; and CEF_k denotes the CEF of the k-th type of fossil energy.

Then, the total ECs of the building sector can be calculated by the following:

$$CEC_b = \sum_{i=1}^n CEC_{ib} = \sum_{i=1}^n (\varepsilon_i \times L_{ib} \times y_b) \tag{11}$$

where CEC_b denotes the total ECs of the building sector; CEC_{ib} denotes the ECs contribution of sector i to the building sector; ε_i denotes the direct CEs of the sector i; L_{ib} denotes the complete consumption coefficient of sector i to the building sector; and y_b denotes the final use of the building sector.

The direct ECs of the building sector e_b can be calculated by Equation (10) and the indirect ECs is $(CEC_b - e_b)$.

3.3. Data

Since the underlying principle of the above two accounting models is the emission-factor approach, the datasets required can be grouped into two categories, namely emission factors and activity data, as shown in Figure 7.

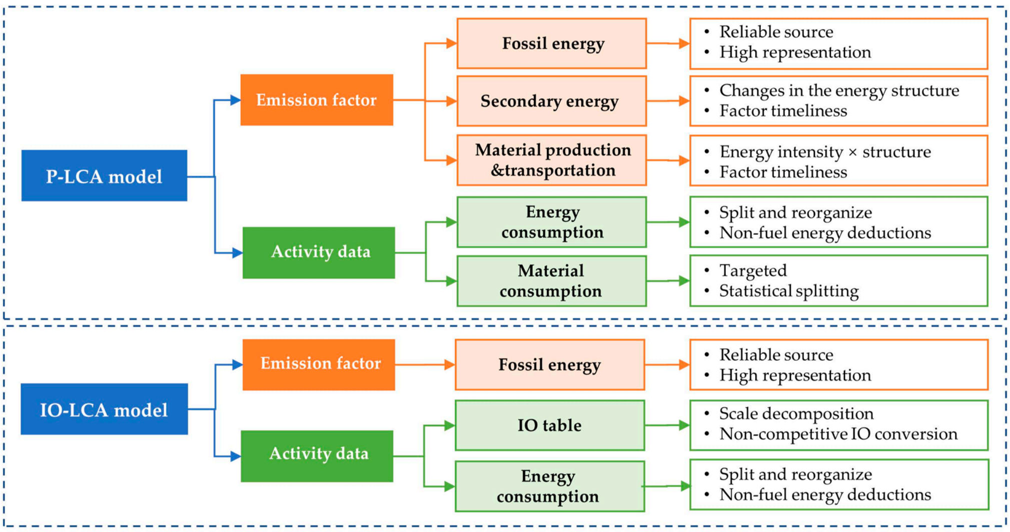

Figure 7. Basic datasets for embodied carbon emission accounting.

3.3.1. Data for the P-LCA Model

1. Emission factors

(1) Fossil energy CEFs

According to the IPCC guidelines [31], national CEFs from peer-reviewed published literature are recommended to reflect the domestic levels and lower the uncertainty. Thus, we adopt the updated emission factors released by the Carbon Emission Accounting & Datasets (CEADs), which are collected from an extensive survey of China's fossil energy quality [34,35]. The data are detailed in the Supplementary Document Table S1.

(2) Electricity and heat CEFs

Regarding the secondary energy CEFs, no continuous time-series data was released by authoritative institutions in China. There are mainly two ways to deal with them in existing studies. One is to directly quote the literature data without considering the dynamic changes of the factors [36,37], which may lead to significant deviations in the results when conducting a long-term accounting study. The other considers the time-varying issue but has shortcomings such as misquotation or underestimation [7,38]. In this study, we adopt an indirect estimation method based on the energy balance sheet to obtain time-dependent datasets of secondary energy CEFs. The CEFs of the secondary energy consumption are equal to the ratio of the total CEs of energy production to the total final consumption. The equations for estimation are as follows:

$$CEF_{ele}^{t} = \sum_{1}^{k}\left(E_{thermal power,k}^{t} \times CEF_{k}\right) / Ele_{final}^{t} \quad (12)$$

$$CEF_{heat}^{t} = \sum_{1}^{k}\left(E_{heatsupply,k}^{t} \times CEF_{k}\right) / Heat_{final}^{t} \quad (13)$$

where CEF_{ele}^{t} and CEF_{heat}^{t} denote the CEFs of electricity and heat in year t, respectively; CEF_k denotes the CEF of the k-th fossil energy; $E_{thermal power,k}^{t}$ and $E_{heatsupply,k}^{t}$ denote the k-th fossil energy consumption of electricity and heat production in year t; and Ele_{final}^{t} and $Heat_{final}^{t}$ denote the total final consumption of electricity and heat in year t, respectively. The mentioned energy data can be collected from the energy balance tables published in the annual *China Energy Statistical Yearbook*. The estimated CEFs of electricity and heat over the years are shown in Figure 8.

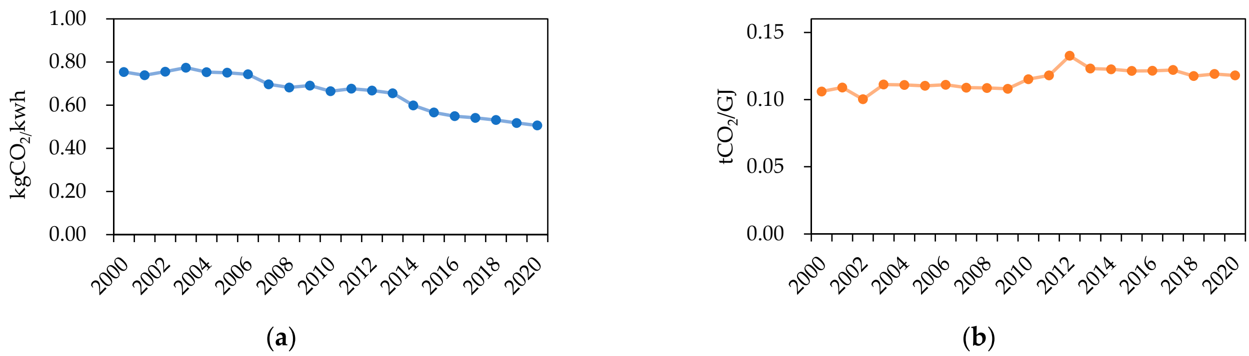

Figure 8. The dynamic CEFs of secondary energies. (**a**) The CEF of electricity; (**b**) The CEF of heat.

(3) Material CEFs

For the CEFs of building materials, most existing studies directly cite various documents [13], ignoring the data quality requirements of consistency, representativeness, comparability, and timeliness [31], which may lead to significant deviations. To improve the reliability and accuracy of accounting results, we draw on the concept of dynamic background inventories to construct temporal datasets of material CEFs [39].

The idea of estimating dynamic material production CEFs is as follows: firstly, we collect annual data on comprehensive energy consumption levels and energy consumption structure of primary materials production published by the National Bureau of Statistics [40], Energy Foundation [41], China Building Material Council [42], etc., and then use energy CEFs of the corresponding years to estimate the annual average CEFs of materials production.

Regarding material transportation CEFs, we adopt statistics-based estimation instead of the widely used case-based assumptions. On the one hand, authoritative statistics data and transparent processes make the accounting results more reliable; on the other hand, time-series statistics data can reflect the timeliness to improve accounting accuracy. The estimation equation is as follows:

$$CEF^t_{mat,tran,j} = \sum\nolimits_{m=railway,road,water} EF^t_m \times \omega^t_m \times dist^t_{m,j} \tag{14}$$

where $CEF^t_{mat,tran,j}$ denotes the transport CEF of material j in year t; m denotes the type of transport mode; EF^t_m denotes CEF of transport mode m in year t, which can be determined by energy consumption per unit transport turnover and energy CEFs; ω^t_m denotes the share of freight using transport mode m in year t; $dist^t_{m,j}$ denotes the average transport distance of material j by transport mode m in year t, which can be calculated by the freight volume and transport turnover. All data are available from the annual *China Transport Statistical Yearbook*, *China Statistical Yearbook,* and relevant literature [43,44]. The estimated material CEFs data are detailed in the Supplementary Document.

2. Activity Data

(1) Energy consumption

The annual *China Energy Statistical Yearbook* Energy Balance Sheet provides statistics on fossil and secondary energy consumption in the construction industry, which involves the production activities of buildings and civil engineering projects. According to the scope definition of this study, the building-related energy consumption data should be split out from data in the statistical yearbook. We refer to the total output value share of subsectors to disaggregate the parent (construction) sector data, which has been adopted by many previous studies [15]. The disaggregation and aggregation of subsectors in the construction industry are shown in Figure 9, and the calculation equations are below.

$$E^t_{bui,k} = E^t_{con,k} \times r^t_{bui} \tag{15}$$

$$r^t_{bui} = \frac{x^t_{bui\_con} + \left(x^t_{ins\_con} + x^t_{dec\_con}\right) \times x^t_{bui\_con} / \left(x^t_{bui\_con} + x^t_{civ\_con}\right)}{x^t_{con}} \tag{16}$$

where $E^t_{bui,k}$ and $E^t_{con,k}$ denote energy consumption in the building construction and the construction industry in the year t, respectively; r^t_{bui} denotes the split ratio coefficient of the building sector in year t; and $x^t_{bui\_con}$, $x^t_{ins\_con}$, $x^t_{dec\_con}$, $x^t_{civ\_con}$, and x^t_{con} denote the total output value of building construction, installation, decoration and others, civil engineering construction, and construction industry in year t, respectively, which are available in the annual *China Statistical Yearbook on Construction*.

(2) Material consumption

The material consumption data are collected from the annual *China Statistical Yearbook on Construction*, including five major materials (steel, cement, wood, glass, and aluminum). Similarly, the material consumption data also has the problem of data aggregation, which needs to be split. The annual building-related material consumption can be estimated by the following equation:

$$m^t_{bui,j} = m^t_{con,j} \times r^t_{bui} \tag{17}$$

where $m^t_{con,j}$ denotes the total material j consumption in the construction industry in year t and r^t_{bui} denotes the split ratio coefficient of the building sector in year t.

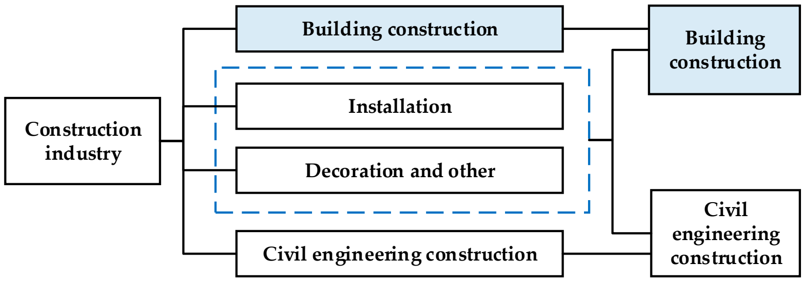

Figure 9. The disaggregation and aggregation of subsectors in the construction industry.

3.3.2. Data for the IO-LCA Model

1. Emission factors

The CEFs used in the IO-LCA accounting model are the same as the P-LCA accounting model. See Section 3.3.1.

2. Activity Data

(1) IO Tables

Considering the data availability and the accounting time frame, we collected the China IO tables for eight years, including 2005, 2007, 2010, 2012, 2015, 2017, 2018, and 2020, released by the National Bureau of Statistics of China [45]. The IO-LCA-based emission accounting requires sectoral economic IO data to be matched with energy consumption data, so we aligned the sectoral classification of the IO table and the energy balance table, as detailed in Table A1. The construction industry is divided into two subsectors, building construction and civil engineering construction, according to the split ratio coefficient measured in Section 3.3.1.

IO tables can be categorized into non-competitive and competitive IO tables based on whether domestic products and imports are distinguished as intermediate use and end-use. Since the sectoral energy data collected from *China Energy Statistical Yearbook* only involves domestic production, non-competitive IO tables are used as the matching data. However, only non-competitive IO tables for 2017, 2018, and 2020 were available. Most of the previous studies on building ECs using the IO-LCA method did not consider the mismatch of accounting data in this aspect [15,21]. To ensure data consistency, we transformed the competitive IO table to the non-competitive one using the scale decomposition method [46]; see the Supplementary Document for details.

(2) Energy consumption

The energy consumption data of various sectors are all collected from the annual *China Energy Statistical Yearbook* and are integrated according to the unified sectoral classification in Table A1. In addition, to avoid duplication or omission, we also made the following data modifications. First, the amount of energy loss was allocated among the final consumption items. Second, industrial non-fuel energy consumption (not generating CEs) was deducted from the energy data of fuel processing and chemical-related industries. Third, the fossil energy consumption of thermal power production and heating supply was added to the energy consumption of the production and supply of electric power and heat power industry.

4. Results and Discussions

4.1. Embodied Carbon Emissions

4.1.1. Results Based on the P-LCA Model

The total ECs of the building sector in 2020 were 2.10 billion tCO_2, accounting for approximately 23.1% of China's total energy-related CEs. Of this, the on-site construction direct ECs were 0.09 billion tCO_2, contributing to 4.5% of the total building ECs; the on-site construction indirect ECs were 0.04 billion tCO_2, accounting for 1.7%; and the indirect material production and transportation ECs were 1.97 billion tCO_2, representing 93.8%, as shown in Figure 10. Of the indirect material ECs, steel, cement, and aluminum are the most dominant emission contributors, representing 92.7% of the total building ECs. The proportion of each component is broadly in line with previous studies [15,22,26]. If measured by the weight of building materials, steel is merely a quarter of the five materials under accounting, while aluminum is even less than 2%. However, the high energy consumption and emissions in steel and aluminum production processes make their emission share significant. Moreover, if the process-related cement production emissions are also considered, the total ECs of China's building sector were 2.5 billion tCO_2, constituting 25.8% of the total national energy-related and cement industrial process-related CEs in 2020.

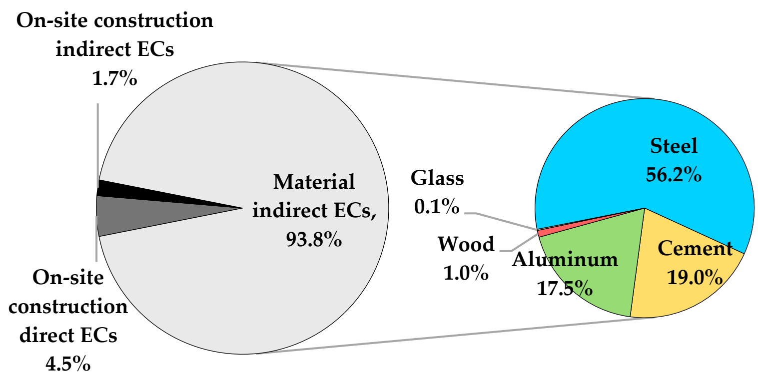

Figure 10. The composition of China's building embodied carbon emissions (2020).

From the perspective of historical evolution, China's annual building ECs have experienced the following stages since 2005, as illustrated in Figure 11. From 2005 to 2009, the total building ECs showed a steady growth trend, with an average annual growth rate of 13.0%. During this period, facing the expanding real estate market, the Chinese government intensively launched a series of regulatory policies on land, credit, taxation, and finance in 2007, which curbed the unreasonably rapid growth of construction development. In addition, the growth of the building sector slowed down due to the direct impact of the international financial crisis in 2008. Then from 2010 to 2012, emissions grew faster, with an average annual growth rate of 40.2%, and by 2012, building ECs reached the highest level in recent years at 2.69 billion tCO_2 (about 3.35 billion tCO_2 if cement industrial process-related CEs are included). This may be mainly influenced by the economic stimulus plan issued by the government after the financial crisis, in which a series of subsidized housing projects, urban and rural infrastructure construction, and other investment initiatives have led to a significant and sustained pulling effect on the construction industry. Subsequently, in 2013, China experienced economic restructuring and transformation, gradually shifting from investment-driven to demand-driven economic growth, and released the national new urbanization development plan for the first time, proposing to take an intensive, smart, green, and low-carbon new urbanization path. These policies and adjustments slowed down the growth of China's construction scale. As shown in the line in Figure 11, the average annual growth rate of building construction area decreases significantly after 2014, from 9.5% (2005–2014) to 3.8% (2015–2020). As a result, building ECs fluctuate around 2.2 billion tCO_2 between 2013 and 2020.

Figure 12 illustrates the composition of ECs from on-site construction during the construction, maintenance, and demolition stages and emission intensity per unit construction area from 2005 to 2020. The total ECs of building on-site construction were 130 million tCO_2 in 2020. Oil energy consumption is the main emission source, accounting for 66.3%, mainly due to the fact that the mechanical equipment and transportation tools at the construction site mostly rely on oil for energy supply. In terms of evolutionary trends, since 2005, the increase in construction ECs has gradually slowed down, with the average annual growth rate of 9.0% during the 11th Five-Year Plan period, 6.1% during the 12th Five Year Plan period, and only 2.4% during the 13th Five Year Plan period. In terms of the emission intensity, from 2005 to 2020, the ECs per unit construction area showed a decreasing trend, which experienced a significant reduction during the 11th and 12th Five Year Plan periods, and then remained stable during the 13th Five Year Plan period. The construction ECs intensity in 2020 was 39.8% lower than that in 2005.

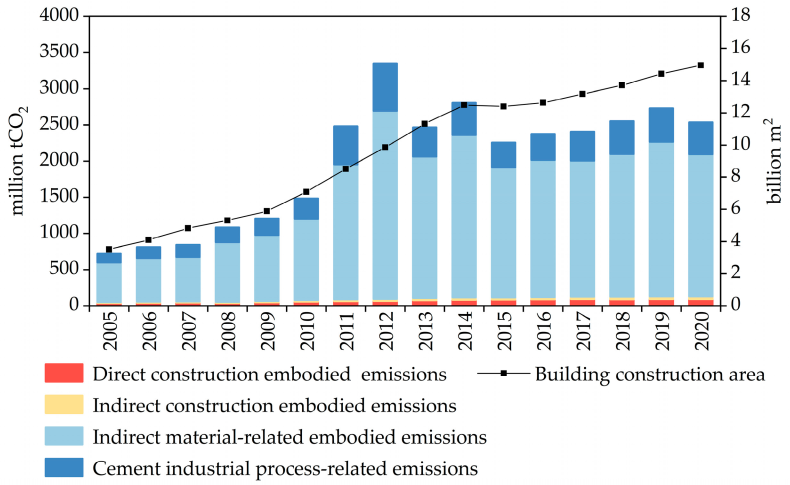

Figure 11. Total annual embodied carbon emissions of China's building sector measured by the P-LCA accounting model (2005–2020).

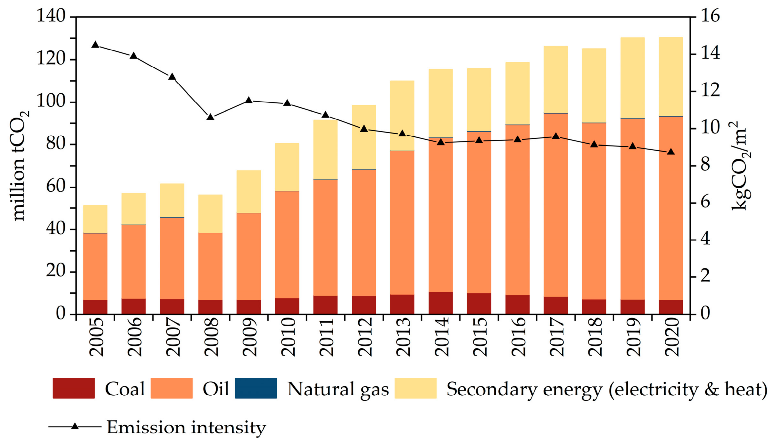

Figure 12. Annual building construction embodied carbon emissions (2005–2020).

4.1.2. Results Based on the IO-LCA Model

Figure 13 shows the total building ECs and their portion in China's total energy-related CEs during 2005–2020. Since China's IO table is not released annually, the figure only shows the accounting results in the year when the statistics are available. The ECs of China's building sector account for an increasingly significant share of the total national CEs. In 2005, the total building ECs were 720 million tCO_2, representing about 14.3% of the total national CEs, and by 2020, the total ECs exceeded three times the emissions in 2005, reaching 2.28 billion tCO_2, contributing 25.2% of China's total CEs. Regarding the emission trend, the total building ECs experienced rapid growth since 2005, reaching 2.21 billion tCO_2 by 2015, with an average annual growth rate of 12.0%. Subsequently, the increase in ECs slowed down significantly since 2016, and total emissions entered a plateau with slight fluctuations, stabilizing at around 2.2 billion tCO_2.

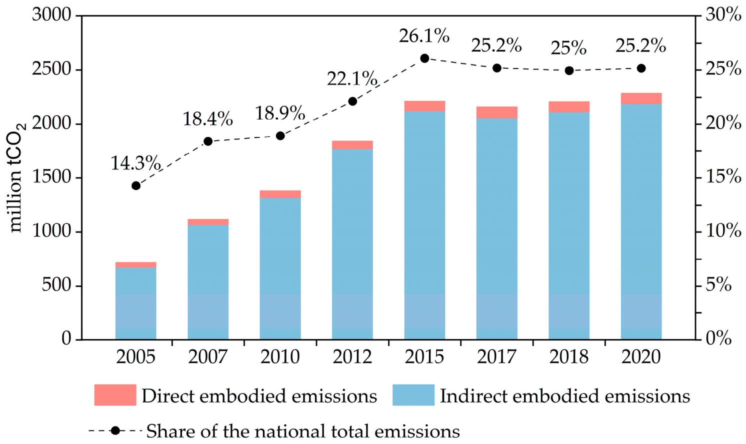

Figure 13. Total annual embodied carbon emissions of China's building sector measured by the IO-LCA accounting model (2005–2020).

From the perspective of ECs composition, the share of each component in the total emissions has not changed noticeably during 2005–2020. The direct ECs from on-site construction while building new construction, maintenance, and demolition stages represent about 5% of the total ECs, and the remaining 95% are indirect ECs from building-related industries. Of the 1.57 billion tCO_2 increase in building ECs in 2020 compared to 2005, 96.5% comes from the indirect building ECs.

From the perspective of emission intensity, it presents a downward trend, as shown in Figure 14, with the ECs intensity in 2020 decreasing by 24.7% compared to that in 2005. However, the total building ECs during the same period has more than tripled, mainly driven by the substantial growth of the construction scale. It can also be seen in Figure 14 that the annual building construction area in 2020 is more than four times that of 2005, and the annual completed building area is nearly twice the level of 2005, which is far greater than the reduction of emissions intensity.

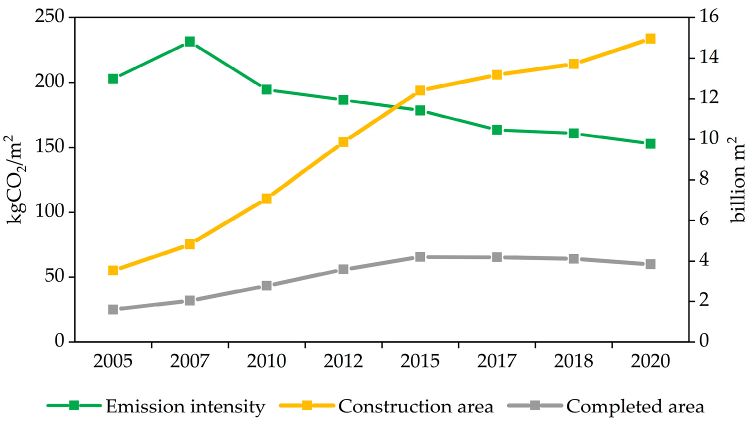

Figure 14. Building embodied emission intensity and construction scale (2005–2020).

As a typical end-of-chain sector, the final demand of the building sector has driven massive indirect ECs from upstream industries. Figure 15 illustrates the contribution of major industries to the total building ECs. Based on the average contribution proportion of the eight accounting years, the five industries cumulatively accounted for 90.2% of total building ECs, namely, the production and supply of electric power and heat power (40.6%), smelting and pressing of metals (25.6%), manufacture of non-metallic mineral products (16.7%), transport, storage, and post (5.0%), and chemical industry (2.2%). Figure 16 further shows the evolution tendency of the emission proportion of five main contributors during 2005–2020. The emission shares of the transport, storage, and post and chemical industry were relatively stable. The proportion of production and supply of electric power and heat power and smelting and pressing of metals showed a slight upward trend, while the share of manufacture of non-metallic mineral products, on the contrary, continued to decline in recent years, with the contribution in 2020 (13.7%) down 39.9% compared to 2007. This change indirectly reflects the low-carbon transition efforts of various industries and the change in the building materials demand structure during these years. Taking the manufacture of non-metallic mineral products (S13) as an example, the total demand for the industry S13, driven by the unit final use of the building sector, decreased by 14.8% from 2005 to 2020, and the emission intensity of the industry S13 also declined by 54.1%. However, the total demand for smelting and pressing of metals (S14) by the unit final demand of the building sector has not changed significantly during this period, and the decline of the emission intensity of the industry S14 (44.6%) is also less than that of the manufacture of non-metallic mineral products (S13). Then, the relative emission shares between industries shows the trend illustrated in Figure 16.

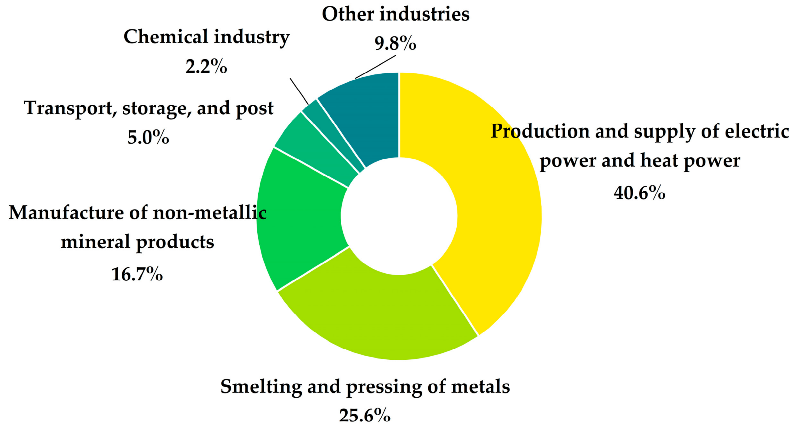

Figure 15. The average share of embodied emissions contributed by various industries.

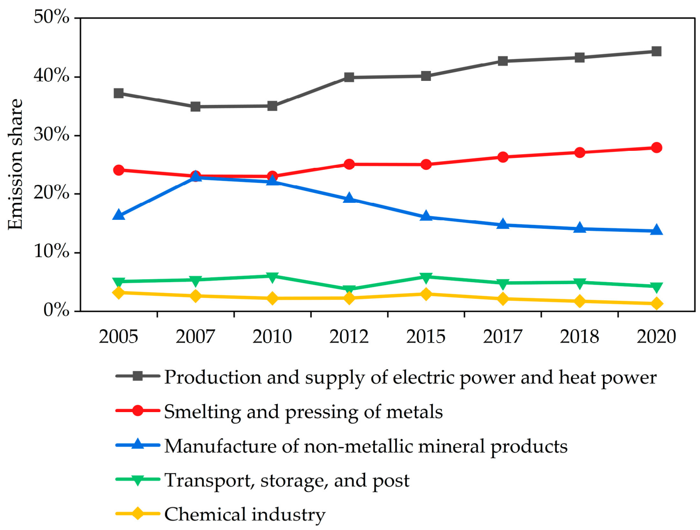

Figure 16. Emission share of main industries (2005–2020).

4.2. Comparison Analysis

4.2.1. Accounting Results of P-LCA and IO-LCA Models

The comparison of accounting results of total ECs in China's building sector based on the P-LCA model and IO-LCA model is shown in Figure 17. It can be observed that the overall evolution trend of ECs obtained by the two accounting models is highly consistent, with emissions first experiencing a rapid growth period and then entering a plateau after

2015. In addition, the contribution of the direct and indirect ECs calculated by both models are approximately 5% and 95%, respectively. However, it is easy to find that ECs obtained based on the IO-LCA model are generally slightly higher than the results obtained based on the P-LCA model (except in 2012). For example, the total building ECs in 2020 based on the bottom-up P-LCA model were 2.10 billion tCO_2, while the ECs calculated by the top-down IO-LCA model were 2.28 billion tCO_2, 8.6% higher than the former. Similar results have been mentioned in previous studies [15].

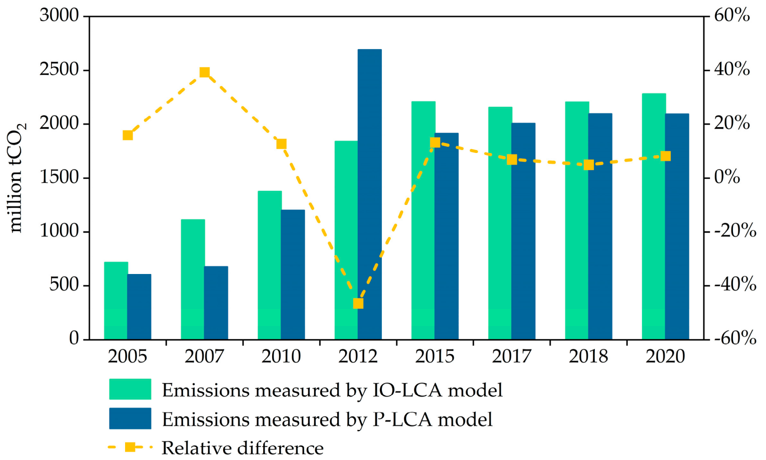

Figure 17. Comparison of the accounting results.

The possible reasons for such differences between the two accounting results may be twofold. On the one hand, there are inherent disparities in the accounting boundaries of the two models. The bottom-up P-LCA model is limited by data availability for complete emission accounting, and the results are usually subject to horizontal and vertical truncation errors, which are more noticeable in macro-level accounting applications. For instance, due to the lack of adequate information on the construction supply chain, the P-LCA accounting model only considers finite processes and major types of energies and building materials, while other related products and services are not involved. In comparison, the emission results based on the top-down IO-LCA accounting model have a complete boundary since the model can fully measure the input and output among all sectors in the economic system. Therefore, according to the model principles, the accounting results of the IO-LCA method are bound to be larger than the P-LCA method.

On the other hand, the result disparities may be caused by the statistical error of the activity data and emission factors. For example, the data on the consumption of major building materials by construction enterprises in the 2012 *China Statistical Yearbook on Construction* differed significantly from those of the adjacent years. Glass consumption in 2012 was twice that in 2011 and 2013. This data anomaly resulted in a significant deviation between the building ECs in 2012 obtained by the P-LCA method and the ECs by the IO-LCA method, as shown in Figure 17.

In summary, although there are some differences between the results of the two accounting models, they are generally consistent in terms of total emissions, composition and evolution trend, and can be corroborated and checked against each other. The effectiveness of the model method is verified to a large extent, which can provide more reliable macro-level annual building ECs for decision-makers.

4.2.2. Embodied and Operational Carbon Emissions

The total emissions in China's building sector (including ECs and OCs) in 2020 were 4.36 billion tCO_2, accounting for 48.0% of the total national energy-related CEs, as shown in Figure 18. The building ECs were 2.28 billion tCO_2, representing 52.4% of the total CEs in the building sector, while the building OCs were 2.07 billion tCO_2, accounting for 47.6%.

The share of building ECs in the total CEs of the building sector is becoming increasingly significant. In 2005, the proportion of building ECs was 42.1%, while after 2010, it was maintained at 50%–56%, equivalent to the OCs.

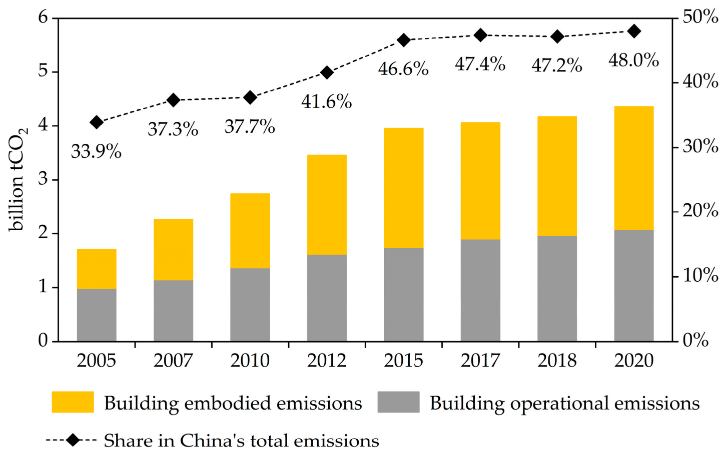

Figure 18. Embodied and operational carbon emissions of China's building sector (2005–2020).

From the perspective of emissions tendency, the growth of total building CEs slowed down and tended to be stable in recent years, as presented in Figure 18. During 2005–2010, the building CEs experienced a steady increase, with an average annual growth rate of 10.1%; between 2011 and 2015, the annual emission growth slowed down to 7.6%; and during 2016–2020, it declined to 2.0%. The overall change indicates that the total emissions have been controlled to some extent for the past few years. In addition, the proportion of total CEs from the building sector in the national CEs generally presents an increasing trend, growing from 33.9% in 2005 to 48.0% in 2020.

In terms of emission contribution, from 2005 to 2020, China's total energy-related CEs increased by 4.06 billion tCO_2, while the total building CEs increased by 2.66 billion tCO_2, contributing 65.5% to the national emission growth. Therefore, the CEs in the building sector are an essential cause of emission growth in China and a key area to achieving energy saving and emission reduction targets. Among them, the building ECs grew by 1.57 billion tCO_2 during 2005–2020, presenting 59.0% and 38.7% of the total CEs growth of the building sector and China, respectively, as illustrated in Figure 19, indicating that building ECs are the main source of the emission increase in the building sector and the key for emission reduction.

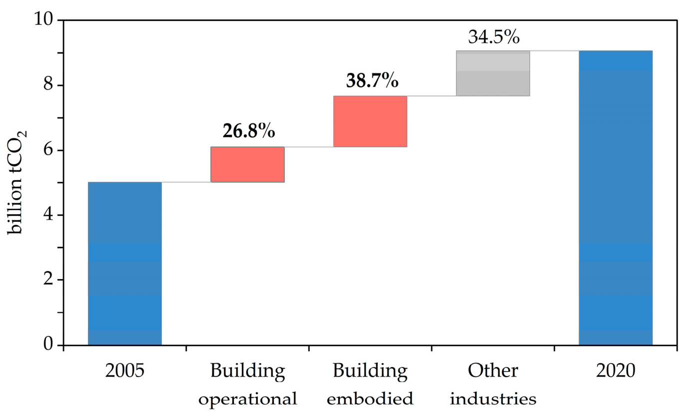

Figure 19. Emission contribution of the building sector to China's total emissions.

5. Conclusions

Targeting the limitations of existing methods in scope definition, coordination with statistical data, etc., this study develops the annual building ECs accounting models to unfold the historical trend and emission characteristics of China's building ECs, which provides feasible methods and data references for scientific understanding of emission status. First, the accounting scope is clearly defined, and the classification rules of direct and indirect emissions for both building ECs and OCs are unified. Second, the improved accounting models for total building ECs are developed based on P-LCA and IO-LCA methods. Third, fully considering the status of China's statistics and data quality requirements, the underlying time-varying datasets are constructed to enhance the reliability of accounting results. Fourth, the ECs of China's building sector during 2005–2020 are evaluated, and the evolution rules of the total emission, intensity, and emission mix are summarized to present a comprehensive emission image. Moreover, two comparative analyses are conducted to clarify the results difference and applicability of the developed methods, as well as the share of OCs and ECs in the total building CEs.

The key research findings are as follows:

- In 2020, the total ECs were about 2.28 billion tCO_2, accounting for 25.2% of China's total energy-related CEs. The indirect ECs represent approximately 95.9%, which is the most significant contributor and the key to alleviating the ECs in the building sector. From the perspective of emission tendency, the evolution of China's building ECs can be grouped into two stages. The embodied emissions during 2005–2015 grew rapidly, with an average annual growth rate of 12.0%, while from 2016 to 2020, the embodied emissions entered the plateau and gradually stabilized at roughly 2.2 billion tCO_2 with the slowdown of construction scale growth in recent years. Moreover, the overall ECs intensity showed a downward trend from 2005 to 2020, which declined by 24.7% in 2020 compared with 2005, indicating that the growth of China's building ECs is significantly scale-driven.
- The comparison of accounting results shows that the ECs estimated by the two models have strong consistency in total emissions, composition, and trend, which largely verifies the methods' effectiveness.
- The total CEs of China's building sector were 4.36 billion tCO_2, representing 48.0% of the total national CEs in 2020, of which ECs accounted for 52.4%. The share of ECs in the total building CEs is becoming increasingly significant, growing from 42.1% in 2005 to 50–56% nowadays, on par with the building OCs. Furthermore, the total CEs from China's building sector contributed 65.5% to the growth of the total national CEs from 2005 to 2020, of which building ECs contributed 38.7%. The analysis results indicate that building ECs are the primary source of emission growth and the key to cutting emissions in the building sector.

According to the accounting results, the following recommendations are proposed. From the demand side, controlling the construction scale by guiding intensive use, extending the lifetime of existing and new buildings, and avoiding unnecessary construction is the key to mitigating ECs from the source. From the supply side, improving the production efficiency of building material industries, promoting the use of green building materials, and optimizing the structure design are effective strategies for emission reduction. Besides, increasing the proportion of low-carbon energy consumption by upgrading construction machinery and equipment can also help cut building ECs.

Although we provide practicable accounting methods and detailed analysis of China's building ECs, there are certain limitations. First, we only consider five primary materials owing to the data availability, which can be further enhanced with the development of national-wide statistics to improve the accuracy of emission accounting. Second, due to the lack of knowledge on differences in the material and energy consumption of buildings and civil engineering projects, there is an assumption of equal consumption per unit economic output of various subsectors when performing sectoral data splitting. With the deepening of related studies, the methods for sectoral data disaggregation can be advanced.

Further research can be conducted to investigate the influencing factors and emission reduction potential of building ECs by using the accounting results obtained from this study, which can provide clearer pathways for the low-carbon development of the building sector. Moreover, the spatial and temporal heterogeneity of building ECs in different regions can be further explored based on accounting models and datasets developed in this study.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13010211/s1.

Author Contributions: Conceptualization, C.Z. and X.L.; Data curation, C.Z.; Funding acquisition, X.L.; Investigation, C.Z. and Z.Y.; Methodology, C.Z.; Supervision, X.L.; Validation, C.Z., Z.Y. and B.H.; Visualization, C.Z. and Z.Y.; Writing—original draft, C.Z.; Writing—review & editing, C.Z., Z.Y., B.H. and X.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number 72071120) and the China National Key R&D Program (grant number 2018YFC0704400).

Data Availability Statement: Data are contained within the article and Supplementary Information. Additional supporting data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Sectoral classification.

Code	Sector	Code	Sector
S1	Agriculture, forestry, animal husbandry, and fishery	S15	Manufacture of metal products
S2	Mining and washing of coal	S16	Manufacture of general and special-purpose machinery
S3	Extraction of petroleum and natural gas	S17	Manufacture of transport equipment
S4	Mining and processing of metal ores	S18	Manufacture of electrical machinery and apparatus
S5	Mining and processing of nonmetal ores	S19	Manufacture of computers, communication, and other electronic equipment
S6	Manufacture of foods and tobacco	S20	Manufacture of measuring instruments and machinery
S7	Manufacture of textile	S21	Other manufacture
S8	Manufacture of textiles, wearing apparel and accessories, leather, fur, feather, related products, footwear, etc.	S22	Production and supply of electric power and heat power
S9	Processing of timber, manufacture of furniture	S23	Production and supply of gas and water
S10	Manufacture of paper, printing, articles for culture, education, andsports activity	S24	Transport, storage, and post
S11	Processing of petroleum, coal, and other fuels	S25	Wholesale and retail trades, hotels, and catering services
S12	Chemical industry	S26	Other service industry
S13	Manufacture of non-metallic mineral products	S27	Building construction
S14	Smelting and pressing of metals	S28	Civil engineering construction

References

1. Zhou, N.; Khanna, N.; Feng, W.; Ke, J.; Levine, M. Scenarios of Energy Efficiency and CO2 Emissions Reduction Potential in the Buildings Sector in China to Year 2050. *Nat. Energy* **2018**, *3*, 978–984. [CrossRef]
2. Intergovernmental Panel on Climate Change. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2022.
3. Zhu, C.; Chang, Y.; Li, X.; Shan, M. Factors Influencing Embodied Carbon Emissions of China's Building Sector: An Analysis Based on Extended STIRPAT Modeling. *Energy Build.* **2022**, *255*, 111607. [CrossRef]
4. BERC. *2021 Annual Report on China Building Energy Efficiency*; China Building Industry Press: Beijing, China, 2021; ISBN 978-7-112-26521-3.
5. Yang, X. *Research on Building Energy Efficiency in China Based on Energy Consumption Data*; Tsinghua University: Beijing, China, 2009.
6. Huo, T.; Ren, H.; Zhang, X.; Cai, W.; Feng, W.; Zhou, N.; Wang, X. China's Energy Consumption in the Building Sector: A Statistical Yearbook-Energy Balance Sheet Based Splitting Method. *J. Clean. Prod.* **2018**, *185*, 665–679. [CrossRef]
7. Cai, W.; Cai, Y. National Construction Carbon Emission Calculation Method Research and Data Analysis. *Constr. Manag. Res.* **2020**, *1*, 61–76.
8. China Association of Building Energy Efficiency. China Building Energy Consumption Research Report (2020). Available online: https://mp.weixin.qq.com/s/9o_ZzWNVrP9QQKZq4Kls9w (accessed on 3 December 2022).
9. Onat, N.C.; Kucukvar, M.; Tatari, O. Scope-Based Carbon Footprint Analysis of US Residential and Commercial Buildings: An Input–Output Hybrid Life Cycle Assessment Approach. *Build. Environ.* **2014**, *72*, 53–62. [CrossRef]
10. U.S. Energy Information Administration. U.S. Energy-Related Carbon Dioxide Emissions. 2020. Available online: https://www.eia.gov/environment/emissions/carbon/ (accessed on 3 December 2022).
11. Chastas, P.; Theodosiou, T.; Bikas, D. Embodied Energy in Residential Buildings-towards the Nearly Zero Energy Building: A Literature Review. *Build. Environ.* **2016**, *105*, 267–282. [CrossRef]
12. Azari, R.; Abbasabadi, N. Embodied Energy of Buildings: A Review of Data, Methods, Challenges, and Research Trends. *Energy Build.* **2018**, *168*, 225–235. [CrossRef]
13. Chen, W.; Yang, S.; Zhang, X.; Jordan, N.D.; Huang, J. Embodied Energy and Carbon Emissions of Building Materials in China. *Build. Environ.* **2022**, *207*, 108434. [CrossRef]
14. Bai, J.; Qu, J. Investigating the Spatiotemporal Variability and Driving Factors of China's Building Embodied Carbon Emissions. *Environ. Sci. Pollut. Res.* **2021**, *28*, 19186–19201. [CrossRef]
15. Zhu, W.; Feng, W.; Li, X.; Zhang, Z. Analysis of the embodied carbon dioxide in the building sector: A case of China. *J. Clean. Prod.* **2020**, *269*, 122438. [CrossRef]
16. Chen, J.; Shi, Q.; Shen, L.; Huang, Y.; Wu, Y. What Makes the Difference in Construction Carbon Emissions between China and USA? *Sustain. Cities Soc.* **2019**, *44*, 604–613. [CrossRef]
17. Zhang, Y.; Yan, D.; Hu, S.; Guo, S. Modelling of Energy Consumption and Carbon Emission from the Building Construction Sector in China, a Process-Based LCA Approach. *Energy Policy* **2019**, *134*, 110949. [CrossRef]
18. Huang, L.; Krigsvoll, G.; Johansen, F.; Liu, Y.; Zhang, X. Carbon Emission of Global Construction Sector. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1906–1916. [CrossRef]
19. Shi, Q.; Chen, J.; Shen, L. Driving Factors of the Changes in the Carbon Emissions in the Chinese Construction Industry. *J. Clean. Prod.* **2017**, *166*, 615–627. [CrossRef]
20. Guan, J.; Zhang, Z.; Chu, C. Quantification of Building Embodied Energy in China Using an Input–Output-Based Hybrid LCA Model. *Energy Build.* **2016**, *110*, 443–452. [CrossRef]
21. Zhang, X.; Wang, F. Hybrid Input-Output Analysis for Life-Cycle Energy Consumption and Carbon Emissions of China's Building Sector. *Build. Environ.* **2016**, *104*, 188–197. [CrossRef]
22. Zhang, Z.; Wang, B. Research on the Life-Cycle CO2 Emission of China's Construction Sector. *Energy Build.* **2016**, *112*, 244–255. [CrossRef]
23. Chang, Y.; Huang, Z.; Ries, R.J.; Masanet, E. The Embodied Air Pollutant Emissions and Water Footprints of Buildings in China: A Quantification Using Disaggregated Input–Output Life Cycle Inventory Model. *J. Clean. Prod.* **2016**, *113*, 274–284. [CrossRef]
24. Peng, C.; Jiang, Y.; Qing, Y. *Low Carbon Buildings and Low Carbon Cities*; China Environment Publishing Group: Beijing, China, 2018.
25. Zhang, X.; Wang, F. Life-Cycle Carbon Emission Assessment and Permit Allocation Methods: A Multi-Region Case Study of China's Construction Sector. *Ecol. Indic.* **2017**, *72*, 910–920. [CrossRef]
26. Wu, P.; Song, Y.; Zhu, J.; Chang, R. Analyzing the influence factors of the carbon emissions from China's building and construction industry from 2000 to 2015. *J. Clean. Prod.* **2019**, *221*, 552–566. [CrossRef]
27. World Green Building Council. *Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon*; World Green Building Council: London, UK, 2019.
28. Zhu, C.; Li, X.; Zhu, W.; Gong, W. Embodied Carbon Emissions and Mitigation Potential in China's Building Sector: An Outlook to 2060. *Energy Policy* **2022**, *170*, 113222. [CrossRef]
29. Dixit, M.K. Embodied Energy Analysis of Building Materials: An Improved IO-Based Hybrid Method Using Sectoral Disaggregation. *Energy* **2017**, *124*, 46–58. [CrossRef]
30. Leontief, W. Environmental Repercussions and the Economic Structure: An Input-Output Approach. *Rev. Econ. Stat.* **1970**, *52*, 262–271. [CrossRef]

31. Intergovernmental Panel on Climate Change. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; The Institute for Global Environmental Strategies: Hayama, Japan, 2006.
32. National Bureau of Statistics of China. *China's Input-Output Table in 2018*; China Statistics Press: Beijing, China, 2020.
33. Miller, R.; Blair, P. *Input-Output Analysis: Fundamentals and Extensions*; Chinese Minmin University Press: Beijing, China, 2019; ISBN 978-7-300-26845-3.
34. Liu, Z.; Guan, D.; Wei, W.; Davis, S.J.; Ciais, P.; Bai, J.; Peng, S.; Zhang, Q.; Hubacek, K.; Marland, G. Reduced Carbon Emission Estimates from Fossil Fuel Combustion and Cement Production in China. *Nature* **2015**, *524*, 335–338. [CrossRef]
35. CEADs Emission Factors. Available online: https://www.ceads.net/data/emission_factors/ (accessed on 3 December 2022).
36. Li, W.; Sun, W.; Li, G.; Cui, P.; Wu, W.; Jin, B. Temporal and Spatial Heterogeneity of Carbon Intensity in China's Construction Industry. *Resour. Conserv. Recycl.* **2017**, *126*, 162–173. [CrossRef]
37. Liu, J.; Liu, Y.; Yang, L.; Hu, Y. Study on the Calculation Method of Carbon Emission from the Whole Building Industry Chain in China. *Urban Dev. Stud.* **2017**, *24*, 28–32.
38. Ministry of Ecology and Environment of the People's Republic of China. 2019 China Regional Power Grid Baseline Emission Factors for Emission Reduction Project. Available online: https://www.mee.gov.cn/ywgz/ydqhbh/wsqtkz/202012/t20201229_815386.shtml (accessed on 3 December 2022).
39. Su, S.; Li, X.; Zhu, Y. Dynamic Assessment Elements and Their Prospective Solutions in Dynamic Life Cycle Assessment of Buildings. *Build. Environ.* **2019**, *158*, 248–259. [CrossRef]
40. National Bureau of Statistics of China. *China Energy Statistical Yearbook*; China Statistics Press: Beijing, China, 2020.
41. Wang, Q. *Energy Data*; Energy Foundation: Beijing, China, 2020.
42. China Building Material Council. Almanac of China Building Materials Industry. Available online: https://data.cnki.net/yearbook/Single/N2022040143 (accessed on 3 December 2022).
43. Tang, Y. Comparison and Analysis of Domestic and Foreign Railway Energy Consumption. *Railw. Transp. Econ.* **2018**, *40*, 93–99. [CrossRef]
44. Pang, S. The Analysis of Impact on Transportation Energy Consumption by Transportation Structure. Master's Thesis, Beijing Jiaotong University, Beijing, China, 2017.
45. National Bureau of Statistics of China. Input-Output Tables. Available online: https://data.stats.gov.cn/ifnormal.htm?u=/files/html/quickSearch/trcc/trcc01.html&h=740. (accessed on 3 December 2022).
46. Chen, Q. *Accounting and Decomposition of China's Industry Carbon Emissions: Based on the Perspective of Input-Output Structure Decomposition Analysis*; Economic Science Press: Beijing, China, 2019; ISBN 978-7-5218-0246-7.