Life Cycle Building Carbon Emissions Assessment and Driving Factors Decomposition Analysis Based on LMDI—A Case Study of Wuhan City in China

Yuanyuan Gong * and Deyong Song

School of Economics, Huazhong University of Science and Technology, Wuhan 430074, China;
dysong@hust.edu.cn
* Correspondence: yygong@hust.edu.cn; Tel.: +86-027-8754-3151

Abstract: Carbon emissions calculation at the sub-provincial level has issues in limited data and non-unified measurements. This paper calculated the life cycle energy consumption and carbon emissions of the building industry in Wuhan, China. The findings showed that the proportion of carbon emissions in the construction operation phase was the largest, followed by the carbon emissions of the indirect energy consumption and the construction material preparation phase. With the purpose of analyzing the contributors of the construction carbon emissions, this paper conducted decomposition analysis using Logarithmic Mean Divisia Index (LMDI). The results indicated that the increasing buidling area was the major driver of energy consumption and carbon emissions increase, followed by the behavior factor. Population growth and urbanization, to some extent, increased the carbon emissions as well. On the contrary, energy efficiency was the main inhibitory factor for reducing the carbon emissions. Policy implications in terms of low-carbon construction development were highlighted.

Keywords: life cycle assessment; carbon emissions; LMDI; low-carbon buildings

1. Introduction

With the increasing environmental awareness, much attention has been paid to the greenhouse emissions, especially the carbon dioxide (CO_2) emissions, among governments and scholars all over the world [1]. Building industry has become a target for environmental improvement as the building sector accounted for about 40% of the world's energy consumption and 33% of the related global greenhouse gas emissions [2].

As the process of industrialization and urbanization is speeding up in China, the ever-growing demand for buildings has inevitably led to a series of issues associated with resources and the environment, particularly with a rapid growth in CO_2 emissions because of the huge energy consumption [3]. Due to the increasing awareness on environmental issues and pressure from various government bodies and environmental activists, many attempts have been made to assess building carbon emissions and to reduce building energy consumption [4]. However, most prior research into building carbon emissions focused on the situations at the national level or provincial level whereas research at the city level was often neglected due to the limited data samples. Therefore, it is important to pay much attention to the carbon emissions assessment at the city level, which may be beneficial to accurately calculate the total carbon emissions.

Additionally, heated discussions have been made by researchers on the methods of identifying relevant factors in affecting carbon emissions reduction [5]. China is facing a tough challenge to reduce carbon emissions, further research on exploring the key factors influencing the building

energy consumption are also necessary as it is crucial for a better understanding of the causes of carbon emissions and its current environmental impacts on the building industry at the city level.

In this study we conduct the life cycle carbon emissions assessment of the building sector in Wuhan, a city in Hubei province of China, and identify the key factors influencing the changes of building energy consumption and building carbon emissions using Logarithmic Mean Divisia Index (LMDI) decomposition analysis. Furthermore, this paper proposes several policy implications for promoting carbon emissions reduction and low-carbon development for the building sector in Wuhan. This study may contribute to achieving regional sustainable development for low-carbon buildings, as well as the carbon emissions reduction target for 2020 in the "new normal" economy of China.

2. Literature Review

Models for building carbon emissions assessment are mostly based on the life cycle theory in previous studies. Adalberth [6] calculated the life cycle energy consumption of buildings at different stages. Michiya, Tatsuo, and Kiyoshi [7] calculated the life cycle energy consumption of Japanese residential buildings, and further calculated the carbon dioxide emissions. Nassen, Holmberg and Wadeskog [8] compared the characteristics and the application range between life cycle and input-output methods. The results revealed that the life cycle method was applicable to the carbon emissions calculation for a single building, while the latter was suitable for analyzing buildings' carbon emissions in the community. Chen [9] analyzed the factors influencing the life cycle carbon emissions of low-carbon buildings and it established a low-carbon assessment system. Chen and Luo [10] revealed that the energy consumption of the building materials preparation stage and the operation stages were important parts of the life cycle building energy consumption.

The mainstream method analyzing the impacting factors of CO_2 emissions is to analyze the annual time series data with different kinds of factor decomposition methods [11–13]. Wang *et al.* [14] adopted the LMDI method to decompose the CO_2 emissions from 1957 to 2000. The results showed that the energy intensity, which was regarded as the technical factor, was the most important factor for the carbon emissions reduction, and the energy structure to some extent contributed to the reduction as well, and economic growth increased the carbon emissions. Fan *et al.* [15], Xu, Liu, and Jiang [16], Tang, Zhang, and Wang [17] decomposed the scale, structure, and the technology factors influencing China's carbon emissions with different methods and data. Although studies reviewed above are vital for the carbon emissions research with distinctive features, they also have some limitations: (1) limited data may lead to uncompleted decomposition; (2) regional differences in terms of the variables that affecting carbon emissions; and (3) a lack of consistent analytic framework.

As for the driving factors of the building carbon emissions, in general, there are four major categories from the published literature. They are: (a) demographic factors, including population number, urbanization rate, and the age structure, *etc.*; (b) economic development factors, including GDP, gross output value of construction [18], *etc.*; (c) the level of urban construction factors, including actual building area, gas penetration, and the central heating area, *etc.*; and (d) the residents' living factors, including the per capita living space, per capita disposable income, and residents' consumption level [19], *etc*. Some scholars analyze the driving factors in two aspects, which are the positive and the negative driving factors affecting the carbon emissions. The positive driving factors caused the carbon emissions increase are residents' consumption level, the energy consumption structure, and the building area [20]. While the key negative driving factors,which decreased the carbon emissions, are the energy efficiency [21], energy structure [22], technology, emissions reduction policy, and energy-saving behaviors. As analyzed above, the highly-cited driving factors on the building carbon emissions growth are population, urbanization rate, building area, and the consumption level, and the driving factors on the carbon emissions reduction are energy efficiency, energy structure, and the technical factor.

In terms of the research regions, the current low-carbon building studies mostly focuses on the data at the national or provincial level. Zhang, Zhou, and Lu [23] constructed a carbon emissions measurement model to analyze the present situation of the urban building carbon emissions. Chen and Zhu [24] quantitatively analyzed the building carbon emissions indexes of Shanghai's residential and public buildings and predicted the future development goals with the scenario analysis method. However, there are few studies assessing the carbon emissions at the provincial level, city level and even the county level considering the situation of China's statistic problems such as limited data access, incomplete statistic data and data deficient, *etc*. Therefore, this paper selects Wuhan, a secondary city in the middle of China, as the research subject and constructs a mathematical model for the life cycle carbon emissions assessment, which provides evidence for assessing carbon emissions at the small and medium-sized city level. It is a significant step to identify scientific policy implications for Wuhan's low-carbon building development.

3. Life Cycle Building Carbon Emissions Assessment

3.1. Life Cycle Assessment Concept in the Building Sector

Life cycle assessment (LCA) is accepted worldwide as a tool to measure industrial products or service related environmental factors by quantitatively evaluating CO_2 emissions and its environmental and ecological impacts, and to evaluate alternatives for environmental improvement in the building industry [25,26].

Nowadays, research on LCA in the building system has increased considerably from building materials to the end-of-life of the building [27]. The implementation of life cycle carbon emissions assessment of the building sector can maximize the overall environmental benefits by facilitating designers, engineers, users, and decision-makers with accurate evaluation of carbon emissions, as well as specific emission reduction plans during different stages [28].

3.2. Stages of LCA in the Building Industry

Energy consumption and carbon emissions in the building industry are more difficult to assess as the construction materials are massive, diverse and their production methods are inconsistent [29]. There are many different methods in dividing the stages of LCA in the building sector. Many attempts on building environmental evaluation primarily focus on the carbon emissions from the production and transportation of the building materials, construction process and operational process, while the environmental impacts from other states are often neglected. Generally, this study on LCA carbon emissions assessment in the building industry intends to consider the total amount of carbon emissions that exhausted in the full life cycle of buildings, which includes the phases of design and planning, resources input, manufacturing, operation and use, maintenance, demolition and recycling [30]. However, the amount of carbon emissions in the design and planning phase is small and hard to measure, this paper will not consider the emissions from the building design and planning stage. Therefore, the life cycle carbon emissions in the building sector can be divided into five stages, which are the stages of material preparation, construction and reformation, operation (including the use and maintenance of the building), demolition, wastes treatment, and recycling [31] (as seen in the Figure 1).
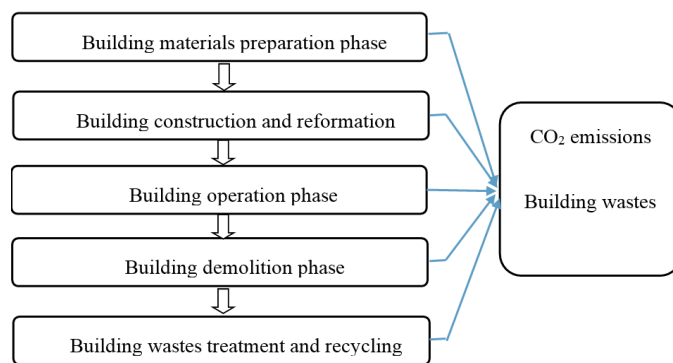
Figure 1. Conceptual couplings between a building life cycle stages and CO_2 emissions (Revised from You *et al.* (2011) [31] and Chau *et al.* (2015) [1]).

Meanwhile, the building equipment production, building materials transportation, as well as the production, processing, and the transportation of the energy that are required during the building construction, known as indirect emissions, can consume energy and CO_2 emission as well. Consequently, it is necessary to add the indirect emissions into the building life cycle carbon emissions assessment.

3.3. Methodology

3.3.1. Life Cycle Carbon Emissions Assessment

From the perspective of LCA, energy consumption in the life cycle of urban building system can be represented by aggregating the energy consumption of each stage. It can be represented mathematically by:

$$E_w = \sum_{i=1}^{5} E_i \qquad (1)$$

where E_w represents the life cycle energy consumption of the building sector in Wuhan city and E_i represents the energy consumption of the building sector during the phase *i* of the life cycle. Carbon emissions can be mathematically determined from the following:

$$CO_2 = E_w \cdot K \qquad (2)$$

where E_w is the life cycle building energy consumption from different phases of the life cycle building. For the convenience of computing, all the energy consumption data are converted into an equivalent of standard coal, *K* is the carbon emission coefficient of the standard coal. Due to the differences of technical conditions and energy structures in different countries and regions, the standards of the coefficient *K* are different. Generally, it adopts the average default value provided by the National Greenhouse Gas Emissions Inventory Guide (IPCC) [32] and the data provided by the national authoritative organizations, which can reduce the deviation of the data provided by different organizations. Therefore, this paper adopts 2.69 tons as the conversion standard, which is viewed as the average value of the CO_2 emission coefficients of energy fuels with an equivalent of standard coal provided by several research agencies. In other words, this means that one ton of standard coal combustion exhaust about 2.69 tons of CO_2 [33].

3.3.2. Data Sources

In this study, data for the life cycle energy consumption of the urban building industry come from the annual *China Statistical Yearbook* (2001–2013) [34], *China Energy Statistical Yearbook* (2001–2013) [35], *Hubei Statistical Yearbook* (2001–2013) [36], and *Wuhan Statistical Yearbook*

(2001–2013) [37]. Due to the availability of data, this study selects the data from the year of 2000 to 2012.

3.4. Life Cycle Energy Consumption Assessment

The life cycle energy consumption assessment of urban building system in Wuhan is calculated in two aspects, including the direct and the indirect energy consumption of the five phases of the life cycle.

3.4.1. Direct Life Cycle Energy Consumption

The direct life cycle energy consumption of the building sector covers the phases of building material preparation, construction and demolition, operation, treatment, and recycling. The following part illustrates the detailed energy consumption in each phase.

Energy Consumption in the Building Material Acquisition Stage

The energy consumption of construction materials include the energy consumption that is produced during the manufacturing processes of building materials such as steel, non-metallic building materials, non-ferrous metal materials, and chemical building materials that needed in the process of building construction (see the Table 1) [38]. All of these construction material data comes from the *China Statistical Yearbook* (2001–2013) [34]. As the specific consumption data of the building materials at the city level is difficult to obtain, this research uses the proportion of energy consumed by building materials to the total national materials to calculate the energy consumption of Wuhan's building materials. On the basis of the previous studies, the percentage of steel, non-metallic materials, non-ferrous metal materials, and chemical building materials consumption accounted for 41% [39], 98% [40], 25% [41], and 25% [42] respectively. In the various energy consumption calculation, it is assumed that the annual building material consumption ratio remains the same. The direct energy consumption E_1 of Wuhan's building materials preparation stage can be estimated by the following formula:

$$E_1 = \sum (m_i Q_i) \times \frac{S_w}{S_z} \tag{3}$$

where m_i is the consumption proportion of the building material i. Q_i is the total energy consumption consumed in the production of the material i. S_w is the total building area of Wuhan city and S_z is the total building area of China.

Table 1. Raw materials consumed in the building material acquisition stage.

Categories	Content
Steel	ferrous metal acquisition black metal smelting and rolling
Non-metallic building materials	non-metallic mineral non-metallic mineral products timber processing
Non-ferrous metal materials	non-ferrous metal selecting non-ferrous metal smelting and rolling
Chemical building materials	plastic

Source: the classification approach was adapted from Li and Jiang [38].

Energy Consumption in the Buildings Operation Stage

The direct energy consumption in the operation stage of the building system is the heating energy consumption. In consideration of the differences between the south and the north in the terms of the heating system, energy consumption in the operation phase to the north of the Yangtze river covers the heating energy consumption E_c (including the urban coal consumption of the

living consumption, heating coal consumption, transportation, warehousing, and postal service coal consumption and the wholesale and retail trade and catering industry coal consumption), the residential energy consumption except the heating energy consumption E_z (including the consumption of electricity, natural gas and liquefied petroleum gas), and the public buildings energy consumption without consisting of the heating energy consumption of E_g (including the power consumption of transportation, warehousing and postal service, wholesale, retail and accommodation, catering and others). Therefore, the direct energy consumption E_3 in the operation stage of Wuhan's urban construction can be represented by the following formula:

$$E_3 = E_c + E_z + E_g \tag{4}$$

As the energy consumption balance data of Wuhan is not available and the heating energy consumption is different from the north to the south, this study employed the data of Hubei province as it is the closest way to estimate Wuhan's situation. Therefore, the energy consumption data in the operation phase mainly come from the energy consumption balance of *Hubei Statistical Yearbook* (2001–2013) [36]. In addition, this study unified the unit of all the energy consumption into ten thousand tons of standard coal when was calculating the energy consumption for the statistical convenience. The electricity, natural gas, and liquefied petroleum gas (LPG) data were converted accordingto the referenced standard coal coefficients of all kinds of energy in the appendix of *China Statistical Yearbook* (2013) [34].

Energy Consumption in the Construction and Demolition Phases

The actual energy consumption data in the construction and demolition stage is not easy to obtain. In the case of the limited data, usually it is a better way to estimate it based on existing research results. Zhang, Zhou, and Lu [23] adopted the energy consumption of the construction industry in the *China Statistical Yearbook* (2001–2013) [34] as the sum of the energy consumption E_2 in the construction phase and the energy consumption E_4 in the demolition phase of urban building system. Their study calculated the direct energy consumption of the construction and demolition phases according to the percentage of Wuhan's construction area out of the national construction area.

Energy Consumption in the Building Treatment and Recycling Phases

Urban construction treatment and recycle stage are mainly to classify and recycle the plastic, glass, metal, and other easy-to-recycle materials. The CO_2 emissions in this process mainly includes the waste transportation and processing [15], which are classified as the indirect energy consumption. On the contrary, the recycle stage can reuse some building materials, which are able to offset some carbon emissions of the energy consumption. However, as the relevant data is difficult to obtain and China's present construction waste recycling rate is less than 5%, this study did not consider the energy consumption that was offset during the recycling phase.

3.4.2. Indirect Life Cycle Energy Consumption

The indirect energy consumption of urban construction is the life cycle energy consumption during the various stages of the building, including the energy consumption of all kinds of construction equipment, construction machinery manufacture, building materials transportation, and the energy production, processing, and transportation. Therefore, the total indirect life cycle energy consumption Q_w of buildings in Wuhan can be represented by the formula:

$$Q_w = \sum (x_i y_i) \times \frac{S_w}{S_z} \tag{5}$$

where x_i is the proportion of the energy consumption of the i kind of indirect energy consumption in the building section, y_i indicates the i kind of total indirect energy consumption of life cycle

buildings, S_w is urban construction area in Wuhan, S_z is the total national building area. As the indirect energy consumption statistical data is difficult to obtain, this research adopts the existing research results to calculate the indirect energy consumption [40–42]. The data of the three parts is from *China Energy Statistical Yearbook* (2001–2013) [35]. Specifically, as seen in Table 2, transportation energy consumption covers the total energy consumption of transportation, warehousing and postal service. Energy processing industry includes coal mining and washing industry, oil and gas industry, oil processing and coking industry, nuclear fuel processing industry energy consumption and the production and supply of electricity and heat. Machinery manufacturing includes total energy consumption of the metal products industry, general equipment energy consumption industry, and total energy consumption of the special manufacturing equipment industry [38]. In conclusion, the indirect energy consumption of the buildings in Wuhan can be computed as the product of the indirect energy consumption of national buildings and the proportion of Wuhan's building area out of the total national building area.

Table 2. Indirect life cycle energy consumption of buildings.

Categories	Content
Transportation energy consumption	total energy consumption of transportation, warehousing, and postal service
Energy consumption in the energy processing industry	coal mining and washing industry, oil and gas industry, oil processing and coking, and nuclear fuel processing industry energy consumption and the production and supply of electricity and heat
Energy consumption in the machinery manufacturing	metal products industry total energy consumption, general equipment energy consumption and special manufacturing equipment total energy consumption

Source: the classification approach was adapted from Li and Jiang [38].

3.4.3. Total Life Cycle Energy Consumption

According to the above analysis, the energy consumption of urban building is mainly composed of the energy consumption in the building materials preparation stage, the building operation stage and the indirect energy consumption stage, which is consistent with the most domestic studies. Thus, the energy consumption of life cycle buildings in Wuhan can be defined as the following formula:

$$E_w = E_1 + E_3 + (E_2 + E_4) + Q_w \tag{6}$$

where E_w denotes the total life cycle of building energy consumption in Wuhan City, E_1 is the energy consumption of the building materials preparation phase, E_3 is the energy consumption of the building operation phase, $(E_2 + E_4)$ is the sum of building energy consumption of the construction and demolition stages, and Q_w stands for the indirect energy consumption that analyzed in the Equation (5).

3.5. Discussions on Life Cycle Building Carbon Emissions Assessment

As the various stages of life cycle energy consumption in the construction industry has converted into standard coal, according to the Equation (2), carbon emissions of life cycle energy consumption of building in Wuhan can be calculated by the product of energy consumption and the corresponding energy consumption coefficient.

As shown in Figure 2, the carbon emissions of total life cycle energy consumption of building increased with a fluctuation from 2000 to 2012 in Wuhan. The carbon emission rose from 17.8459 million tons of CO_2 in 2000 to 23.7226 million tons of CO_2 in 2012, which has increased by 33%. Among them, the carbon emissions of direct energy consumption (including the energy consumption from the phases of building material preparation, construction and demolition,

operation, treatment, and recycling) and the carbon emissions of total energy consumption of buildings were both on a rise. Compared with 2000, the direct energy consumption carbon emissions increased by 81% in 2012. Obviously, the carbon emissions of energy consumption were growing rapidly during this period. This is mainly because of the industry's energy consumption is relatively stable as the indirect energy consumption mainly comes from the machinery manufacturing industry, transportation industry and energy industry. On the contrary, the carbon emissions of indirect energy consumption (including the energy consumption of all kinds of construction equipment, construction machinery manufacture, building materials transportation, and the energy production, processing and transportation) changed a little and had a slight decline, where the carbon emissions of indirect energy consumption dropped by 16% from 2012 to 2000. According to the division of the direct and indirect energy consumption emissions, the direct energy consumption carbon emissions was the major contributor of the total energy consumption carbon emissions of the building industry, while the indirect energy consumption accounted for about a third of the total carbon emissions.
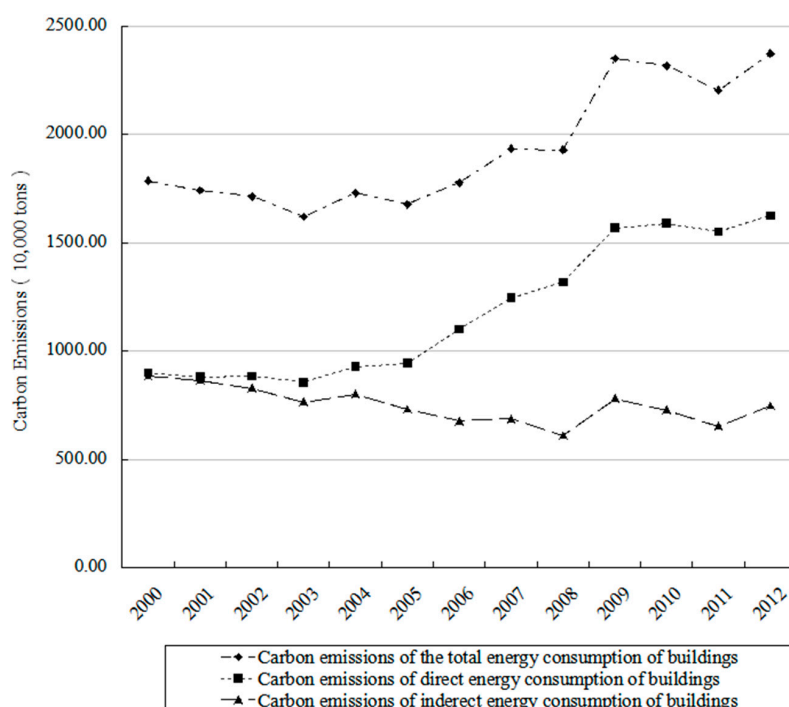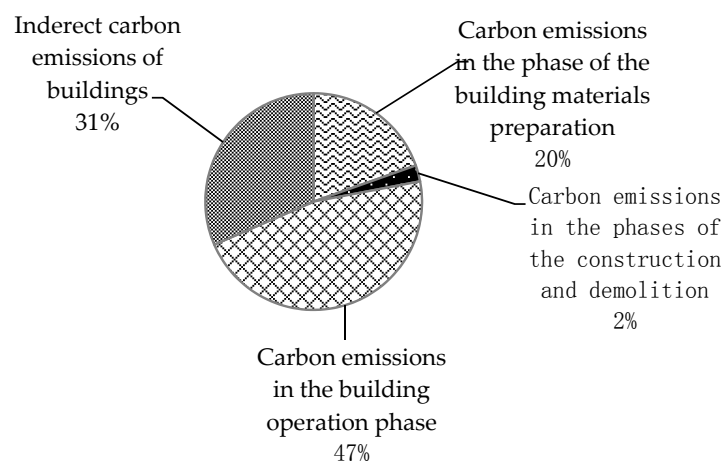

Figure 2. Carbon emissions of life cycle building energy consumption in Wuhan.

Figure 3 shows the proportions of various stages' carbon emissions of life cycle energy consumption of buildings in Wuhan city in the year of 2012. Among them, the direct energy consumption and the operation stage accounted for the largest amount of carbon emissions and accounted for 47% of total carbon emissions. Most literature in China has shown a similar result, which viewed that the carbon emissions from the operation stage accounted for the 60%–80% emissions of life cycle building carbon emissions [43]. It was followed by the indirect energy consumption carbon emissions, accounting for 31%. The percentage of the carbon emissions in the material preparation stage was 20%. However, this calculation result was not consistent with previous studies. Li and Jiang held the opinion that energy consumption in the preparation stage was higher than the indirect energy consumption in China [38]. That is to say, it consumed more energy in the production, processing and shipment of the construction equipment and building materials. Carbon emissions of construction and demolition phases occupied the smallest proportion, which accounted for 2% of the total carbon emissions.

Figure 3. Proportion of each phase's life cycle building carbon emissions in Wuhan in 2012.

In the context of direct carbon emissions of the building energy consumption in Wuhan city, the carbon emissions of building materials preparation phase maintained at a similar level, which basically fluctuated up and down around five million tons of CO_2 emissions (as shown in Figure 4). Carbon emissions of construction and demolition phases stayed around 220,000 tons of CO_2 from 2000 to 2003. It began to rise steadily since 2004, and it rose to 57.5100 tons of CO_2 till 2012. However, the carbon emissions in the building operation phase rose significantly. It basically stayed at the level of four million tons carbon emissions before 2005. It began to rise rapidly since 2006 that went over 10 million tons carbon emissions and jumped to 11.0315 million tons of CO_2 emissions with the growth rate of 197% in 2012.
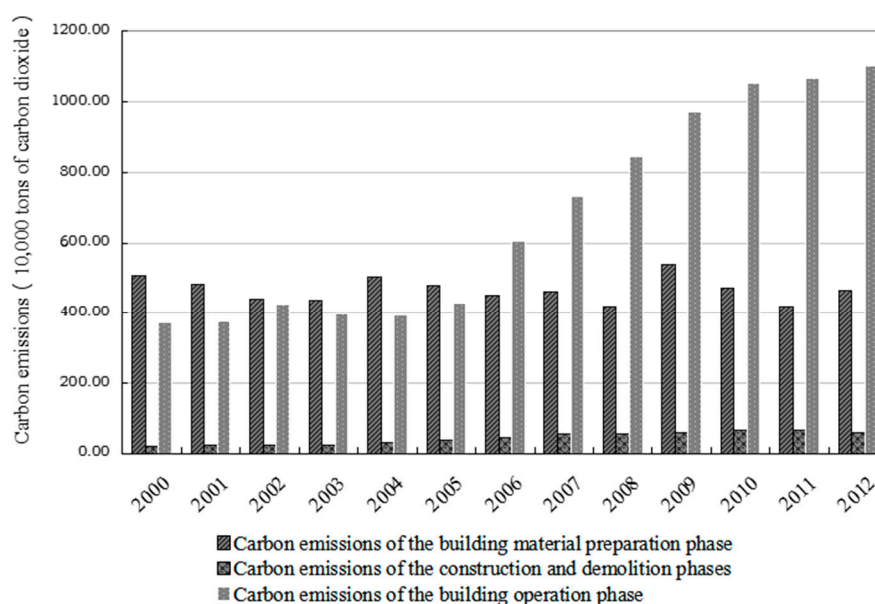
Figure 4. Major phases' life cycle building carbon emissions in Wuhan.

4. Driving Factors of Building Carbon Emission Growth in Wuhan

4.1. Factor Decomposition Analysis

Decomposition method is widely applied to identify the driving factors that change energy consumption and carbon emissions. Structural decomposition analysis (SDA) and index

decomposition analysis (IDA) are two broad categories of decomposition techniques to examine the driving factors on the changes of carbon emissions quantitatively. SDA method has its advantages in analyzing detailed industrial sector emissions but requires the complete input-output table [44], which is a big challenge for one special industry. It is therefore mainly used at the national level. IDA method uses index number concept in decomposition analysis and has its advantages in temporal analysis [45,46].

In comparison with several different IDA methods, such as the divisia index decomposition analysis and the Laspeyres index decomposition analysis, LMDIis considered as a relatively superior method due to its advantages in theoretical background, practicability [47], adaptability [48], results interpretation [49], and its ability to handle zero-value problem [50,51]. Therefore, this study adopted the LMDI method to decompose the driving factors influencing the changes of the life cycle building carbon emissions in Wuhan City.

Among all the data analysis methods for the index decomposition, there are mainly two kinds of methods named the time series manner and the period-wise manner [19]. Period-wise manner compares indices between the first and the last year of a given period without considering the details during the study period. As the decomposition analysis results are sensitive to the choices of the baseline year and the final year, it is sometimes unable to track the changes of the effects on the decomposed factors over the study period [45]. On the other hand, the time-series analysis can solve this problem by comparing the indices on the annual basis. Therefore, this study employed the time-series LMDI methods to study on the driving factors that can change the life cycle energy consumption of buildings in Wuhan City.

4.2. Driving Factors

In the study of the factors that changes the energy consumption and carbon emissions, IPAT model is frequently adopted in many studies. Ehrlich and Holdren's study was the first with the idea of IPAT to study the relationship among economic growth, resources and environment of the form. The equation can be described as I = P × A × T, where *P* refers to population, *A* represents per capita level of consumption or affluence, and *T* is the environmental impact per unit of consumption under the existing technology [52]. IPAT's main strengths are because it is a specification of the key driving forces behind the environmental change, and it further identifies the relationship between those driving forces and impacts precisely [53]. It continues to be widely utilized as a framework for analyzing the driving forces of environmental change (see, e.g., Raskin, 1995 [54]; York, Rosa, Dietz, 2002 [55]). However, IPAT model has certain restrictions on studying the effects of human factors acted on the environment. Thus, different scholars reconstructed and extended the IPAT model according to their requirements. Schulze assumed behavioral choices was an important factor affecting the environmental pressure, while the IPAT model did not attach great value to the function of behavior. An extended model with the behavior factor was suggested, and the IPAT model was turned into the I-PBAT model [56].

The leading factors in promoting building energy consumption and carbon emissions growth are total population, urbanization rate, construction area and consumption level. Energy efficiency studies in buildings are not only influenced by the energy consumption per unit building area, but also affected by the behavior factor. For instance, the improvement of resident's living standard will lead to the increase of the energy consumption per unit building area. Therefore, this study considered population, including the total population and the urbanization rate, building area, residents' behaviors, and the technical level as the driving factors of life cycle building carbon emissions growth in Wuhan.

4.3. Methodology

4.3.1. Decomposition Model

According to the above analysis of the driving factors that caused the carbon emissions growth of the life cycle building energy consumption in the case of Wuhan, this research employed I-PABT model to further analyze the quantitative relationship among the driving factors. The decomposition analysis model of the driving factors can be conducted through the following equation:

$$E = \sum PUABT \tag{7}$$

where E is the energy consumption of the building sector, P is the total population in Wuhan, U is the proportion of the urban population, A is the per capita floor area of the urban residents, B is the behavioral impact factor, and T is energy consumption per unit floor area. Specifically, B is used to evaluate the influences of the building energy consumption given by the behavioral factor. Assuming that the influence degree of the residents' behavioral factors on building energy consumption is proportional to the index I of per capita building energy consumption, and it is given as follows:

$$B = kI \tag{8}$$

where k is the coefficient which will not affect the calculation of the decomposition factors B and T as k will be balanced out during the calculative process. I is the per capita building energy consumption index indicating the changes in terms of direction and degree of per capita building energy consumption during different time periods. It can be expressed by:

$$I_t = 100 \times \frac{E_t}{E_0} \tag{9}$$

where I_t is the per capita building energy consumption index in the period t, per capita building energy consumption index in the base period is indicated by $I_0 = 100$, E_t is per capita building energy consumption in the t time period, E_0 is the per capita building energy consumption in the base period. T in the Equation (7) is the per capita comparable building energy consumption which is used to measure the effective factor of the buildings. The following equation shows the per capita comparable building energy consumption by eliminating the behavioral factor B [57]:

$$T = \frac{E^s}{B} \tag{10}$$

In the time period of (0, t), the contribution of the building energy consumption variation to the total population, urbanization rate, building area, behavioral factor, and building energy efficiency are respectively represented by ΔE_P, ΔE_U, ΔE_A, ΔE_B, ΔE_T, and the changes in proportion of each factor can be denoted by D_P, D_U, D_A, D_B, D_T.

4.3.2. Data Sources

The model in this study uses the data ranging from the year of 2000 to 2012. The total construction energy consumption data come from the above calculation results, and the total population, urban population and construction area can be obtained from the *Wuhan Statistical Yearbook* (2001–2013) [37]. In the light of these statistical data, the proportion of urban population, per capita urban building area and the energy consumption per unit floor area can be computed. Per capita building energy consumption index can be calculated according to the Equation (9).

4.4. Discussions on Factor Decomposition Analysis

In order to study the effects of various factors on building energy consumption changes, as shown in Figure 5, this study decomposed the driving factors based on the building energy consumption data from 2000 to 2012 in Wuhan City.
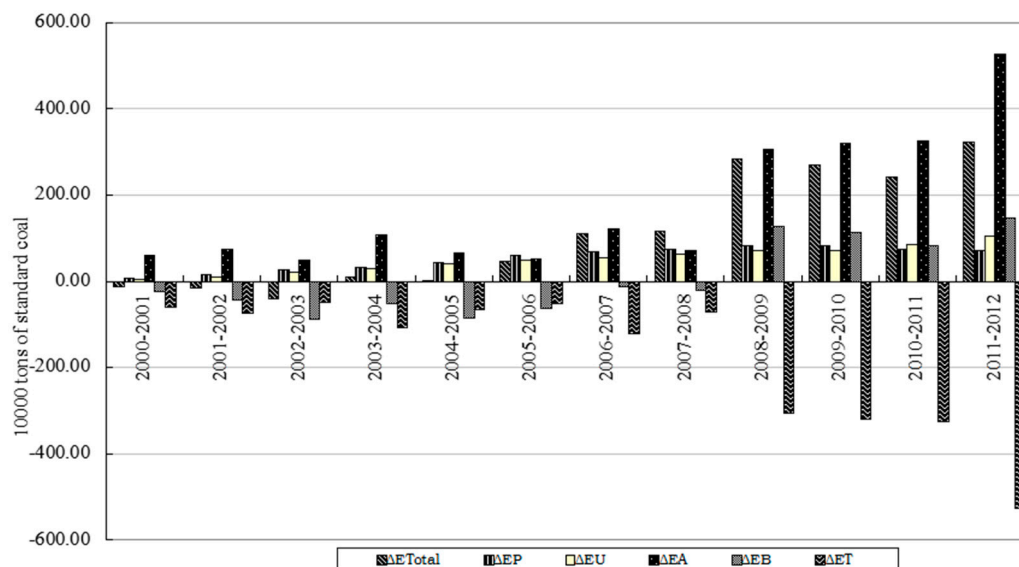
Figure 5. Driving factors decomposition of construction energy consumption changes in Wuhan.

Through the driving factors decomposition of construction energy consumption change, it can be concluded that the increase of construction area is the leading contributor for the increase of building energy consumption and carbon emissions in Wuhan. From Figure 6 we can see, the building energy consumption variation ΔE_A caused by the building area factor remains a higher position. Especially since 2008, its change of proportion went over 1.5 and reached 2.0 in the period from 2011 to 2012.
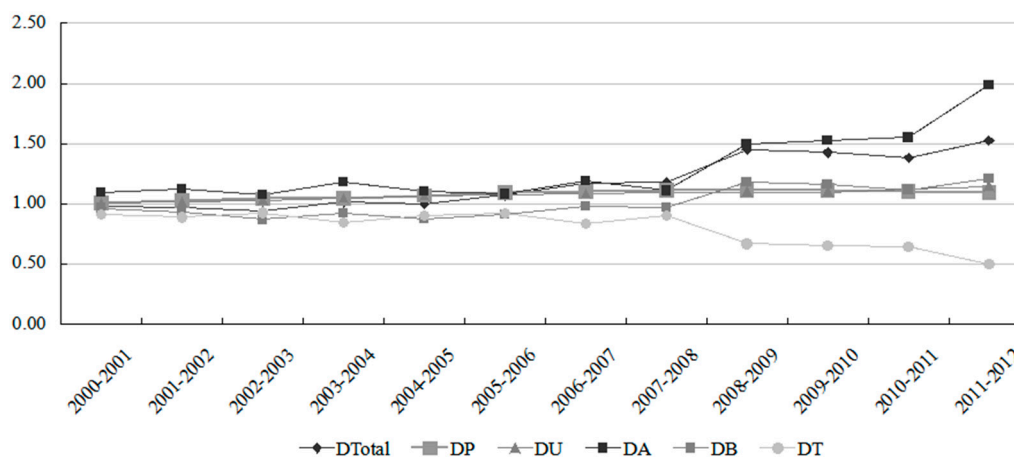
Figure 6. Changes of the proportion of the influencing factors decomposition of the building energy consumption in Wuhan.

The contribution of the behavior factors on the increase of building energy consumption remained the second place, which became the second major contributor on building energy consumption and carbon emissions increases in Wuhan. However, Hu and Guo considered that residents' consumption level was the core driving force on the carbon emission growth, while the

energy consumption structure and the building area were the secondary factors [20]. As shown in Figure 6, behavior factor and building energy consumption were negatively correlated before 2008. But the building energy consumption began to grow rapidly since 2008. The influence coefficient of behavior factor D_B on building energy consumption change surpassed 1.0, while the average annual influence coefficient was 1.17 ranging from 2008 to 2012. The improvement of residents' living standards was the main reason for the building energy consumption growth. That is, the improvement of people's living standard has improved the demand for buildings and, thus, it further pushed the construction energy consumption as well as the carbon emissions to rise.

Population growth and urbanization, to some extent, also made contributions to the increase of Wuhan's building energy consumption. This was consistent with Cai's study [19]. In specific, the contribution of the population factor on the changes of the building energy consumption ΔE_P was greater than the contribution of urbanization factor on the changes of the building energy consumption ΔE_U. Whereas, the impacts of urbanization surpassed the impacts of population factor after 2010 as shown in Figure 5. Figure 6 showed that the impacts of population factor and urbanization factor on building energy consumption growth were relatively small. Both influence coefficients remained around 1.0 and they wandered up and down around 1.1 after 2005, which indicated that the total population had greater influence on the growth of building energy consumption in the earlier stage, while the population structure had greater impacts on the building energy consumption growth than the total population since 2010.

Building energy efficiency factor was the dominant factor in inhibiting building energy consumption growth. Most researchers agreed with this results that energy efficiency is vital for the carbon emission reduction [20,22]. As can be seen from Figure 5, the contribution of energy efficiency on the building energy consumption was negative, indicating that the technical factors, to a large extent, could reduce the energy consumption and the carbon emissions. Figure 6 revealed that the influence coefficient of energy efficiency on building energy consumption growth reduced gradually, and the influence coefficient became smaller especially after 2007. This could be due to the continuous technological progresses and the impacts of energy efficiency on reducing building energy consumption gradually became weaker.

5. Recommendations for Wuhan's Low-Carbon Building Development

In order to achieve building energy conservation and emissions reduction, it is necessary to consider all aspects of the whole life cycle of buildings, from the project planning and design, construction, use and operation, to the demolition and recycling. According to the above life cycle building carbon emissions assessment and the factor decomposition analysis, energy consumption in the building operation phase, indirect energy consumption and energy consumption in the material preparation stage need to be reduced with special attention in order to reduce the life cycle building carbon emissions. After considering the building energy efficiency factor, the dominating emission reduction factor, as well as the key driving factors such as the building area and the behavior factor, it is suggested to reduce carbon emissions from the major perspectives of improving the building energy efficiency, using new energy and promoting energy-saving behaviors.

Firstly, it is wise to enhance building's operational efficiency to reduce the energy consumption in the use stage of buildings. Wuhan, on the one hand, should pay great attention to developing the cutting edge green low-carbon building technologies with the assistant of the Donghu National Independent Innovation Demonstration Zone, and to taking full advantage of scholars and researchers from universities in the intellectual cluster with the aim of fully promoting the development of low carbon buildings. On the other hand, Wuhan should design and build the heat preservation and insulation of the building envelopes well and improve the efficiency of the heating, lighting, ventilation, and air conditioning systems according to the climate characteristics of the Yangtze river.

Secondly, it is suggested to use the clean energy to reduce the indirect energy consumption caused by the production, processing and transportation of the building materials. Wuhan should make full use of the advanced science and technology to realize building materials' reuse and recycling with the aim of low consumption, low emission and high efficiency. Additionally, it is highly recommended to produce and generalize the energy conservation materials. Additionally, it is necessary to take full advantage of the building materials from the areas nearby Wuhan that can shorten the shipment distance and clean energy, such as natural gas, electronic, and solar power, which should be used to further reduce the energy consumption during the transportation.

Thirdly, energy behavior improvement is vital for enhancing the efficiency of the energy-saving and emission reduction. Government, enterprises and the public should take the responsibility and remain fully engaged throughout the energy saving and carbon emissions reduction action. Concretely speaking, the local government should influence the public's low-carbon behaviors by thoroughly instilling the low carbon architectural idea, formulating and completing the relevant laws, regulations and standards. At the enterprise level, architectural design companies, the research and development institutions, producers, suppliers, and the construction units of the construction materials should establish or implement the low-carbon construction technical standard system strictly. Furthermore, the public should form the low-carbon living habits and choose the low-carbon buildings in the terms of purchasing patterns. This are significant steps in achieving the regional sustainable development in terms of resources and the environment in the building sectors.

6. Conclusions

The primary objective of this study is to assess the carbon emissions of the life cycle energy consumption and further identify the main factors driving carbon emissions growth in the building sector at the city level. In this paper, it calculated the life cycle energy consumption and carbon emissions of the building industry based on the life cycle theory in a case of Wuhan City, China. The results showed that the proportion of carbon emissions in the building operation phase remained the largest, and the carbon emissions of the indirect energy consumption and the construction material preparation phase were the second largest contributors. In order to analyze the driving factors of the construction carbon emissions, this paper adopted the decomposition analysis with the LMDI method. The findings indicated that the increasing buidling area was the main driver of the energy consumption and the carbon emissions increase, and it followed by the behavior factor. Population growth and urbanization, to some extent, increased the carbon emissions as well. On the contrary, energy efficiency contributed to the carbon emissions reduction of the life cycle buildings. It also provided some relevant policy recommendations for carbon emissions mitigation in Wuhan.

However, there exists several limitations in terms of data collection and interpretation. The construction area data of Wuhan City is not available due to the limited statistics at the city level in China. Given the lack of data, this paper adopted an indirect method, employing the proportion of Wuhan's building area out of the total national building area instead of using the real data, which is acceptable considering the situation of China's statistic problem. Further research is needed to examine the differences of the carbon emissions with more accurate data of different building types by regions. Diverse driving factors should also be investigated to gain a more comprehensive understanding of the reasons affecting the carbon emissions of different building types. Despite these challenges, this study provides insight into a standardized methodology for life cycle building carbon emissions assessment at the city level under the condition of limited data, which enables policy makers, designers, engineers and building users to make more sensible judgements in promoting sustainable development in the future.

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References

1. Chau, C.K.; Leung, T.M.; Ng, W.Y. A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Appl. Energy* **2015**, *143*, 395–413

2. United Nations Environment Program. *Common Carbon Metric for Measuring Energy Use and Reporting Greenhouse Gas Emissions from Building Operations*; United Nations Environment Program: Nairobi, Kenya, 2009.

3. Xu, Z. Analysis on the causes of the slow development of city low-carbon construction. *Urban Probl.* **2012**, *5*, 51–53.

4. Singh, A.; Berghorn, G.; Joshi, S.; Syal, M. Review of life-cycle assessment applications in building construction. *J. Archit. Eng.* **2011**, *17*, 15–23. [CrossRef]

5. Fang, G.C.; Tian, L.; Fu, M.; Sun, M. The impacts of carbon tax on energy intensity and economic growth: A dynamic evolution analysis on the case of China. *Appl. Energy* **2013**, *110*, 17–28. [CrossRef]

6. Adalberth, K. Energy Use during the Life Cycle of Buildings. *Build. Environ.* **1997**, *32*, 317–320. [CrossRef]

7. Michiya, S.; Tatsuo, O.; Kiyoshi, O. The Estimation of Energy Consumption and CO_2 Emission due to Housing Construction in Japan. *Energy Build.* **1995**, *22*, 165–169.

8. Nassen, J.; Holmberg, J.; Wadeskog, A. Direct and Indirect Energy Use and Carbon Emissions in the Production Phase of Buildings: An Input-Output Analysis. *Energy* **2007**, *32*, 1593–1602. [CrossRef]

9. Chen, L.L. *Research on the Evaluation Index and Methods of Low-Carbon Buildings*; Southwest Jiaotong University: Chengdu, China, 2009.

10. Chen, W.K.; Luo, F. Research on the building energy consumption based on life cycle theory. *Build. Sci.* **2008**, *10*, 23–27.

11. Ang, B.W.; Zhang, F.Q. A Survey of Index Decomposition Analysis in Energy and Environmental Studies. *Energy* **2000**, *25*, 1149–1176. [CrossRef]

12. Wang, W.C. *Research on the Driving Factors and the Forecast of the Provincial Energy Consumption and Carbon Dioxide Emissions in China*; Dalian University: Dalian, China, 2013.

13. Lin, X.; Polenske, K.R. Input-Output Anatomy of China's Energy-Use Changes in the 1980s. *Econ. Syst. Res.* **1995**, *7*, 67–84. [CrossRef]

14. Wang, C.; Chen, J.; Zou, J. Decomposition of Energy-related CO_2 Emission in China: 1957–2000. *Energy* **2005**, *30*, 73–83. [CrossRef]

15. Fan, Y.; Liu, L.-C.; Wu, G.; Tsai, H.-T.; Wei, Y.-M. Changes in carbon intensity in China: Empirical findings from 1980–2003. *Ecol. Econ.* **2007**, *62*, 683–691. [CrossRef]

16. Xu, G.Q.; Liu, Z.Y.; Jiang, Z.H. Decomposition analysis model and empirical analysis of carbon emissions in China: 1995–2004. *China Popul. Resour. Environ.* **2006**, *6*, 158–161.

17. Tang, J.R.; Zhang, B.Y.; Wang, Y.H. Research on the driving factors of carbon emissions based on the LMDI method. *Stat. Inf. Forum* **2011**, *11*, 19–25.

18. Zhu, Z.L. Driving factors analysis for building energy consumption growth based on STIRPAT model. *Electron. Energy* **2015**, *2*, 251–255.

19. Cai, W.G. Analyzing Impact Factors of Building Energy Consumption: Modeling and Empirical Study. Ph.D. Thesis, Chongqing University, Chongqing, China, 2011.

20. Hu, F.W.; Guo, S.T. An empirical discussion on factorial decomposition of carbon emission from Chinese residential buildings during operation. *J. Tongji Univ.(Nat. Sci.)* **2012**. [CrossRef]

21. Tan, C.P.; Fan, L.; Wang, Y. Driving factors decomposition model and empirical analysis of urban residential buildings' carbon emissions in Gansu. *Stat. Decis.* **2014**, *7*, 109–111.

22. Feng, B.; Wang, X.Q. Research on Carbon Decoupling Effect and Influence Factors of Provincial Construction Industry in China. *China Popul. Resour. Environ.* **2015**, *25*, 28–34.

23. Zhang, T.X.; Zhou, Y.Y.; Lu, P. The connotation of low-carbon buildings of cities in China and assessment models of carbon emissions. *J. Hunan Univ. Technol.* **2011**, *1*, 77–80.

24. Chen, F.; Zhu, D.J. Research on the existing problems and targeting polices of the low-carbon building development in Shanghai. *City Obs.* **2010**, *5*, 144–155.

25. Fay, R.; Treloar, G.; Iyer-Raniga, U. Life-cycle energy analysis of buildings: A case study. *Build. Res. Inf.* **2000**, *28*, 31–41. [CrossRef]

26. Guinée, J.B. *Handbook on Life Cycle Assessment*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002; p. 692.

27. Chen, G.Q.; Chen, H.; Chen, Z.M.; Zhang, B.; Shao, L.; Guo, S.; Zhou, S.Y.; Jiang, M.M. Low-Carbon Building Assessment and Multi-Scale Input–Output Analysis. *Commun. Nonlinear Sci. Numer. Simulat.* **2011**, *16*, 583–595. [CrossRef]

28. Han, G.; Srebric, J. Life-cycle Assessment Tools for Building Analysis. Available online: https://cms.engr.psu.edu/portals/phrc/assets/docs/Publications/RB0511.pdf (accessed on 9 December 2015).

29. Rashid, A.F.A.; Yusoff, S. A review of life cycle assessment method for building industry. *Renew. Sustain. Energy Rev.* **2015**, *45*, 244–248. [CrossRef]

30. Gustavsson, L.; Joelsson, A.; Sathre, R. Life Cycle Primary Energy Use and Carbon Emission of an Eight-Storey Wood-Framed Apartment Building. *Energy Build.* **2010**, *42*, 230–242. [CrossRef]

31. You, F.; Hu, D.; Zhang, H.; Guo, Z.; Zhao, Y.; Wang, B.; Yuan, Y. Carbon Emissions in the Life Cycle of Urban Building System in China—A Case Study of Residential Buildings. *Ecol. Complex.* **2011**, *8*, 201–212. [CrossRef]

32. Intergovernmental Panel on Climate Change. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC/OECD/IEA, UK Meteorological Office: Bracknell, UK, 1996.

33. Yin, S.C. *Full Life Cycle Carbon Emissions Calculation Analysis of Buildings*; Harbin Institute of Technology: Harbin, China, 2012.

34. National Bureau of Statistics. *China Statistical Yearbook*; China Statistics Press: Beijing, China, 2001–2013.

35. Energy Statistics Division. *China Energy Statistical Yearbook*; National Bureau of Statistics: Beijing, China, 2001–2013.

36. Hubei Bureau of Statistics. *Hubei Statistical Yearbook*; China Statistics Press: Wuhan, China, 2001–2013.

37. Wuhan Bureau of Statistics. *Wuhan Statistical Yearbook*; China Statistics Press: Wuhan, China, 2001–2013.

38. Li, Z.J.; Jiang, Y. Analysis and thinking on generalized building energy consumption in China. *Archit. J.* **2006**, *53*, 30–33.

39. Wei, B.R.; Yagita, H. China's steel output and its energy demands and CO_2 emissions scenario analysis. *Metall. Energy* **2005**, *24*, 3–6.

40. Feng, Q. The comparison of the steel consumption of ten years between China and America. *Metall. Econ. Manag.* **2001**, *5*, 15–17.

41. Wang, S.; Liu, W. The status quo and the characteristics of the copper tube manufacturing in China. *World Nonferr. Met.* **2004**, *7*, 21–28.

42. Liu, J. Plastic building materials industry begun to take shape with huge potential in China. *China Pet. Chem. Ind.* **2005**, *10*, 91–92.

43. Lin, R.B. Comparative study on international building life cycle energy consumption and carbon emissions. *Build. Sci.* **2013**, *8*, 22–27.

44. Diakoulaki, D.; Mavrotas, G.; Orkopoulos, D.; Papayannakis, L. A bottom-up decomposition analysis of energy-related CO_2 emissions in Greece. *Energy* **2006**, *31*, 2638–2651. [CrossRef]

45. Liu, Z.; Sai, L.; Geng, Y. Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: The case of Beijing, Tianjin, Shanghai and Chongqing. *Energy* **2012**, *37*, 245–254. [CrossRef]

46. Wang, Y.; Zhu, Q.; Geng, Y. Trajectory and driving factors for GHG emissions in the Chinese cement industry. *J. Clean. Prod.* **2013**, *53*, 252–260. [CrossRef]

47. Ang, B.W.; Lee, S.Y. Decomposition of Industrial Energy Consumption: Some Methodological and Application Issues. *Energy Econ.* **1994**, *16*, 83–92. [CrossRef]

48. Ang, B.W.; Zhang, F.Q.; Choi, K.-H. Factorizing changes in energy and environmental indicators through decomposition. *Energy* **1998**, *23*, 489–495. [CrossRef]

49. Ang, B.W. Decomposition analysis for policymaking in energy: Which is the preferred method? *Energy Policy* **2004**, *32*, 1131–1139. [CrossRef]

50. Ang, B.W.; Liu, N. Handling zero values in the logarithmic mean divisia index decomposition approach. *Energy Policy* **2007**, *35*, 238–246. [CrossRef]

51. Liu, L.C. China's Carbon Dioxide Emissions Policy Modeling and Empirical Research. Ph.D. Thesis, University of Science and Technology of China, Anhui, China, 2006.

52. Ehrlich, P.; Holdren, J. A bulletin dialogue on the 'closing circle': Critique: One-dimensional ecology. *Bull. At. Sci.* **1972**, *28*, 16–27.

53. York, R.; Rosa, E.A.; Dietz, T. STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts. *Ecol. Econ.* **2003**, *46*, 351–365. [CrossRef]

54. Raskin, P.D. Methods for estimating the population contribution to environmental change. *Ecol. Econ.* **1995**, *15*, 225–233. [CrossRef]

55. York, R.; Rosa, E.A.; Dietz, T. Bridging environmental science with environmental policy: Plasticity of population, affluence, and technology. *Soc. Sci. Q.* **2002**, *83*, 18–34. [CrossRef]

56. Schulze, P.C. I=PBAT. *Ecol. Econ.* **2002**, *40*, 149–150. [CrossRef]

57. Cai, W.G. *Research on the Analysis Model and the Implementation of the Driving Factors of China's Building Energy Consumption*; Chongqing University: Chongqing, China, 2011.