

Article

Decomposition and Decoupling Analysis of Life-Cycle Carbon Emission in China's Building Sector

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Abstract: With accelerating urbanization, building sector has been becoming more important source of China's total carbon emission. In this paper, we try to calculate the life-cycle carbon emission, analyze influencing factors of carbon emission, and assess the delinking index of carbon emission in China's building sector. The results show: (i) Total carbon emission in China's building industry increase from 984.69 million tons of CO₂ in 2005 to 3753.98 million tons of CO₂ in 2013. The average annual growth rate is 18.21% per year. Indirect carbon emission from building material consumption accounted to 96–99% of total carbon emission. (ii) The indirect emission intensity effect was leading contributor to change of carbon emission. The following was economic output effects, which always contributed to increase in carbon emission. Energy intensity effect and energy structure effect took negligible role to offset carbon emission. (iii) Delinking index show the status between carbon emission and economic output in China's building industry during 2005–2006 and 2007–2008 was weak decoupling; during 2006–2007 and during 2008–2010 was expansive decoupling; and during 2010–2013 was expansive negative decoupling.

Keywords: life-cycle; building sector; decomposition; delinking analysis; China

1. Introduction

According to National Economical Industry Classification (GB/T4754-2012) [1], the building industry includes: construction of buildings, civil engineering, renovation and decoration four categories. The energy consumption of building industry includes the energy consumed during occupancy in the various buildings. The sources of carbon emissions are distinguished as two scopes: (i) direct emissions, which refer to the CO₂ emissions from the consumption of energy of building industry; and (ii) indirect emissions, which refer to CO₂ emissions from the consumption of construction materials. Buildings accounted for 32% of total global final energy use (equal to 117 ExaJoules), 19% of energy-related GHG emissions, 51% of global electricity consumption, 33% of black carbon emissions, and an eighth to a third of F-gases emission (large differences in F-gases data are due to differing accounting conventions) [2–4]. In particular, the building energy consumption in China recently surpassed the US building consumption, and it is expected to increase significantly in the next decades, pushed by the demand for new residential buildings [5–8]. In 2009, the building sector was responsible for one fifth of China's total primary energy consumption and 18% of the overall Chinese GHG emissions.

China has experienced urbanization with an excessively large number of building projects in the past decades [9,10]. Even more, China's urbanization is projected to be accelerating in the future [11–13]. The accelerating urbanization will lead to a rapid growth of energy usage and material consumption,

and a commensurate increase in carbon emission, which means carbon emission from building industry will become more important source of China's total carbon emission. Thus, curbing China's building sector carbon emission, and even China's total carbon emission, requires a better understanding of carbon emission from China's building industry.

Growth in building energy use poses a challenge for the Chinese government; in recent years, to curb energy consumption in buildings, the Chinese government has undertaken many actions at national level, as shown in Table 1. Other countries also face this problem and issue building codes and regulations for energy efficiency [8,14–17], as presented in Table 2.

In addition, a large number of scholars have studied carbon emission from building industry at global-level [2,3,18–20], national-level [8,17,21–29], sub-national-level [30–34], etc. What attracted these scholars are three issues: (i) they usually conducted empirical analysis to estimate or predict carbon emission in building industry; (ii) they use quantitative model to quantify these influencing factors of carbon emission in building industry; and (iii) they use qualitative or quantitative model to explore the relationship between economic output and carbon emission in building industry.

In this paper, we try to calculate carbon emission in China's building industry, to explore its influencing factors, and to assess its decoupling status. To be more specific, we firstly estimate direct (fossil fuel combustion) and indirect (building material consumption) carbon emission in building industry, using China's official data and carbon emission coefficient from IPPCC. Then, we conduct a quantitative analysis of the key influencing factors of carbon emission in China's building industry, using the combination method of Kaya identity and logarithmic mean Divisia index (LMDI) model. Finally, we assess the decoupling status between economic output and carbon emission in China's building industry, using Tapio method and decoupling effort index. Given that many developing countries have experienced, or will experience urbanization, which lead to building industry booming, and a commensurate rapidly increase in carbon emission [12,35], our work would bring some implications for carbon emission of building industry in some other developing countries.

Table 1. The actions of Chinese government to curb energy consumption in buildings.

Time	Action	Purpose and Specific Content
September 2005	“Circular of the general office of the State Council on further promoting the reform and popularization of wall materials”	Further promote the reform of wall materials and promote energy-efficient construction, effective protection of arable land and energy conservation.
November 2005	Civil building energy conservation management regulations	In order to strengthen the administration of energy conservation, improve the efficiency of energy utilization and improve the quality of indoor thermal environment, the Ministry of construction has formulated the regulations in accordance with the relevant laws and regulations.
August 2007	Measures for the administration of green building evaluation marks	These measures are formulated for the purpose of standardizing the work of green building evaluation and marking and guiding the healthy development of green buildings.
September 2007	Green construction guidelines	Green construction refers to the construction of the project, in ensuring the quality, safety and other basic requirements under the premise of scientific management and technological progress, to maximize the resources and reduce the negative impact on the construction activities of the environment to achieve energy saving, land, water, Materials and environmental protection.
August 2008	Civil building energy conservation regulations	This Ordinance is to strengthen the management of civil building energy conservation, reduce energy consumption in the use of civil buildings, improve energy efficiency.
October 2008	Interim Measures for the administration of financial subsidies for renewable energy efficient building materials	To support the Wenchuan earthquake construction waste treatment and recycling, national finance will arrange special funds to support the production of energy-saving building materials and recycling utilization.
December 2010	“National Green Building Innovation Award” and “National Green Building Innovation Award”	To do a good job in the management and evaluation of the National Green Building Innovation Award, and guide the healthy development of green building in China.
January 2011	On further deepening the northern heating area of existing residential building heating metering and energy conservation work notice	During the Twelfth Five-Year Guideline, the Ministry of finance, and department of housing and urban rural development will further intensify efforts to improve the relevant policies to carry out heating metering and energy conservation work.
December 2011	“Housing Ministry of Urban and Rural Construction on the implementation of the” State Council on the issuance of “the Twelfth Five-Year Guideline” energy-saving emission reduction comprehensive work program notice “implementation plan”	This program requires all levels of housing urban and rural construction departments to fully understand the housing urban and rural areas in the field of energy conservation and emission reduction work of the importance and urgency, establish a high degree of political responsibility and sense of mission, strengthen cooperation with relevant departments, solid work to ensure Complete the task of energy-saving emission reduction.
January 2013	Forward the development and reform of the Ministry of Housing and Urban Construction “Green Building Action Program” notice	In order to thoroughly implement the scientific concept of development, effectively transform the urban and rural construction mode and the development of the construction industry, improve the efficiency of resource utilization, achieve energy conservation and emission reduction targets, and actively respond to global climate change, build a resource-saving and environment-friendly society, Civilized level, improve people’s quality of life.

Table 2. The buildings code and regulation for energy efficiency in different countries.

Time	Country	Action	Specific Content
April 1989	China	“Standardization law”	It stipulates development and supervision related to standardization laws. It also specifies the penalties on products, which fail to meet compulsory standards for production, sales, and imports.
March 2002	China	“Management Method of National Supervision and Random Inspection of Product Quality”	National supervision and random in section is one method of maintaining product quality by the State. Regular supervision and random inspections are conducted every quarter, and irregular supervision and inspections are conducted according to the status of the product quality.
January 1998	China	“Energy Conservation Law”	It regulates energy conservation management, energy utilization, improvement of energy conservation technologies, and legal liabilities.
2002	China	“Management Method of Energy Conservation Product Certification”	Product certifications adopt the principal of voluntarism. The method stipulates certification conditions, procedures, usage of energy conservation marks, and treatment after certification.
December 2004	China	“Medium and Long-term Energy Conservation Plan”	It promotes key energy conservation sectors during the “11th Five-Year Plan”: industry, traffic and transportation, commercial and civil applications. The Plan also puts forward the organization and implementation of key energy conservation projects, such as modification of industrial coal-burning boilers, regional combined heat and power generation, utilization of excessive heat and pressure, saving and replacing oil, energy conservation of buildings, a green lighting project, establishment of energy conservation monitoring and a technical service system, etc.
2005	China	“China Buildings Program Strategy”	Its main goal is to promote building energy efficiency through appliance energy efficiency standards and building codes. It states that it is possible to do so using the following actions.
2005	China	“Design Standard for Energy Efficiency of Public Buildings”	More attention is paid to this particular Standard, as this is the only standard focusing on the energy efficiency of commercial buildings.
2010	China	The Chinese energy codes consist of three options for compliance	First, a prescriptive path which contains detailed specifications for individual components, second, an alternative to the prescriptive approach allowing trade-offs between envelope components, and third, a performance path that requires that the energy consumption of the design features of the proposed new building does not exceed energy consumption of a reference building [36].
2007	India	Energy Conservation Building Code (ECBC)	This code is designed to control building energy consumption and applies to commercial buildings with a connected load of 100 kW or 120 kVA.
2010	US	The building energy codes in the U.S. become more stringent	The U.S. building energy program started to focus on compliance and developed a plan to achieve 90% compliance with the model energy code by 2017, which requires active training and enforcement programs as well as annual measurement of the rate of compliance.
2015	Italy and Europe	The building energy codes in the U.S. become more stringent	Provide an overview on EPBD implementation in Europe and a Geocluster Italian distribution of BERCs in order to show their geographical distribution and their influence on the construction sector practices, focusing in particular on the region of Lombardy, describe the methodology followed for the definition of BERCs in nine municipalities in the same region and present the practical application of one of the nine BERCs to a NZEB residential case study as an example of what the EBPD recast define as NZEB.

2. Methods and Data

2.1. Methodologies

2.1.1. Method for Calculating CO₂ Emission

According to National Economical Industry Classification (GB/T4754-2012), the building industry includes: construction of buildings, civil engineering, and renovation and decoration four categories. Based on the previous studies [29,37–41] and the IPCC method of carbon emission inventories [2], we build the CO₂ emission calculation model for China's building industry. The CO₂ emission calculation of building industry includes two parts: first part is the direct CO₂ emissions and second part is indirect CO₂ emissions shown in the following equation:

$$C = C_{\text{dir}} + C_{\text{ind}} \quad (1)$$

where C represents total carbon emissions in China's building industry; C_{dir} represents the direct CO₂ emissions, which refer to the CO₂ emissions from the consumption energy of building industry; and C_{ind} represents indirect CO₂ emissions, which refer to CO₂ emissions from the consumption construction materials.

$$C_{\text{dir}} = \sum_i E_i \times F_i \quad (2)$$

where E_i is the i -th energy consumption, and F_i (kgCO₂/kg or kgCO₂/m³ or kgCO₂/kWh) indicates the total energy consumption and the total CO₂ emission coefficient of i -th energy, which is shown in Tables 3 and 4.

$$C_{\text{ind}} = \sum_j M_j \times \beta_j \quad (3)$$

where M_j is the quantity of j -th kind of consumption construction materials, and β_j represents the CO₂ emission coefficient of j -th kind of consumption construction materials, which is shown in Table 5 [42].

Table 3. The carbon coefficients of different kinds of energy.

Energy	Default Value of Carbon Content	Carbon Oxidation Rate	Average Lower Heating Value	Carbon Coefficient
	tC/TJ	%	kJ/kg or kJ/m ³	kg CO ₂ /kg or kgCO ₂ /m ³
Raw Coal	26.37	98%	20,908	1.981
Washed coal	25.41	98%	26,344	2.405
Other washed coal	25.41	98%	10,454	0.955
Coal products	33.6	98%	17,793	2.148
#: briquette	33.6	90%	17,584	1.950
coal water slurry	33.6	98%	19,854	2.397
Pulverized coal	33.6	98%	20,933	2.527
Coke	29.5	93%	28,435	2.860
Natural Gas	15.3	99%	389,310	2.1622
Liquefied natural gas	15.3	100%	51,498	2.889
Crude Oil	20.1	98%	41,816	3.020
Gasoline	18.9	98%	43,070	2.925
Kerosene	19.6	98%	43,070	3.033
Diesel Oil	20.2	98%	42,652	3.096
Fuel Oil	21.1	98%	41,816	3.170
Liquefied petroleum gas	17.2	98%	50,179	3.101
Refinery Gas	18.2	98%	46,055	3.012
Other petroleum products	20.0	98%	35,168	2.527

Table 4. The carbon coefficients of electricity.

Year	The Ratio of Thermal Power (%)	The Ratio of Other (Water, Nuclear, Wind) (%)	Consumption Standard of Power (kgce/kW·h)	Carbon Coefficient (tCO ₂ /tce)
2005	81.89	18.11	0.343	6.264
2006	82.69	17.31	0.342	6.307
2007	82.98	17.02	0.332	6.144
2008	80.48	19.52	0.322	5.780
2009	80.3	19.7	0.32	5.731
2010	79.2	20.8	0.312	5.511
2011	81.34	18.66	0.308	5.588
2012	78.05	21.95	0.305	5.309
2013	78.19	21.81	0.302	5.262

Table 5. The carbon coefficients of consumption construction materials.

Building Material	Carbon Coefficient (kgCO ₂ /kg or Kg/m ³)
Cement	0.815
Steel	1.789
Glass	0.966
Wood	842.8
Aluminum	2.6

2.1.2. Logarithmic Mean Divisia Index Technique

IDA is an analytical tool originated from energy studies. Based on IDA, many specific decomposition methods can be developed and the LMDI approach introduced by Ang and Choi [43] has become the most popular IDA (Index Decomposition Analysis) methodology in the last decade among researchers [44]. The reasons are clear: its theoretical and practical advantages (demonstrated by Ang et al. [45]) make it superior to other alternatives. LMDI is an exhaustive (or refined) decomposition method, which ensures decompositions with identically null residual terms. The LMDI can be expressed as an extended Kaya identity, which was first proposed by Kaya [46]. Assume that V is an aggregate composed of n factors (x_1, \dots, x_n), i.e., $V = \sum_i V_i$ and $V_i = x_{1,i}x_{2,i} \cdots x_{n,i}$. Further assume that from period 0 to T the aggregate changes from V^0 to V^T . The objective is to derive the contributions of the n factors to the change in the aggregate which can be expressed as [47]:

Additive form

$$\Delta V_{\text{tot}} = V^T - V^0 = \Delta V_{x_1} + \Delta V_{x_2} + \cdots + \Delta V_{x_n} \quad (4)$$

Multiplicative form

$$D_{\text{tot}} = V^T/V^0 = D_{x_1}D_{x_2} \cdots D_{x_n} \quad (5)$$

General Formulae of LMDI

$$\Delta V_{x_k} = \sum_i L(V_i^T, V_i^0) \ln \left(\frac{x_{k,i}^T}{x_{k,i}^0} \right) \quad (6)$$

$$D_{x_k} = \exp \left(\sum_i \frac{L(V_i^T, V_i^0)}{L(V^T, V^0)} \ln \left(\frac{x_{k,i}^T}{x_{k,i}^0} \right) \right) \quad (7)$$

where $L(a, b) = (a - b)/(\ln a - \ln b)$ is the logarithmic mean of a and b , and $L(a, b) = a$. Because Additive form is easy to understand and calculate, this article uses this form. The extended Kaya identity and LMDI is combined shown in the following formula:

$$C_t = C_{\text{dir}} + C_{\text{ind}} = \sum \frac{C_{it}}{E_{it}} \times \frac{E_{it}}{E_t} \times \frac{E_t}{Q_t} \times Q_t + \frac{C_{\text{ind}}}{Q_t} \times Q_t = \sum F_{it} \times S_{it} \times I_t \times Q_t + P_t \times Q_t \quad (8)$$

In this expression, we define the following variables, where

C_t represents the carbon emissions in the t year, the subscript i represents energy type; the superscript t represents year;

C_{it} is the carbon emissions from the i -th energy in the t year;

E_{it} is the consumption of the i -th energy in the t year;

E_t is total energy consumption in the t year;

Q_t is the economical outputs of building industry;

$F_{it} = \frac{C_{it}}{E_{it}}$ denotes the carbon coefficient of i -th energy;

$S_{it} = \frac{E_{it}}{E_t}$ illustrates the energy structure effect of i -th energy;

$I_t = \frac{E_t}{Q_t}$ represents energy intensity; and

$P_t = \frac{C_{ind}}{Q_t}$ is the effects of intensity of indirect carbon emission.

According to the LMDI method, the change of carbon consumption between a base year 0 and a target year t , is denoted by ΔC , and we use the additive decomposition to make further decomposition of Equation (8) to get the following formula:

$$\Delta C_t = C_t - C_0 = \Delta C_{Ft} + \Delta C_{St} + \Delta C_{It} + \Delta C_{Qt} + \Delta C_{Pt} \quad (9)$$

In this expression, we can consider the F_{it} is basically unchanged, so ΔC_{Ft} is 0. Thus, ΔC can be decomposed into the following determinant factors:

$$\Delta C_t = C_t - C_0 = \Delta C_{St} + \Delta C_{It} + \Delta C_{Qt} + \Delta C_{Pt} \quad (10)$$

where ΔC refers to the total changes in carbon emissions, which can be further decomposed into the following indicators: ΔC_{St} (the effect of energy structure: changes in the amount of CO₂ emissions caused by changes in the proportion of nine energy consumption in total energy consumption), ΔC_{It} (the effect of energy intensity: changes in the amount of CO₂ emissions caused by changes in the proportion of total energy consumption in the gross industrial output value), ΔC_{Qt} (the effect of industrial scale: changes in the amount of CO₂ emissions caused by changes in gross output value of construction industry;), and ΔC_{Pt} (the effect of indirect carbon emission intensity: changes in the amount of CO₂ emissions caused by the changes in the proportion of indirect carbon emissions and gross industrial output value). Equations (11)–(17) are used to calculate the changes in the amount of CO₂ emissions caused by the change of the factors of decomposition; based on the LMDI method, ΔC_{St} , ΔC_{It} , ΔC_{Qt} , ΔC_{Pt} can be expressed as follows:

$$\Delta C_{St} = \sum_{i=1}^9 (w_{it}) \ln \frac{S_{it}}{S_{i0}} \quad (11)$$

$$\Delta C_{It} = w_t \ln \frac{I_t}{I_0} \quad (12)$$

$$\Delta C_{Qt} = w_t \ln \frac{Q_t}{Q_0} + w_{ind} \ln \frac{Q_t}{Q_0} \quad (13)$$

$$\Delta C_{Pt} = w_{ind} \ln \frac{P_t}{P_0} \quad (14)$$

$$w_{it} = \frac{C_{it} - C_{i0}}{\ln C_{it} - \ln C_{i0}} \quad (15)$$

$$w_t = \frac{C_t - C_0}{\ln C_t - \ln C_0} \quad (16)$$

$$w_{\text{ind}} = \frac{C_{\text{indt}} - C_{\text{indo}}}{\ln C_{\text{indt}} - \ln C_{\text{indo}}} \quad (17)$$

2.1.3. Decoupling Elasticity Model

The decoupling model is proposed by the Tapio model, which has been developed the OECD decoupling model, which has been widely used to analyze the relationship between economic growth and carbon emission [48,49]. In this paper, based on the additive decomposition results of CO₂ emission changes [50], the decoupling elasticity e can be formulated as follows:

$$e_{(C,GDP)} = \frac{\%C}{\%GDP} = \frac{\Delta C/C}{\Delta GDP/GDP} \quad (18)$$

In this expression, e is the decoupling elasticity, $\%C$ is the percent change in carbon emissions, and $\%GDP$ is the percent change of economic output of building industry. Carbon emission is the carbon emission of construction for the current year, Δ carbon is the variation of carbon emission at the current time compared with the base period, GDP is the economic output of building industry in the current year, and Δ GDP is the variation of economic output of building industry at the current time compared with the base period. According to the values of e , there are eight logical possibilities [51,52], including weak decoupling, expansive decoupling, expansive negative decoupling, strong negative decoupling, weak negative decoupling, recessive coupling, recessive decoupling, and strong decoupling.

2.1.4. Decoupling Effort Index

In this paper, we identify the factors contributing to carbon emission of building industry in China using the Kaya identity and LMDI techniques; however, they cannot specifically and objectively measure the actual effects of energy conservation and pollution reduction efforts on CO₂ emissions. Effort is a general term referring to the actions that decrease the carbon emissions, both directly and indirectly, such as reducing energy intensity, improving energy efficiency, as well as optimizing the energy structure and excluding the expansion of economical outputs [53]. Thus, the effort in absolute terms or absolute effort during the period starting from the base year 0 to year t can be represented as the sum of the three factors identified [54]:

$$\Delta C_{\text{ut}} = \Delta C_t - \Delta C_{\text{Qt}} = \Delta C_{\text{St}} + \Delta C_{\text{It}} + \Delta C_{\text{Pt}} \quad (19)$$

The decoupling effect index D from a base year 0 to a target year t takes the following values and is evaluated according to the standards below [54]:

$$D_t = -\frac{\Delta C_{\text{ut}}}{\Delta C_{\text{Qt}}} = -\left(\frac{\Delta C_{\text{St}}}{\Delta C_{\text{Qt}}} + \frac{\Delta C_{\text{It}}}{\Delta C_{\text{Qt}}} + \frac{\Delta C_{\text{Pt}}}{\Delta C_{\text{Qt}}}\right) = -(DS_t + DI_t + DP_t) \quad (20)$$

$D_t \leq 0$, denotes no decoupling effort, carbon emissions increase faster than economic outputs because of inefficient emission reduction efforts [55]. $0 < D_t < 1$ denotes weak decoupling effort, the efforts of carbon emission reduction have only compensated for a small part of the carbon emissions from economic outputs growth. $D_t \geq 1$ denotes strong decoupling effort, the emission reduction achieved through various efforts was three or two times higher than the carbon emission increase.

2.2. Data Sources and Definition

The data of economic output and energy consumption in China's building industry are from China Energy Statistical Yearbook for the different sectors [56–58]. The unit of economic output is RMB (Yuan) at constant price of 2005. The unit of energy consumption is ton of coal equivalent (tce). The data of consumption of building materials and building industry output data are from China Statistical Yearbook on Construction [59–61]. The default value of carbon content, carbon oxidation rate, average lower heating value, and carbon coefficient for different kinds of energy are shown in

Tables 3 and 4, based on the GHG Protocol Tool for Energy Consumption in China [62]. It should be noted that the carbon coefficients of power sector vary due to the china's energy structure for power generation varying every year. The default value of the ratio of thermal power (%), the ratio of other (water, nuclear, and wind) (%), consumption standard of power and carbon coefficient is represented in Table 4 [17,63]. Carbon emission coefficients of building materials are shown in Table 5, according to the reference [64,65].

3. Result and Analysis

3.1. Estimation of CO₂ Emissions from China's Building Industry

Based on previous studies [17,29,37–40], carbon emissions from the building industry should include two parts: one is direct carbon emission from direct fossil fuel combustion in building industry and the other is indirect carbon from building material consumption.

3.1.1. Estimated Direct Carbon Emission

Using Equation (2) and carbon emission coefficients shown in Tables 3 and 4, we computed the direct carbon emission of China's building industry (see Figure 1). Total direct carbon emission of China's building industry increased from 32.06 million tons of CO₂ in 2005 to 50.12 million tons of CO₂ in 2013. The compound annual growth rate of direct carbon emission in China's industry was 5.74% during 2005–2013.

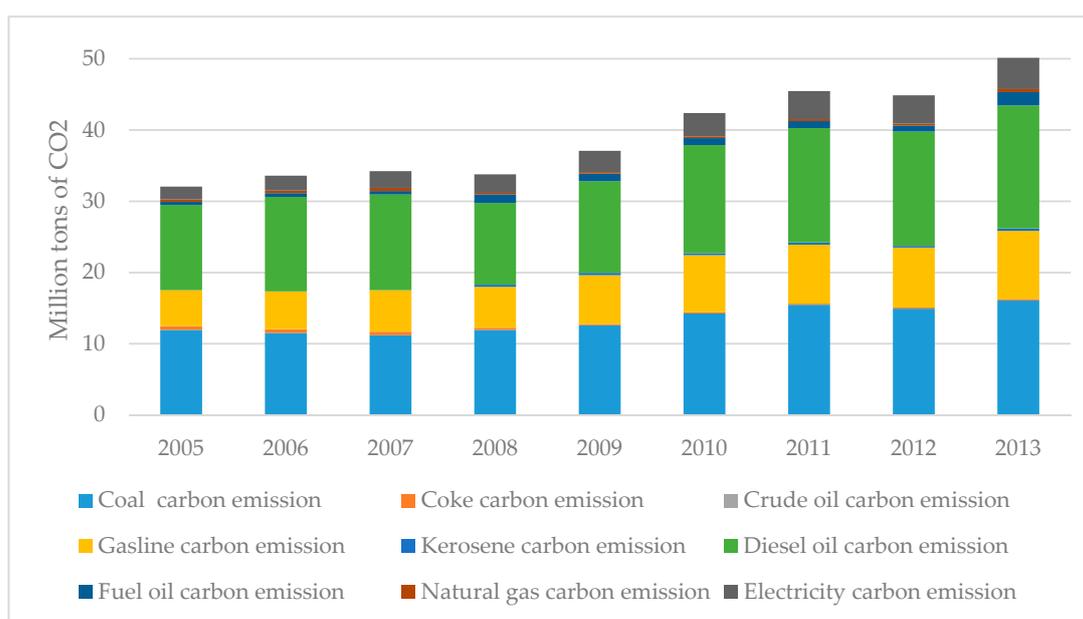


Figure 1. Direct carbon emission of China's building industry 2005–2013.

As shown in Figure 1, the direct carbon emission includes carbon emission from eight type of fuels (coal, coke, crude oil, fuel oil, gasoline, kerosene, diesel oil and natural gas) and electricity of building industry. The main sources of direct carbon emission in China's building industry are diesel oil coal, gasoline, and electricity. In 2005, burning diesel oil, coal, gasoline, and electricity consumption contributions to total direct carbon emission in China's building industry were 37.34%, 37.29%, 15.70% and 5.62%, respectively. In 2013, burning diesel oil, coal, gasoline, electricity consumption contributions to total direct carbon emission in China's building industry were 34.41%, 32.07%, 19.05% and 8.72%, respectively. Thus, burning diesel oil is the biggest source of direct carbon emission in China's building industry, followed by coal, gasoline, and electricity between 2005 and 2013.

3.1.2. Estimated Indirect Carbon Emission

Using Equation (3) and carbon emission coefficients shown in Table 5, we calculated the indirect carbon emission of China's building industry (see Figure 2). Total direct carbon emission of China's building industry increased from 86.61 million tons of CO₂ to 370.37 million tons of CO₂ between 2005 and 2013. The compound annual growth rate of direct carbon emission was 18.50% for this period. It should be noted that direct carbon emission was not always rising. Instead, direct carbon emission decreased from 518.56 million tons of CO₂ in 2012 to 370.37 million tons of CO₂ in 2013.

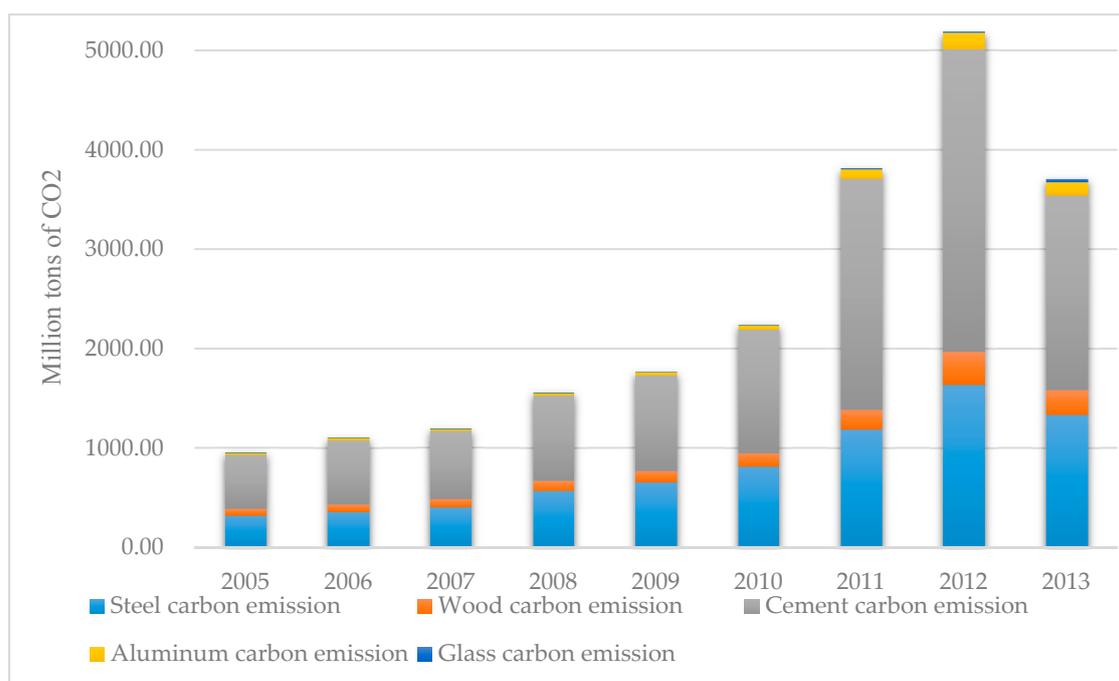


Figure 2. Indirect carbon emission of China's building industry 2005–2013.

The indirect carbon emission includes five types of building materials: cement, steel, wood, aluminum and glass. As shown in Figure 2, the dominant source of indirect carbon emission in China's building industry is the carbon emission from cement. Because the consumption of building materials is large and their carbon emission coefficient is high, the proportion of indirect carbon emissions is large.

In 2005, carbon emission from cement, steel, wood, aluminum and glass consumption produced 56.64%, 33.69%, 7.08%, 2.36% and 0.24% of total indirect carbon emission in China's building industry, respectively. In 2013, carbon emission from cement, steel, wood, aluminum and glass consumption contributed to total direct carbon emission in China's building industry were 52.80%, 35.91%, 6.86%, 3.62%, and 0.81%, respectively.

3.1.3. Estimated Total Carbon Emission

Total carbon emission in China's building industry was calculated using Equation (3). As shown in Figure 3, total carbon emission in China's building industry increased from 984.69 million tons of CO₂ in 2005 to 3753.83 million tons of CO₂ in 2013. The compound annual growth rate of total carbon emission was 18.21%, which was close to the compound annual growth rate of direct carbon emissions. The overwhelming dominant source of total carbon emission was indirect carbon emission, which accounted for 96–99% of total carbon emission from China's building industry during 2005–2013.

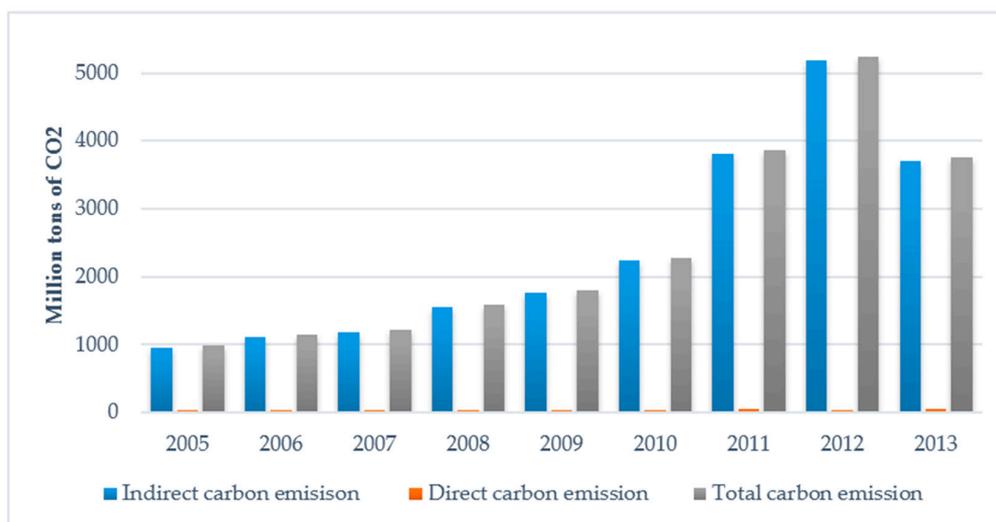


Figure 3. Direct, indirect and total carbon emission from China’s building industry between 2005 and 2013.

3.2. Decomposition Analysis

Inspired by earlier studies [66–75], the total changes in carbon emissions ΔC is decomposed into the four indicators: ΔC_{St} (the effect of energy structure), ΔC_{It} (the effect of energy intensity), ΔC_{Qt} (the effect of industrial scale), and ΔC_{Pt} (the effect of indirect carbon emission intensity). Using Equations (11)–(17), we qualify effects of energy structure, energy intensity, economy, and indirect emission on change in total carbon emission from China’s building industry between 2005 and 2013. The results are shown in Figure 4.

3.2.1. Economic Effects

As shown in Figure 4, economic effects (economic output from building industry) were the biggest contributor to the increase in carbon emission. During 2005–2013, economic effect contributed to increase carbon emission by 71.22%. Economic effects have always taken a positive role in increasing carbon emission. However, it should also be noted that economic effects became the second biggest contributor after indirect emission intensity since 2009.

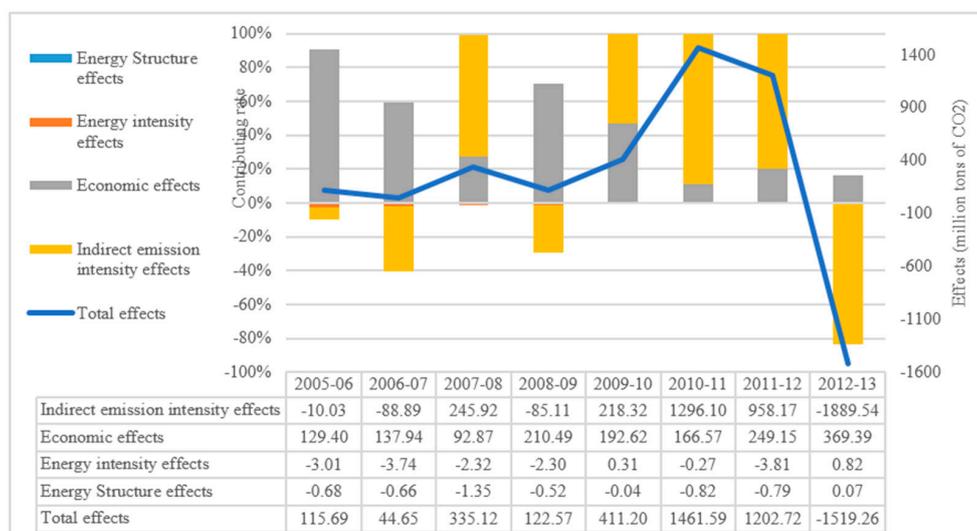


Figure 4. Decomposition of carbon emission of building industry 2005–2013 unit: (million tons of CO₂).

3.2.2. Indirect Emission Intensity Effects

Generally, indirect emission intensity (indirect carbon emission economic output of building industry) effects are the second contributor to increase in total carbon emission of China's building industry. From 2005 to 2013, the accumulated contributing rate of indirect emission effects to increase total carbon emission reached 29.66%. However, the contribution from indirect emission intensity was not always positive. Indeed, indirect emission intensity effects offset the increase in carbon emission during 2005–2008, 2009–2010, and 2012–2013. During 2010–2012, indirect emission intensity offset became the leading contributor to increase in carbon emission. The change of indirect emission intensity effects might be related to the massive RMB 4 trillion (~US\$0.6 trillion) infrastructure plan, which was proposed to deal with the 2008 global finance crisis in November 2008. Such rapid large-scale infrastructure investment might lead to inefficient material consumption. Indirect carbon emission intensity (indirect carbon emission per unit of GDP) increased from 0.96 kgCO₂/Yuan in 2009 to 1.07 kg CO₂/Yuan in 2010, to 1.66 kg CO₂/Yuan in 2011, and further to 2.05 kg CO₂/Yuan in 2012. Fortunately, the indirect carbon emission intensity decreased to 1.34 kg CO₂/Yuan in 2013. The indirect carbon emission intensity was reversed to leading contributor to offset the increase in carbon emission between 2012 and 2013.

3.2.3. Energy Intensity Effects and Energy Structure Effects

Both energy intensity effects and energy structure effects contributed to offset carbon emission. The accumulated contributing rate of energy intensity effects and energy structure effects to increase in carbon emission from 2005 to 2013 were −0.66% and −0.22%, respectively. This is closely related to the energy consumption structure in China's building industry. Coal and oil were the overwhelming dominant sources of energy consumption in China's building industry, whereas clean energy remained a smaller proportion. Given the energy consumption structure has not changed, the energy structure effects and energy intensity effects were minimal.

3.3. Decoupling Analysis

Based on former studies [49,54,76–87], we develop decoupling elasticity model and decoupling efforts model. Using Equations (18)–(20), we calculated the decoupling elasticity and decoupling efforts index. As illustrated in Figure 5, the growth rate of carbon emission and economical outputs, and the decoupling elasticity values of economic outputs are positive during the whole period. The values of Decoupling elasticity (e) is less than 0.8 in 2006 and 2008; the e is between 0.8 and 1.2 in 2007 and 2010; and the e is more than 1.2 in 2009 and 2011–2013. Consequently, the economic outputs decoupling states exhibit weak decoupling in 2006 as well as 2008, expansive decoupling in 2007 as well as 2010, and turn into expansive negative decoupling in 2009 and during 2011–2013. That means the growth rate of carbon emission is slower than the growth rate of economical outputs in 2006, 2008 and 2010, however, the growth rate of carbon emission is faster than the growth rate of economical outputs in 2007, 2009 and during 2011–2013, which is mainly attributed to the economy increase in China mainly depending on the infrastructure. The 2008–2009 Chinese economic stimulus plan is a US\$586 billion stimulus package announced by the State Council of the People's Republic of China as an attempt to minimize the impact of the global financial crisis; in addition, China has experienced urbanization and industrialization. Its urbanization and industrialization has been accelerated in the past decade. The accelerating urbanization and industrialization led to booming of building industry, which means more energy were consumed and more building materials were used. Especially the indirect carbon emission from the building materials is the leading contributor of carbon emission, which is consistent with the estimated indirect carbon emission analysis.

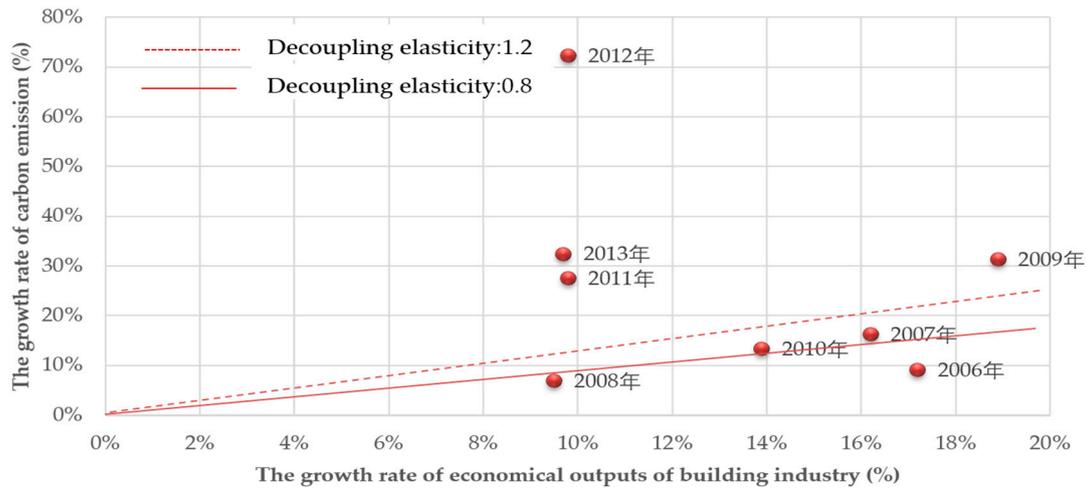


Figure 5. The change of decoupling elasticity of carbon emissions during 2006–2013.

We can see in Figure 6 that the change of decoupling effort indexes is consistent with the change of decoupling elasticity of carbon emissions. In addition, it is concluded that the reducing of intensity of indirect carbon emissions is a key factor in decoupling from the construction industry, however, the efforts of the energy structure effect and energy intensity are rarely small, which indicates the current status of unreasonable energy structure and energy intensive industry, and the energy supply is still dominated by high-carbon energy supply when the demand of energy is increasing while the supply of clean low-carbon energy supply cannot keep up with the economic development.

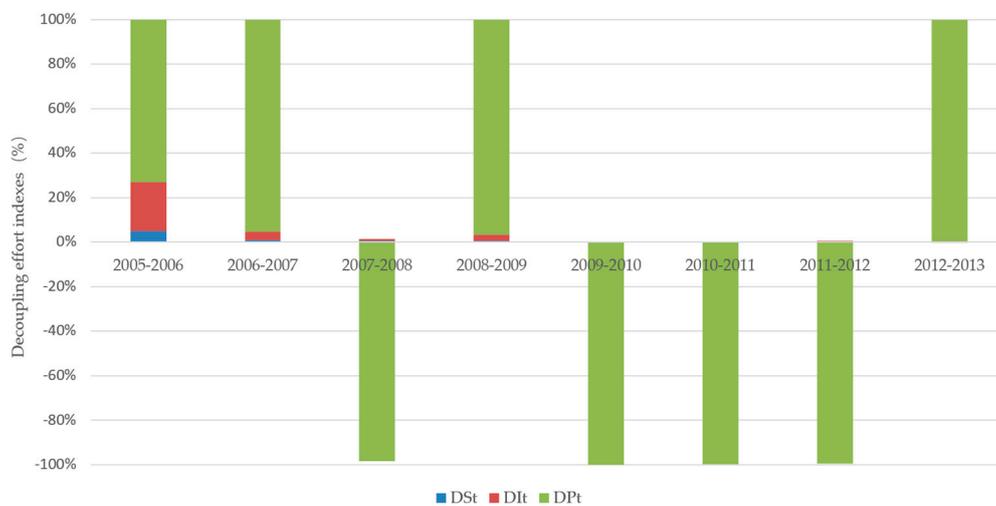


Figure 6. The change of decoupling effort indexes during 2006–2013.

4. Conclusions and Policy Implication

4.1. Conclusions

In this paper, we calculated the direct and indirect carbon emission in China’s building industry from 2005 to 2013, then analyzed the drivers of carbon emission in China’s building industry, and finally estimated the decoupling status of China’s building industry. The main conclusions are as follows.

Using data of energy consumption and materials in China’s building industry from China’s official statistics, and carbon emission coefficient from IPCC, we calculated that the total carbon emission in China’s building industry increased from 984.69 million tons of CO₂ in 2005 to 3753.98 million tons

of CO₂ in 2013. The average annual growth rate is 18.21% per year. Indirect carbon emission from building material consumption accounted for 96–99% of total carbon emission.

Using LMDI technique, we qualify the four key influencing factors for carbon emission in China's building industry. The indirect emission intensity effect was leading contributor to change of carbon emission. It was followed by economic output effects, which always contributed to increase carbon emission. Energy intensity effect and energy structure effect took a negligible role to offset carbon emission.

The status between carbon emission and economic output in China's building industry during 2005–2006 and during 2007–2008 was weak decoupling; during 2006–2007 and during 2008–2010 was expansive decoupling; and during 2010–2013 was expansive negative decoupling. Indirect carbon intensity decoupling index was a leading contributor to the total decoupling index in China's building industry. It was followed by the energy structure and energy intensity decoupling index.

4.2. Policy Implication

Based on the above analysis, three policy recommendations are offered to decouple China's building industry from carbon emission (Figure 7).

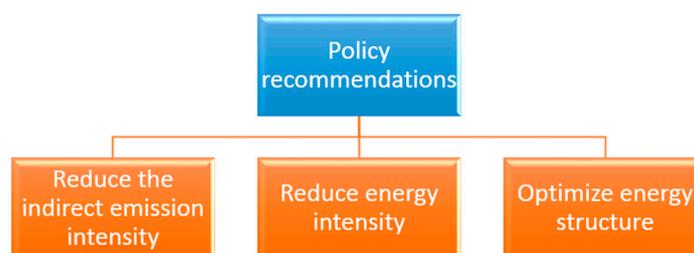


Figure 7. The suggestions based on the data analysis.

- (1) Reducing the indirect emission intensity: Above all, the reduction of indirect emission intensity is a key to delinking economic output from carbon emission, given that indirect emission is the overwhelming dominant source of carbon emission in China's building industry. The measures to reduction of indirect emission intensity include, but are not limited to: (i) development of new building materials to reduce the consumption of traditional building materials, such as cement, steel, and aluminum; (ii) improving energy efficiency to lower carbon intensity of traditional building materials; and (iii) phasing out the low energy efficient building materials as soon as possible.
- (2) Reducing energy intensity: As shown in our study, energy intensity effects were leading contributor to offset carbon emission in China's building industry. Improving energy efficiency is a cost-effective approach to decouple between economic output and carbon in China's building industry. The government should introduce policies and establish financial support systems to promote the development of low-carbon technologies, and encourage construction companies to adopt low-carbon construction technology to optimize building design, thereby improving energy efficiency and improving the suppression effect of energy intensity on carbon emission.
- (3) Optimizing energy structure: We can fully develop the use of hydropower, wind energy, solar energy and other clean energy, reduce dependence on high-carbon energy, and establish a sound energy-saving emission reduction standard building system.

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