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LMDI Decomposition of Energy-Related CO_2 Emissions Based on Energy and CO_2 Allocation Sankey Diagrams: The Method and an Application to China

Linwei Ma [1,2], Chinhao Chong [1,2,3], Xi Zhang [1], Pei Liu [1], Weiqi Li [1,3,*], Zheng Li [1] and Weidou Ni [1]

1 State Key Laboratory of Power Systems, Department of Energy and Power Engineering, Tsinghua-BP Clean Energy Research and Education Centre, Tsinghua University, Beijing 100084, China; malinwei@tsinghua.edu.cn (L.M.); zjh08@tsinghua.org.cn (C.C.); zhangxi14@mails.tsinghua.edu.cn (X.Z.); liu_pei@tsinghua.edu.cn (P.L.); lz-dte@tsinghua.edu.cn (Z.L.); niwd@tsinghua.edu.cn (W.N.)

2 Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development, Tsinghua University, Beijing 100084, China

3 Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610200, China

* Correspondence: liweiqi@tsinghua-eiri.org; Tel.: +86-10-6279-5734-302

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Abstract: This manuscript develops a logarithmic mean Divisia index I (LMDI) decomposition method based on energy and CO_2 allocation Sankey diagrams to analyze the contributions of various influencing factors to the growth of energy-related CO_2 emissions on a national level. Compared with previous methods, we can further consider the influences of energy supply efficiency. Two key parameters, the primary energy quantity converted factor (K_{PEQ}) and the primary carbon dioxide emission factor (K_C), were introduced to calculate the equilibrium data for the whole process of energy unitization and related CO_2 emissions. The data were used to map energy and CO_2 allocation Sankey diagrams. Based on these parameters, we built an LMDI method with a higher technical resolution and applied it to decompose the growth of energy-related CO_2 emissions in China from 2004 to 2014. The results indicate that GDP growth per capita is the main factor driving the growth of CO_2 emissions while the reduction of energy intensity, the improvement of energy supply efficiency, and the introduction of non-fossil fuels in heat and electricity generation slowed the growth of CO_2 emissions.

Keywords: carbon dioxide emissions; influencing factor; LMDI; Sankey diagram; primary carbon emission factor

1. Introduction

Facing the challenge of global climate change, most countries have come to a consensus that it is urgent to control anthropogenic GHG (greenhouse gas) emissions, especially energy-related carbon dioxide (CO_2) emissions [1]. Therefore, it is essential for policy makers in various countries to understand the main factors influencing the growth of energy-related CO_2 emissions and quantitatively evaluate their contributions [2]. In previous studies, the logarithmic mean Divisia index I (LMDI) decomposition method has been widely applied to analyzing the influencing factors of CO_2 emissions growth in many countries (see the literature review in the following section and Appendix B Table A7). Through the LMDI decomposition method, researchers can identify the contribution of each influencing factor to reducing or increasing CO_2 emissions quantitatively. For example, the increasing proportion

of thermal power in the end-use sector will increase the CO_2 emissions while increasing end-use energy efficiency will reduce CO_2 emissions.

According to the literature review and Table A7, the population growth, GDP, economic structure, energy intensity, and energy mix are commonly considered influencing factors. However, it is still difficult to evaluate the contributions of some technical influencing factors such as the efficiency of energy conversion and transportation, which are important for making national energy policies to reduce energy-related CO_2 emissions. We conclude that most studies cannot finely reflect the network features of the physical energy system because they use a top-down decomposition approach based on macro-level influencing factors, such as population, GDP (gross domestic product), energy intensity, and structure of primary energy consumption. In a national energy system, the primary energy is first processed, transported, and converted into various secondary energies, generating some emissions, especially in electricity and heat generation based on fossil energy. Then the secondary energy is distributed to a large number of end-use sectors, which are also emissions sources such as fuel burning. Thus, the efficiency of energy conversion and distribution can also greatly influence the total emissions of the system besides the emissions generated in end-use sectors. Therefore, the environment would benefit by further improving the LMDI method and considering more technical details about the structural and efficiency changes through the national energy system including stages of energy sources, energy conversion, and energy end-use.

Hence, we introduce the Sankey diagram as a key for depicting the complex energy system and its CO_2 emissions. The Sankey diagram is a popular tool for illustrating and analyzing the detailed flows of energy and mass in a complex energy system. It is usually adopted for analyzing the energy balance and energy efficiency of an energy system. In addition, it can also be applied to further analyze the GHG emissions. Though there are some published works on Sankey diagrams of GHG emissions [3–6], few works have attempted to use them to improve the LMDI method of GHG emissions growth. In our previous studies, we improved the LMDI method by mapping energy allocation Sankey diagrams to analyze the driving forces of coal consumption growth in China [7] and energy consumption in Jing-Jin-Ji Area, China [8]. Therefore, we decided to develop a method of mapping the CO_2 allocation Sankey diagram and use it to improve the LMDI method for the decomposition of CO_2 emissions growth on a national level.

The aim of this study was to develop an LMDI method to decompose and analyze the contributions of the main influencing factors including both the conventional factors and the technical factors mentioned above and the growth of energy-related CO_2 emissions. First, we proposed two parameters including the derived primary energy quantity conversion factor (K_{PEQ}) and the primary carbon dioxide emission factor (K_C) of each secondary energy, which were key technical influencing factors for the LMDI method. Second, we built a method using K_{PEQ} and K_C to calculate the equilibrium data of energy and CO_2 for the whole physical process of energy use and its CO_2 emissions from primary energy supply to end-use energy consumption. We used this data to map the energy allocation Sankey diagram and carbon dioxide allocation Sankey diagram of energy consumption for visual presentations. Based on this mapping, we developed an LMDI method including both the conventional influencing factors and the technical influencing factors to decompose the contributions of each influencing factor to the growth of CO_2 emissions.

To develop an LMDI method, it is better to apply it to actual objects. China is a prominent case as the world's largest source of CO_2 emissions, which was responsible for 29.6% of global emissions in 2014 [9] and with a growth rate of 106% for CO_2 emissions from 2004 to 2014. Currently, it is urgent for China to control rapidly increasing CO_2 emissions, especially energy-related emissions, that account for 77% of the total CO_2 emissions in China [10,11]. Referring to the Intended Nationally Determined Contribution (INDC) of China [12] and the U.S.–China Joint Presidential Statement on Climate Change [13], China has promised to reach a peak in CO_2 emissions around 2030 with a strong effort to peak early and decrease CO_2 emissions per unit of GDP by 60 to 65% from the 2005 level. Moreover, the 13th Five-Year-Plan of China was enacted in 2016, which contained corresponding

planned targets between 2016 and 2020 that were decomposed from the above 2030 targets to promote the implementation [14]. Therefore, the case study on China not only ensures the data source for the method development, but may also examine the applicability of the method by comparing the results with current policies.

In this study, we attempt to develop an LMDI method suitable for analyzing the CO_2 emissions growth of countries with complex energy systems and to apply the method to analyze the influencing factors of CO_2 emissions growth in China. First, by mapping energy allocation Sankey diagrams and CO_2 allocation Sankey diagrams, we studied the physical processes of energy use and CO_2 emissions from the primary energy supply to the end-uses. We derived extra influencing factors to include in the decomposition. Then, using these extra influencing factors, we developed an improved LMDI method suitable for analyzing complex energy systems and applied it to analyze the CO_2 emissions growth in China from 2004 to 2014.

The main contribution of this work is that the extra influencing factors which we derived can contribute to a more elaborate LMDI decomposition method for CO_2 emissions growth. Additionally, the Sankey diagrams and results of LMDI decomposition together can help us to comprehensively understand China's energy-related CO_2 emissions and driving forces behind the growth. The rest of this paper includes a literature review in Section 2, methodology and data input in Section 3, results and discussion in Section 4, and conclusions in Section 5.

2. Literature Review

2.1. Energy and CO_2 Emissions Sankey Diagram

Sankey diagrams are popular tools in energy system analysis. In an energy Sankey diagram, energy flow appears as arrows from one side to another with the color indicating energy types and width indicating energy quantities. There are no losses reflected in the energy allocation Sankey diagrams, which means we can trace the primary energy along the flows, while the energy efficiency Sankey diagrams show energy losses for efficiency analysis. Based on those diagrams, we can depict comprehensive pictures of complex energy system in various countries or regions with high technical resolution. For example, Cullen and Allwood [15,16] presented global energy flows and energy efficiency, Ma et al. [17] presented China's energy flows and compared it with the global energy flow, and Chong et al. [7,18] presented the coal flows in China. The main challenge of mapping those diagrams is how to treat a huge number of primary data points from the energy balance table especially through manual methods. To solve it, Chong et al. [18] presented a programmed data-processing method for mapping energy allocation Sankey diagram and introduced primary energy quantity converted factor (K_{PEQ}) to connect end-use energy consumption and primary energy consumption. After that, Chong et al. [19] further introduced an input–output approach to acquire K_{PEQ} and generate the data for mapping an energy allocation Sankey diagram. Based on those works and others, Soundararajan et al. [20] provided a review of energy allocation Sankey diagrams and suggested a framework to use it for national level analysis.

Based on energy balance and emission factors, it is also possible to present the flows of CO_2 (as well as greenhouse gases) emissions through Sankey diagrams based on the equilibrium of the carbon element. There are two types of CO_2 Sankey diagrams, according to the treatment method of emission flows of heat and electricity. In the first type, the emission flows start with primary energy sources, energy conversion, and end-use sectors. For example, Mu and Li [3,4] presented the carbon dioxide emissions allocation Sankey diagrams of China, which depict in detail the energy sources and energy conversion sectors. However, it is difficult to clearly observe the emission allocation in end-use sectors. The research determines that energy losses in energy conversion are responsible for the emissions and so end-use sectors are only responsible for a part of total emissions. In the second type, the emission flows start with main sectors of emission sources, such as transport, electricity and heat generation, industry, and agriculture, and then go to detailed sub-sectors. For example, WRI

(World Resources Institute) presented the flows of global [5] and U.S. [6] GHG emissions (carbon dioxide, methane, and nitrogen oxide) by using the Sankey diagram in this way.

Through the literature review, we conclude that there are few published works on CO_2 emissions Sankey diagrams based on the energy allocation Sankey diagram, which may present that CO_2 emissions are responsible for main sectors in each stage of the energy system including energy sources, energy conversion, and end-use sectors. Based on our previous works on energy allocation Sankey diagrams [7,18,19], we can acquire the K_{PEQ} of each secondary energy to establish the connection between end-use energy consumption and primary energy consumption. Additionally, we can further derive corresponding parameters by emission factors to establish the connection between end-use energy consumption and CO_2 emissions. Therefore, we are able to develop a methodology for mapping CO_2 allocation Sankey diagrams, which can determine the full responsibility of CO_2 emissions of various sectors in each stage of the energy system and use it as a foundation to improve the LMDI decomposition method of CO_2 emissions growth.

2.2. LMDI Decomposition

The index decomposition analysis (IDA) method has been widely applied for analyzing the influencing factors of the growth of CO_2 emissions including those based on the Laspeyres index and the Divisia index. Ang et al. [21–25] presented a review of the development and applications of IDA methods and recommended the logarithmic mean Divisia index I (LMDI) method because it is robust and convenient for many applications. Many studies have utilized the LMDI method to decompose the total CO_2 growth of various sectors and regions. We present a summary of these studies in Table A7. In Table A7, we categorize the previous studies into five groups (A–E) according to the sector they analyzed, as follows.

(1) Whole sector (A1–A15) including both the economic sector and residential sector;
(2) Economic sector (B1–B20) including several main sectors, which can be further divided into specific sub-sectors according to the study purpose;
(3) Industrial sector (C1–C12), which can be further divided into specific sub-sectors according to the study purpose;
(4) Residential sector (D1–D8);
(5) Specific sector (E1–E8) like the power sector, iron, and steel industry, cement industry, etc.

In these studies, the commonly considered influencing factors are population growth, GDP (or gross output), economic structure (measured by value added or output of the sectors), energy intensity, end-use energy structure, and CO_2 emission factors. There are two major ways to allocate the responsibility of CO_2 emissions of electricity and heat generation: (1) considered as direct emissions of the generation; and (2) considered as indirect emissions of end-use sector. The emission factors of electricity and heat are calculated by the fuel structure of the generation. The latest way is more meaningful as it can show the contribution of the changes of electricity proportion in end-use sectors to the total CO_2 emissions. However, except those only focused on the power sector, most of the studies do not consider the influences of energy efficiency of heat and electricity generation.

Using the literature review, we conclude that in previous studies on a national level, neither the influence of the efficiency of electricity and heat generation nor the influence of efficiency of energy transportation and distribution can be decomposed. Based on K_{PEQ} and other parameters derived from mapping the energy allocation Sankey diagram and CO_2 emission allocation Sankey diagram, we can develop an LMDI method that can analyze the influence of technical energy efficiency to improve the accuracy of the method. Since the energy losses in energy transportation and distribution are normally small and also lack statistical accounting, the technical energy efficiency is mainly decided by the efficiency of electricity and heat generation in this study.

3. Methodology and Data Input

In this section, we first introduce the primary energy quantity conversion factor (K_{PEQ}) in Section 3.1 and the primary carbon dioxide emission factor (K_C) in Section 3.2. Then these key parameters are used to map the energy allocation Sankey diagram and the CO_2 allocation Sankey diagram of energy consumption, which is introduced in Section 3.3. Next, the data obtained by the mapping is used in Section 3.4 to develop an LMDI method suitable for analyzing all influencing factors including both normal and extra factors. In the end, we briefly introduce the data input in Section 3.5.

3.1. Primary Energy Converted Factor

K_{PEQ}, the primary energy quantity conversion factor, which was suggested by authors in previous studies [7,18,19,26], is a key parameter for establishing the connection between energy consumption of end-use sectors and primary energy consumption. K_{PEQ} is defined as the total number of units of primary energy that are consumed to produce one unit of secondary energy. In previous studies [7,18], the authors presented a method that can generate K_{PEQ} based on a series of standardized steps and rigid equations that can be programmed. In this method, we can express end-use energy consumption in standard quantity (SQ) form or in primary energy quantity (PEQ) form. The SQ form denotes the heat value of secondary energy consumed by end-use sectors while the PEQ form denotes the total primary energy consumed to produce secondary energy by compensating all energy losses upstream. However, the compensating process for the energy losses upstream is complex and involves many interacting conversion sub-sectors. Thus, the authors further introduced an input–output method to acquire the K_{PEQ} of each energy type in a prior study [19].

The input–output method has been widely applied to reveal internal relationships among the economic sectors. The establishment of an input–output table can reflect the balance of material or capital flows among all sectors while the Leontief inverse matrix of the table can establish the connection between the end-use consumption and the total consumption (which includes intermediate and end-use consumption) of the flows. Therefore, using the input–output method, we can construct the energy input–output table of the energy sectors to establish the connection between end-use energy consumption and primary energy consumption by using the Leontief inverse matrix.

3.1.1. Establishment of the Energy Input–Output Table

The energy balance table of China [27,28] has provided detailed data on energy supply, energy conversion, and end-use consumption. Hence, we can modify the energy balance table into an energy input–output table according to the energy balance. However, the 30 energy types in an energy balance table should be combined into 11 energy types according to the sectoral classification in the energy balance table. This is due to the limitation of the input–output method where each intermediate sector can only have one kind of output. The classification of the intermedia sectors and their outputs are listed in Table A1.

Based on the classification, we establish the energy input–output table by using the energy balance table as shown in Table A2. Q_{ij} is the quantity of energy i consumed to produced energy j, Y_i is the final demand of energy i (including net exports and end-use consumption of energy i), and Q_i is the total output of energy i. All data in the table are expressed in SQ form.

3.1.2. Leontief Inverse Matrix of Energy Input–Output Table

The mathematical relationship among the elements in Table A2 is expressed in Equation (1) which means the total output of energy i (Q_i) equals the sum of intermedia consumption of energy i for energy conversion $\left(\sum_j Q_{ij}\right)$ and the final demand of energy i for end-use consumption (Y_i). Equation (1) can be further expressed in matrix form, which is shown in Equation (2).

$$\begin{array}{c} Q_{11} + Q_{12} + Q_{13} + \ldots + Q_{1j} + Y_1 = Q_1 \\ Q_{21} + Q_{22} + Q_{23} + \ldots + Q_{2j} + Y_2 = Q_2 \\ Q_{31} + Q_{32} + Q_{33} + \ldots + Q_{3j} + Y_3 = Q_3 \\ \vdots \\ Q_{i1} + Q_{i2} + Q_{i3} + \ldots + Q_{ij} + Y_i = Q_i \end{array} \quad (1)$$

$$\begin{pmatrix} Q_{11} & Q_{12} & Q_{13} & \cdots & Q_{1j} \\ Q_{21} & Q_{22} & Q_{23} & \cdots & Q_{2j} \\ Q_{31} & Q_{32} & Q_{33} & \cdots & Q_{3j} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Q_{i1} & Q_{i2} & Q_{i3} & \cdots & Q_{ij} \end{pmatrix} + \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \cdots \\ Y_i \end{pmatrix} = \begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \\ \cdots \\ Q_i \end{pmatrix} \quad (2)$$

After that, we define direct consumption efficiency a_{ij} as the energy i. This should be consumed to produce one unit of energy j, which is shown in Equation (3).

$$a_{ij} = \frac{Q_{ij}}{Q_j} \quad (3)$$

Hence, Equation (2) can be further expressed in Equation (4) and simplified as Equation (5).

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1j} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2j} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3j} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{i1} & a_{i2} & a_{i3} & \cdots & a_{ij} \end{pmatrix} \begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \\ \cdots \\ Q_i \end{pmatrix} + \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \cdots \\ Y_i \end{pmatrix} = \begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \\ \cdots \\ Q_i \end{pmatrix} \quad (4)$$

$$AQ + Y = Q \quad (5)$$

Equation (5) can be further rewritten as Equation (6). Q is the total output of energy, Y is the final demand of energy, and $(I - A)^{-1}$ is the Leontief inverse matrix, which is denoted with symbol L' as shown in Equation (7).

$$Q = (I - A)^{-1} Y \quad (6)$$

$$Q = L'Y \quad (7)$$

In the Leontief inverse matrix, $L_{ij}{}'$ indicates the total unit of energy i that should be produced in the energy sector in order to provide one unit of energy j for end-use. Thus, we can further calculate the total unit of fossil fuel that should be consumed in the conversion sector to provide one unit of energy j, $K_{PEQ,j}$, by using Equation (8).

$$K_{PEQj} = L_{1,j}{}' + L_{2,j}{}' + L_{3,J}{}' + L_{4,J}{}' \quad (8)$$

$K_{PEQ,j}$ Primary energy quantity conversion factor of energy j
$L_{1,j}{}'$ Raw coal to be consumed to provide one unit of end-use energy j in the conversion sector
$L_{2,j}{}'$ Crude oil to be consumed to provide one unit of end-use energy j in the conversion sector
$L_{3,j}{}'$ Natural gas to be consumed to provide one unit of end-use energy j in the conversion sector
$L_{4,j}{}'$ Other fossil fuels to be consumed to provide one unit of end-use energy j in the conversion sector

Considering that electricity and heat are generated not only from fossil fuels but also from non-fossil fuels, Equation (8) was revised as below.

$$K_{PEQj} = L_{1,j} + L_{2,j} + L_{3,J} + L_{4,J} + L_{5,J} \quad (9)$$

where

$$L_{5,j} = K_{PEQ,j} \cdot \frac{E_{SQ,j,non-fossil}}{E_{SQ,j,fossil} + E_{SQ,j,non-fossil}} \quad (10)$$

while $L_{1,j}'$, $L_{2,j}'$, $L_{3,j}'$ and $L_{4,j}'$ were revised using Equation (11), in which m included raw coal, crude oil, natural gas, and other fossil fuels.

$$L_{m,j} = L_{m,j}' \cdot \frac{E_{SQ,j,fossil}}{E_{SQ,j,fossil} + E_{SQ,j,non-fossil}} \quad (11)$$

$K_{PEQ,j}$ Primary energy quantity conversion factor of energy j

$L_{m,j}'$ Primary energy to be consumed to provide one unit of end-use energy j in the conversion sector, including raw coal, natural gas, crude oil, and other fossil fuels

$L_{m,j}$ Primary energy to be consumed to provide one unit of end-use energy j including raw coal, natural gas, crude oil, other fossil fuels, and non-fossil fuel

$E_{SQ,j,fossil}$ Total energy type j which is converted from fossil fuels expressed in SQ form

$E_{SQ,j,non\text{-}fossil}$ Total energy type j which is converted from non-fossil fuels expressed in SQ form

3.1.3. K_{PEQ} of Each Energy Type in China

According to the results of above calculations and data input from the energy balance table [27,28], the K_{PEQ} of each energy type in China is presented in Table 1. K_{PEQ} is further adopted to derive the primary carbon dioxide emission factor in Section 3.2, to obtain the data for mapping the energy allocation Sankey diagram of China in Section 3.3, and to develop the LMDI method to decompose the growth of energy-related CO_2 emissions in China in Section 3.4.

Table 1. K_{PEQ} of each secondary energy type and its structure.

Year	K_{PEQ} and Its Structure	Energy Type						
		Electricity	Heat	Coal Preparation Products	Coking Products	Oil Products	LNG	Briquette
2004	K_{PEQ}	2.88	1.41	1.05	1.08	1.04	-	1.13
	-Raw coal	77.2%	89.5%	100.0%	99.9%	0.0%	-	100.0%
	-Crude oil	3.5%	6.8%	0.0%	0.1%	99.9%	-	0.0%
	-Natural gas	0.3%	2.9%	0.0%	0.0%	0.0%	-	0.0%
	-Other fossil fuels	0.4%	0.7%	0.0%	0.0%	0.1%	-	0.0%
	-Non-fossil fuels	18.5%	0.0%	0.0%	0.0%	0.0%	-	0.0%
2014	K_{PEQ}	2.54	1.41	1.10	1.15	1.03	1.07	1.35
	-Raw coal	71.6%	73.1%	100.0%	100.0%	0.8%	0.0%	100.0%
	-Crude oil	0.3%	3.5%	0.0%	0.0%	99.1%	0.0%	0.0%
	-Natural gas	1.9%	3.3%	0.0%	0.0%	0.1%	100.0%	0.0%
	-Other fossil fuels	1.8%	6.4%	0.0%	0.0%	0.0%	0.0%	0.0%
	-Non-fossil fuels	24.4%	13.7%	0.0%	0.0%	0.0%	0.0%	0.0%

3.2. Primary Carbon Dioxide Emission Factor

After introducing the acquirement of K_{PEQ} of each energy type for mapping the energy allocation Sankey diagram, we further introduce the acquirement of the primary carbon dioxide emission factor (K_C) in this section, which is a key parameter for establishing the connection between energy consumption expressed in PEQ form and CO_2 emissions. K_C is defined as the total number of units of CO_2 emissions when one unit of end-use energy expressed in PEQ form is consumed, which can be calculated using Equation (12). The CO_2 emissions factors of each primary energy are given in Table 2 [29]. Equation (12) can be further modified as Equation (13), in which $K_{C,SQ,j}$ is defined as the total number of units of CO_2 emissions when one unit of end-use energy expressed in SQ form is consumed.

$$KC,j = \sum_m \frac{Lm,j}{KPEQ,j} \cdot KC,m \quad (12)$$

$$\begin{aligned} KC,SQ,j &= KC,j \cdot KPEQ,j \\ &= \sum_m \frac{Lm,j}{KPEQ,j} \cdot KC,m \cdot KPEQ,j \\ &= \sum_m Lm,j \cdot KC,m \end{aligned} \quad (13)$$

$K_{C,j}$ Primary carbon dioxide emission factor of end-use energy j, which establishes the relationship between energy consumption expressed in PEQ form and CO_2 emissions

$K_{C,SQ,,j}$ Primary carbon dioxide emission factor of end-use energy j, which establishes the relationship between energy consumption expressed in SQ form and CO_2 emissions

$K_{C,m}$ CO_2 emission factor of primary energy m

$L_{m,j}$ Primary energy m to be consumed to provide one unit of end-use energy j

$K_{PEQ,j}$ Primary energy quantity converted factor of energy j

Subscription j Energy type j

Subscription m Primary energy type m, including (1) raw coal; (2) crude oil; (3) natural gas; (4) other fossil fuels; and (5) non-fossil fuels.

Table 2. CO_2 emission factor of primary energy [29].

Primary Energy Type m	$K_{C,m}$	Unit
Raw coal	2.459	t/tce
Crude oil	2.148	t/tce
Natural gas	1.643	t/tce
Other fossil fuels	2.459	t/tce
Non-fossil fuels	0	t/tce

The K_C of each energy type in China is presented in Table 3. K_C is further adopted to derive the data for mapping the CO_2 (energy-related) allocation Sankey diagram in China in Section 3.3 and to develop the LMDI decomposition method of total CO_2 emissions growth in China in Section 3.4.

Table 3. K_C and $K_{C,SQ}$ of each secondary energy type and their structure.

Year	K_C and Its Structure	Energy Type						
		Electricity	Heat	Coal Preparation Products	Coking Products	Oil Products	LNG	Briquette
2004	$K_{C,SQ,j}$ (Unit: t/tce)	5.73	3.40	2.59	2.67	2.23	-	2.79
	K_C (Unit: t/tce)	1.99	2.41	2.46	2.46	2.15	-	2.46
	-Raw coal	95.4%	91.2%	100.0%	99.9%	0.0%	-	100.0%
	-Crude oil	3.8%	6.1%	0.0%	0.1%	99.9%	-	0.0%
	-Natural gas	0.3%	2.0%	0.0%	0.0%	0.0%	-	0.0%
	-Other fossil fuels	0.5%	0.7%	0.0%	0.0%	0.1%	-	0.0%
	-Non-fossil fuels	0.0%	0.0%	0.0%	0.0%	0.0%	-	0.0%
2014	$K_{C,SQ,j}$ (Unit: t/tce)	4.67	2.94	2.70	2.70	2.22	1.75	3.31
	K_C (Unit: t/tce)	1.84	2.09	2.46	2.46	2.15	1.64	2.46
	-Raw coal	95.6%	86.2%	100.0%	100.0%	0.9%	0.0%	100.0%
	-Crude oil	0.3%	3.6%	0.0%	0.0%	99.0%	0.0%	0.0%
	-Natural gas	1.7%	2.6%	0.0%	0.0%	0.1%	100.0%	0.0%
	-Other fossil fuels	2.4%	7.6%	0.0%	0.0%	0.0%	0.0%	0.0%
	-Non-fossil fuels	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

3.3. Sankey Diagram

3.3.1. Diagram Structure

In this study, the energy allocation Sankey diagrams and the CO_2 allocation Sankey diagrams in China are divided into three stages, including primary energy supply, energy conversion, and end-use sector, as specified by previous studies [7,18,26]. The word "allocation" means there are no energy or mass losses reflected in these Sankey diagrams. By compensating all losses during energy conversion and transport, we can express the consumption of secondary energy in PEQ form to indicate the amount of primary energy consumption required to produce it, and express the CO_2 emissions in mass form. This will indicate the responsibility of each sector in various stages for total CO_2 emissions.

The 13 energy types in the mapping are defined in Table A3 and described in previous studies [7,18,19]. To illustrate the structure of the final energy consumption and CO_2 emissions of each subsector in the diagram, we re-categorized the subsectors as shown in Table A4.

3.3.2. Original Data and Data Processing

The energy balance table and the table of final energy consumption by the industrial sector in the China Energy Statistical Yearbook [27,28] are used as original data sources for mapping the energy allocation Sankey diagram and the CO_2 allocation Sankey diagram of energy consumption.

However, in addition to the oil consumption data in the transport, storage, and post subsector classifications, the actual oil consumption of various vehicles is partly separated into statistical energy consumption in other subsectors due to the current method of constructing the energy balance tables. To determine this portion of energy consumption, we include in the transportation sector from the original statistical data [30], all gasoline consumption and 95% of diesel consumption in the primary industrial and residential sector, 95% of gasoline consumption and 35% of diesel consumption in the secondary and tertiary industries, all kerosene consumption in other sectors, and 100% of gasoline, diesel, kerosene, fuel oil, LPG (liquefied petroleum gas), natural gas, LNG (liquefied natural gas), and 40% of electricity in the original transport, storage, and post subsector classifications noted in the energy balance table. As such, the energy consumption in the transportation sector only includes the oil consumption for driving various vehicles such as cars, planes, and trucks while the rest of the energy consumption in the transport, storage, and post subsectors is separated into energy consumption for buildings.

3.3.3. Final Data for Diagram Mapping

As demonstrated in previous studies [7,18,19,26], we can use Equation (14) to obtain the data for constructing the energy allocation Sankey diagram, in which $K_{PEQ,j}$ is used to amplify secondary energy to the primary energy, which is required to produce the secondary energy by compensating the energy losses in the conversion sector. The acquisition of $K_{PEQ,j}$ is described in Section 3.1.

$$EPEQ,j = ESQ,j \cdot KPEQ,j \tag{14}$$

$E_{PEQ,,j}$ Energy j consumption expressed in PEQ form, which is used for mapping the energy allocation Sankey diagram

$E_{SQ,j}$ Energy j consumption expressed in SQ form, which is given in the energy balance table

$K_{PEQ,j}$ Primary energy conversion factor of energy j

Equation (14) can be further modified with $K_{c,j}$ as seen in Equation (15) to express the data for constructing the CO_2 allocation Sankey diagram of energy consumption, in which $K_{c,j}$ is used to calculate the CO_2 emissions of each type of end-use energy. The acquisition of $K_{c,j}$ is described in Section 3.2.

$$Cj = ESQ,j \cdot KPEQ,j \cdot KC,j \tag{15}$$

$C_{,j}$ CO_2 emissions, which is used for mapping the carbon dioxide allocation Sankey diagram of energy consumption

E_{SQ} Energy j consumption expressed in SQ form, which is given in the energy balance table

$K_{PEQ,j}$ Primary energy conversion factor of energy j

$K_{C,j}$ Primary carbon dioxide emission factor of end-use energy j, which establishes the relationship between energy consumption expressed in PEQ form and CO_2 emissions.

3.4. Additive LMDI Decomposition Method

Based on Equation (15), we can extend the conventional CO_2 identity to further consider technical details about structural and efficiency changes through the complex energy system along stages of the energy supply chain. In this study, we classify the CO_2 emissions of China into two groups, according to the energy statistical data of China. We discuss their influencing factors such as the economic sector, which includes the primary, secondary, and tertiary sectors, and the residential sector, which includes urban and rural areas. These constitute all energy-related CO_2 emissions in China.

For the economic sector, most previous studies have adopted Equation (16) to express the CO_2 emissions and to consider influencing factors such as population (P), GDP per capita ($\frac{GDP}{P}$), economic structure ($\frac{GDPi}{GDP}$), energy intensity ($\frac{ESQ,i}{GDPi}$), energy proportional use ($\frac{ESQ,ij}{ESQ,i}$), and CO_2 emission factor ($K_{C,j}{}'$) where i represents the economic sector and j represents the energy type.

$$Ceconomic = \sum_{ij} P \cdot \frac{GDP}{P} \cdot \frac{GDPi}{GDP} \cdot \frac{ESQ,i}{GDPi} \cdot \frac{ESQ,ij}{ESQ,i} \cdot K'_{c,j} \tag{16}$$

Our literature review shows that neither the influence of electricity efficiency and heat generation has been decomposed in previous studies nor the influence of efficiency of energy transportation and distribution. Therefore, we modified Equation (16) to overcome the challenge mentioned above as shown in Equation (17).

$$Ceconomic = \sum_{ij} P \cdot \frac{GDP}{P} \cdot \frac{GDPi}{GDP} \cdot \frac{ESQ,i}{GDPi} \cdot \frac{ESQ,ij}{ESQ,i} \cdot KPEQ,j \cdot K_{c,j} \tag{17}$$

For the residential sector, we consider the influencing factors, including urban residential CO_2 emissions and rural residential CO_2 emissions. The residential CO_2 emissions can be expressed by population (P), urban and rural structure ($\frac{Pi}{P}$), residential energy consumption per capita ($\frac{ESQ,i}{Pi}$), energy proportional use ($\frac{ESQ,ij}{ESQ,i}$), primary energy conversion factor ($K_{PEQ,j}$), and primary carbon dioxide emission factor ($K_{C,j}$), which is shown in Equation (18).

$$Cresidential = \sum_{ij} P \cdot \frac{Pi}{P} \cdot \frac{ESQ,i}{Pi} \cdot \frac{ESQ,ij}{ESQ,i} \cdot KPEQ,j \cdot KC,j \tag{18}$$

The symbols used in Equations (17) and (18) are defined in Tables A5 and A6. In this study, we adopt additive LMDI decomposition. The additive LMDI formulae for decomposing energy-related CO_2 emissions growth in the composite economic and residential sectors of China are presented in Tables 4 and 5.

Table 4. Additive LMDI formulae for decomposing the CO_2 emissions growth of economic sector in China.

IDA Identity	$\boldsymbol{Ceconomic = \sum_i \sum_j P \cdot \frac{GDP}{P} \cdot \frac{GDPi}{GDP} \cdot \frac{ESQ,i}{GDPi} \cdot \frac{ESQ,ij}{ESQ,i} \cdot KPEQ,j \cdot KC,j}$	
Change Scheme	$\Delta Ctot,economic$	$= C^T economic - C^0 economic$ $= (\Delta Cpop + \Delta Caff + \Delta Cstr + \Delta CInt + \Delta Cmix + \Delta Cpeq + \Delta Cemi) economic$
Influencing Factors	**Symbols**	**Additive LMDI Formulae**
Population	P	$\Delta C_{pop,economic} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{P^T}{P^0}\right)$
GDP per capita	$Q = \frac{GDP}{P}$	$\Delta C_{aff,economic} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{Q^T}{Q^0}\right)$
Economic structure	$Si = \frac{GDPi}{GDP}$	$\Delta C_{str,economic} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{S_i^T}{S_i^0}\right)$
Energy intensity	$Ii = \frac{ESQ,i}{GDPi}$	$\Delta C_{\text{int},economic} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{I_i^T}{I_i^0}\right)$
Energy proportional use	$Mij = \frac{ESQ,ij}{Ei,SQ}$	$\Delta C_{mix,economic} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{M_{ij}^T}{M_{ij}^0}\right)$
Primary energy quantity converted factor	$K_{PEQ,j}$	$\Delta C_{peq,economic} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{K_{PEQ,ij}^T}{K_{PEQ,ij}^0}\right)$
Primary carbon dioxide emission factor	$K_{C,j}$	$\Delta C_{emi,economic} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{K_{C,j}^T}{K_{C,j}^0}\right)$

Note: The superscripts 0 and T specify the parameter value at time 0 and time T, respectively.

Table 5. Additive LMDI formulae for decomposing CO_2 emissions growth of residential sector in China.

IDA Identity	$\boldsymbol{Cresidential = \sum_i \sum_j P \cdot \frac{Pi}{P} \cdot \frac{ESQ,i}{Pi} \cdot \frac{ESQ,ij}{ESQ,i} \cdot KPEQ,j \cdot KC,j}$	
Change Scheme	$\Delta Cresidential$	$= C^T residential - C^0 residential$ $= (\Delta Cpop + \Delta Cstr + \Delta CInt + \Delta Cmix + \Delta Cpeq + \Delta Cemi) residential$
Influencing Factors	**Symbols**	**Additive LMDI Formulae**
Population	P	$\Delta C_{pop,residential} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{P^T}{P^0}\right)$
Urban and rural structure	$Si = \frac{Pi}{P}$	$\Delta C_{str,residential} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{S_i^T}{S_i^0}\right)$
Residential energy consumption per capita	$Ii = \frac{ESQ,i}{Pi}$	$\Delta C_{\text{int},residential} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{I_i^T}{I_i^0}\right)$
Energy mix	$Mij = \frac{ESQ,ij}{Ei,SQ}$	$\Delta C_{mix,residential} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{M_{ij}^T}{M_{ij}^0}\right)$
Primary energy quantity converted factor	$K_{PEQ,j}$	$\Delta C_{peq,residential} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{K_{PEQ,ij}^T}{K_{PEQ,ij}^0}\right)$
Primary carbon dioxide emission factor	$K_{C,j}$	$\Delta C_{emi,residential} = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \ln\left(\frac{K_{C,j}^T}{K_{C,j}^0}\right)$

Note: The superscripts 0 and T give the parameter at time 0 and time T, respectively.

3.5. Data Input

We obtained energy data from the China Energy Statistical Yearbook [27,28] and economic data from the China Statistical Yearbook [31]. The K_{PEQ} and K_C of each fuel for China in 2004 and 2014 are provided in Tables 1 and 3, which can be found in Sections 3.1 and 3.2, respectively.

4. Results and Discussion

4.1. Energy and CO_2 Allocation Sankey Diagrams in China

The energy allocation Sankey diagrams and CO_2 allocation Sankey diagrams of energy consumption in China for 2004 and 2014 are presented in Figures 1–4. The main advantage of this CO_2 allocation Sankey diagram is that it can show the full responsibility for CO_2 emissions of various sectors at each stage of the energy supply chain. For example, it illustrates that the energy supply stage determines the amounts of carbon which flows into the system and has the responsibility for introducing more low carbon and non-fossil energy. The energy transformation stage determines the carbon amounts required to provide certain amounts and types of secondary energy and has the responsibility for improving energy conversion efficiency and deploying low-carbon energy sources. The end-use sector has the responsibility for improving the energy efficiency of end-use equipment including industrial boilers, electric motors, and household appliances, etc., as well as controlling the direct burning of fossil fuels.

According to these diagrams, the main features and dynamics of China's energy use and energy-related CO_2 emissions are as follows:

(1) Energy supply: raw coal supply contributed 78.8% and 77.5% to energy-related CO_2 emissions in China in 2004 and 2014, respectively. The contributions of crude oil and natural gas supply to energy-related CO_2 emissions were 18.6% and 1.6% in 2004, and 15.1% and 4.2% in 2014, respectively.

(2) Transformation: Although the electricity production of China increased from 778 Mtce in 2004 to 1758 tce in 2014, which is an increase of 126%, the related CO_2 emissions only increased by 109% from 1548 Mt to 3238 Mt. The same phenomena can also be found in heat production. The heat production increased from 0.93 Mtce in 2004 Mtce to 1.82 Mtce in 2014, which is an increase of 96%, while the CO_2 emissions only increased by 70% from 223 Mt to 379 Mt.

(3) End-use: The proportion of energy related CO_2 emissions in the manufacturing sector decreased from 72% in 2004 to 71% in 2014 while the contributions of building increased from 16.6 to 17.4%. The contribution of the transportation sector remains unchanged. In 2014, coal products, oil products, natural gas, heat, and electricity were responsible for 40.3%, 15.3%, 3.4%, 4.3%, and 36.7% of energy-related CO_2 emissions in China, respectively.

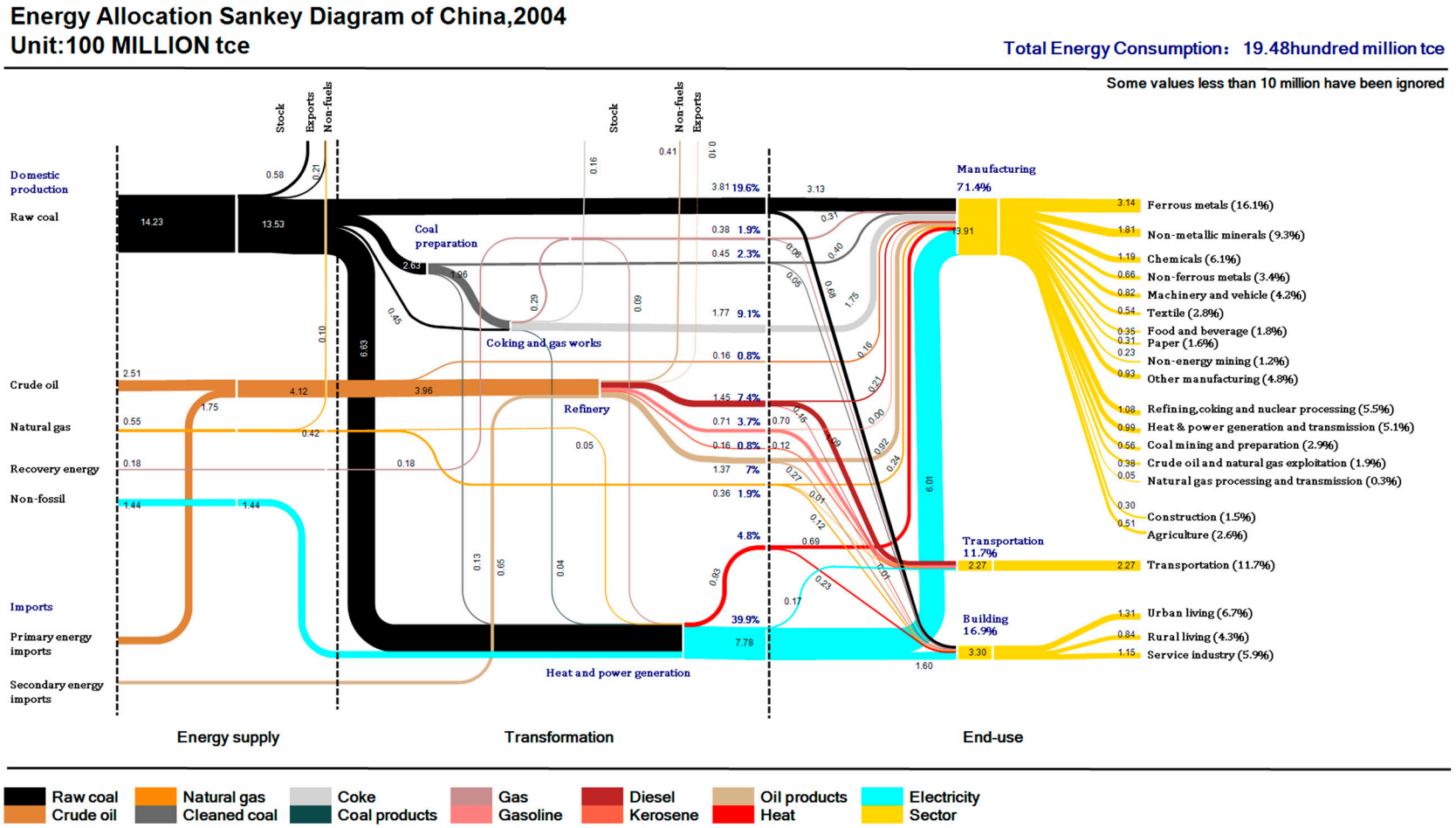

Figure 1. Energy allocation Sankey diagram of China, 2004.

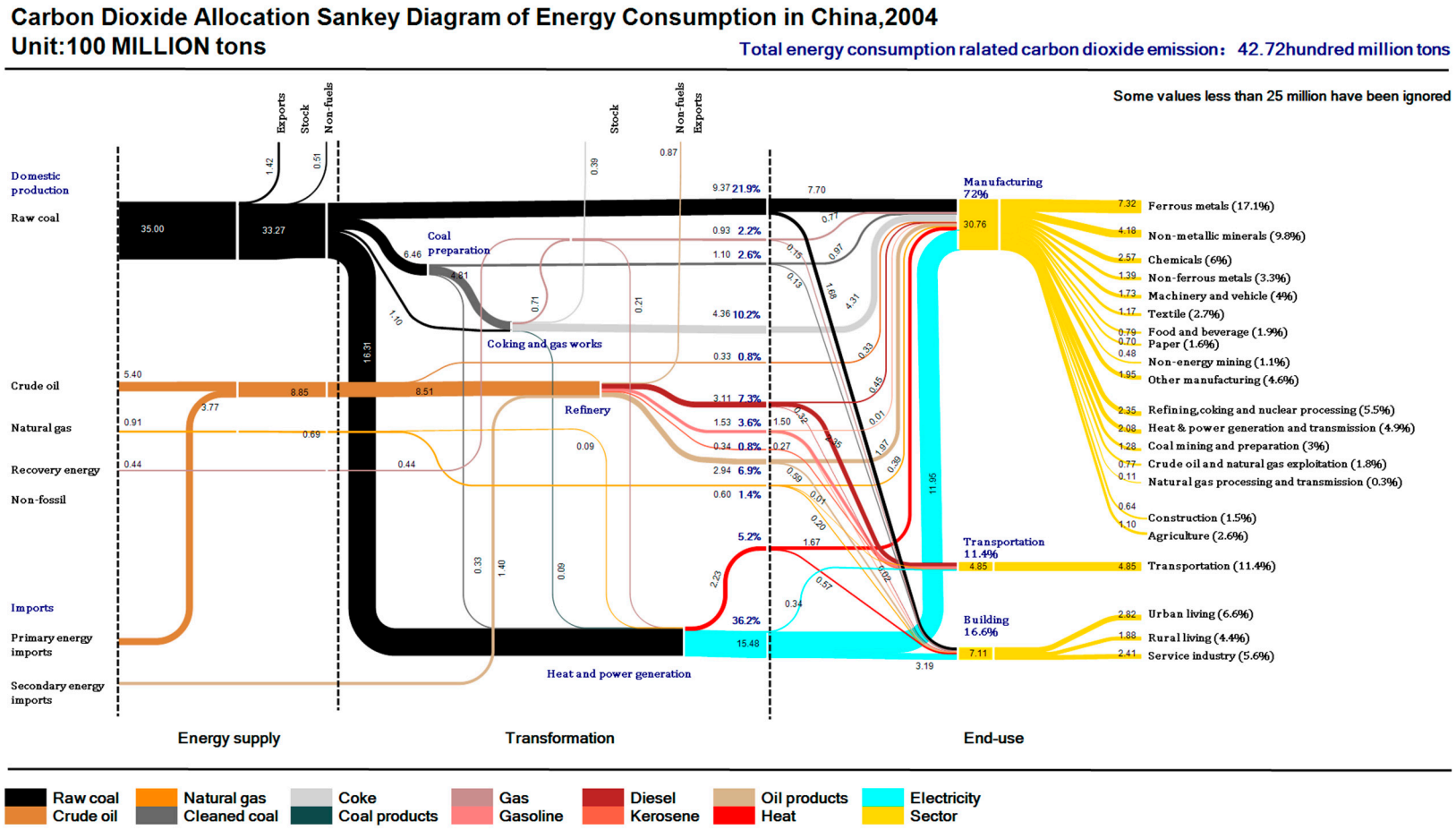

Figure 2. Carbon dioxide allocation Sankey diagram of energy consumption in China, 2004.

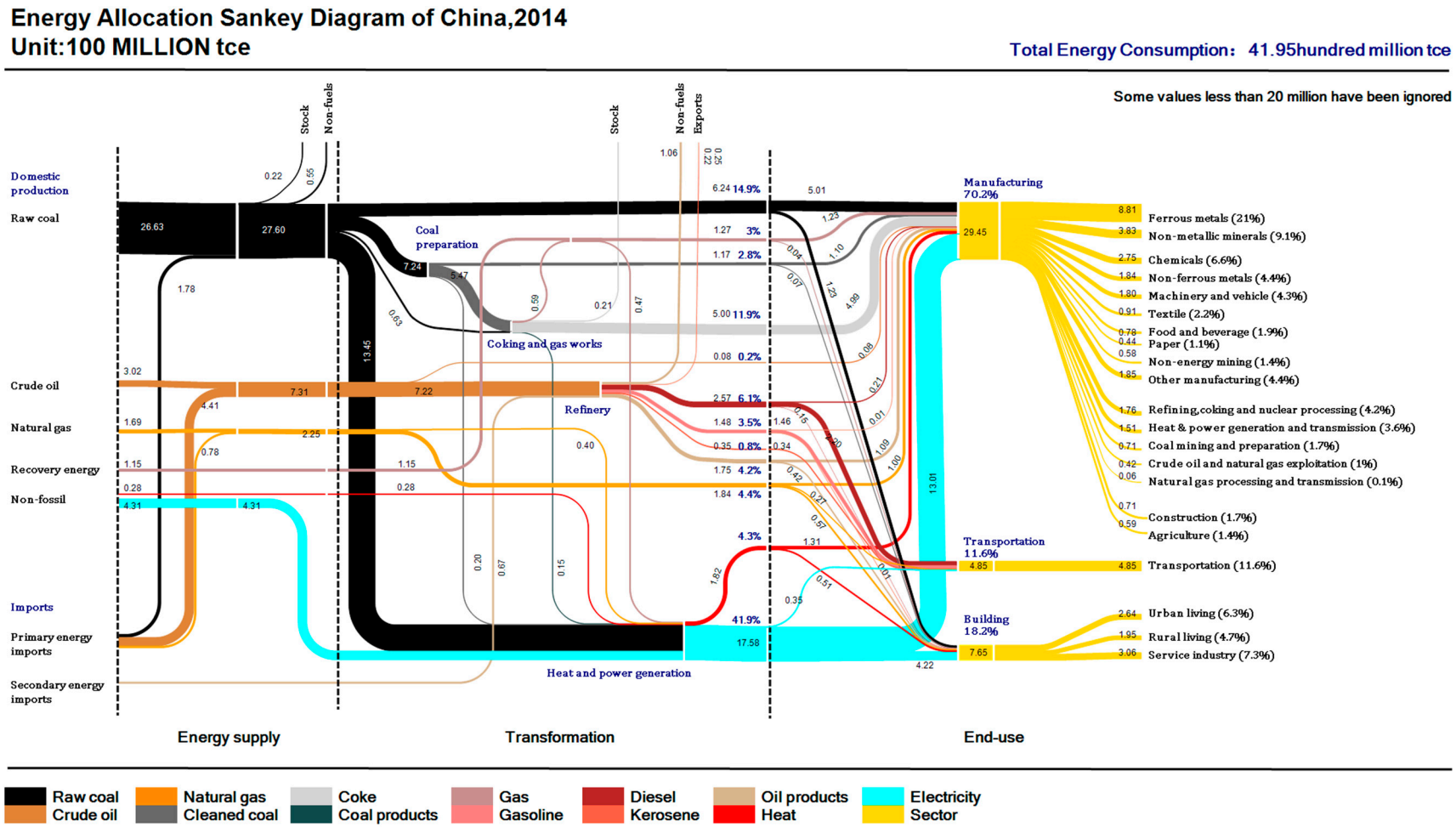

Figure 3. Energy allocation Sankey diagram of China, 2014.

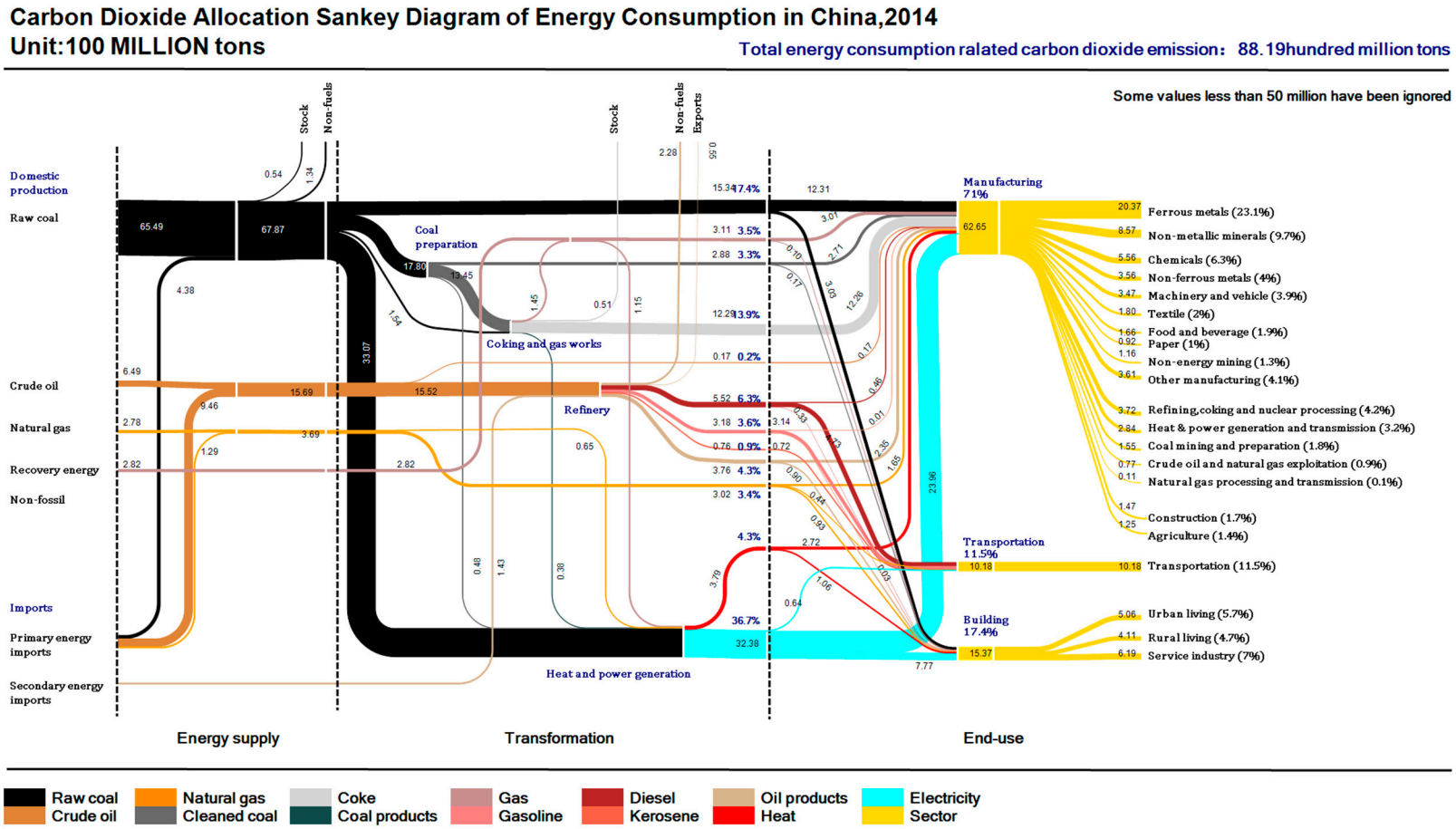

Figure 4. Carbon dioxide allocation Sankey diagram of energy consumption in China, 2014.

4.2. Additive LMDI Decomposition Results for CO_2 Emissions Growth in Economic Sector

Through additive LMDI decomposition, we determine the increment in energy-related CO_2 emissions of China's entire economic sector including primary, secondary, and tertiary industries. This was caused by each influencing factor between 2004 and 2014, which accounted for 88.7% and 88.5% of the total energy-related CO_2 emissions, respectively. The decomposition results are given in Table 6 and the summarized decomposition results of the economic sector are shown in Figure 5. The growth of GDP per capita is the dominant factor driving CO_2 emissions growth in 2004–2014, while other influences are relatively small. In the following sections, we discuss each of these influencing factors.

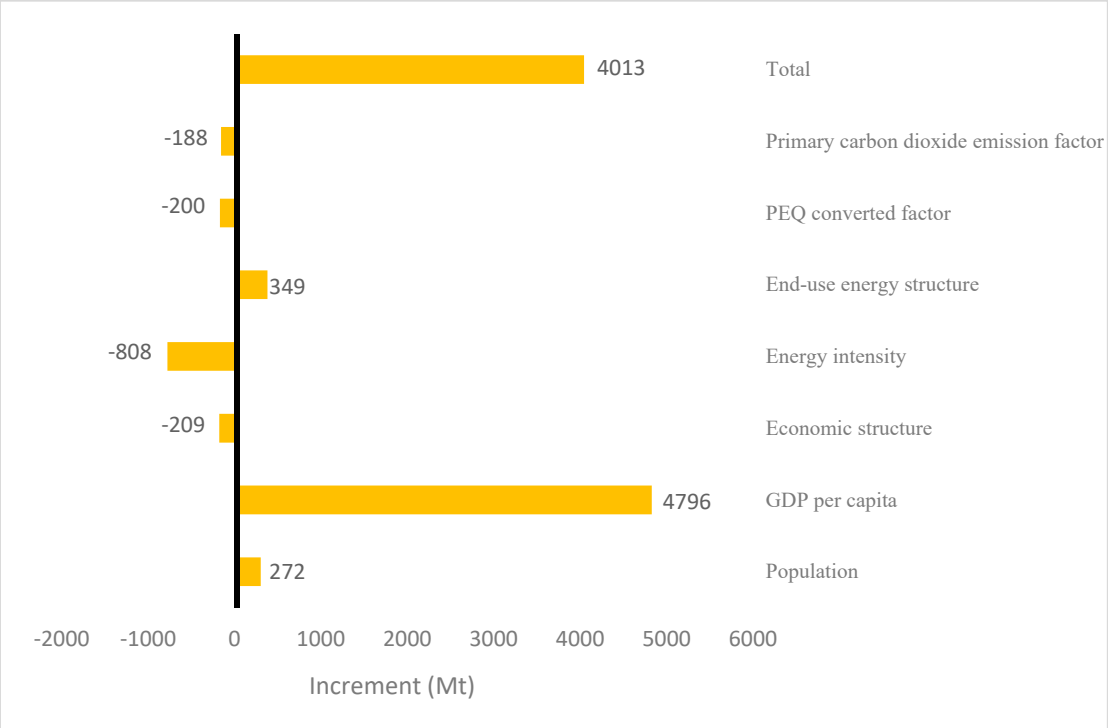

Figure 5. LMDI additive decomposition results for CO_2 emissions increment in the economic sector in China from 2004 to 2014 (Units: Mt).

Table 6. LMDI additive decomposition results for CO_2 emissions increment in the economic sector in China from 2004 to 2014 (Units: Mt).

Economic Subsector	Population	GDP per Capita	Economic Structure	Energy Intensity	End-Use Energy Structure	PEQ Converted Factor	Primary Carbon Dioxide Emission Factor	Total
Primary	8.63	152.32	−58.60	−90.82	6.31	−8.06	−4.73	5.05
Secondary	215.2	3796.32	−296.05	−520.35	300.38	−154.57	−160.57	3180.36
Tertiary	48.03	847.22	145.97	−196.64	42.62	−37.38	−22.36	827.45
Entire	271.86	4795.85	−208.67	−807.82	349.31	−200.00	−187.66	4012.87

4.2.1. The Influence of Population

Population growth in China contributed to CO_2 emissions growth during 2004 to 2014. However, the contribution is rather limited. The reason may be that population growth in China was relatively small, with a total increase of 5.2% in 2014 when compared to 2004, which is shown in Figure 6. This is due to the rigid population restriction policy that has been in place since the 1970s.

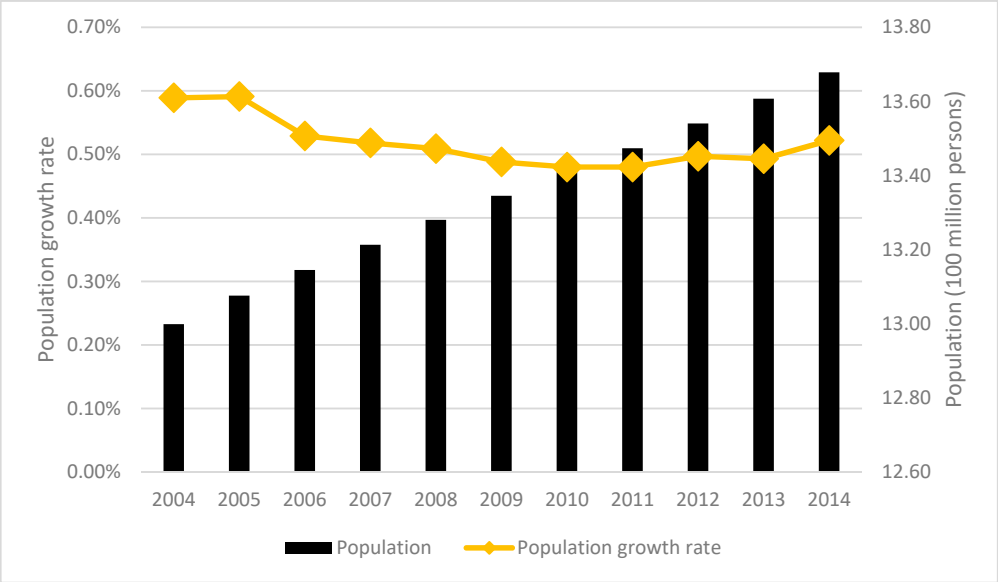

Figure 6. Population and its growth rate in China from 2004 to 2014.

4.2.2. The Influence of GDP per Capita

Along with rapid industrialization, urbanization, and motorization, the GDP per capita of China increased 11.1% annually from 2004 to 2014 and had a significant influence on CO_2 emissions in China. Referring to Reference [7], gross capital formation, which is accompanied by a rapid expansion of energy-intensive industries such as steel, cement, and chemicals, is a main driving force of economic growth in China. This further accelerated the growth of CO_2 emissions. Moreover, with a large capacity of energy-intensive products domestically, the net exports depend more on the export of these products. The rapid economic growth in China is guided by the political goals of the Communist Party in China since China is a collectivist society with a strong central government ruled by the Party [32]. The transition of political goals can be summarized in three stages as follows: (1) President Jiang Zemin announced plans to construct a well-off society (four times higher GDP compared to the year 2000) by 2020 during the 16th National Congress of the Communist Party of the People's Republic of China (NCCPC) in 2002; (2) President Hu Jintao announced his intention to inherit the political goals of President Jiang and emphasized economic structure optimization and economic efficiency improvement during the 17th NCCPC in 2007; (3) President Hu Jintao further announced plans to vigorously build an ecological civilization during the 18th NCCPC in 2012. Referring to these political goals, we can summarize that rapid economic growth was always a prioritized political goal in the 2004 to 2014 period, while ecological and environmental protection was more and more emphasized to optimize the economic structure and control the speed of growth.

4.2.3. The Influence of Economic Structure and Energy Intensity

Although changes in economic structure and energy intensity both decreased CO_2 emissions from 2004 to 2014, the influence of energy intensity was more significant. The proportion of primary industry, secondary industry, and tertiary industry adjusted from 12.9%, 45.9%, and 41.2% in 2004 to 9.1%, 43.1%, and 47.8% in 2014. The energy intensities of China are illustrated in Table 7.

Although China experienced a rapid expansion of energy-intensive secondary industries, especially iron and steel, cement, and chemicals, the government of China devoted much more effort than before to restricting the extensive development and energy consumption of these industries. The major goal was setting energy intensity as a constraint in the 11th Five Year Plan, including setting reduction targets for each economic subsector [33]. These efforts led to a great reduction of CO_2 emissions from 2004 to 2014.

Table 7. Energy intensities of China.

Economic Sector	2004	2014	Rate
	tce/RMB 10,000		
Primary industry	0.1841	0.1077	−41.5%
Secondary industry	0.8406	0.7431	−11.6%
Tertiary industry	0.2224	0.1805	−18.8%
Economic sector	0.5005	0.4141	−17.3%

The energy value type is expressed in SQ form, and the price is based on the 2014 constant price.

4.2.4. The Influence of Energy Structure in End-Use

The progression of the end-use energy structure in the end-use sector in China with increased CO_2 emissions and the influence of each energy type are shown in Figure 7.

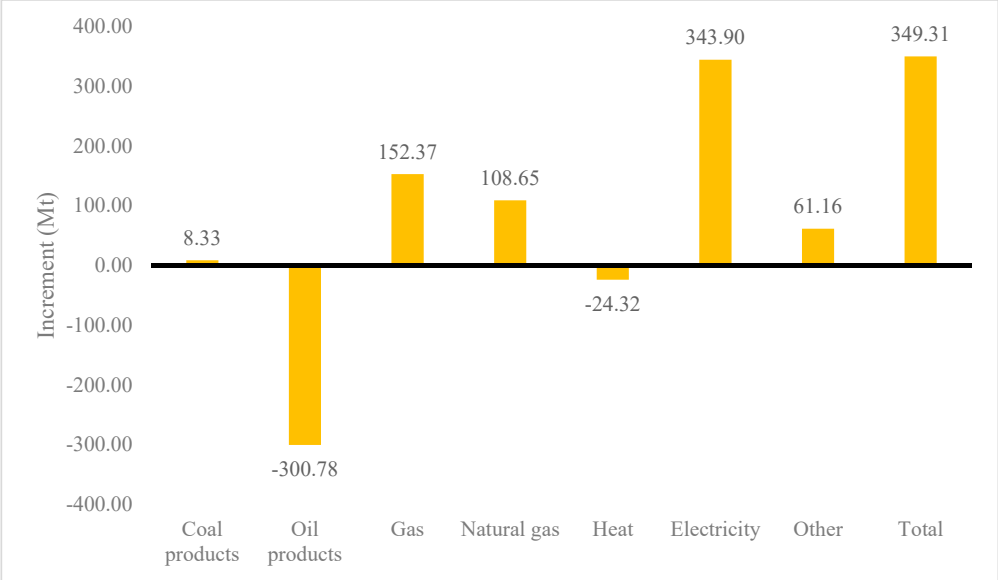

Figure 7. The increment of CO_2 emissions of economic sector in China caused by the proportional change of energy use.

The increased proportion of electricity, gas, and natural gas in end-use energy consumption in the economic sector in China significantly increased CO_2 emissions, while the decreased proportion of oil products reduced those CO_2 emissions. The increased proportion of electricity has been a major contributor to CO_2 emissions growth. For example, when 1 tce of electricity is consumed, 2.54 tce of primary energy will be consumed and 4.67 tons of CO_2 will be emitted.

4.2.5. The Influence of Primary Energy Conversion Factors

The increase in energy conversion efficiency, represented by $K_{PEQ,j}$ and shown in Figure 8, is primarily due to improved electricity supply efficiency. This is the main factor that reduced CO_2 emissions growth in China from 2004 to 2014. In the last decade, the government of China has shut down power plants with low efficiency and promoted advanced power plants with high efficiency and large capacity [34]. In addition, the introduction of natural gas combined with cycle power plants that have higher energy conversion efficiency also helped to gradually improve the primary energy consumption per unit of supplied electricity.

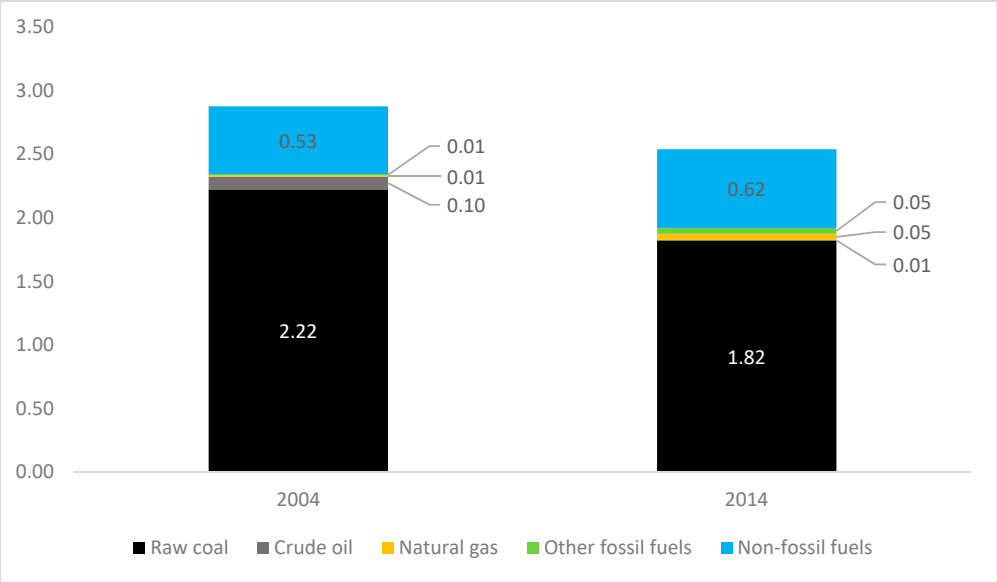

Figure 8. The K_{PEQ} of electricity and its structure in 2004 and 2014.

4.2.6. The Influence of the Primary Carbon Emissions Factor

The decrease in the carbon emissions factor, represented by $K_{C,j}$, is primarily due to the increment in the proportion of non-fossil fuels with low CO_2 emissions and in the proportion of natural gas with a smaller carbon emissions factor compared to raw coal in the fuel mix of heat and electricity generation. This is mainly because the government of China struggled to diversify the fuel mix in heat and electricity generation in China and to introduce non-fossil fuels and natural gas. The fuel mix in heat and electricity generation can be seen in Figure 9.

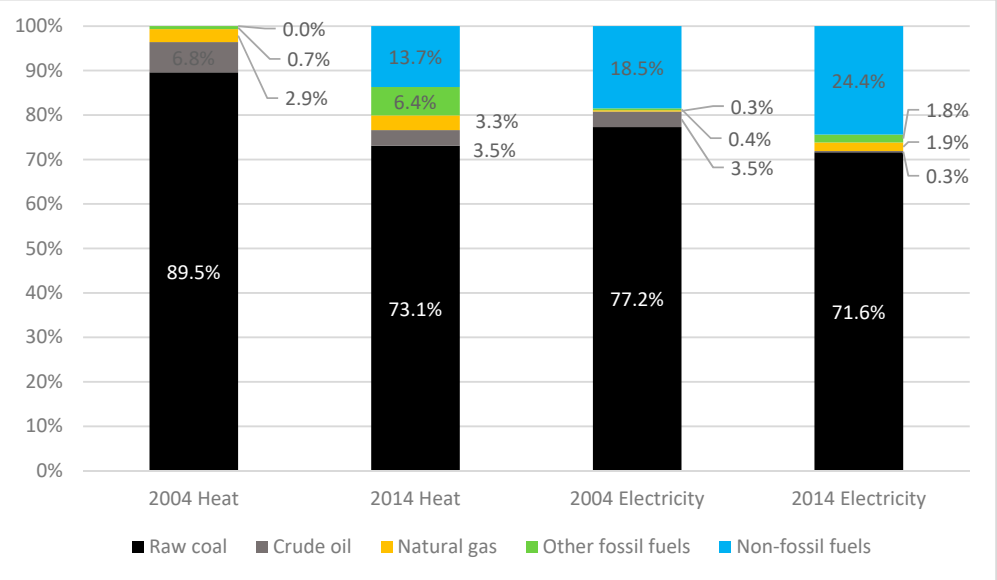

Figure 9. The energy mix in heat and electricity generation in China.

4.3. LMDI Additive Decomposition Results for Emissions Growth in the Residential Sector

Through LMDI additive decomposition, we acquired the incremental energy-related CO_2 emissions for China in its residential sector driven by each influencing factor between 2004 and

2014, which accounted for 11.3% and 11.5% of the total energy-related CO_2 emissions, respectively. The LMDI additive decomposition results for the residential sector are illustrated in Table 8. A summary of the decomposition results of the residential energy consumption is shown in Figure 10.

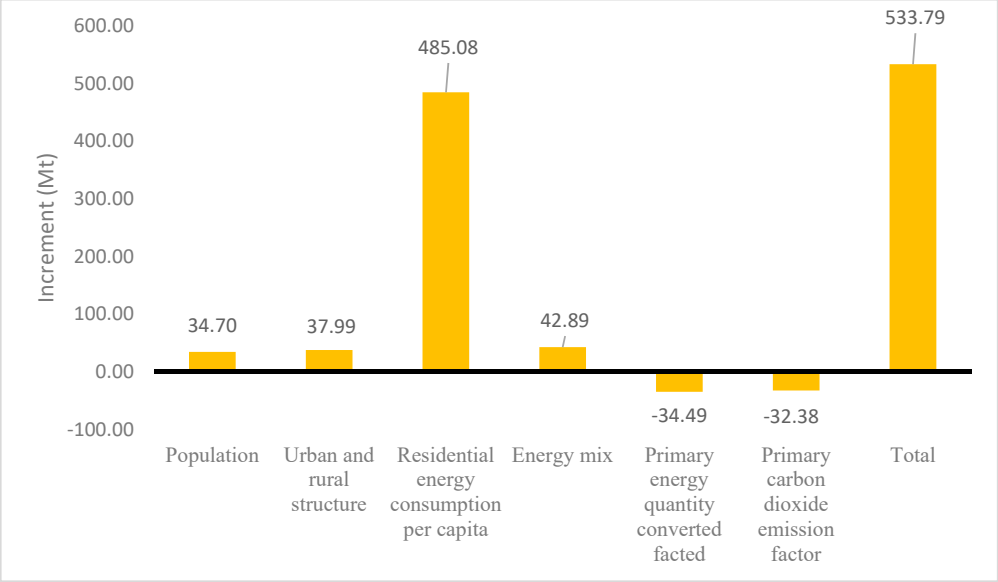

Figure 10. LMDI additive decomposition results for CO_2 emissions increment of residential sector in China from 2004 to 2014 (Units: Mt).

Table 8. LMDI additive decomposition results for CO_2 emissions increment of residential sector in China from 2004 to 2014 (Units: Mt).

Region	Population	Urban and Rural Structure	Residential Energy Consumption per Capita	Energy Mix	Primary Energy Converted Factor	Primary Carbon Dioxide Emission Factor	Total
Urban	20.43	108.77	185.01	7.80	−20.03	−22.64	279.35
Rural	14.26	−70.78	300.07	35.09	−14.46	−9.74	254.44
Urban and rural	34.70	37.99	485.08	42.89	−34.49	−32.38	533.79

In 2014, residential-energy-related CO_2 emissions accounted for 11.5% of the total energy-related CO_2 emissions in China. Population growth, urban and rural structure change, residential energy consumption per capita growth, and end-energy proportional use change are the main contributors to the residential energy-related CO_2 emissions growth, while the primary energy conversion factor and primary carbon dioxide emission factor change helped to decrease the residential CO_2 emissions in China.

From 2004 to 2014, the urbanization rate of China increased from 41.8 to 54.8%, which caused an increase in CO_2 emissions since the residential energy consumption per capita of urban areas was higher than rural areas. Along with GDP growth per capita, residential energy consumption growth per capita also increased rapidly between 2004 and 2014 especially in rural areas. From 2004 to 2014, the residential energy consumption per capita in urban and rural areas in China increased from 0.1685 tce/person to 0.2672 tce/person and 0.0801 tce/person to 0.2339 tce/person, respectively.

The changing energy structures in the residential end-use sector contributed to residential CO_2 emissions growth in China from 2004 to 2014 due to an increased proportion of electricity, natural gas, and gas. However, the decreased proportion of coal products is the main negative contributor to residential CO_2 emissions growth. The influence of the changing residential end-use energy consumption structure is shown in Figure 11.

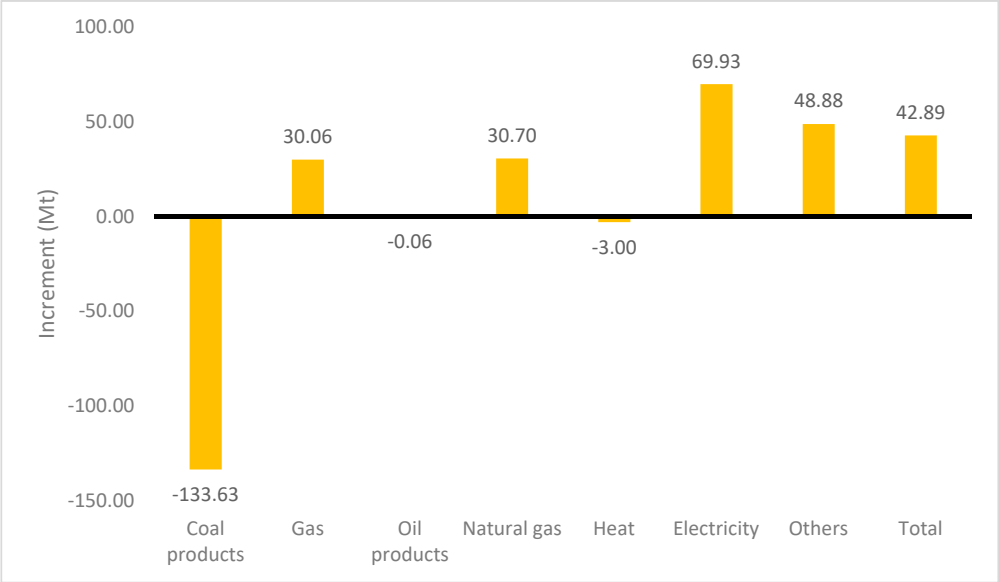

Figure 11. The increment of residential energy-related CO_2 emissions in China caused by the change of energy proportional use.

The influence of population growth and the primary energy quantity type conversion factor are also discussed in Sections 4.2.1 and 4.2.6.

4.4. Comparison with Current Policies to Reduce CO_2 Emissions

Currently, the government of China has made many efforts to fulfill its promise [12,13] to reduce CO_2 emissions by 2030, as mentioned in the introduction. One of the most important policies is the 13th Five-Year-Plan [35] enacted in 2016, which announced several targets to control CO_2 emissions from 2016 to 2020. They include reducing the energy intensity by 15% when compared to energy intensity in 2015, reducing the CO_2 emission intensity by 18% when compared to the emission intensity in 2015, increasing the proportion of non-fossil energy to 15% of total primary energy consumption by 2020, and increasing the proportion of the tertiary industry to 56% in total GDP by 2020.

Compared with our LMDI additive decomposition results, this policy is quite consistent with the research findings that reducing energy intensity was a major contributor to reducing CO_2 emissions growth between 2004 and 2014, which is followed by the optimization of the economic structure and the increase of the proportion of low carbon energy supply (reflected by the decreased primary CO_2 emission factor).

However, there are still many challenges facing China when fulfilling its promise. The major challenge is the continuously rapid GDP per capita growth of China. In the 13th Five-Year Plan, a limitation of average GDP growth rate of 6.5% is set as the lower limit and no upper limit is set. The GDP per capita of China in 2015 was 8028 USD and still lags behind the world (10,058 USD) and the Asia Pacific region (9398 USD) [36]. As such, there is still a gap for China to increase its GDP per capita. Furthermore, the urbanization and industrialization of Western China are not yet complete. Therefore, fixed-asset investment in Western China will still make a significant contribution to the GDP growth and CO_2 emissions growth in the future. Hence, the government in China should carefully control its GDP per growth by constraining unnecessary infrastructure construction to avoid energy waste. The same view is also provided by Zhang et al. [37] in their scenario analysis.

Moreover, the reduction of energy intensity and CO_2 emissions intensity should be a goal further distributed to specific sub-sectors to determine the responsibility of each sub-sector for reducing energy consumption and CO_2 emissions.

4.5. Uncertainties

Although the method and data used in this work represent the best attempts of the authors, uncertainties do exist because of the lack of more accurate data. This is explained as follows:

1. The emissions factor of raw coal and coal products is arguable, as the coal quality—which is mainly denoted by its heat value, volatile component, and ash content—is quite different across China depending on the production mines. The default CO_2 emissions factor of raw coal suggested by the IPCC was adopted in this study.
2. We assumed that all fossil fuels are combusted completely in all sectors and that the elemental carbon they contain is 100% converted into CO_2.
3. Non-commercial energy consumption (mainly biomass including straw and wood) related to CO_2 emissions is not audited in this study due to a lack of official statistical data.
4. Carbon capture and storage technology is not discussed in this study.

5. Conclusions

In this study, we first constructed an energy input–output table for China and acquired the K_{PEQ} and K_C of each energy type using the Leontief inverse matrix of the energy input–output table. After that, we constructed energy allocation diagrams and CO_2 emissions allocation diagrams of China to present the energy balance and carbon balance from the primary energy supply stage to the end-use energy consumption stage in 2004 and 2014. Based on these, we developed an LMDI method to decompose and analyze the contributions of the main influencing factors, which includes both the normal factors and the extra factors, to the growth of energy-related CO_2 emissions on a national level. Compared with the conventional LMDI method, our method can further consider the impact of the efficiency of energy conversion and transportation, especially electricity efficiency and heat generation. This LMDI method was then applied to analyze the influencing factors of energy-related CO_2 emissions growth in China in both the economic and residential sectors from 2004 to 2014.

We conclude that the main features of energy-related CO_2 emissions in China are that raw coal supply is the major carbon contributor to energy-related CO_2 emissions in China, accounting for 77.5% of total CO_2 emissions in 2014. Additionally, the CO_2 emissions per unit heat and electricity generation decreased from 2004 to 2014 due to the introduction of non-fossil fuels and the improvement of energy conversion efficiency. Lastly, the manufacturing sector is the main CO_2 emitter in China and accounted for 71% of the total CO_2 emissions.

The results of the LMDI additive decomposition regarding the growth of energy-related CO_2 emissions indicate that GDP growth per capita is the main driving force of CO_2 emissions growth in China. In addition, the improvement of energy intensity and electricity supply efficiency helps reduce the CO_2 emissions growth in China. This same effect is seen with the introduction of non-fossil fuels in heat and electricity generation. The residential energy-related CO_2 emissions sector grew 8.9% annually due to the increased residential energy consumption per capita and the increased proportion of electricity in end-use energy.

In this study, although we extended the conventional top-down LMDI decomposition approach by using K_{PEQ} to consider the contributions of improved energy conversion and transportation efficiency to the growth of CO_2 emissions, more detailed technical influencing factors should be further considered in the next step, such as the end-use energy efficiency. Considering its importance to reducing CO_2 emissions, most countries have enacted policies to improve end-use energy efficiency. For example, China's government has forbidden the use of industrial boilers with low efficiency and inferior environmental performance. As such, the energy efficiency of end-use equipment such as furnaces, electric motors, and transport engines should be considered further in future experiments. Moreover, in future experiments, we suggest analyzing the contribution of various influencing factors to energy-related SO_2 and NO_x emissions growth due to the damage of air pollution in China and the lack of studies that use similar methods to those seen in this work.

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Author Contributions: Linwei Ma, Chinhao Chong and Xi Zhang coordinated the main theme of this paper and wrote this manuscript. Linwei Ma proposed the methodology and constructed the analysis framework. Chinhao Chong and Xi Zhang processed the energy and CO_2 emissions data through input–output approach and launched additive LMDI decomposition to analyze the contribution of each influencing factor to the CO_2 emissions growth. Chinhao Chong mapped the Sankey diagrams. Pei Liu and Weiqi Li discussed the research results and commented on the manuscript. Final review was done by Zheng Li and Weidou Ni. All the authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Subscript *i*	Economic sub-sector *i* involved in the LMDI decomposition of CO_2 emissions growth in the economic sector including primary industry, secondary industry, and tertiary industry/Area *i* involved in the LMDI decomposition of CO_2 emissions growth in the residential sector including urban areas or rural areas
Subscript *j*	Energy type *j*
CO_2	Carbon dioxide
LMDI	Logarithmic mean Divisia index I
tce	Ton of standard coal equivalent
t	Ton
SQ	Standard quantity
PEQ	Primary energy quantity
$E_{SQ,j}$	Energy type *j* expressed in SQ form
$E_{SQ,i}$	Total energy consumption of economic sub-sector *i* expressed in SQ form during the LMDI decomposition of CO_2 growth in economic sector/Total energy consumption of area *i* expressed in SQ form during the LMDI decomposition of CO_2 emissions growth in the residential sector
$E_{SQ,ij}$	Energy type *j* consumption of economic sub-sector *i* expressed in SQ form during the LMDI decomposition of CO_2 growth in economic sector/Energy type *j* consumption of area *i* expressed in SQ form during the LMDI decomposition of CO_2 emissions growth in the residential sector
$E_{PEQ,j}$	Energy type *j* consumption expressed in PEQ form
$C_{economic}$	Total CO_2 emissions of economic sector
$C_{residential}$	Total CO_2 emissions of residential sector
$C_{,j}$	CO_2 emissions used for mapping the carbon dioxide allocation Sankey diagram of energy consumption
Q_{ij}	The quantity of energy *i* consumed to produced energy *j* in energy input–output table
Q_i	The total output of energy *i* in energy input–output table
Y_i	The final demand of energy *i* in energy input–output table
L_{ij}	The element of the Leontief inverse matrix of the energy input–output table, which indicates the quantity of energy *i* consumed to provide one unit of end-use energy *j*
$L_{m,j}{}'$	Primary energy *m* to be consumed to provide one unit of end-use energy *j* in the conversion sector including raw coal, natural gas, crude oil, and other fossil fuels
$L_{m,j}$	Primary energy *m* to be consumed to provide one unit of end-use energy *j*, including raw coal, natural gas, crude oil, other fossil fuels, and non-fossil fuel
$E_{SQ,j,fossil}$	Total energy type *j* which is converted from fossil fuels expressed in SQ form
$E_{SQ,j,non\text{-}fossil}$	Total energy type *j*, which is converted from non-fossil fuels expressed in SQ form
K_C	Primary carbon dioxide emission factor of end-use energy *j*, which established the relation between energy consumption expressed in PEQ form and CO_2 emissions

$K_{C,SQ,,j}$	Primary carbon dioxide emission factor of end-use energy j, which established the relation between energy consumption expressed in SQ form and CO_2 emissions
$K_{C,m}$	Carbon dioxide emissions factor of primary energy m
C^0	Total energy related CO_2 emissions at time 0
C^T	Total energy related CO_2 emissions at time T
P	Population
GDP	Gross domestic production
GDP_i	Value added within economic sub-sector i
Q	GDP per capita
S_i	Proportion of the economic sub-sector i in the LMDI decomposition of CO_2 emissions growth in economic sector/Population proportion of area i in the LMDI decomposition of CO_2 emissions growth in the residential sector
I_i	Energy intensity of the economic sub-sector i in the LMDI decomposition of CO_2 emissions growth in economic sector/Residential energy consumption per capita in area i in the LMDI decomposition of CO_2 emissions growth in the residential sector
M_{ij}	Proportion of energy type j consumption in economic sub-sector i in the LMDI decomposition CO_2 emissions growth in economic sector/Proportion of energy type j consumption in area i in the LMDI decomposition of CO_2 emissions growth in the residential sector
K_{PEQ}	Primary energy quantity conversion factor
$K_{PEQ,j}$	Primary energy quantity conversion factor of energy type j
ΔC_{pop}	Increment of CO_2 emissions caused by a change in population
ΔC_{aff}	Increment of CO_2 emissions caused by a change in GDP per capita
ΔC_{str}	Increment of CO_2 emissions caused by changes in economic structure in the LMDI decomposition of CO_2 emissions growth in economic sector/Increment of CO_2 emissions caused by changes of urban and rural structure in the LMDI decomposition of CO_2 emission growth in the residential sector
ΔC_{int}	Increment of CO_2 emissions caused by changes of energy intensity in the LMDI decomposition of CO_2 emissions growth in economic sector/Increment of CO_2 emissions caused by changes of residential energy consumption per capita in the LMDI decomposition of CO_2 emissions growth in the residential sector
ΔC_{mix}	Increment of CO_2 emissions caused by changes of M_{ij}
ΔC_{peq}	Increment of CO_2 emissions caused by changes of $K_{PEQ,j}$
ΔC_{emi}	Increment of CO_2 emissions caused by changes of $K_{C,j}$
ΔC_{tot}	Total increment of CO_2 emissions

Appendix A. The Detailed Description of the Figures and Equations

Table A1. The intermediate sectors in the energy input–output table of China and their production.

Sector	Symbol	Output
Raw coal production	1	Raw coal
Crude oil production	2	Crude oil
Natural gas production	3	Natural gas
Other fossil fuels production	4	Other primary energy: Blast furnace gas, converter gas, and other primary energy
Electricity generation	5	Electricity
Heat generation	6	Heat
Coal preparation	7	Coal preparation products: Cleaned coal, other cleaned coal, and gangue
Coking	8	Coking products: Coke, other gas, and other coking products
Oil refining	9	Oil refining products: Petrol, diesel, kerosene, fuel oil, naphtha, lubricants, paraffin waxes, white spirit, bitumen asphalt, petroleum coke, LPG, refinery gas, and other petroleum products
Liquefaction of natural gas	10	LNG
Briquette formation	11	Briquette

Table A2. Energy input–output table.

		Intermedia Consumption					Final Demand	Total Output
		1	2	3	…	j	Y	Q
Intermediate input	1	Q_{11}	Q_{12}	Q_{13}	…	Q_{1j}	Y_1	Q_1
	2	Q_{21}	Q_{22}	Q_{23}	…	Q_{2j}	Y_2	Q_2
	3	Q_{31}	Q_{32}	Q_{33}	…	Q_{3j}	Y_3	Q_3
	…	…	…	…	…	…	…	…
	i	Q_{i1}	Q_{i2}	Q_{i3}	…	Q_{ij}	Y_i	Q_i

Table A3. The 13 energy types involved in the energy allocation Sankey diagram and the carbon dioxide allocation Sankey diagram of energy consumption in China.

Flows
1. Raw coal
2. Crude oil
3. Natural gas: Natural gas and LNG
4. Cleaned coal: Cleaned coal
5. Coke
6. Other coal products: Briquettes, gangue, and other coking products
7. Coal gas: Coke oven gas, blast furnace gas, converter gas, and other gas
8. Gasoline
9. Diesel
10. Kerosene
11. Other oil products: Fuel oil, naphtha, lubricants, paraffin waxes, white spirit, bitumen asphalt, petroleum coke, LPG, refinery gas, and other petroleum products
12. Heat
13. Electricity

Table A4. The re-categorized end-use subsectors of final energy consumption and CO_2 emissions.

A. Manufacturing Sector
1. Agriculture, forestry, animal husbandry, fishery, and water conservancy
2. Construction
3. Non-energy mining
• Mining and processing of ferrous metal ores
• Mining and processing of non-ferrous metal ores
• Mining and processing of non-metal ores
• Mining of other ores
• Auxiliary mining operations
4. Smelting and pressing of ferrous metals
5. Smelting and pressing of non-ferrous metals
6. Manufacturing of non-metallic mineral and chemical products
7. Manufacturing of raw chemical materials and chemical products
8. Manufacturing of food and beverages
• Processing of food from agricultural products
• Manufacturing of food
• Manufacturing of liquor, beverages, and refined tea

Table A4. *Cont.*

A. Manufacturing Sector

9. Manufacturing of textiles
    - Manufacturing of textiles
    - Manufacturing of textiles, clothing, other apparel, and accessories
10. Manufacturing of machinery and vehicles
    - Manufacturing of general purpose machinery
    - Manufacturing of special purpose machinery
    - Manufacturing of automobiles
    - Manufacturing of railways, ships, aerospace equipment, and other transportation equipment
    - Manufacturing of electrical machinery and equipment
    - Manufacturing of metal products
    - Repair service of metal products, machinery, and equipment
11. Manufacturing of paper and paper products
12. Other non-energy industrial subsectors
    - Manufacturing of tobacco
    - Manufacturing of leather, fur, feather, and related products and footwear
    - Processing of timber and manufacturing of wood, bamboo, rattan, palm, and straw products
    - Manufacturing of furniture
    - Printing and reproducing recording media
    - Manufacturing of articles for culture, education, arts and crafts, sports, and entertainment activities
    - Manufacturing of medicines
    - Manufacturing of rubber and plastics products
    - Manufacturing of computers, communications products, and other electronic equipment
    - Manufacturing of chemical fibers
    - Manufacturing of measuring instruments and machinery
    - Utilization of waste resources
    - Production and supply of water
    - Other manufacturing
13. Energy industry subsector
    - Production and supply of electric power and heat
    - Production and supply of gas
    - Mining and preparation of coal
    - Extraction of petroleum and natural gas
    - Processing of petroleum, coking, and nuclear fuel

B. Transportation sector

C. Building

1. Urban living
2. Rural living
3. Service industry

Table A5. Symbols used in Equation (16).

Items	Descriptions
Subscript *i*	1. Primary industry 2. Secondary industry 3. Tertiary industry
Subscript *j*	Raw coal, cleaned coal, briquettes, gangue, coke, coke oven gas, blast furnace gas, converter gas, other gas, other coking products, crude oil, oil products (gasoline, kerosene, diesel oil, fuel oil, naphtha, lubricants, paraffin waxes, white spirit, bitumen asphalt, petroleum coke, LPG, refinery gas, and other petroleum products), natural gas, LNG, heat, and electricity
P	Population
GDP	Gross domestic product
GDP_i	Value added of economic sub-sector *i*
$E_{SQ,i}$	Energy consumption of economic sub-sector *i* expressed in SQ form
$E_{SQ,ij}$	Fuel *j* consumption of economic sub-sector *i* expressed in SQ form
$K_{PEQ,j}$	Primary energy quantity conversion factor of energy type *j*
$K_{C,j}$	Primary carbon dioxide emission factor of energy type *j*

Table A6. Symbols used in Equation (18).

Items	Descriptions
Subscription *i*	1. Urban area 2. Rural area
Subscription *j*	Raw coal, cleaned coal, briquettes, gangue, coke, coke oven gas, blast furnace gas, converter gas, other gas, other coking products, crude oil, oil products (gasoline, kerosene, diesel oil, fuel oil, naphtha, lubricants, paraffin waxes, white spirit, bitumen asphalt, petroleum coke, LPG, refinery gas, and other petroleum products), natural gas, LNG, heat, and electricity.
P	Population
P_i	Population of area *i*
$E_{SQ,i}$	Energy consumption of area *i* expressed in SQ form
$E_{SQ,ij}$	Fuel *j* consumption of area *i* expressed in SQ form
$K_{PEQ,j}$	Primary energy quantity conversion factor of energy type *j*
$K_{C,j}$	Primary carbon dioxide emission factor of energy type *j*

Appendix B. A Summary of LMDI Decomposition of Energy-Related CO_2 Emissions in Recent Years

Table A7. A summary of LMDI decomposition of energy related CO_2 emissions in recent years.

No	Sector	Identity	CO_2 Emission of Electricity	Author	Region
A1	All sector	$C_{all} = P \cdot \frac{Q}{P} \cdot \frac{E}{Q} \cdot \frac{FF}{E} \cdot \frac{C}{FF}$	The CO_2 emission factor of electricity is considered to be zero.	Wang et al. [38]	China
A2				Wang et al. [39]	Guangdong Province
A3		$C_{all} = \sum_j P \cdot \frac{Q}{P} \cdot \frac{E}{Q} \cdot \frac{FF_j}{E} \cdot \frac{C_j}{FF_j}$		Jung et al. [40,41]	Industrial Park, South Korea
A4		$C_{all} = \sum_j P \cdot \frac{RE}{P} \frac{Q}{RE} \cdot \frac{E}{Q} \cdot \frac{FF_j}{E} \cdot \frac{C_j}{FF_j}$		Moutinho et al. [42]	Europe
A5		$C_{all} = P \cdot \frac{Q}{P} \cdot \frac{E}{Q} \cdot \frac{CF}{E} \cdot \frac{FF}{CF} \cdot \frac{C}{FF}$		Ma and Stern [43]	China
A6		$C_{all} = \sum_j P \cdot \frac{Q}{P} \cdot \frac{E}{Q} \cdot \frac{E_j}{E} \cdot \frac{C_j}{E_j}$		Hatzigeorgiou et al. [44]	Greece
A7				Gonzalez et al. [45,46]	EU-27
A8				Li et al. [47]	China
A9				Jiang et al. [48]	USA
A10				Wang et al. [49]	China
A11		$C_{all} = Q \cdot \frac{E}{Q} \cdot \frac{C}{E}$		Marcucci and Fragkos [50]	China, India, Europe and USA
A12				Zhang et al. [51]	China
A13				Qi et al. [52]	China
A14		$C_{all} = P \cdot \frac{Q}{P} \cdot \frac{E}{Q} \cdot \frac{C}{E}$		Sonnenschein and Mundaca [53]	South Korea
A15		$C_{all} = \sum_j P \cdot \frac{Q}{P} \cdot \frac{E}{Q} \cdot \frac{E_j}{E} \cdot \frac{C_j}{E_j}$		Sumabat et al. [54]	Philippine

Table A7. *Cont.*

No	Sector	Identity	CO_2 Emission of Electricity	Author	Region
B1	Economic sector	$C_{eco} = \sum_{ij} P \cdot \frac{Q}{P} \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is considered to be zero.	Li et al. [47]	China
B2				Wang and Yang [55]	Jing-Jin-Ji area, China
B3				Freitas and Kaneko [56]	Brazil
B4				Xu et al. [57]	China
B5				Tan et al. [58,59]	Chongqing City, China.
B6				Wang et al. [60]	Tianjin City, China
B7				Wu et al. [61]	Inner Mongolia, China
B8		$C_{eco} = \sum_{ij} IS \cdot \frac{Q}{IS} \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is considered to be zero.	Chen and Yang [53]	China
B9		$C_{eco} = \sum_{ij} Q \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is calculated according to the fuel mix in electricity generation sectors.	Tunc et al. [62]	Turkey
B10				Ren et al. [63]	China
B11				Jiao et al. [64]	China
B12		$C_{eco} = \sum_{ij} Q \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is considered to be zero.	Cruz and Dias [65]	EU-27
B13				Xu et al. [66,67]	China
B14				Zhang and Da [68]	China
B15				Zhang et al. [69]	Beijing City, China
B16				Liu G et al. [70]	China
B17		$C_{eco} = \sum_{ij} Q \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{FF_i}{E_i} \cdot \frac{FF_{ij}}{FF_i} \cdot \frac{C_{ij}}{FF_{ij}}$	The CO_2 emission factor of electricity is considered to be zero. However, the energy consumption to generate that electricity is counted into each sector according to its electricity consumption and the fuel mix of electricity generation of the region.	Mahony et al. [71,72]	Ireland
B18		$C_{eco} = \sum_{i} Q \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{C_i}{E_i}$	The CO_2 emission factor of electricity is considered to be zero.	Jiang et al. [73]	China
B19		$C_{eco} = \sum_{i} P \cdot \frac{Q}{P} \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{C_i}{E_i}$	The CO_2 emission factor of electricity is considered to be zero.	Cansino [74]	Spain
B20				Dong et al. [75]	China

Table A7. *Cont.*

No	Sector	Identity	CO_2 Emission of Electricity	Author	Region
C1	Industrial sector	$C_{ind} = \sum_{ij} Q \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factors of electricity and heat are calculated according to the fuel mix in electricity and heat generation sectors.	Liu et al. [76]	China
C2				Akbostanci et al. [77]	Turkey
C3				Jeong and Kim [78]	South Korea
C4				Ren et al. [79]	China
C5				Yan and Fang [80]	China
C6				Wang et al. [81]	China
C7		$C_{ind} = \sum_{ij} Q \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is considered to be zero.	Chen et al. [82]	Dalian City, China
C8				Kopidou et al. [83]	EU
C9		$C_{ind} = \sum_{i} Q \cdot \frac{Q_i}{Q} \cdot \frac{E_i}{Q_i} \cdot \frac{C_i}{E_i}$	The CO_2 emission factor of electricity is calculated according to the fuel mix in electricity generation sectors.	Zhao et al. [84]	Shanghai City, China
C10		$C_{ind} = \sum_{ij} Q \cdot \frac{Q_i}{Q} \cdot \frac{I_i}{Q_i} \cdot \frac{R_i}{I_i} \cdot \frac{Q_i}{R_i} \cdot \frac{E_i}{Q_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is considered to be zero.	Shao et al. [85]	Shanghai City, China
C11		$C_{ind} = \sum_{i} IS \cdot \frac{Q}{IS} \cdot \frac{E}{Q} \cdot \frac{FF}{E} \cdot \frac{C}{FF}$	The CO_2 emission factor of electricity is considered to be zero.	Ouyang and Lin [86]	China
C12				Lin and Liu [87]	China
D1	Residential sector	$C_{res} = \sum_{ij} P \cdot \frac{P_i}{P} \cdot \frac{E_i}{P_i} \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is considered to be zero.	Zhang et al. [69]	Beijing City, China
D2		$C_{res} = \sum_{j} P \cdot \frac{Income}{P} \cdot \frac{E}{Income} \cdot \frac{E_j}{E} \cdot \frac{C_j}{E_j}$	The CO_2 emission factor of electricity is considered to be zero.	Liu et al. [70]	China
D3				Tan et al. [58,59]	Chongqing City, China
D4		$C_{res} = \sum_{j} P \cdot \frac{\mathrm{GDP}}{P} \cdot \frac{E}{\mathrm{GDP}} \cdot \frac{E_j}{E} \cdot \frac{C_j}{E_j}$	The CO_2 emission factor of electricity is considered to be zero.	Yeo et al. [88]	China and India
D5		$C_{res} = \sum_{ij} THN \cdot \frac{E_j}{THN} \cdot \frac{FF_j}{E_j} \cdot \frac{FF_{ij}}{FF_j} \cdot \frac{C_{ij}}{FF_{ij}}$	The CO_2 emission factor of electricity is considered to be zero. However, the energy consumption to generate that electricity was counted into each sector according to its electricity consumption and the fuel mix of electricity generation of the region.	Mahony et al. [42]	Ireland

Table A7. *Cont.*

No	Sector	Identity	CO_2 Emission of Electricity	Author	Region
D6	Residential sector	$C_{res} = \sum_{ij} THN \cdot AHI \cdot \frac{E_i}{Income} \cdot \cdot \frac{E_{ij}}{E_i} \cdot \frac{C_{ij}}{E_{ij}}$	The CO_2 emission factor of electricity is considered to be zero.	Chen and Yang [53]	China
D7				Wang et al. [60]	Tianjin City, China
D8		$C_{res} = \sum_{j} P \cdot \frac{Q}{P} \cdot \frac{E}{Q_j} \cdot \frac{E_j}{E} \cdot \frac{C_j}{E_j}$	The CO_2 emission factor of electricity is calculated according to the fuel mix in electricity generation sectors.	Ma et al. [89]	China
E1	Power sector	$C_{pow} = \sum_{j} Ele \cdot \frac{Ele_{FF}}{Ele} \cdot \frac{Ele_{FF,j}}{Ele_{FF}} \cdot \frac{E_j}{Ele_{FF,j}} \cdot \frac{C_j}{E_j}$	These studies only consider thermal power.	Zhou et al. [90]	China
E2				Jiang and Li [91]	USA
E3		$C_{pow} = \sum_{j} Ele \cdot \frac{Ele_{FF}}{Ele} \cdot \frac{Ele_{FF,j}}{Ele_{FF}} \cdot \frac{E_j}{Ele_{FF,j}} \cdot \frac{C_j}{E_j}$	Renewable energy and nuclear power are considered.	Ang and Su [92]	Global
E4		$C_{pow} = P \cdot \frac{Q}{P} \cdot \frac{Ele}{Q} \cdot \frac{Ele_{FF}}{Ele} \cdot \frac{E}{Ele_{FF}} \cdot \frac{C}{E}$	Renewable energy and nuclear power are considered.	Yang and Lin [93]	China
E5		$C_{pow} = \sum_{j} Q \cdot \frac{Ele_{need}}{Q} \cdot \frac{Ele_{dom}}{Ele_{need}} \cdot \frac{FF}{Ele_{dom}} \cdot \frac{FF_j}{FF} \cdot \frac{C_j}{FF_j}$	Renewable energy and nuclear power are considered.	Karmellos et al. [94]	EU-28
E6		$C_{pow} = \sum_{j} \mathrm{Q} \cdot \frac{Ele}{Q} \cdot \frac{Ele_j}{Ele} \cdot \frac{E_j}{Ele_j} \cdot \frac{C_j}{E_j}$	Renewable energy and nuclear power are considered.	Tian and Yang [95]	Guangdong Province, China
E7	Non-metallic mineral sector	$C_{nom} = IS \cdot \frac{Q}{IS} \cdot \frac{E}{Q} \cdot \frac{FF}{E} \cdot \frac{C}{FF}$	Indirect CO_2 emissions are not considered nor counted in these studies.	Lin et al. [96–100] Ouyang et al. [86]	China
E8	Iron and steel industry	$C_{steel} = \sum_{j} P \cdot \frac{E}{P} \cdot \frac{E_j}{E} \cdot \frac{C_j}{E_j}$	The CO_2 emission factor of electricity is calculated according to the fuel mix in electricity generation sectors.	Sun et al. [101]	China

Note: Some elements in the identities have been modified with unified abbreviations based on the classification need. The abbreviations can be referred as below. Subscription *i*: Economic sector *i* or industrial sector *i*; Subscription *j*: Energy *j*; C_{all}: Total CO_2 emissions of the region; C_{eco}: Total CO_2 emissions of economic sector; C_{ind}: Total CO_2 emissions of industrial sector; C_{pow}: Total CO_2 emissions of power sector; C_{sec}: Total CO_2 emissions of specific sector; *P*: Population; *Q*: Level of activity, normally indicated by GDP or gross output; Q_i: Value-added or gross output of sector *i*; *E*: Total energy consumption; E_i: Total energy consumption of sector *i*; E_j: Consumption of energy *j*; E_{ij}: Consumption of energy *j* in sector *i*; *FF*: Total fossil fuel consumption; FF_i: Total fossil fuel consumption of sector *i*; FF_j: Total consumption of fossil fuel *j*; FF_{ij}: Consumption of fossil fuel *j* in sector *i*; *C*: Total CO_2 emissions; C_j: Total CO_2 emissions of sector *i*; C_j: CO_2 emissions of energy *j*; C_{ij}: CO_2 emissions of energy *j* in sector *i*; *RE*: Total renewable energy consumption; *CF*: Fossil fuel and biomass consumption; I_i: Fixed asset investment of sector *i*; R_i: R&D expenditure of sector *i*; *THN*: Total household number; *Income*: Total disposable income; *AHI*: Disposable income per household; *Ele*: Electricity output in power sector; Ele_{FF}: Fossil fuel consumption for power generation; $Ele_{FF,j}$: Fossil fuel *j* consumption for power generation; Ele_{need}: Electricity consumption; Ele_{dom}: Domestic electricity production; *IS*: Employment of the sector.

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