

# Decomposing Industrial Energy-Related CO<sub>2</sub> Emissions in Yunnan Province, China: Switching to Low-Carbon Economic Growth

## Authors:

Mingxiang Deng, Wei Li, Yan Hu

*Date Submitted:* 2018-10-23

*Keywords:* low-carbon pilot, Yunnan province, less-developed regions, structural decomposition analysis, drivers, CO<sub>2</sub> emissions

## Abstract:

As a less-developed province that has been chosen to be part of a low-carbon pilot project, Yunnan faces the challenge of maintaining rapid economic growth while reducing CO<sub>2</sub> emissions. Understanding the drivers behind CO<sub>2</sub> emission changes can help decouple economic growth from CO<sub>2</sub> emissions. However, previous studies on the drivers of CO<sub>2</sub> emissions in less-developed regions that focus on both production and final demand have been seldom conducted. In this study, a structural decomposition analysis-logarithmic mean Divisia index (SDA-LMDI) model was developed to find the drivers behind the CO<sub>2</sub> emission changes during 1997-2012 in Yunnan, based on times series energy consumption and input-output data. The results demonstrated that the sharp rise in exports of high-carbon products from the metal processing and electricity sectors increased CO<sub>2</sub> emissions, during 2002-2007. Although increased investments in the construction sector also increased CO<sub>2</sub> emissions, during 2007-2012, the carbon intensity of Yunnan's economy decreased substantially because the province vigorously developed hydropower and improved energy efficiency in energy-intensive sectors. Construction investments not only carbonized the GDP composition, but also formed a carbon-intensive production structure because of high-carbon supply chains. To further mitigate CO<sub>2</sub> emissions in Yunnan, measures should promote the development and application of clean energy and the formation of consumption-based economic growth.

*Record Type:* Published Article

*Submitted To:* LAPSE (Living Archive for Process Systems Engineering)

*Citation (overall record, always the latest version):*

LAPSE:2018.0764

*Citation (this specific file, latest version):*

LAPSE:2018.0764-1

*Citation (this specific file, this version):*

LAPSE:2018.0764-1v1

*DOI of Published Version:* <https://doi.org/10.3390/en9010023>

*License:* Creative Commons Attribution 4.0 International (CC BY 4.0)

Article

# Decomposing Industrial Energy-Related CO<sub>2</sub> Emissions in Yunnan Province, China: Switching to Low-Carbon Economic Growth

Mingxiang Deng, Wei Li \* and Yan Hu

Received: 28 July 2015; Accepted: 7 December 2015; Published: 4 January 2016

Academic Editor: Robert Lundmark

State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China; dmx221@163.com (M.D.); isabella9210@hotmail.com (Y.H.)

\* Correspondence: weili@bnu.edu.cn; Tel./Fax: +86-10-6220-2877

**Abstract:** As a less-developed province that has been chosen to be part of a low-carbon pilot project, Yunnan faces the challenge of maintaining rapid economic growth while reducing CO<sub>2</sub> emissions. Understanding the drivers behind CO<sub>2</sub> emission changes can help decouple economic growth from CO<sub>2</sub> emissions. However, previous studies on the drivers of CO<sub>2</sub> emissions in less-developed regions that focus on both production and final demand have been seldom conducted. In this study, a structural decomposition analysis-logarithmic mean Divisia index (SDA-LMDI) model was developed to find the drivers behind the CO<sub>2</sub> emission changes during 1997–2012 in Yunnan, based on times series energy consumption and input-output data. The results demonstrated that the sharp rise in exports of high-carbon products from the metal processing and electricity sectors increased CO<sub>2</sub> emissions, during 2002–2007. Although increased investments in the construction sector also increased CO<sub>2</sub> emissions, during 2007–2012, the carbon intensity of Yunnan’s economy decreased substantially because the province vigorously developed hydropower and improved energy efficiency in energy-intensive sectors. Construction investments not only carbonized the GDP composition, but also formed a carbon-intensive production structure because of high-carbon supply chains. To further mitigate CO<sub>2</sub> emissions in Yunnan, measures should promote the development and application of clean energy and the formation of consumption-based economic growth.

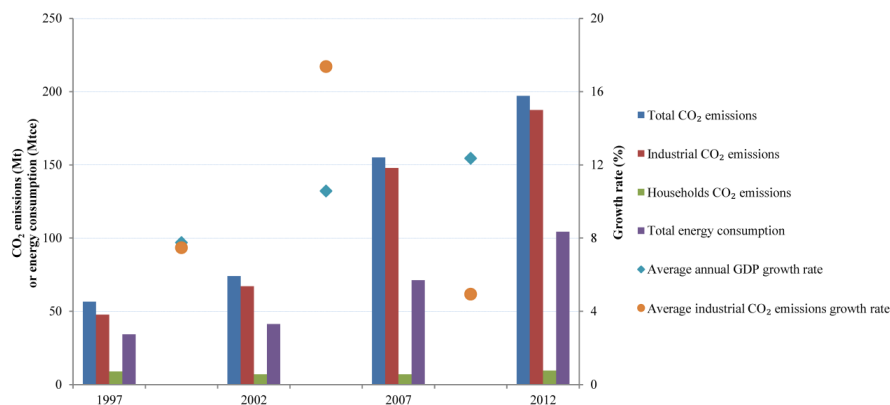
**Keywords:** CO<sub>2</sub> emissions; drivers; structural decomposition analysis; less-developed regions; low-carbon pilot; Yunnan province

## 1. Introduction

As the top CO<sub>2</sub> emitter in the world, China’s annual CO<sub>2</sub> emissions in 2013 were more than the sum of the amount from the United States and the European Union (EU) [1]. In addition, its per capita CO<sub>2</sub> emissions exceeded the EU for the first time [1]. Facing severe international pressure to mitigate its CO<sub>2</sub> emissions, China has pushed its provinces to reduce their CO<sub>2</sub> emissions. As a mitigating action, China’s central government has chosen provinces to conduct pilot work in low-carbon development in alignment with the development stage and characteristics of the different regions. Yunnan province was chosen as a pilot province and tasked with finding ways to achieve low-carbon transition by utilizing its underdevelopment to its advantage [2]. Yunnan is located in southwest China and is famous for its abundant hydropower, tourism and biological and cultural diversity [3] (see Figure S1 in the Supplementary Materials (SM)). The per capita gross domestic product (GDP) in Yunnan is approximately 60% of the national average [4]. In 2012, approximately 17% of the population (approximately eight million) was labeled as living in poverty [5]. Thus, Yunnan faces challenges to develop its economy and reduce poverty.

Since the 12th Five Year Plan (FYP) period (2010–2015), the central government has set a compulsory target to reduce the carbon intensity (CO<sub>2</sub> emissions per unit of GDP) by 17% and has disaggregated the target to its provinces [6]. As one of China's low-carbon pilot provinces, the carbon intensity reduction target in Yunnan is higher than the national government's standard for the country as a whole [2]. In 2014, the central government further committed to prevent CO<sub>2</sub> emissions from increasing after 2030 [7] instead of only reducing the carbon intensity. Under these circumstances, in the near future, Yunnan will face an even stricter target for controlling the volume of its CO<sub>2</sub> emissions. To achieve these targets, Yunnan faces large challenges in its transition to a low-carbon future.

From 1997–2012, Yunnan's total energy consumption more than tripled, rising from 34.3 million tons (Mt) of coal equivalent in 1997 to 104.3 in 2012 (Figure 1). The total energy-related CO<sub>2</sub> emissions grew 3.5-times during the same period, from 56.6 Mt–197.1 Mt (Figure 1). The CO<sub>2</sub> emissions are predicted to reach 216.6 Mt in 2015 and 278.3 Mt in 2020 [8]. Industrial CO<sub>2</sub> emissions in Yunnan increased by 209.6% during the period 1997–2007, a figure that is 102.4% higher than the national growth rate over the same period [9]. This growth rate is 4.6-, 2.6- and 1.5-times greater than that of Beijing municipality [10], Liaoning province [11] and Jiangsu province [12], respectively. These facts raise a question: what are the driving forces behind the rapid growth of CO<sub>2</sub> emissions in a less-developed region with abundant low-carbon resources? From 1997–2012, the carbonization process of Yunnan's economy experienced three different stages (Figure 1). From 1997–2002, low CO<sub>2</sub> emission growth was accompanied by low economic growth. During this period, the average annual CO<sub>2</sub> emission elasticity ratio (CEER) (industrial CO<sub>2</sub> emissions' growth rate/GDP growth rate) was one. From 2002–2007, a high CO<sub>2</sub> emissions increase was accompanied by rapid economic growth. The average annual CEER in this period was 1.6. From 2007–2012, a low CO<sub>2</sub> emissions increase was accompanied by rapid economic growth. During this period, the average annual CEER was 0.4. It can be seen that from 2007–2012, Yunnan experienced relatively low-carbon economic growth. The factors driving the changes in the economic growth pattern in Yunnan have attracted our attention because the question of how to achieve rapid economic growth in less-developed regions while maintaining relatively low CO<sub>2</sub> emissions is important and is a challenge for policy makers [13].



**Figure 1.** Annual GDP growth rate, total energy consumption and related CO<sub>2</sub> emissions in Yunnan from 1997–2012.

Currently, research on CO<sub>2</sub> emissions in Yunnan focuses on CO<sub>2</sub> inventories [14], and prediction analysis is based on the realization of carbon intensity reduction targets [8]. These studies have provided some data resources and analytical approaches for low-carbon development in Yunnan. However, empirical studies on the drivers of Yunnan's CO<sub>2</sub> emissions that focus on the entire economic system from both production and final demand perspectives have been insufficient, lacking a relevant basis for formulating a low-carbon economic growth policy. Thus, an in-depth analysis to identify the drivers of CO<sub>2</sub> emission changes is helpful for finding a way to decouple the economic growth from CO<sub>2</sub> emissions in Yunnan.

There are two main decomposition techniques for identifying the drivers: structural decomposition analysis (SDA) and index decomposition analysis (IDA) [15]. The latest comparisons between IDA and SDA are shown in [16]. IDA has been applied to analyze the drivers of CO<sub>2</sub> emissions in China [17–19]. However, it can only analyze direct CO<sub>2</sub> emissions and provides fewer details about economic sectors than SDA. [20]. Compared to IDA, SDA is based on environmental input-output analysis [21], which is a widely-accepted method for quantifying sectoral CO<sub>2</sub> emissions considering both direct effects from the production process and indirect effects from the entire supply chain [16]. For the regional economy in Yunnan, SDA can analyze more comprehensive issues and is helpful for the low-carbon management of the entire economic chain from production to final demand. Because of the advantages of SDA, it was widely applied to analyze the drivers of the increase of CO<sub>2</sub> emissions in China as a whole [9,20,22] and in specific regions, such as Beijing [10,23], Jiangsu [12] and Liaoning [11]. These studies contributed to understanding the determinants of changes in CO<sub>2</sub> emissions and to forming policy implications that are suitable for local conditions. However, all of these studies focus on the national level or on developed regions in eastern China. Studies for less-developed regions (such as Yunnan province) in central or western China are not sufficient. Low-carbon development in less-developed regions is vital to achieve China's national carbon reduction target, because emissions in those regions are projected to increase substantially in the coming decades. In the time scale, most of these studies analyzed drivers from 1997–2007, but the impact of the 2008 Global Financial Crisis on changes in regional CO<sub>2</sub> emission drivers has seldom been analyzed. Moreover, these studies did not analyze the impact of changes in the GDP composition on CO<sub>2</sub> emissions. For the less-developed regions, GDP composition greatly changed over time; therefore, it is very important to study how GDP composition changes affect regional CO<sub>2</sub> emissions.

There are different decomposition forms in SDA, such as additive and multiplicative SDA [16]. The specific decomposing methods in SDA are also abundant, such as the method developed by Dietzenbacher and Los [24] (D&L) and the logarithmic mean Divisia index (LMDI) method [16]. Su and Ang [16] reviewed the new development of SDA in energy and emission fields and provided a guide on method selection in additive SDA for empirical studies. According to the review of the literature from 2000–2010 by Su and Ang [16], most energy and emission SDA research applied an additive SDA form and D&L method. However, recent SDA research on changes in the CO<sub>2</sub> emissions embodied in exports [25] and carbon intensity [26] in China applied the multiplicative SDA form. Due to the advantages of the simple decomposition process and the easy results representation [16], the additive SDA form is adopted in this study. The wide applications of additive SDA in China have proven its applicability and practicality. For methods selection in additive SDA, Su and Ang [16] have suggested that the LMDI method should be selected when the factors are more than four. However, all of the SDA studies in China's regions applied the D&L method [24]. The SDA-D&L model has non-unique decomposition problems, and when the drivers increase, the calculation will increase greatly [16]. Compared to the SDA-D&L model, the SDA-LMDI model is characterized by a simple expression, and its computation requirements are minimal [27]. The advantages of the SDA-LMDI model are more obvious for studies with four or more drivers [16]. Since the number of factors is seven in this study and the LMDI method is easy to use and has a simple computation in this situation, the LMDI method was selected in the decomposition analysis following the suggestions by Su and Ang [16]. At present, the SDA-LMDI model has been widely used in different countries and regions to analyze the driving forces behind changes in the economic systems [27], energy consumption and energy intensity [28,29] and greenhouse gas (GHG) emissions [30]. All of the previous research indicated that the SDA-LMDI model is applicable to this study.

This paper has two aims. The first is to understand the factors that drove the rapid CO<sub>2</sub> emissions' growth in Yunnan from 1997–2012. The second is to determine how the drivers contributed to the relatively low-carbon economic growth pattern in Yunnan from 2007–2012. We focused on the low-carbon development of the less-developed regions, of which Yunnan is the best case. Based on newly-released data, the time scale was extended to 2012. Seven drivers were analyzed in our

decomposition analysis, including changes in the GDP composition. We focused on analyzing energy-related CO<sub>2</sub> because of the availability of data and the large share of energy-related CO<sub>2</sub> in the total emissions. According to China's GHG inventories [31], energy-related CO<sub>2</sub> accounted for more than 90% of the total CO<sub>2</sub> emissions. Following other SDA research, we focused on the emissions created by the production of goods and services for consumers and did not consider the direct fuel use of households [20]. Direct CO<sub>2</sub> emissions from household energy consumption accounted for 4%–16% of the total emissions in Yunnan and continued to decline with the development of the economy (Figure 1).

The contents of the next sections are as follows: Section 2 is the description of the SDA-LMDI model employed in this paper, along with information on the data sources and the required preparation processes for using the data. Section 3 presents the results from the analysis, an in-deep discussion of them and a number of policy recommendations. Section 4 offers conclusions.

## 2. Method and Data

### 2.1. Method

Before conducting SDA, some assumptions in the input-output analysis framework should be made. The most important assumptions are “processing and normal exports” [32] and “competitive versus non-competitive imports” [33]. Uniform exports are assumed in this study, which means that processing and normal exports have the same input structures, since the processing exports in Yunnan are less and the data of processing and normal exports in the interregional exports for a region in China are unavailable. Imports are assumed as a competitive import assumption. Since Yunnan's primary input-output tables (IOTs) are compiled based on the competitive import assumption, excluding imports from these IOTs will cause the information on regional imports to be missed and will introduce uncertainties into the final results (see more discussions on the technology assumption about imports in the SM).

Changes in regional CO<sub>2</sub> emissions are affected by many factors [34]. The SDA-LMDI model can be used to analyze each factor's contribution to CO<sub>2</sub> emission changes from the perspective of the entire economic system. The model can be expressed mathematically as Equation (1):

$$e = F(I - A)^{-1}y = FLy \quad (1)$$

where  $e = (e_i)$  is the  $n \times 1$  vector of CO<sub>2</sub> emissions from  $n$  sectors in an industrial system and  $e_i$  is the direct CO<sub>2</sub> emissions from the  $i$ -th sector's production. This means the CO<sub>2</sub> emission responsibilities are allocated to the producers under Equation (1). In addition,  $F = (f_{ij})$  is an  $n \times n$  diagonal matrix, where the diagonal element  $f_{ii}$  is the ratio of the CO<sub>2</sub> emissions from sector  $i$  to the sector's total output; *i.e.*, the direct carbon intensity (DCI) of sector  $i$ .  $I$  is the  $n \times n$  identity matrix. The  $n \times n$  matrix  $A = (a_{ij})$  is the direct requirement coefficient matrix, where  $a_{ij}$  is the value of the intermediate products sector  $i$  required to bring about a unit increase in the output of sector  $j$ .  $L = (I - A)^{-1} = (l_{ij})$  is the  $n \times n$  Leontief inverse matrix, where  $l_{ij}$  represents the output increase of sector  $i$  by a unit increase in final demand in sector  $j$ .  $y = (y_i)$  is an  $n \times 1$  vector, where  $y_i$  represents the final demand of sector  $i$ .

The vector  $y$  can be further divided into four components: final demand structure,  $W$ ; GDP composition,  $v$ ; per capita GDP,  $g$ ; and population,  $p$ . Each element,  $w_{ik}$ , in the  $n \times m$  matrix,  $W$ , represents the contribution rates of the products demanded by sector  $i$  to the sum of the  $k$ -th final demand column, where  $k$  indicates the final demand categories, such as household consumption, government consumption, capital investment, exports and imports and  $m$  indicates the number of final demand categories. The element  $v_k$  in the  $m \times 1$  vector  $v$  indicates the total of  $k$ -th final demand column divided by GDP. Similarly,  $F$  can be further divided into three components: CO<sub>2</sub> emission coefficient,  $c$ ; energy structure,  $J$ ; and energy intensity,  $Q$ . The element  $c_d$  in the  $1 \times z$  vector  $c$  is the CO<sub>2</sub> emission coefficient of energy  $d$ , and  $z$  indicates number of energy types. Each element,  $j_{di}$ , in the  $z \times n$  matrix,  $J$ , represents the proportion of the amount of energy  $d$  in the total energy consumption by

sector  $i$ .  $Q = (q_{ij})$  is an  $n \times n$  diagonal matrix, where the diagonal element  $q_{ii}$  is the ratio of the energy consumption from sector  $i$  to the sector's total output; *i.e.*, the energy intensity of sector  $i$ . As a result, CO<sub>2</sub> emissions (Equation (2)) can be specified as follows:

$$e = cJQLWv_g p \quad (2)$$

As CO<sub>2</sub> emission coefficient  $c$  is constant in different years, changes in the technology (or energy efficiency) of the economic system are captured by two drivers, which are the changes in the energy structure and changes in the energy intensity. Therefore, seven CO<sub>2</sub> emission drivers are finally included in this study. The purpose of decomposition is to demonstrate changes in CO<sub>2</sub> emissions,  $\Delta e$ , in a particular period through the variation of each factor in Equation (2) as follows (Equation (3)):

$$\Delta e = \Delta J + \Delta Q + \Delta L + \Delta W + \Delta v + \Delta g + \Delta p \quad (3)$$

where  $\Delta J$  indicates changes in the energy structure;  $\Delta Q$  represents changes in the energy intensity;  $\Delta L$  means changes in the Leontief inverse matrix (*i.e.*, changes in the production structure);  $\Delta w$  is changes in the final demand structure;  $\Delta v$  is changes in the GDP composition;  $\Delta g$  is changes in the per capita GDP; and  $\Delta p$  is changes in the population.

In this study, changes in the CO<sub>2</sub> emissions have been decomposed into seven factors. De Boer [27] has developed the detailed model on which our work is based by utilizing two factors as an example. By extending De Boer's development in a similar manner to seven factors, we obtain the following:  $e = cJQLWv_g p$ , where  $e_i = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m c_{d,j,d_i} q_{ii} l_{ij} w_{jk} v_k g p$ . Taking 0 and 1 to represent the base year and end year, respectively, and setting  $e_{dijk} = c_{d,j,d_i} q_{ii} l_{ij} w_{jk} v_k g p$ , the following equations can be deduced (Equations (3a)–(3g)):

$$\Delta J = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m \frac{e_{dijk}(1) - e_{dijk}(0)}{\ln \left[ \frac{e_{dijk}(1)}{e_{dijk}(0)} \right]} \ln [j_{di}(1) / j_{di}(0)] \quad (3a)$$

$$\Delta Q = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m \frac{e_{dijk}(1) - e_{dijk}(0)}{\ln \left[ \frac{e_{dijk}(1)}{e_{dijk}(0)} \right]} \ln [q_{ii}(1) / q_{ii}(0)] \quad (3b)$$

$$\Delta L = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m \frac{e_{dijk}(1) - e_{dijk}(0)}{\ln \left[ \frac{e_{dijk}(1)}{e_{dijk}(0)} \right]} \ln [l_{ij}(1) / l_{ij}(0)] \quad (3c)$$

$$\Delta W = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m \frac{e_{dijk}(1) - e_{dijk}(0)}{\ln \left[ \frac{e_{dijk}(1)}{e_{dijk}(0)} \right]} \ln [w_{jk}(1) / w_{jk}(0)] \quad (3d)$$

$$\Delta v = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m \frac{e_{dijk}(1) - e_{dijk}(0)}{\ln \left[ \frac{e_{dijk}(1)}{e_{dijk}(0)} \right]} \ln [v_k(1) / v_k(0)] \quad (3e)$$

$$\Delta g = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m \frac{e_{dijk}(1) - e_{dijk}(0)}{\ln \left[ \frac{e_{dijk}(1)}{e_{dijk}(0)} \right]} \ln [g(1) / g(0)] \quad (3f)$$

$$\Delta p = \sum_{d=1}^z \sum_{j=1}^n \sum_{k=1}^m \frac{e_{dijk}(1) - e_{dijk}(0)}{\ln \left[ \frac{e_{dijk}(1)}{e_{dijk}(0)} \right]} \ln [p(1) / p(0)] \quad (3g)$$

The model is characterized by simple expressions, and the calculations are straight-forward. However, difficulty in applying the model arises when there is a zero or negative number in the dataset. To solve this problem, we follow the practice of De Boer [27] and replace the zero value in the preliminary dataset with  $10^{-29}$ . For negative numbers, we follow the processing method of Ang and Liu [35].



From the consumption perspective, CO<sub>2</sub> emissions can be allocated to the sectors whose products were consumed by the final demand categories [36,37], which can be expressed mathematically as (Equation (4)):

$$e^f = F^f(I - A)^{-1}y^f = Ty^f \quad (4)$$

where  $e^f = (e_i^f)$  is the  $1 \times n$  vector of CO<sub>2</sub> emissions caused by the  $n$  sectors' final demand consumption and  $e_i^f$  is the CO<sub>2</sub> emissions from the consumption of  $i$ -th sector's products. This means that the CO<sub>2</sub> emission responsibilities are allocated to the consumers under Equation (4). In addition,  $F^f = (f_i^f)$  is a  $1 \times n$  vector, where the element  $f_i^f$  is the DCI of sector  $i$ .  $T = F^f(I - A)^{-1} = (t_i)$  is a  $1 \times n$  vector, where the element  $t_i$  is the total carbon intensity (TCI) of sector  $i$ , which represents CO<sub>2</sub> emissions from sector  $i$ 's supply chains (including direct and indirect emissions) by the final demand unit products' value from sector  $i$ . Therefore, indirect carbon intensity (ICI) can be obtained by TCI minus DCI.  $y^f = (y_{ij}^f)$  is an  $n \times n$  diagonal matrix, where the diagonal element  $y_{ii}^f$  represents the final demand of sector  $i$ .

## 2.2. Data Sources and Processing

Two datasets were employed in our analysis: the input-output tables (IOTs) in time series and the sectoral energy use and CO<sub>2</sub> emission factor statistics. In China, provincial IOTs are published every five years, and the most recent IOT is from 2012. Yunnan's IOTs for 1997, 2002, 2007 and 2012 were obtained from the Yunnan Statistical Bureau. The 1997 Table contained 40 sectors, whereas other tables contained 42 sectors. Nineteen types of energy sources were included in the calculations: raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, natural gas, other petroleum products, other coke products, heat, electricity and other energy. The energy data for agriculture, industry, construction, transport, storage and post, wholesale, retail trade and hotels, restaurants and other services originated from Yunnan's energy balance sheets from 1997, 2002, 2007 and 2012, which can be found in the China Energy Statistical Yearbooks for the various years [38]. Energy data for the industrial sub-sectors for the years 2002, 2007 and 2012 came from the Yunnan Energy Statistical Yearbook [39]. Energy data for the industrial sub-sectors in 1997 were missing. To compensate, these data were estimated based on the total industrial energy data that are provided in available energy balance sheets and the energy proportion of industrial sub-sectors in 2000.

The energy and CO<sub>2</sub> emission statistics were processed following the method proposed by Peters *et al.* [40] and the National Development and Reform Commission of China [31]. Because coal usage in China is usually inefficient [41], instead of the default values of the Intergovernmental Panel on Climate Change (IPCC), we employed the specific CO<sub>2</sub> emission factors (including carbon content, net calorific value and carbon oxidation factors), which are more suitable for China [31]. The final demand columns of Yunnan's 2007 and 2012 IOTs consisted of rural residential consumption, urban residential consumption, government consumption, fixed capital formation, stock changes, interprovincial and international exports and interprovincial and international imports. One of the final demand columns in the Yunnan 1997 IOT is called "others", which represents the margin of error among different data sources [20]. In our analysis, each sector's total output in 1997 was calculated as the sum of intermediate deliveries and final demand; thus, the "others" column was excluded [12]. Because Yunnan's 1997 and 2002 IOTs did not differentiate interprovincial and international trade, they were combined into two columns titled exports and imports. Since we do not know the detailed sources of imports, we assumed that all imports are produced under the same conditions in Yunnan; therefore, the emissions embodied in these imports were designated as the "emissions avoided in Yunnan through imports" [20]. By synthesizing sectors in the IOTs and sectors with available energy data, all of the sectors were combined into a total of 29 sectors according to "classification of national economic industries (GB/T 4754-2011, GB/T represents the recommended national standards and it is the abbreviation of Guo Biao/Tui in Chinese.)" [42] (Table 1). To avoid the influence of price changes,

we utilized the double deflation method [43] and transformed all of the IOTs into constant prices in 2002. Price index data were obtained from the Yunnan Survey Yearbook 2014 [5], and population data were taken from the Yunnan Statistical Yearbook [4] (see more discussions on the double deflation method in the SM).

After comprehensively considering the availability of sectoral energy data and the consistency of sector classification in IOTs from different years, 29 sectors were finally adopted in this study. However, this would cause sector aggregation issues mentioned by Su *et al.* [44]. Through comparing the results of CO<sub>2</sub> emissions embodied in China and Singapore's exports under different sector aggregation situations, Su *et al.* [44] suggested a sector aggregation of more than 40 sectors. If so, the 29 sector aggregation in this study might cause some uncertainties to the results. In addition, the extended IOTs in 2000, 2005 and 2010 were not compiled in Yunnan, instead being done at the national scale or for some developed regions, such as Beijing. Therefore, the time intervals of IOTs were determined as 5 years in this study. This would cause the temporal aggregation issues mentioned by Su and Ang [45], and also cause some uncertainties to the results. Furthermore, the trend of changes in the drivers would be missed and regarded as some kind of average values within the sub-periods 1997–2002, 2002–2007 and 2007–2012, respectively. Missing some peculiarities of the drivers would increase the uncertainties when the results were discussed. As these uncertainties existed, the results in this study were regarded as approximate values. However, these uncertainties were unlikely to extremely affect the scale and trend of the results in any one direction [46]. Keeping these uncertainties in mind, detailed and in-depth analysis and discussions were conducted by combining our results with other statistics and materials in both official publications and literature, before policy suggestions were made. The results and discussions could be improved when more detailed data are available.

**Table 1.** Sectoral carbon intensity in 1997, 2002, 2007 and 2012 in Yunnan (unit: tons/10<sup>4</sup> Yuan of 2002 constant price).

	Sectors	Direct Carbon Intensity				Indirect Carbon Intensity				Total Carbon Intensity			
		1997	2002	2007	2012	1997	2002	2007	2012	1997	2002	2007	2012
1-AGR	Agriculture	0.3	0.4	0.4	0.3	1.2	2.0	1.4	1.4	1.5	2.4	1.8	1.7
2-MWC	Mining and washing of coal	8.2	4.1	2.0	0.2	1.4	7.5	5.6	4.1	9.6	11.6	7.6	4.3
3-EPN	Extraction of petroleum and natural gas	0.0	0.0	0.0	0.0	0.0	5.4	0.0	0.0	0.0	5.4	0.0	0.0
4-MPM	Mining and processing of metal ores	1.4	1.6	1.7	1.1	2.8	7.2	6.5	5.5	4.2	8.8	8.2	6.6
5-MPN	Mining and processing of nonmetal ores	1.1	1.1	3.8	1.6	3.5	6.5	6.8	5.5	4.6	7.6	10.6	7.1
6-MFT	Processing and manufacture of food and tobacco	0.2	0.1	0.2	0.1	0.7	1.8	1.0	0.8	0.9	1.9	1.2	0.9
7-MOT	Manufacture of textiles	0.4	0.5	2.7	1.0	2.1	4.4	3.6	2.3	2.5	4.9	6.3	3.3
8-MCL	Manufacture of clothes, leather and related products	0.3	0.3	0.5	0.1	2.3	3.5	3.1	1.7	2.6	3.8	3.6	1.8
9-MWF	Manufacture of wood products and furniture	0.2	0.5	0.6	0.1	4.5	5.0	3.0	1.3	4.7	5.5	3.6	1.4
10-PMP	Paper making, printing and articles manufacture	0.5	0.4	0.8	0.5	3.5	4.0	2.1	2.0	4.0	4.4	2.9	2.5
11-PPC	Petroleum processing and coking	6.3	10.6	1.5	1.2	4.5	7.4	3.6	2.8	10.8	18.0	5.1	4.0
12-CHE	Chemistry	3.9	4.0	1.9	1.9	5.9	6.7	5.9	3.7	9.8	10.7	7.8	5.6
13-MNM	Manufacture of non-metallic mineral products	6.0	4.6	15.5	7.0	5.2	6.9	7.7	5.3	11.2	11.5	23.2	12.3
14-SPM	Smelting and pressing of metals	5.8	5.2	2.8	2.8	6.9	8.1	4.2	3.6	12.7	13.3	7.0	6.4
15-MMP	Manufacture of metal products	0.2	0.3	0.2	0.1	8.0	8.5	4.3	3.3	8.2	8.8	4.5	3.4
16-MGS	Manufacture of general and special purpose machinery	0.3	0.3	0.2	0.1	3.8	6.8	3.5	3.2	4.1	7.1	3.7	3.3



Table 1. Cont.

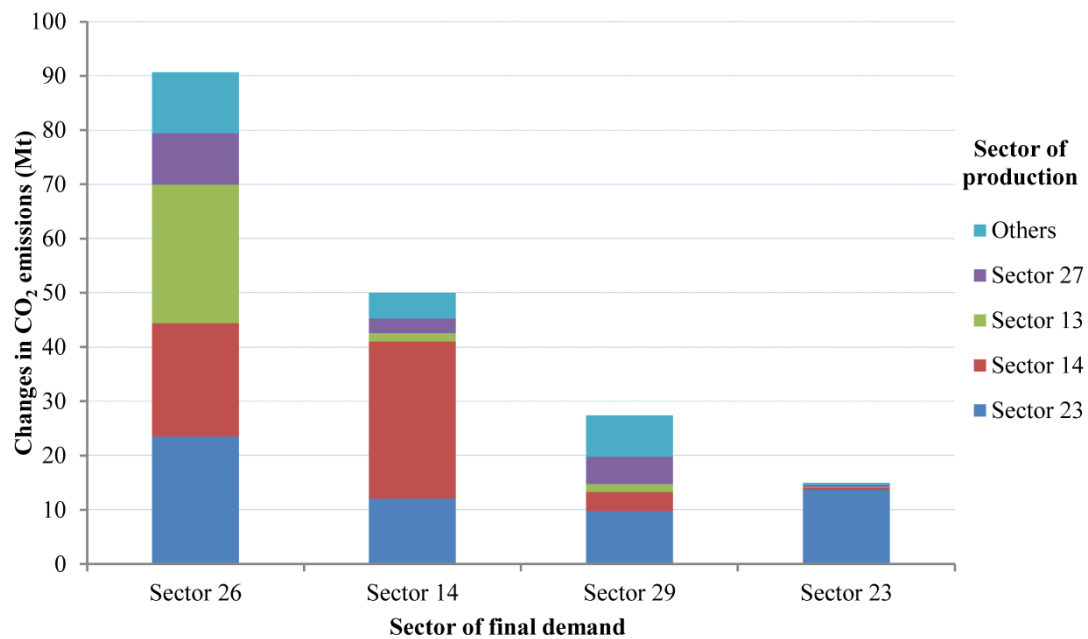
	Sectors	Direct Carbon Intensity				Indirect Carbon Intensity				Total Carbon Intensity			
		1997	2002	2007	2012	1997	2002	2007	2012	1997	2002	2007	2012
17-MTE	Manufacture of transportation equipment	0.3	0.2	0.1	0.2	4.1	5.9	2.7	2.6	4.4	6.1	2.8	2.8
18-MEM	Manufacture of electrical machinery and equipment	0.0	0.1	0.0	0.0	5.9	6.7	4.6	3.8	5.9	6.8	4.6	3.8
19-MCE	Manufacture of communication and electronic equipment	0.9	0.5	0.0	0.0	3.8	4.5	2.5	1.4	4.7	5.0	2.5	1.4
20-IMC	Manufacture of measuring instruments and machinery for cultural activity and office work	0.0	0.0	0.0	0.0	4.4	5.6	2.8	1.9	4.4	5.6	2.8	1.9
21-MAO	Manufacture of artwork and other manufacturing	0.0	0.1	0.3	0.7	4.2	6.1	3.2	2.4	4.2	6.2	3.5	3.1
22-RDW	Recycling and disposal of waste	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.3	0.1	0.1	0.1	0.3
23-PSE	Production and supply of electric and heat power	30.2	11.1	12.9	6.8	3.9	5.2	8.7	4.5	34.1	16.3	21.6	11.3
24-PSG	Production and supply of gas	5.3	2.8	4.6	0.1	5.5	7.0	3.7	1.4	10.8	9.8	8.3	1.5
25-PSW	Production and supply of water	0.1	0.0	0.0	0.0	2.9	5.1	1.6	2.5	3.0	5.1	1.6	2.5
26-CON	Construction	0.1	0.1	0.1	0.1	5.4	7.2	5.8	4.5	5.5	7.3	5.9	4.6
27-TSP	Transport, storage and post	1.5	3.3	3.7	4.1	2.8	6.3	2.3	2.2	4.3	9.6	6.0	6.3
28-WRH	Wholesale, retail trade and hotel, restaurants	0.1	0.1	0.1	0.2	1.6	2.1	1.4	1.2	1.7	2.2	1.5	1.4
29-OSE	Other services	0.1	0.1	0.0	0.1	1.5	2.7	1.7	1.5	1.6	2.8	1.7	1.6

### 3. Results and Discussion

#### 3.1. Overall Trend of CO<sub>2</sub> Emission Variations in Yunnan from 1997–2012

From 1997–2012, Yunnan's industrial CO<sub>2</sub> emissions grew from 47.8 Mt–187.6 Mt, a four-fold increase. Most of this total growth of 139.8 Mt was concentrated in the period 2002–2007. In this period, CO<sub>2</sub> emissions grew by 80.9 Mt, which constitutes 57.9% of the growth that occurred in the 1997–2012 period, with the remaining 28.2% (39.5 Mt) in 2007–2012 and 13.9% (19.4 Mt) in 1997–2002.

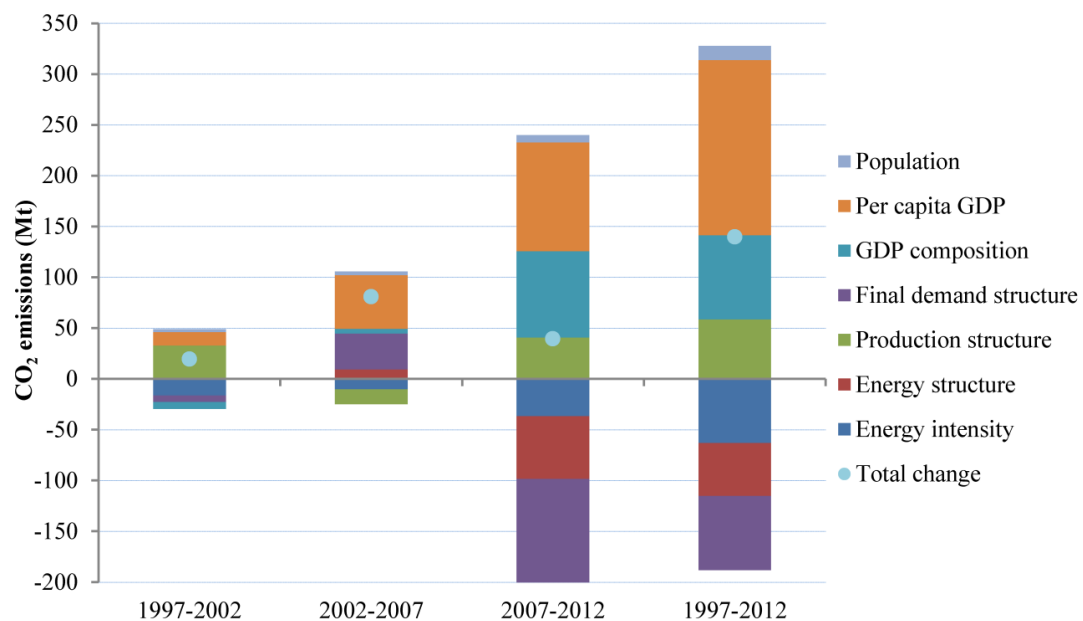
From a production perspective, 23-PSE (production and supply of electric and heat power) (33.7%), 14-SPM (smelting and pressing of metals) (29.6%), 27-TSP (transport, storage and post) (12.3%) and 13-MNM (manufacture of non-metallic mineral products) (10.6%) contributed 86.2% (120.5 Mt) of the total CO<sub>2</sub> emissions increase during 1997–2012 (see Table S1 in SM). These sectors have a high DCI in their production processes (Table 1) and their contributions to the CO<sub>2</sub> emissions increase were much larger than their contributions to GDP growth (Table S1). From a final demand perspective, 26-CON (construction) (64.8%), 14-SPM (35.7%), 29-OSE (other services) (19.6%) and 23-PSE (10.7%) contributed 130.9% (183.0 Mt) of the total CO<sub>2</sub> emissions increase (Table S2 in SM). 14-SPM and 23-PSE not only have a high DCI, but also a high TCI (Table 1). The DCI for 26-CON and 29-OSE is extremely low, whereas their TCI is much higher than their DCI (Table 1). The expansion of the final demand volume of products in these sectors will boost their carbon-intensive supply chains. For example, the final demand sector 26-CON increased its CO<sub>2</sub> emissions by 90.7 Mt during 1997–2012 with 28.2% contributed by 13-MNM, 25.9% by 23-PSE, 23% by 14-SPM and 10.4% by 27-TSP in the construction supply chains (Figure 2). Compared to most other sectors, 29-OSE has lower carbon intensity in both DCI and TCI (Table 1). The increments of expenditure on products from 29-OSE have a 33.7% share in GDP, while contributing only 19.6% to the CO<sub>2</sub> emissions increase (Table S2) (see more analysis about sectoral carbon intensity changes in the SM).



**Figure 2.** Major sectors contributing to the CO<sub>2</sub> emissions increase from the final demand perspective during 1997–2012 and their carbon-intensive supply chains.

### 3.2. Drivers from Decomposition Analysis

The largest driver of changes in CO<sub>2</sub> emissions was the growth of per capita GDP, leading to a 172.5-Mt CO<sub>2</sub> emissions increase from 1997–2012 (Figure 3). In the previous decades, Yunnan had been struggling to develop its economy and reduce poverty. The per capita GDP of Yunnan in 2012 was more than 3.5-times that of 1997 [4]. Yunnan’s per capita GDP is expected to continue increasing to catch up with other developed regions in China, which will signify its contribution to CO<sub>2</sub> emission increments in the following decades.



**Figure 3.** Drivers contributing to changes in Yunnan’s industrial CO<sub>2</sub> emissions in different time periods from a decomposition analysis.

The second largest driver was GDP composition change, causing an 82.7-Mt increase in CO<sub>2</sub> emissions from 1997–2012 (Figure 3). The sub-periods data showed a positive correlation between changes in the fraction of capital investment in GDP and CO<sub>2</sub> emissions (see Figure 3 and Table 2). The Yunnan government was aware of the problem and aimed to decrease capital investment in its economy since the 11th FYP period (2006–2010) [47], but this policy did not achieve the desired effect because of the Global Financial Crisis. Under the impact of the four-trillion-Yuan stimulus plan in China [48], the fraction of capital investment in GDP increased by 38.9% during 2007–2012 in Yunnan (Table 2). This GDP composition change caused an 84.9-Mt increase in CO<sub>2</sub> emissions during this period (Figure 3).

**Table 2.** Changes in the GDP composition in Yunnan from 1997–2012 (unit: %).

Year	Fraction of Investment in GDP	Fraction of Consumption in GDP	Fraction of Exports in GDP
1997	42.8	59.8	33.3
2002	39.8	68.4	38.1
2007	44.3	61.9	63.8
2012	83.2	61.2	51.5

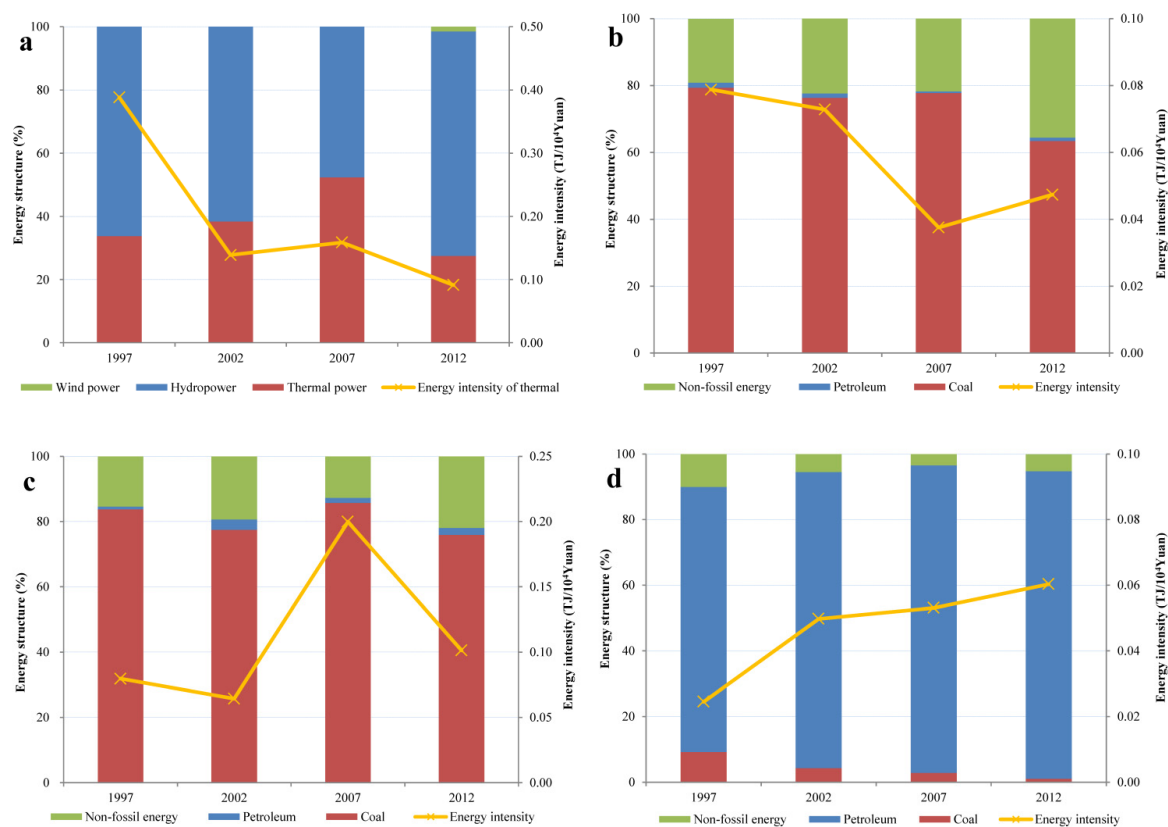
Production structure modifications caused a 58.6-Mt increase in the total CO<sub>2</sub> emissions during 1997–2012 (Figure 3). This production structure change reflects the expansion of the heavy industry in Yunnan as it transitioned from an economy dominated by the tobacco industry [49]; the proportion of heavy industry among total industry increased from 47.8% in 1997 to 69.5% in 2012 [4]. During 2002–2007, changes in the production structure had a positive effect decreasing CO<sub>2</sub> emissions by 14.9 Mt (Figure 3). This seemed to be the policy dividend of Yunnan’s promotion of development in the green economy since 2000 [50]. Relatively low-carbon industries, such as biological development and tourism, developed rapidly during this period [47], but these benefits were stopped by the 2008 Global Financial Crisis. Under China’s four-trillion-Yuan stimulus plan [48], capital investments (most in the construction sector) in Yunnan increased rapidly (Table 2), and the carbon-intensive supply chains of the construction sector increased sharply during 2007–2012. Carbonization of the production structure increased CO<sub>2</sub> emissions by 40.9 Mt during this period (Figure 3).

The driving effect of population growth was small; its contribution to the growth in CO<sub>2</sub> emissions was only 14.0 Mt from 1997–2012 (Figure 3). This was primarily due to the strict implementation of the “one-child policy” in Yunnan. In each FYP, a target is set to control the population growth rate. It is expected that Yunnan will continue following the population planning policy formulated by the central government to control the population growth rate. The contribution of changes in population to CO<sub>2</sub> emissions will remain small (see more information about the “one-child policy” in China in the SM).

From 1997–2012, the largest driver leading to a reduction in industrial CO<sub>2</sub> emissions was changes in the carbon intensity (the sum of changes in the energy intensity and energy structure; Figure 3). Of the 115.1-Mt CO<sub>2</sub> emissions offset by improvements in carbon intensity during this period, 45.1% was from 23-PSE, 37.1% was from 13-MNM and 12.0% was from 14-SPM (Table S3 in SM). However, a DCI increase in 27-TSP led to 5.9 Mt in carbon intensity-related CO<sub>2</sub> increments (Table 1 and Table S3). Figure 4 shows the changes in energy intensity and energy structure in these four energy-intensive sectors. It highlights the expansion of renewable electricity (mostly from hydropower) share in total electricity generation during 2007–2012. Hydropower generation in Yunnan grew seven-fold, from 16.8 terawatt hours in 1997 to 123.8 terawatt hours in 2012, and the share of hydropower in total electricity generation was 71% in 2012 [39]. The application of non-fossil energy in sectors 13-MNM and 14-SPM also increased through a “combination of mineral industry and hydropower” policy in Yunnan [47]. Changes in the energy structure led to a reduction of CO<sub>2</sub> emissions as much as 61.8 Mt during 2007–2012 (Figure 3 and Table S4). From a sector perspective, 14-SPM, 13-MNM

and 23-PSE contributed to 26.2-, 16.2- and 13.4-Mt energy structure-related CO<sub>2</sub> emissions decreases during this period, respectively (Table S4). Although the process was lengthy and complex, the implementation of key energy-saving projects and the elimination of backward production capacity under a mandatory target set by the central government to encourage the provincial government to reduce energy intensity since the 11th FYP period (2006–2010) [47] resulted in significant improvements in energy intensity in key energy consumption sectors, such as 13-MNM, 14-SPM and thermal power. From 1997–2012, changes in the energy intensity reduced CO<sub>2</sub> emissions constantly by 63.1 Mt, with 58.0% of this reduction in 2007–2012, 25.8% in 1997–2002 and only 16.2% in 2002–2007 (Figure 3 and Table S4). From a sector perspective, 23-PSE and 13-MNM contributed 65.6% (−41.4 Mt) and 45.4% (−28.7 Mt) to energy intensity-related CO<sub>2</sub> emissions reduction during 1997–2012, respectively (Table S4). However, coal and petroleum still dominated energy use in the 13-MNM, 14-SPM and 27-TSP sectors. Meanwhile, energy intensity and structure improvements were mostly found in industrial sectors. For transportation (27-TSP), both the energy intensity and structure deteriorated. Road transportation composes more than 90% of total transportation in Yunnan, and most roads in Yunnan are labeled as low grade [4].

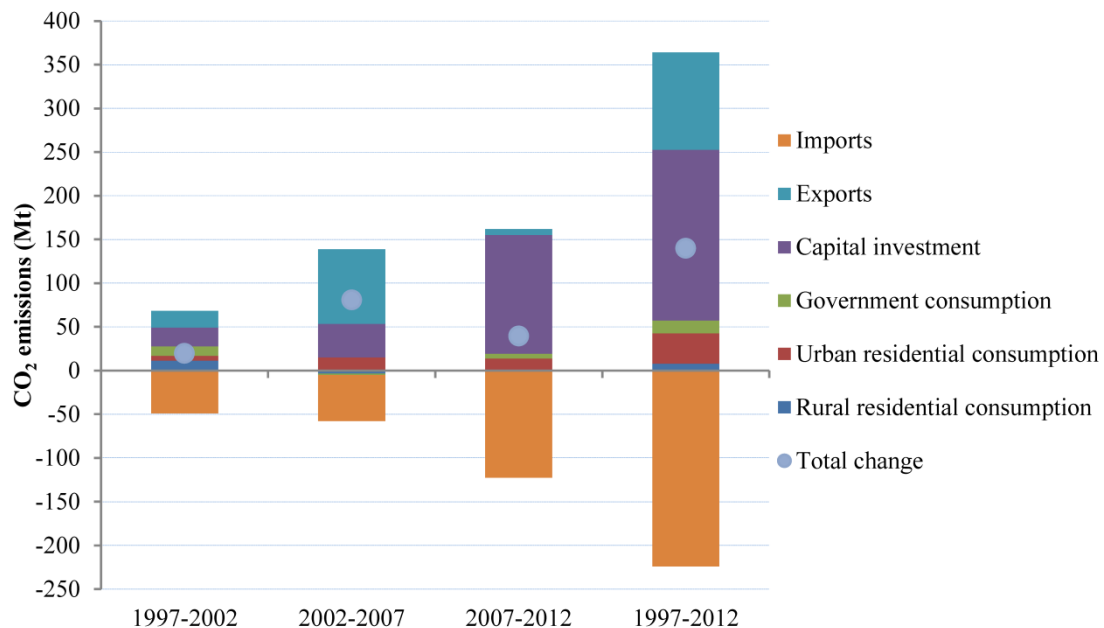
Optimization of the final demand structure was another driving force offsetting the increase of CO<sub>2</sub> emissions by 72.9 Mt between 1997 and 2012 (Figure 3). However, it has not always played a positive role in CO<sub>2</sub> mitigation. During 2002–2007, changes in the final demand structure increased CO<sub>2</sub> emissions by 35.3 Mt (Figure 3). The next section presents a detailed analysis showing how changes in the final demand structure affect CO<sub>2</sub> emissions in separate final demand categories.



**Figure 4.** Energy intensity and structure change in major sectors from a production perspective from 1997–2012. (a) 23-PSE; (b) 14-SPM; (c) 13-MNM; and (d) 27-TSP.

### 3.3. Drivers from a Final Demand Perspective

From a final demand perspective, capital investment (the sum of fixed capital formation and stock changes) was the largest driving force between 1997 and 2012. It drove a CO<sub>2</sub> emissions increase of 195.3 Mt, 69.5% of which occurred in the period 2007–2012 (Figure 5). To reduce the impact of the Global Financial Crisis on the economy, the Chinese government adopted the four-trillion-Yuan stimulus plan, of which 45% was invested in constructing infrastructure, such as roads, airports and buildings [6]. This plan caused the growth of CO<sub>2</sub> emissions in construction investments in Yunnan to explode (Figures 6a and 7a).

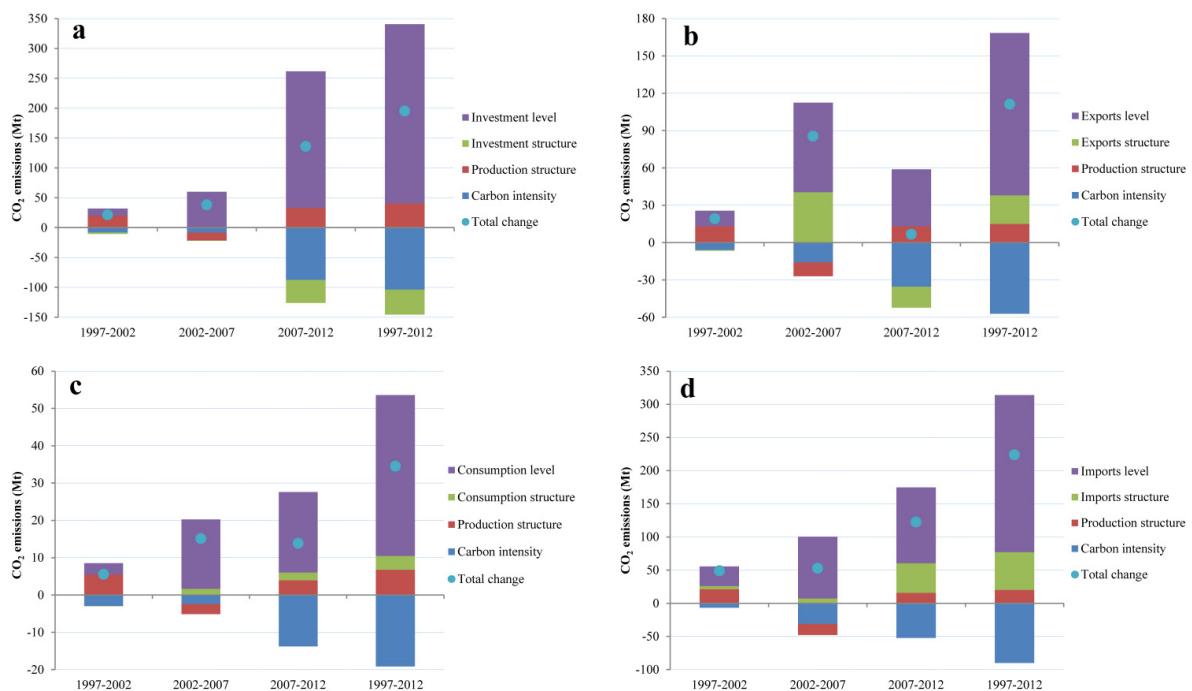


**Figure 5.** Drivers contributing to changes in Yunnan's industrial CO<sub>2</sub> emissions in different time periods when analyzed from a final demand perspective.

Exports were the second largest driver of the CO<sub>2</sub> emissions increase in Yunnan during 1997–2012. Of the 111.2-Mt increase in export-related CO<sub>2</sub> emissions during this period, 76.8% occurred in 2002–2007, 17.2% occurred in 1997–2002 and only 6.0% in 2007–2012 (Figure 5). Figures 6b and 7b demonstrate the main decomposition drivers and sectors contributing to the increase in export-related CO<sub>2</sub> emissions. They indicate that from 2002–2007, the export-related CO<sub>2</sub> emissions increase was caused primarily by growth in the exports of carbon-intensive products from 14-SPM and 23-PSE. During this period, exports from these two sectors increased by 1106.2% and 269.6%, respectively (Table S5). This change also caused carbonization of the exports' structure, which led to an increase of 40.5 Mt in export-related CO<sub>2</sub> during this period (Figure 6b). The share of carbon-intensive products from 14-SPM and 23-PSE in total exports increased from 9.4% and 2.7% in 2002 to 38.7% and 3.4% in 2007, respectively (Table S5). During 2007–2012, the situation was different. Although carbon-intensive product exports from 14-SPM and 23-PSE increased by 0.3% and 3.2%, respectively, their shares in total exports decreased to 26.6% and 2.4% in 2012 (Table S5). Low-carbon products from the agriculture and service sectors increased their share in total exports during the same period (Table S5). Changes in the exports' structure led to a decrease of 16.8 Mt CO<sub>2</sub> during this period (Figure 6b). Most of Yunnan's exports were raw materials to support the development of developed coastal regions in China. For example, Yunnan was important to China's "West to East Transmission Scheme", increasing deliveries of electricity to developed eastern areas (e.g., Guangdong Province) [3] from 0.2 terawatt hours in 1997 to 42.6 in 2012 [39].

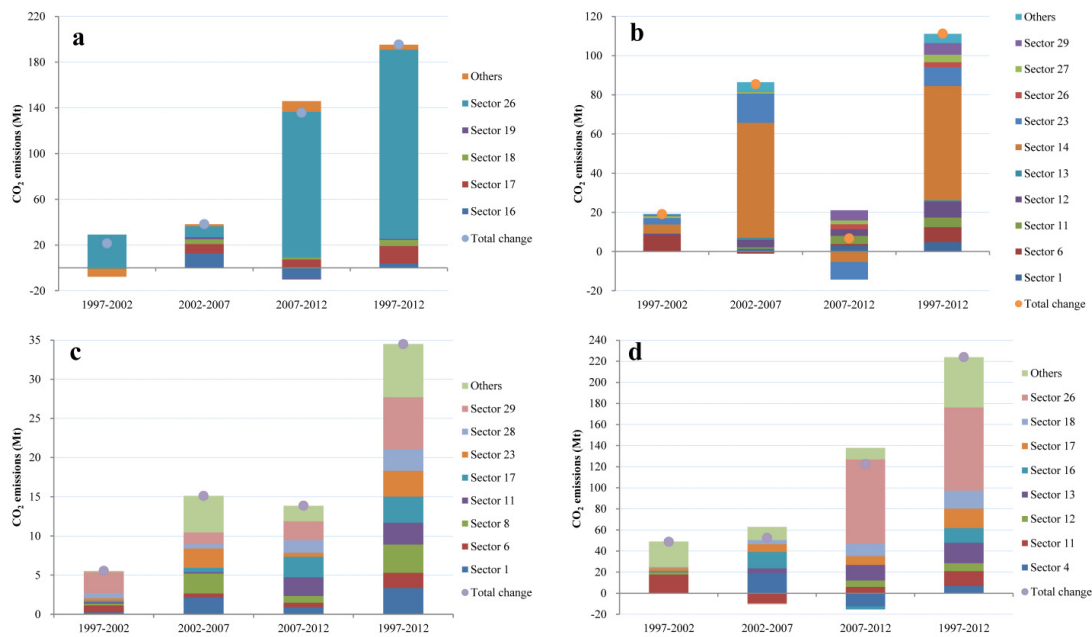
Urban residential consumption was another important driver of the growth of CO<sub>2</sub> emissions. This was especially the case between 2002 and 2007, when urban residential consumption exceeded both rural residential consumption and government consumption and became the third largest driving force (Figure 5). The urban population of Yunnan grew from 23.4% of the total population in 2000 to 39.3% in 2012, increasing by 8.4 million in these twelve years [4]. The increase in urban population strengthened the driving effect of urban residential consumption, which increased CO<sub>2</sub> emissions by 34.5 Mt during 1997–2012 (Figure 5). Growth in consumption level was the primary driver of the 43.2-Mt increase in urban-related CO<sub>2</sub> emissions during 1997–2012 (Figure 6c). From a sectoral perspective, increased consumption of life-cycle carbon-intensive products, such as electricity, petroleum and cars, contributed to an urban-related CO<sub>2</sub> emissions increase in recent years (Figures 6c and 7c). The urbanization rate in Yunnan is far below the national average. In 2012, 39.3% of Yunnan's population was classified as urban, whereas the figure was 52.6% for the country as a whole [4]. With increasing urbanization, it is foreseeable that urban residential consumption in Yunnan will continue to strengthen as a driving force.

Rural residential consumption and government consumption had lesser driving effects during 1997–2012, increasing CO<sub>2</sub> emissions by only 7.9 Mt and 14.8 Mt, respectively (Figure 5). Meanwhile, for the period 1997–2012, increasing imports of carbon-intensive products from construction and heavy manufacturing sectors avoided a 224.0-Mt CO<sub>2</sub> emissions increase if these products were produced in Yunnan (see Figures 5, 6d and 7d). Nonetheless, it will increase the carbon footprint (CO<sub>2</sub> emissions caused by final demand within a region) of Yunnan. Furthermore, it will intensify the debate regarding the responsibility for the redistribution of CO<sub>2</sub> emissions [37]. Thus, fundamentally decreasing local carbon footprint should become the focus of policy makers.



**Figure 6.** Main decomposition drivers contributing to changes in CO<sub>2</sub> emissions by different final demand categories from 1997–2012. (a) Capital investment; (b) exports; (c) urban residential consumption; and (d) imports.





**Figure 7.** Main sectors contributing to changes in CO<sub>2</sub> emissions by different final demand categories from 1997–2012. (a) Capital investment; (b) exports; (c) urban residential consumption; and (d) imports.

### 3.4. Policy Recommendations for Further Mitigating CO<sub>2</sub> Emissions in Yunnan

Based on the above analysis, policy recommendations are suggested to further mitigate CO<sub>2</sub> emissions in Yunnan from the perspective of both production and final demand.

#### 3.4.1. Policy Recommendations from a Production Perspective

##### Promote the Development and Application of Clean Energy

Developing hydropower substantially decarbonized Yunnan's energy structure in recent years, but applying clean energy in the production sectors is not enough. Thus, policy makers should formulate policies supporting the development of clean energy, such as hydropower, wind, solar and biomass, according to local conditions. However, some details should be considered in this process: (1) the cooperation among the Yunnan government, China's central government and power grid company; (2) the ecological environment problems coupled with clean energy development; and (3) the coordination of the layout of the clean energy and industrial sectors. In addition, building a distributed clean energy supply network can increase the use of clean energy and a greener energy structure in production sectors. Increasing the use of clean energy, such as hydropower, hydrogen and natural gas, in the transportation system can also reduce a sector's dependence on carbon-intensive petroleum products.

##### Further Improve the Energy Efficiency in Energy-Intensive Sectors

According to the front analysis, the decreased energy intensity in energy-intensive sectors was greatly due to the administrative measures, such as mandatory reduction targets. To further reduce sectoral energy intensity, more economic measures should be taken. If economic instruments (for example, financial subsidies and tax rebates) are integrated into sectoral low-carbon policies, the effects of technology improvements in reducing CO<sub>2</sub> emissions are expected to be critical. For less-developed regions, such as Yunnan, technology and funds for research and development (R&D) are limited. Therefore, the forming of mechanism to promote the transfer of funds and low-carbon technologies from developed regions is worth the consideration for policy makers.

The above analysis indicated that sectors 13-MNM, 14-SPM, 23-PSE and 27-TSP were the most energy-intensive sectors, and their production processes contributed over 80% of the CO<sub>2</sub> emissions increase during 1997–2012 in Yunnan. Therefore, strengthening the measures to improve energy efficiency in these sectors will play a more effective role in reducing CO<sub>2</sub> emissions. For the cement sector (13-MNM), typical measures, including upgrading the existing equipment (such as the rotary kilns, mills and dryers), developing new energy-saving technologies (such as heat recovery for power generation in rotary kilns, raw meal blending systems in dry process and process control systems in all kilns) and eliminating backward production techniques (such as wet kilns and dry hollow kilns), can be applied [51]. For the metal processing sector (14-SPM), the blast furnace top gas recovery turbine (TRT) unit, converter negative energy steelmaking technology, blast furnace gas and converter gas should be well applied and used in the iron and steel making process; oxygen-rich flash and oxygen-enriched bath smelting, large pre-baked electrolytic cells, oxygen bottom blown technology and wet processing technology should be applied in copper, aluminum, lead and zinc smelting, respectively. For the electricity sector (23-PSE), encouraging the construction of large coal-fired units over 600 megawatts (MW) and large-capacity gas combined cycle plants to replace smaller and less efficient units is essential. Actively developing a smart and ultra-high voltage power grid and phasing out the low voltage electricity distribution network can reduce the electricity loss in the transmission process. For Yunnan's carbon-intensive transportation system (27-TSP), strengthening the relatively low-carbon railway transportation system can reduce the dependence on high-carbon road transportation. Meanwhile, upgrading the road transportation system (such as building more high-grade roads), improving the fuel economy of vehicles and promoting intelligent traffic management systems are also important measures to improve the energy efficiency in the transportation sector [8].

#### Adjust the Industrial Structure According to the Total Carbon Intensity of Sectors and Local Advantageous Resources

It is very important to construct a low-carbon industrial system for Yunnan's low-carbon development. Both sides, including the carbon intensity of the entire industrial supply chain (*i.e.*, total carbon intensity of a sector) (Table S6) and the combination with local advantageous resources, should be considered in this process. Thus, policy measures should continue to promote low-carbon industries, such as plateau characteristic agriculture (1-AGR), clean power, bio-resources (6-MFT (processing and manufacture of food and tobacco)), tourism (29-OSE) and ethnic culture (29-OSE). Vigorously developing the productive service industry (29-OSE) not only increases the economic share of the low-carbon service industry, but also promotes the development of technology-intensive industries. In addition, the policy encouraging the transfer of labor-intensive (7-MOT (manufacture of textiles), 8-MCL (manufacture of clothes, leather and related products), 10-PMP (paper making, printing and articles manufacture) and 28-WRH (wholesale, retail trade and hotel, restaurants)) and technology-intensive industries (19-MCE (manufacture of communication and electronic equipment) and 22-RDW (recycling and disposal of waste)) to Yunnan from developed regions can gradually replace resource-intensive industries and create a lighter production structure.

#### 3.4.2. Policy Recommendations from a Final Demand Perspective

##### Reduce the Dependence of Economic Growth on Investments and Exports and Encourage a Consumption-Based Economic Growth

Capital investments in infrastructure construction and exports of raw materials not only carbonized the GDP composition, but also formed a carbon-intensive production structure due to the high-carbon supply chains. Compared to capital investments and exports, consumption is more dependent on the relatively low-carbon service and agriculture industries, which contribute less to CO<sub>2</sub> emissions' growth (Table S7). Therefore, policy makers should vigorously promote policies that are conducive to consumption-based economic growth. For example, improving the minimum

wage standards and establishing a sound social security system can effectively promote the growth of consumer spending.

#### Optimize the Life-Cycle Supply Chains for Final Demand Products

For the carbon-intensive supply chain in the construction, metal processing and electricity sectors, strengthening the recycling of resources in the production process can reduce new production of high-carbon raw materials, such as coal, cement, steel and electricity. Thus, improving the standards for clean production and developing circular economy from a life-cycle perspective in a sector's supply chain is important.

#### Adjust the Final Demand Structure

The adjustment of the final demand structure is very important for Yunnan's low-carbon development. Policy makers should focus on adjusting the export structure, the consumption structure of urban residents and the infrastructure investment direction.

Taking effective measures to reduce the exports of high-carbon raw materials is very important. China's central government had canceled export tax rebates and levied export tariffs for international exports of products with high resource consumption and high emissions. For interprovincial exports, there are no export tariffs, because the central government promotes free trade among all regions of the country. On this background, policies that subsidize the exports of low-carbon products from the service and agriculture industries and strengthen cooperation among trade partners are necessary. Considering that Yunnan exports a great deal of electricity to Guangdong, a compensatory mechanism should be formed to encourage Guangdong to provide renewable energy technology to Yunnan to reduce the carbon intensity of Yunnan's exports.

Optimizing the consumption structure for urban residents is essential. For example, the implementation of new established policies by the Chinese government, such as a ladder price for electricity, higher taxes on oil and a ban on disposable plastic bags, will encourage a low-carbon consumption structure in Yunnan. For urban transportation, it is imperative to increase investments in public transportation and to improve low-carbon transportation, such as walking and bicycling, to reduce the dominance of cars.

The direction of infrastructure investments will play a vital role in decreasing Yunnan's CO<sub>2</sub> emissions. For example, investments in mass transit or renewable energy production will benefit future low-carbon development. Thus, a low-carbon investment plan should be developed to guide long-term infrastructure investments.

## 4. Conclusions

In this study, a structural decomposition analysis-logarithmic mean Divisia index (SDA-LMDI) model was developed to find the drivers behind the CO<sub>2</sub> emission changes during 1997–2012 in Yunnan, a low-carbon pilot province in China. The potential relationship between economic growth and CO<sub>2</sub> emissions in a less-developed region was explored in order to promote the low-carbon economic development strategy.

As a less-developed region undergoing rapid development of industrialization and urbanization, the growth of per capita GDP driving by the export and capital investment increase was the primary driver of CO<sub>2</sub> emissions' growth in Yunnan. However, changes in the export and investment structure have become more important driving forces for CO<sub>2</sub> emissions' growth in Yunnan in recent years. Therefore, adjusting the economic structure to a low-carbon direction should have more attention paid to it. Vigorously developing hydropower and improving energy efficiency in energy-intensive sectors have become the backbone of CO<sub>2</sub> emissions' reduction. Thus, enhancing the application of clean energy and energy efficient technologies in production sectors can be essential measures to decrease the CO<sub>2</sub> emissions.

Maintaining economic growth and eliminating poverty are still important tasks for Yunnan. However, the pillar industries of Yunnan's economy are high-carbon product sectors depending more on imports from other regions, which are not conducive to the low-carbon development in Yunnan from a long-term perspective. Hence, economic structure adjustment and technological improvements should be encouraged in the future. Based on this analysis, the further policy recommendations from both production and final demand perspectives to mitigate CO<sub>2</sub> emissions in Yunnan are proposed. The most important measures should focus on promoting the development and application of clean energy and the formatting of consumption-based economic growth.

This study provided a theoretical basis for developing a low-carbon policy in Yunnan by revealing driving forces behind changes in local CO<sub>2</sub> emissions, which also offered guidance for a low-carbon development mode in other less-developed regions undergoing rapid development of industrialization and urbanization. However, key economic entities in Yunnan's CO<sub>2</sub> emissions, such as major cities and industrial parks, were not analyzed due to the lack of relevant input-output tables in China. The ecological network analysis procedures might be helpful in compiling the input-output tables for the economic entities; however, more studies are needed in the future. Furthermore, as for the SDA-LMDI model, some improvements should be made in the future. For example, the use of more than two matrices or logarithms in the model will complicate the calculations; thus, a strengthened programming of this model is needed in the future.

**Supplementary Materials:** The following are available online at [www.mdpi.com/1996-1073/9/1/23/s1](http://www.mdpi.com/1996-1073/9/1/23/s1).

**Acknowledgments:** We are grateful for the contributions of emeritus Prof. Robert B. Wenger from the University of Wisconsin-Green Bay, for his kind help in providing language and structural improvements to the manuscript. Thanks for the support provided by the Grant-Funded Projects of the China Clean Development Mechanism Fund (fund-key: 1213075) supervised by the National Development and Reform Commission, China. Additionally, we also want to thank the three anonymous reviewers for their valuable comments on this paper.

**Author Contributions:** Mingxiang Deng and Wei Li designed the framework of this research. Mingxiang Deng and Yan Hu collected the initial data and processed the data. Mingxiang Deng and Wei Li discussed the results and formed the policy recommendations and conclusions. All the authors wrote the paper.

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

## References

1. Friedlingstein, P.; Andrew, R.M.; Rogelj, J.; Peters, G.P.; Canadell, J.G.; Knutti, R.; Luderer, G.; Raupach, M.R.; Schaeffer, M.; van Vuuren, D.P.; *et al.* Persistent growth of CO<sub>2</sub> emissions and implications for reaching climate targets. *Nat. Geosci.* **2014**, *7*, 709–715. [CrossRef]
2. Qi, Y. *Annual Review of Low-Carbon Development in China (2013)*; Social Science Academic Press: Beijing, China, 2013. (In Chinese)
3. Hennig, T.; Wang, W.L.; Feng, Y.; Ou, X.K.; He, D.M. Review of Yunnan's hydropower development. Comparing small and large hydropower projects regarding their environmental implications and socio-economic consequences. *Renew. Sustain. Energy Rev.* **2013**, *27*, 585–595. [CrossRef]
4. Statistical Bureau of Yunnan Province (SBYP). *Yunnan Statistical Yearbook 1998–2013*; China Statistics Press: Beijing, China, 2013.
5. National Bureau of Statistics Survey Office in Yunnan (NBSSOY). *Yunnan Survey Yearbook 2014*; China Statistics Press: Beijing, China, 2014.
6. Guan, D.B.; Klasen, S.; Hubacek, K.; Feng, K.S.; Liu, Z.; He, K.B.; Geng, Y.; Zhang, Q. Determinants of stagnating carbon intensity in China. *Nat. Clim. Chang.* **2014**, *4*, 1017–1023. [CrossRef]
7. Tollefson, J. US-China climate deal raises hopes for Lima talks. *Nature* **2014**, *515*, 473–474. [CrossRef] [PubMed]
8. Yunnan Development and Reform Commission (YDRC). Low-carbon development plan in Yunnan (2011–2020). 2011. Available online: [http://www.yn.gov.cn/yn\\_zwlanmu/yn\\_srmzfgb/201108/t20110804\\_537.html](http://www.yn.gov.cn/yn_zwlanmu/yn_srmzfgb/201108/t20110804_537.html) (accessed on 13 November 2014). (In Chinese).
9. Minx, J.C.; Baiocchi, G.; Peters, G.P.; Weber, C.L.; Guan, D.B.; Hubacek, K. A “Carbonizing Dragon”: China's fast growing CO<sub>2</sub> emissions revisited. *Environ. Sci. Technol.* **2011**, *45*, 9144–9153. [CrossRef] [PubMed]

10. Wang, Y.F.; Zhao, H.Y.; Li, L.Y.; Liu, Z.; Liang, S. Carbon dioxide emission drivers for a typical metropolis using input-output structural decomposition analysis. *Energy Policy* **2013**, *58*, 312–318. [CrossRef]
11. Geng, Y.; Zhao, H.Y.; Liu, Z.; Xue, B.; Fujita, T.; Xi, F.M. Exploring driving factors of energy-related CO<sub>2</sub> emissions in Chinese provinces: A case of Liaoning. *Energy Policy* **2013**, *60*, 820–826. [CrossRef]
12. Liang, S.; Zhang, T.Z. What is driving CO<sub>2</sub> emissions in a typical manufacturing center of South China? The case of Jiangsu Province. *Energy Policy* **2011**, *39*, 7078–7083. [CrossRef]
13. Guan, D.B.; Barker, T. Low-carbon development in the least developed region: a case study of Guangyuan, Sichuan province, southwest China. *Nat. Hazards* **2012**, *62*, 243–254. [CrossRef]
14. Tang, X.L.; Zhang, Y.Y.; Yi, H.H.; Ma, J.Y.; Pu, L. Development a detailed inventory framework for estimating major pollutants emissions inventory for Yunnan Province, China. *Atmos. Environ.* **2012**, *57*, 116–125. [CrossRef]
15. Hoekstra, R.; van der Bergh, J. Comparing structural and index decomposition analysis. *Energy Econ.* **2003**, *25*, 39–64. [CrossRef]
16. Su, B.; Ang, B.W. Structural decomposition analysis applied to energy and emissions: Some methodological developments. *Energy Econ.* **2012**, *34*, 177–188. [CrossRef]
17. Chen, L.; Yang, Z.F.; Chen, B. Decomposition analysis of energy-related industrial CO<sub>2</sub> emissions in China. *Energies* **2013**, *6*, 2319–2337. [CrossRef]
18. Lu, J.C.; Fan, W.G.; Meng, M. Empirical research on China's carbon productivity decomposition model based on multi-dimensional factors. *Energies* **2015**, *8*, 3093–3117. [CrossRef]
19. Pan, L.Y.; Guo, Z.; Liu, P.; Ma, L.W.; Li, Z. Comparison and analysis of macro energy scenarios in China and a decomposition-based approach to quantifying the impacts of economic and social development. *Energies* **2013**, *6*, 3444–3465. [CrossRef]
20. Peters, G.P.; Weber, C.L.; Guan, D.B.; Hubacek, K. China's growing CO<sub>2</sub> emissions—A race between increasing consumption and efficiency gains. *Environ. Sci. Technol.* **2007**, *41*, 5939–5944. [CrossRef] [PubMed]
21. Leontief, W. *Input-Output Economics*; Oxford University Press: New York, NY, USA, 1986.
22. Guan, D.B.; Hubacek, K.; Weber, C.L.; Peters, G.P.; Reiner, D.M. The drivers of Chinese CO<sub>2</sub> emissions from 1980 to 2030. *Glob. Environ. Change* **2008**, *18*, 626–634. [CrossRef]
23. Tian, X.; Chang, M.; Tanikawa, H.; Shi, F.; Imura, H. Structural decomposition analysis of the carbonization process in Beijing: A regional explanation of rapid increasing carbon dioxide emission in China. *Energy Policy* **2013**, *53*, 279–286. [CrossRef]
24. Dietzenbacher, E.; Los, B. Structural decomposition techniques: sense and sensitivity. *Econ. Syst. Res.* **1998**, *10*, 307–324. [CrossRef]
25. Su, B.; Ang, B.W. Attribution of changes in the generalized Fisher index with application to embodied emission studies. *Energy* **2014**, *69*, 778–786. [CrossRef]
26. Su, B.; Ang, B.W. Multiplicative decomposition of aggregate carbon intensity change using input–output analysis. *Appl. Energy* **2015**, *154*, 13–20. [CrossRef]
27. De Boer, P. Additive structural decomposition analysis and index number theory: an empirical application of the Montgomery decomposition. *Econ. Syst. Res.* **2008**, *20*, 97–109. [CrossRef]
28. Chai, J.; Guo, J.E.; Wang, S.Y.; Lai, K.K. Why does energy intensity fluctuate in China? *Energy Policy* **2009**, *37*, 5717–5731. [CrossRef]
29. Wachsmann, U.; Wood, R.; Lenzen, M.; Schaeffer, R. Structural decomposition of energy use in Brazil from 1970 to 1996. *Appl. Energy* **2009**, *86*, 578–587. [CrossRef]
30. Wood, R. Structural decomposition analysis of Australia's greenhouse gas emissions. *Energy Policy* **2009**, *37*, 4943–4948. [CrossRef]
31. National Development and Reform Commission (NDRC). *China Greenhouse Gas Inventory Study 2005*; China Environmental Press: Beijing, China, 2014. (In Chinese).
32. Su, B.; Ang, B.W.; Low, M. Input-output analysis of CO<sub>2</sub> emissions embodied in trade and the driving forces: Processing and normal exports. *Ecol. Econ.* **2013**, *88*, 119–125. [CrossRef]
33. Su, B.; Ang, B.W. Input-output analysis of CO<sub>2</sub> emissions embodied in trade: Competitive versus non-competitive imports. *Energy Policy* **2013**, *56*, 83–87. [CrossRef]
34. Hubacek, K.; Feng, K.S.; Chen, B. Changing lifestyles towards a low carbon economy: an IPAT analysis for China. *Energies* **2012**, *5*, 22–31. [CrossRef]

35. Ang, B.W.; Liu, N. Negative-value problems of the logarithmic mean Divisia index decomposition approach. *Energy Policy* **2007**, *35*, 739–742. [CrossRef]
36. Davis, S.J.; Caldeira, K. Consumption-based accounting of CO<sub>2</sub> emissions. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 5687–5692. [CrossRef] [PubMed]
37. Peters, G.P. From production-based to consumption-based national emission inventories. *Ecol. Econ.* **2008**, *65*, 13–23. [CrossRef]
38. National Bureau of Statistics (NBS). *China Energy Statistical Yearbook 1998–2013*; China Statistics Press: Beijing, China, 2013.
39. Statistical Bureau of Yunnan Province (SBYP). *Yunnan Energy Statistical Yearbook 2000–2013*; Yunnan Science and Technology Press: Kunming, China, 2013.
40. Peters, G.P.; Weber, C.L.; Liu, J.R. *Construction of Chinese Energy and Emissions Inventory*; Norwegian University of Science and Technology: Trondheim, Norway, 2006.
41. Guan, D.B.; Liu, Z.; Geng, Y.; Lindner, S.; Hubacek, K. The gigatonne gap in China's carbon dioxide inventories. *Nat. Clim. Chang.* **2012**, *2*, 672–675. [CrossRef]
42. National Bureau of Statistics (NBS). Classification of national economic industries (GB/T 4754–2011). 2011. Available online: <http://www.stats.gov.cn/tjsj/tjbz/hyflbz/> (accessed on 13 November 2014). (In Chinese).
43. United Nations Department for Economic and Social Affairs Statistics Division (UNDESASD). *Hand Book of Input-Output Table Compilation and Analysis*; United Nations: New York, NY, USA, 1999.
44. Su, B.; Huang, H.C.; Ang, B.W.; Zhou, P. Input-output analysis of CO<sub>2</sub> emissions embodied in trade: The effects of sector aggregation. *Energy Econ.* **2010**, *32*, 166–175. [CrossRef]
45. Su, B.; Ang, B.W. Structural decomposition analysis applied to energy and emissions: aggregation issues. *Econ. Syst. Res.* **2012**, *24*, 299–317. [CrossRef]
46. Weber, C.L.; Peters, G.P.; Guan, D.B.; Hubacek, K. The contribution of Chinese exports to climate change. *Energy Policy*. **2008**, *36*, 3572–3577. [CrossRef]
47. People's Government of Yunnan Province (PGYP). The Eleventh Five Year Plan for economic and social development in Yunnan province. 2006. Available online: [http://xxgk.yn.gov.cn/bgt\\_Model1/newsview.aspx?id=130772](http://xxgk.yn.gov.cn/bgt_Model1/newsview.aspx?id=130772) (accessed on 13 November 2014). (In Chinese).
48. Yuan, C.Q.; Liu, S.F.; Xie, N.M. The impact on Chinese economic growth and energy consumption of the Global Financial Crisis: An input-output analysis. *Energy* **2010**, *35*, 1805–1812. [CrossRef]
49. Eng, I. Agglomeration and the local state: The tobacco economy of Yunnan, China. *Trans. Inst. Br. Geogr.* **1999**, *24*, 315–329. [CrossRef]
50. People's Government of Yunnan Province (PGYP). The Tenth Five Year Plan for economic and social development in Yunnan province. 2001. Available online: [http://www.bjpc.gov.cn/fzgh\\_1/guihua/10\\_5/gj\\_ws/200710/P020071024539269370799.pdf](http://www.bjpc.gov.cn/fzgh_1/guihua/10_5/gj_ws/200710/P020071024539269370799.pdf) (accessed on 13 November 2014). (In Chinese).
51. Wang, Y.; Zhu, Q.H.; Geng, Y. Trajectory and driving factors for GHG emissions in the Chinese cement industry. *J. Clean. Prod.* **2013**, *53*, 252–260. [CrossRef]



© 2016 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons by Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).