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Decomposition Analysis of Regional Electricity Consumption Drivers Considering Carbon Emission Constraints: A Comparison of Guangdong and Yunnan Provinces in China

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Abstract: Electricity consumption is closely linked to economic growth, social development, and carbon emissions. In order to fill the gap of previous studies on the decomposition of electricity consumption drivers that have not adequately considered carbon emission constraint, this study constructs the Kaya extended model of electricity consumption and analyzes the effects of drivers in industrial and residential sectors using the Logarithmic Mean Divisia Index (LMDI) method, and empirically explores the temporal and spatial differences in electricity consumption. Results show that: (1) During 2005–2021, the total final electricity consumption growth in Guangdong was much higher than that in Yunnan, but the average annual growth rate in Guangdong was lower, and the largest growth in both provinces was in the industrial sector. (2) The labor productivity level effect is the primary driver that increases total final electricity consumption (Guangdong: 78.5%, Yunnan: 87.1%), and the industrial carbon emission intensity effect is the primary driver that decreases total final electricity consumption (Guangdong: −75.3%, Yunnan: −72.3%). (3) The year-to-year effect of each driver by subsector is overall positively correlated with the year-to-year change in the corresponding driver, and declining carbon emission intensity is a major factor in reducing electricity consumption. (4) The difference in each effect between Guangdong and Yunnan is mainly determined by a change in the corresponding driver and subsectoral electricity consumption. Policy implications are put forward to promote energy conservation and the realization of the carbon neutrality goal.

Keywords: regional electricity consumption; LMDI; decomposition analysis; carbon emissions constraint; temporal and spatial differences

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1. Introduction

In order to achieve the purpose and long-term goals of the Paris Agreement, much more global mitigation and adaptation action and support are needed now on all fronts; otherwise, the window of opportunity for creating a livable and sustainable future for all will rapidly close [1]. Low GHG emissions development is an important way to achieve sustainable development, contributing to addressing the climate crisis. Electricity consumption is closely related to socio-economic development and improvement in living standards [2,3]. As is well known, China's dual carbon goals are achieving carbon peaking by 2030 and carbon neutrality by 2060 [4]. However, fossil fuel consumption is the main source of carbon emissions in China's energy sector, of which coal consumption accounts for the highest proportion, and coal electricity accounts for the highest proportion of total power generation at present [5]. Hence, the carbon emission reduction task of China's energy sector is arduous.

Different regions face varying pressures on electricity supply and sale, security risk, and carbon emissions reduction [6]. Therefore, it is important to understand the differences in regional electricity consumption in relation to economic growth, social development, and carbon emissions between different regions. This study takes Guangdong Province and Yunnan Province in China as examples. Guangdong is one of the most developed provinces in China, and in 2021, its GDP, permanent population, and total energy consumption were the highest in the country, accounting for 10.82%, 8.98%, and 7.00% of the country's total, respectively [7]. Guangdong's energy resources are relatively scarce, and electricity consumption is dominated by thermal power, with renewable energy generation and electricity imported from other provinces also accounting for a certain percentage. While Yunnan's relative lag in economic development, and in 2021, its GDP, permanent population, and total energy consumption accounted for 2.36%, 3.32%, and 2.55% of the country's total, respectively [8]. Yunnan is relatively rich in energy resources, and its renewable energy power generation accounts for 87.93% of total power generation in 2021, with hydropower accounting for 80.32% of that total. As can be seen, there are significant differences between Guangdong and Yunnan in terms of socio-economic development, population, energy resource endowment, energy and electricity consumption, etc. Therefore, exploring the differences in the drivers of electricity consumption is an important research topic, which can clarify the different impacts of multiple drivers on electricity consumption in these two provinces and provide locally adapted strategies for economic development, energy conservation, and carbon emission reduction, as well as provide theoretical and methodological references and empirical evidence for other provinces, which will help China's dual-carbon goals to be realized.

2. Literature Review

Decomposition analysis has been widely used in the study of energy–economic–environmental systems. Index decomposition analysis (IDA) [9], structural decomposition analysis (SDA) [10], and production–theoretical decomposition analysis (PDA) [11] are the three types of decomposition analysis methods that have been applied more commonly. Because of the simplicity and applicability of IDA, it is suitable for analyzing the effects of multiple factors based on time series data, especially for the study of issues related to energy consumption and carbon emissions. The Logarithmic Mean Divisia Index (LMDI) method is one of the IDA methods, which is more advantageous due to no residual terms, ease of dealing with zero value, and the fact that addition and product decomposition forms can be converted to each other [12–14]. In addition, the LMDI method effectively avoids the pseudo-regression problem, can maintain a high degree of consistency among the various decomposition indicators [15], and makes it easy to compare the degree of contribution of different drivers [16]. Therefore, the LMDI method is frequently adopted to analyze the drivers of electricity consumption.

Many previous studies decomposed and analyzed the drivers of carbon emissions [17–19], water resources [20–22], and energy consumption [23–25] using the LMDI method. Scholars conducted extensive analysis and discussion from the perspectives of a country, region, sector, and so on and tapped many factors affecting electricity consumption. Electricity share, energy consumption intensity, economic structure, economic activity, and population are often considered to be influencing factors on electricity consumption in a country or region [26–28]. Praene et al. [29] obtained three different effects related to the number of consumers that influenced the variation in electricity consumption: activity effect, structural effect, and intensity effect. Fang et al. [30] decomposed China's electricity consumption into four factors: economic scale, economic geographical structure, electricity consumption intensity, and industrial electricity consumption structure. Fang et al. [31] explored the impact of eight drivers on total electricity consumption in China's Key Economic Regions, of which three quantitative factors (GDP scale, capital stock, and population) and five relative factors (output electricity consumption intensity, investment electricity consumption intensity, per capita electricity consumption, per capita output, and proportion of investment in GDP).

From a sectoral perspective, the existing literature considers different drivers. Park et al. [32] assessed how production, structure, fuel efficiency, and electrification affected the increase in electricity consumption in 11 industrial sectors in Korea. Shi et al. [33] estimated the effects of advanced technology, structural effects, income effects, and population effects on the production power consumption changes of the Yangtze River Economic Zone. Huang [34] factorized residential electricity consumption in Taiwan, considering climate, household, floor area, ownership, efficiency, and usage effects. Meng et al. [35] studied the growth of residential electricity consumption in China and obtained three factors: living standards, population, and provincial demographic structure. Zhang et al. [36] decomposed the change in total electricity consumption in the Yangtze River Delta region of China into industry effect (economic growth, industrial structure, and industry electricity consumption intensity) and domestic effect (population scale, urbanization, and domestic electricity consumption intensity).

The existing literature has analyzed the drivers of electricity consumption by geographic region or sector, with the drivers being categorized as economic, demographic, and social factors. To the best of our knowledge, almost no literature considers carbon emission constraints, such as carbon emission intensity, which motivates us to conduct research to fill the research gap. There are significant differences in the mechanisms influencing industrial and residential electricity consumption, but there is less literature on the division of total regional electricity consumption into industrial and residential electricity consumption to study their evolutionary driving mechanisms separately [36]. Based on the research deficiencies mentioned above, this study conducts a decomposition analysis of the drivers of electricity consumption considering carbon emission constraints in two typical regions to formulate more targeted energy-saving and emission-reduction policies in accordance with the local conditions.

The three main contributions of this study are as follows: (1) This study introduces carbon emission-related factors, such as carbon emission intensity and energy consumption per unit of carbon emission, into the LMDI decomposition model of electricity consumption in order to explore the evolution of electricity consumption, which fills the gap in the research field. (2) This study constructs the Kaya extended models of electricity consumption in industrial and residential sectors, respectively, and analyzes the impact of each driver on electricity consumption in each subsector using the LMDI method. It is an important addition to studies related to electricity consumption. (3) This study takes Guangdong and Yunnan, which have typical characteristics, as the research areas and empirically explores the temporal and spatial differences in electricity consumption so as to provide locally adapted strategies for economic development, energy conservation, and carbon emission reduction, as well as provide theoretical and methodological references and empirical evidence for other provinces.

3. Methods and Data Sources

3.1. Decomposition Modeling of Electricity Consumption Drivers

The basic expression of Kaya Identity [37] is as follows:

$$\mathrm{CO_2} = \frac{\mathrm{CO_2}}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \tag{1}$$

It was initially used to explore the relationship between anthropogenic CO_2 emissions and factors such as energy consumption, economic development, and population. However, as research in the field of energy-economy-environment has developed in-depth, a variety of Kaya extended models applicable to different research objects have been constructed and applied more widely. In this section, based on the basic principle of Kaya Identity and taking into account the carbon emissions factor, we construct the Kaya extended model of electricity consumption and analyze the decomposition of the drivers of electricity consumption in the industrial sector and residential sector using the LMDI decomposition method, respectively.

3.1.1. LMDI Decomposition Model of Electricity Consumption in Industrial Sector

The Kaya extended model of electricity consumption in the industrial sector is constructed as follows:

$$El_1 = \sum_i \left(\frac{El_i}{FE_i} \times \frac{FE_i}{FCE_i} \times \frac{FCE_i}{GDP_i} \times \frac{GDP_i}{GDP} \times \frac{GDP}{PE} \times PE \right) = \sum_i (a_i \times b_i \times c_i \times d_i \times e_i \times f_i) \quad (2)$$

where EL_1 denotes the final electricity consumption in the industrial sector; i denotes the type of industrial subsector, including six subsectors, namely, agriculture (abbreviation for agriculture, forestry, animal husbandry, fishery and water conservancy), industry, construction, transportation (abbreviation for transportation, warehousing, and postal services), commercial services (abbreviation for wholesale, retail, lodging, and catering). and other services; EL_i denotes the final electricity consumption in industrial subsector i, excluding grid transmission loss, and unless otherwise specified, electricity consumption in this study refers to final electricity consumption. FE_i denotes the final energy consumption in industrial subsector i; FCE_i denotes the final energy consumption related to carbon emissions in industrial subsector i; GDP_i denotes the value added in industrial subsector i; GDP denotes the Gross Domestic Product or Gross Regional Product, i.e., the sum of GDP of all industrial subsectors; and PE denotes the number of employed people at the end of the year.

Then, let:

$$a_i = \frac{El_i}{FE_i},\ b_i = \frac{FE_i}{FCE_i},\ c_i = \frac{FCE_i}{GDP_i},\ d_i = \frac{GDP_i}{GDP},\ e_i = \frac{GDP}{PE},\ f_i = PE \quad (3)$$

where a_i denotes the share of electricity in final energy consumption in industrial subsector i, representing the electrification level; b_i denotes the average final energy consumption per unit of carbon emissions (or called energy consumption intensity in this study) in industrial subsector i; c_i denotes the carbon emissions intensity in industrial subsector i; d_i denotes the ratio of value-added to GDP in industrial subsector i, representing industrial structure; e_i denotes the average output per employed person, representing the labor productivity level, which also reflects technological progress; and f_i denotes the employed population size.

The electricity consumption in a region will change year by year with the changes of various related influencing factors. Set the baseline year as T_0, the final electricity consumption of the industrial sector in the baseline year as El_1^0, and the final electricity consumption of the industrial sector in year n as El_1^n, then the change of the final electricity consumption of the industrial sector from the baseline year to year n is $\Delta El_1^{0\to n}$. $\Delta El_1^{0\to n}$ is calculated as follows:

$$\Delta El_1^{0\to n} = El_1^n - El_1^0 = \sum_i (a_i^n \times b_i^n \times c_i^n \times d_i^n \times e_i^n \times f_i^n) - \sum_i \left(a_i^0 \times b_i^0 \times c_i^0 \times d_i^0 \times e_i^0 \times f_i^0 \right) \quad (4)$$

There are eight forms of LMDI decomposition models based on different weights, decomposition methods, and indicators [38]. In order to facilitate the analysis and discussion of the results at the subsector level, this study uses the additive form of the LMDI decomposition method to decompose the change in the final electricity consumption, then let:

$$\Delta El_1^{0\to n} = \Delta El_a^{0\to n} + \Delta El_b^{n0\to n} + \Delta El_c^{0\to n} + \Delta El_d^{0\to n} + \Delta El_e^{0\to n} + \Delta El_f^{0\to n} \quad (5)$$

$$\Delta El_a^{0\to n} = \sum_i \frac{El_i^n - El_i^0}{lnEl_i^n - lnEl_i^0} \times ln\frac{a_i^n}{a_i^0} \quad (6)$$

$$\Delta El_b^{0\to n} = \sum_i \frac{El_i^n - El_i^0}{lnEl_i^n - lnEl_i^0} \times ln\frac{b_i^n}{b_i^0} \quad (7)$$

$$\Delta El_c^{0\rightarrow n} = \sum_i \frac{El_i^n - El_i^0}{lnEl_i^n - lnEl_i^0} \times ln\frac{c_i^n}{c_i^0} \quad (8)$$

$$\Delta El_d^{0\rightarrow n} = \sum_i \frac{El_i^n - El_i^0}{lnEl_i^n - lnEl_i^0} \times ln\frac{d_i^n}{d_i^0} \quad (9)$$

$$\Delta El_e^{0\rightarrow n} = \sum_i \frac{El_i^n - El_i^0}{lnEl_i^n - lnEl_i^0} \times ln\frac{e_i^n}{e_i^0} \quad (10)$$

$$\Delta El_f^{0\rightarrow n} = \sum_i \frac{El_i^n - El_i^0}{lnEl_i^n - lnEl_i^0} \times ln\frac{f_i^n}{f_i^0} \quad (11)$$

where $\Delta El_a^{0\rightarrow n}$ denotes industrial electrification level effect (ELE_1); $\Delta El_b^{0\rightarrow n}$ denotes industrial energy consumption intensity effect (CEE_1); $\Delta El_c^{0\rightarrow n}$ denotes industrial carbon emission intensity effect (CIE_1); $\Delta El_d^{0\rightarrow n}$ denotes industrial structure effect (ISE_1); $\Delta El_e^{0\rightarrow n}$ denotes labor productivity level effect (LPE_1); and $\Delta El_f^{0\rightarrow n}$ denotes employed population size effect (EPE_1). The above effect parameters represent cumulative effects from the baseline year to year n.

$\Delta El_1^{n-1\rightarrow n}$, which denotes the year-to-year effect in the industrial sector from year $n-1$ to year n, is calculated as follows:

$$\Delta El_1^{n-1\rightarrow n} = \Delta El_1^{0\rightarrow n} - \Delta El_1^{0\rightarrow n-1} \quad (12)$$

3.1.2. LMDI Decomposition Model of Electricity Consumption in Residential Sector

The Kaya extended model of electricity consumption in the residential sector is constructed as follows:

$$El_2 = \sum_j \left(\frac{El_j}{FE_j} \times \frac{FE_j}{FCE_j} \times \frac{FCE_j}{TI_j} \times \frac{TI_j}{P_j} \times \frac{P_j}{P} \times P \right) = \sum_j \left(h_j \times k_j \times l_j \times m_j \times o_j \times p_j \right) \quad (13)$$

where EL_2 denotes the final electricity consumption in the residential sector; j denotes the type of residential subsector, including urban residential subsector and rural residential subsector; EL_j denotes the final electricity consumption in residential subsector j. FE_j denotes the final energy consumption in residential subsector j; FCE_j denotes the final energy consumption related to carbon emissions in residential subsector j; TI_j denotes the total income of the residents in residential subsector j; P_j denotes permanent population at the end of the year in residential subsector j; and P denotes the total permanent population at the end of the year.

Then, let:

$$h_j = \frac{El_j}{FE_j},\ k_j = \frac{FE_j}{FCE_j},\ l_j = \frac{FCE_j}{TI_j}, m_j = \frac{TI_j}{P_j},\ o_j = \frac{P_j}{P}, p_j = P \quad (14)$$

where h_j denotes the share of electricity in final energy consumption in residential subsector j, representing the electrification level; k_j denotes residential energy consumption intensity related carbon emissions in residential subsector j; l_j denotes the ratio of energy consumption related carbon emissions to the total income of residents in residential subsector j; m_j denotes the income per capita in residential subsector j; o_j denotes the urban–rural population structure; and p_j denotes the total permanent population size at the end of the year.

Set the final electricity consumption of the residential sector in the baseline year as El_2^0, and the final electricity consumption of the residential sector in year n as El_2^n, then the change of the final electricity consumption in the residential sector from the baseline year to year n is $\Delta El_2^{0\rightarrow n}$. $\Delta El_2^{0\rightarrow n}$ is calculated as follows:

$$\Delta El_2^{0\to n}=El_2^n-El_2^0=\sum_j\left(h_j^n\times k_j^n\times l_j^n\times m_j^n\times o_j^n\times p_j^n\right)-\sum_j\left(h_j^0\times k_j^0\times l_j^0\times m_j^0\times o_j^0\times p_j^0\right) \quad (15)$$

then, let:

$$\Delta El_2^{0\to n}=\Delta El_h^{0\to n}+\Delta El_k^{0\to n}+\Delta El_l^{0\to n}+\Delta El_m^{0\to n}+\Delta El_o^{0\to n}+\Delta El_p^{0\to n} \quad (16)$$

$$\Delta El_h^{0\to n}=\sum_j\frac{El_j^n-El_j^0}{lnEl_j^n-lnEl_j^0}ln\frac{h^n}{h^0} \quad (17)$$

$$\Delta El_k^{0\to n}=\sum_j\frac{El_j^n-El_j^0}{lnEl_j^n-lnEl_j^0}ln\frac{k^n}{k^0} \quad (18)$$

$$\Delta El_l^{0\to n}=\sum_j\frac{El_j^n-El_j^0}{lnEl_j^n-lnEl_j^0}ln\frac{l^n}{l^0} \quad (19)$$

$$\Delta El_m^{0\to n}=\sum_j\frac{El_j^n-El_j^0}{lnEl_j^n-lnEl_j^0}ln\frac{m^n}{m^0} \quad (20)$$

$$\Delta El_o^{0\to n}=\sum_j\frac{El_j^n-El_j^0}{lnEl_j^n-lnEl_j^0}ln\frac{o^n}{o^0} \quad (21)$$

$$\Delta El_p^{0\to n}=\sum_j\frac{El_j^n-El_j^0}{lnEl_j^n-lnEl_j^0}ln\frac{p^n}{p^0} \quad (22)$$

where $\Delta El_h^{0\to n}$ denotes residential electrification level effect (ELE_2); $\Delta El_k^{0\to n}$ denotes residential energy consumption intensity effect (CEE_2); $\Delta El_l^{0\to n}$ denotes residential carbon emission intensity effect (CIE_2); $\Delta El_m^{0\to n}$ denotes residential income per capita effect (RIE_2); $\Delta El_o^{0\to n}$ denotes urban–rural population structure effect (UPE_2); And $\Delta El_p^{0\to n}$ denotes permanent population size effect (PSE_2). All of the above effect parameters represent cumulative effects from the baseline year to year n.

$\Delta El_2^{n-1\to n}$, which denotes the year-to-year effect in the residential sector from year $n-1$ to year n, is calculated as follows:

$$\Delta El_2^{n-1\to n}=\Delta El_2^{0\to n}-\Delta El_2^{0\to n-1} \quad (23)$$

See Table 1 for abbreviated names of effects.

Table 1. Abbreviated names of effects.

Abbreviated Name	Effect	Abbreviated Name	Effect
ELE_1	industrial electrification level effect	ELE_2	residential electrification level effect
CEE_1	industrial energy consumption intensity effect	CEE_2	residential energy consumption intensity effect
CIE_1	industrial carbon emissions intensity effect	CIE_2	residential carbon emissions intensity effect
ISE_1	industrial structure effect	RIE_2	residential income per capita effect
LPE_1	labor productivity level effect	UPE_2	urban–rural population structure effect
EPE_1	employed population size effect	PSE_2	permanent population size effect
TEC_1	cumulative effect in the industrial sector	TEC_2	cumulative effect in the residential sector
YEC_1	year-to-year effect in the industrial sector	YEC_2	year-to-year effect in the residential sector

3.2. Data Sources

Guangdong Province and Yunnan Province are used as the study area for the empirical study, and the study period is 2005–2021, with 2005 as the baseline year. The major data is extracted from China Energy Statistical Yearbook (2006–2022) [39], Guangdong Statistical Yearbook (2006–2022) [7], and Yunnan Statistical Yearbook (2006–2022) [8]. Energy consumption data by sector and by energy type are taken from the energy balance sheets of the two provinces in the China Energy Statistical Yearbook. Electricity is converted to standard coal by equivalent value (10^4 tons of standard coal = 1.229 × 10^4 kWh). Final energy consumption-related carbon emissions data (Tables A1 and A2) are calculated with reference to the carbon emission factors in [40]. The socio-economic data, such as GDP, residents' incomes, and the permanent population and employed population at the end of the year, are taken from the Guangdong Statistical Yearbook and the Yunnan Statistical Yearbook, respectively. The current price GDP from 2006 to 2021 is converted at constant 2005 prices to eliminate the influence of price change factors.

4. Results and Discussion

4.1. Historical Trends in Electricity Consumption

As shown in Figure 1, the total final electricity consumption and the electricity consumption by subsector in Guangdong and Yunnan showed growing trends from 2005 to 2021. The total final electricity consumption in Guangdong and Yunnan increased from 2543 × 10^8 kWh and 506 × 10^8 kWh in 2005 to 7624 × 10^8 kWh and 2016 × 10^8 kWh in 2021, with an average annual growth rate of 7.1% and 9.0%, respectively. The total final energy consumption in Guangdong and Yunnan increased from 10,315 × 10^4 tce and 4247 × 10^4 tce in 2005 to 20,100 × 10^4 tce and 8572 × 10^4 tce in 2021, with an average annual growth rate of 4.3% and 4.5%, respectively. Therefore, in these two provinces, the electrification level increased from 26.4% and 12.6% in 2005 to 38.6% and 25.0% in 2021, respectively. Although the total final electricity or energy consumption in Yunnan was much lower than that in Guangdong, the growth rate was higher than that in Guangdong.

From a sectoral perspective, the industrial sector accounted for a major share (more than 82%) of total final electricity consumption relative to the residential sector both in Guangdong and Yunnan from 2005 to 2021. From a subsector perspective, the industry accounted for a major share (more than 57%) of total final electricity consumption, but the share went down slowly from 2005 to 2021. The industry electricity consumption in Guangdong and Yunnan increased from 1717 × 10^8 kWh and 374 × 10^8 kWh in 2005 to 4391 × 10^8 kWh and 1381 × 10^8 kWh in 2021, with an average annual growth rate of 6.0% and 8.5%, respectively. It indicates that growth in industry electricity consumption is the main source of growth in total final electricity consumption. Of course, other subsectors also contributed to the growth in electricity consumption.

4.2. Cumulative Effects of Drivers

The cumulative effects of each driver on changes in total final electricity consumption are listed in Tables 2 and 3**.** From 2005 to 2021, the electricity consumption of industrial and residential sectors in Guangdong increased by 4093 × 10^8 kWh (TEC_1) and 989 × 10^8 kWh (TEC_2), or 1.85 times and 3.01 times, respectively, while in Yunnan increased by 1309 × 10^8 kWh (TEC_1) and 202 × 10^8 kWh (TEC_2), or 3.03 times and 2.74 times, respectively. It indicates that the industrial sector dominated the growth in electricity consumption. The result is similar to that of Lv et al. [2], who explored the influencing factors of electricity consumption in China's Yangtze River Delta region. In addition, although the growth rate of electricity consumption in Yunnan's industrial sector is much higher than that in Guangdong, the amount of growth is much lower. The reason is that in the base year of 2005, Guangdong's industrial electricity consumption was 2214 × 10^8 kWh, while Yunnan's was 432 × 10^8 kWh, with a significant gap between the two provinces.

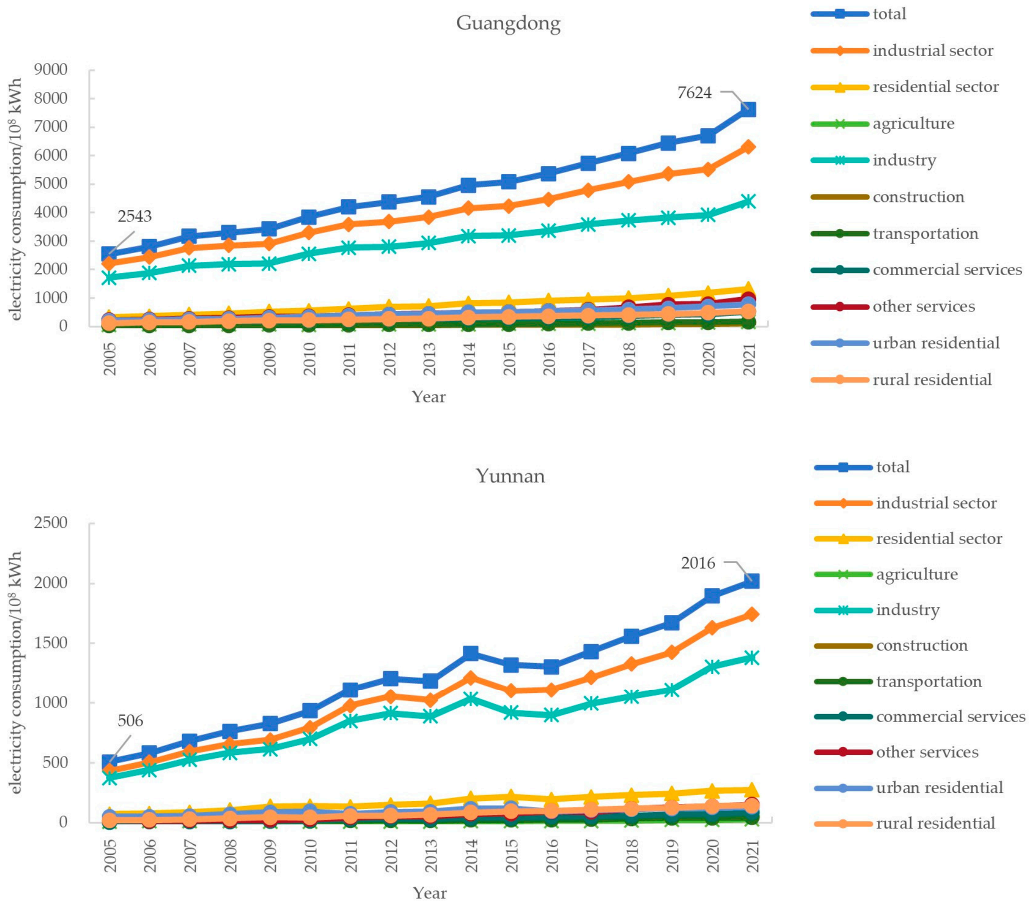

Figure 1. Trends of electricity consumption in Guangdong and Yunnan from 2005 to 2021.

Table 2. Cumulative effects of each driver in the industrial sector.

Province	Year	ELE_1	CEE_1	CIE_1	ISE_1	LPE_1	EPE_1	TEC_1
Guangdong	2005–2010	−184	213	−673	117	1099	506	1077
	2005–2015	372	532	−2106	101	2282	833	2014
	2005–2020	798	942	−3067	−14	3431	1218	3308
	2005–2021	1144	1442	−3828	14	3988	1333	4093
Yunnan	2005–2010	162	28	−225	65	256	75	360
	2005–2015	333	100	−617	86	671	98	670
	2005–2020	507	196	−921	103	1193	117	1196
	2005–2021	615	248	−1092	112	1315	111	1309

Note: The unit is 10^8 kWh.

Table 3. Cumulative effects of each driver in the residential sector.

Province	Year	ELE_2	CEE_2	CIE_2	RIE_2	UPE_2	PSE_2	TEC_2
Guangdong	2005–2010	75	34	−153	214	−1.4	55	223
	2005–2015	103	50	−267	508	−8.1	131	517
	2005–2020	177	81	−466	875	−26	211	851
	2005–2021	265	147	−623	1002	−31	229	989
Yunnan	2005–2010	29	4	−46	66	9.5	3.4	66
	2005–2015	74	20	−143	166	21	6.1	144
	2005–2020	95	15	−193	244	24	8.7	192
	2005–2021	98	17	−208	263	25	7.8	202

Note: The unit is 10^8 kWh.

Both in Guangdong and Yunnan, LPE_1, CEE_1, EPE_1, and ELE_1 show a positive growth trend during the 2005–2021 period. As shown in Figures 2 and 3, LPE_1 gave the largest positive contribution to the increase in industrial electricity consumption, with 3988×10^8 kWh (contribution rate of 78.5%, the same as below) in Guangdong and 1315×10^8 kWh (87.1%) in Yunnan. The finding is similar to that of Fang et al. [31], who analyzed the impact of the drivers on total electricity consumption in China's Key Economic Regions. In contrast, CIE_1 gave the largest negative contribution to the increase in industrial electricity consumption, with -3828×10^8 kWh (−75.3%) in Guangdong and -1092×10^8 kWh (−72.3%) in Yunnan. ISE_1 in Guangdong shows an increasing trend during 2005–2011 and a decreasing trend during 2011–2020, then a slight increase during 2020–2021, while ISE_1 in Yunnan shows an increasing trend during 2005–2021. It reflects the differences in the industrial structure adjustment between Guangdong and Yunnan. During the period of 2005–2021, RIE_2, ELE_2, CEE_2, and PSE_2 had an overall increase effect on residential electricity consumption, respectively, of which RIE_2 gave the largest positive contribution to the increase in residential electricity consumption, with 1002×10^8 kWh (19.7%) in Guangdong and 263×10^8 kWh (17.4%) in Yunnan. In contrast, CIE_2 contributed the largest negative to the increase in residential electricity consumption, with -623×10^8 kWh (−12.3%) in Guangdong and -208×10^8 kWh (−13.8%) in Yunnan. It is worth noting that UPE_2 had a negative contribution of -30.7×10^8 kWh (−0.6%) in Guangdong and a positive contribution of 24.7×10^8 kWh (1.6%) in Yunnan. It reflects the differences in the changes in urban–rural population structure between these two provinces. Permanent population size is a factor influencing the increase in electricity consumption, although its impact is weak. This result is consistent with Zhang et al. [36].

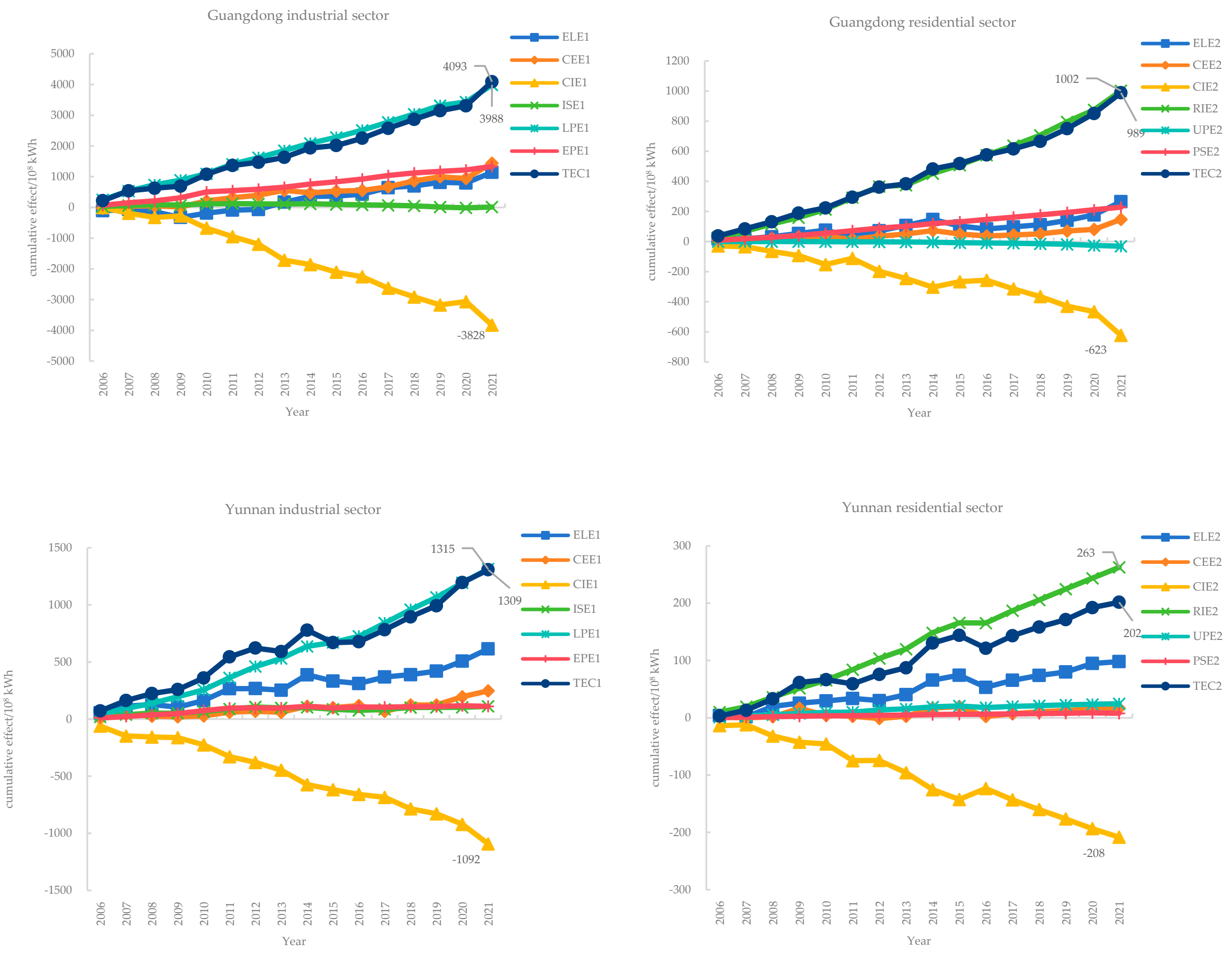

Figure 2. Cumulative effects of each driver on changes in final electricity consumption from 2005 to 2021.

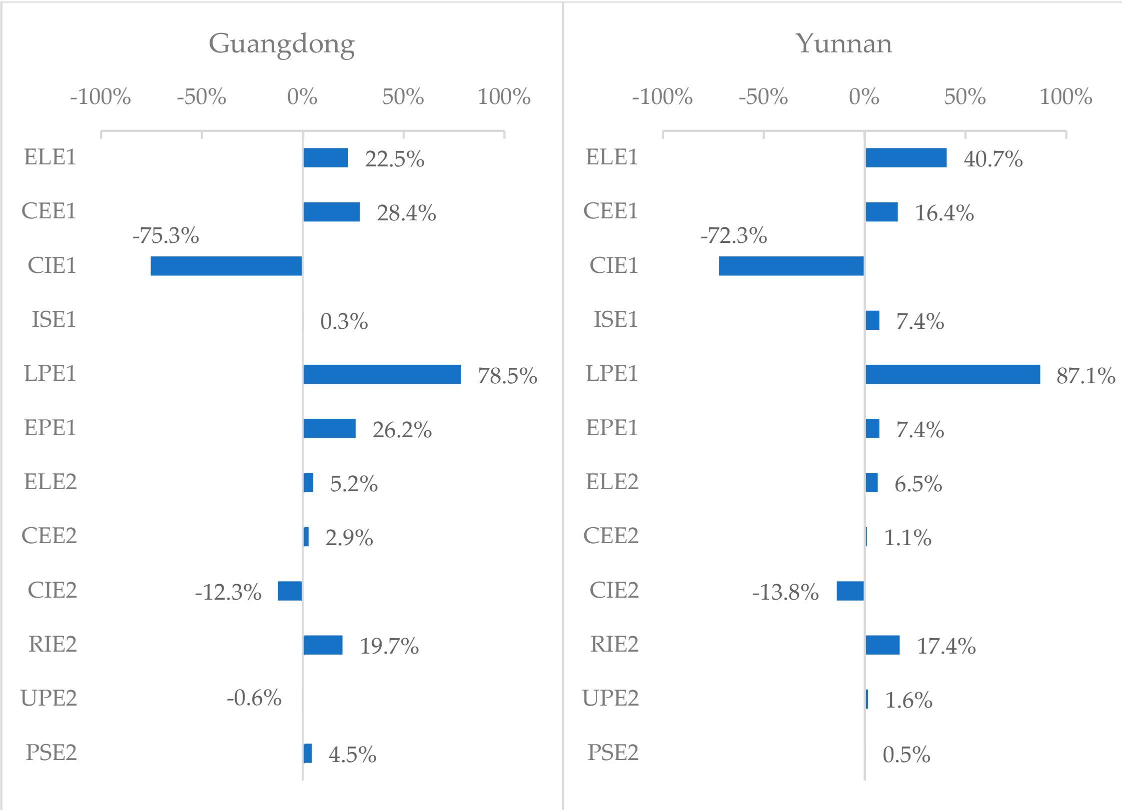

Figure 3. Cumulative contribution rates of drivers to changes in total final electricity consumption during the period of 2005–2021.

4.3. Year-to-Year Effects of Drivers

The year-to-year effects of each driver on changes in total final electricity consumption are listed in Tables A3 and A4. As shown in Figure 4, during the period of 2005–2021, the year-to-year effects of each driver fluctuated up and down both in Guangdong and Yunnan. The maximum value of the year-to-year effect in the industrial sector (YEC_1) was 784×10^8 kWh in 2020–2021 (Guangdong) and 203×10^8 kWh in 2019–2020 (Yunnan), respectively. The year-to-year LPE_1 in Guangdong and Yunnan were all positive, with the maximum value of 557×10^8 kWh in 2020–2021 (Guangdong) and 127×10^8 kWh in 2019–2020 (Yunnan), respectively. The year-to-year CIE_1 were all negative values in Yunnan, with the largest negative contribution of -171×10^8 kWh in 2020–2021. In comparison, the year-to-year CIE_1 were mostly negative values in Guangdong, with the largest negative contribution of -762×10^8 kWh in 2020–2021. The year-to-year effects of other drivers in the industrial sector were positive or negative in different years in these two provinces.

During the period of 2005–2021, the maximum value of year-to-year effect in the residential sector (YEC_2) was 138×10^8 kWh in 2020–2021 (Guangdong) and 43×10^8 kWh in 2013–2014 (Yunnan), respectively. The year-to-year RIE_2 were all positive, with the maximum value of 127×10^8 kWh in 2019–2020 (Guangdong) and 28.7×10^8 kWh in 2013–2014 (Yunnan), respectively. The year-to-year PSE_2 were all positive in Guangdong but mostly positive values, with two negative values in Yunnan (in 2015–2016 and in 2020–2021). The year-to-year CIE_2 was mostly negative in these two provinces, with the largest negative contribution of -157×10^8 kWh in 2020–2021(Guangdong) and -29.7×10^8 kWh in 2013–2014(Yunnan), respectively. The year-to-year effects of other drivers in the residential sector are positive or negative in different years in these two provinces.

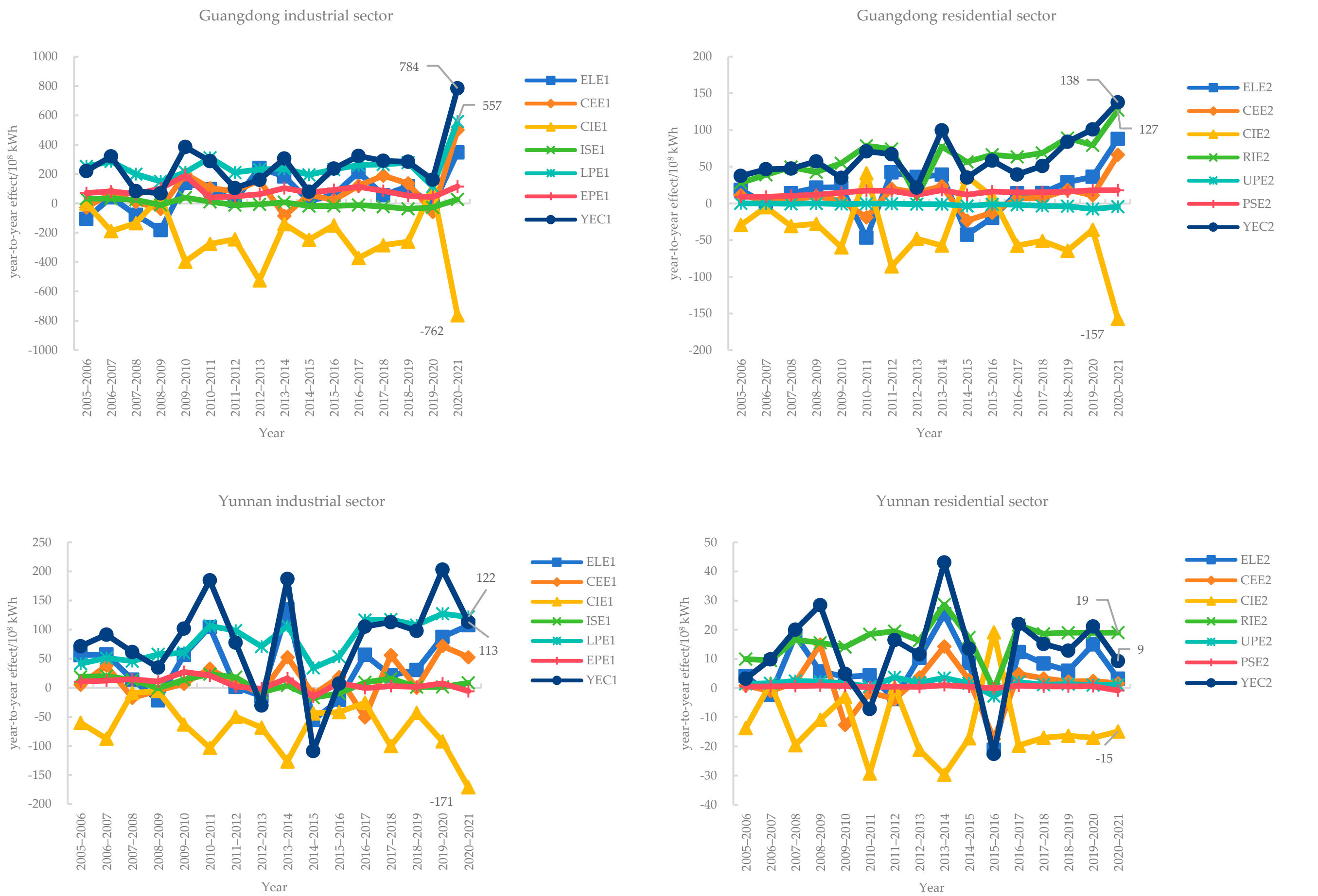

Figure 4. Year-to-year effects of each driver on changes in final electricity consumption from 2005 to 2021.

4.4. Decomposition Analysis of Drivers by Subsector

In order to explore the impact of each driver on electricity consumption, a detailed description and decomposition analysis of drivers by subsector is given as follows.

4.4.1. Relationship between Driver Changes and Corresponding Effects

Scatterplots are obtained based on the year-to-year changes in each driver and the corresponding year-to-year effects. It is found that each of the year-to-year effects by subsector is overall positively correlated with the year-to-year change in corresponding drivers both in Guangdong and Yunnan from 2005 to 2021. Consequently, the increase in one driver promotes electricity consumption, and the decrease in one driver inhibits electricity consumption. Figure 5 presents scatterplots for the four drivers: electrification level, carbon emission intensity, labor productivity level, and residential income per capita.

4.4.2. Electrification Level Effect

Table 4 lists the cumulative effects of each driver by subsector from 2005 to 2021. The top three subsectors in terms of cumulative electrification level effect were industry (914×10^8 kWh, 64.9%), urban residential (174×10^8 kWh, 12.3%), transportation (93×10^8 kWh, 6.6%) in Guangdong, and industry (508×10^8 kWh, 71.3%), rural residential (88×10^8 kWh, 12.3%), and other services (37×10^8 kWh, 5.3%) in Yunnan. As shown in Figure 6, the trends of electrification levels fluctuated upwards in both Guangdong and Yunnan during 2005–2021. The cumulative electrification level effect increased with increasing electrification level and decreased with decreasing electrification level. The overall electrification level in Guangdong increased from 26.4% to 38.6%, while Yunnan increased from 12.6% to 25.0%. There is a large gap in the overall electrification level, but the electrification level varies in different subsectors in the two provinces. Compared to Guangdong, there is more room for improvement in electrification levels in all subsectors except the construction and urban residential subsectors. The electrification level of transportation in both provinces is low, which also means that there is great potential for growth in electricity consumption.

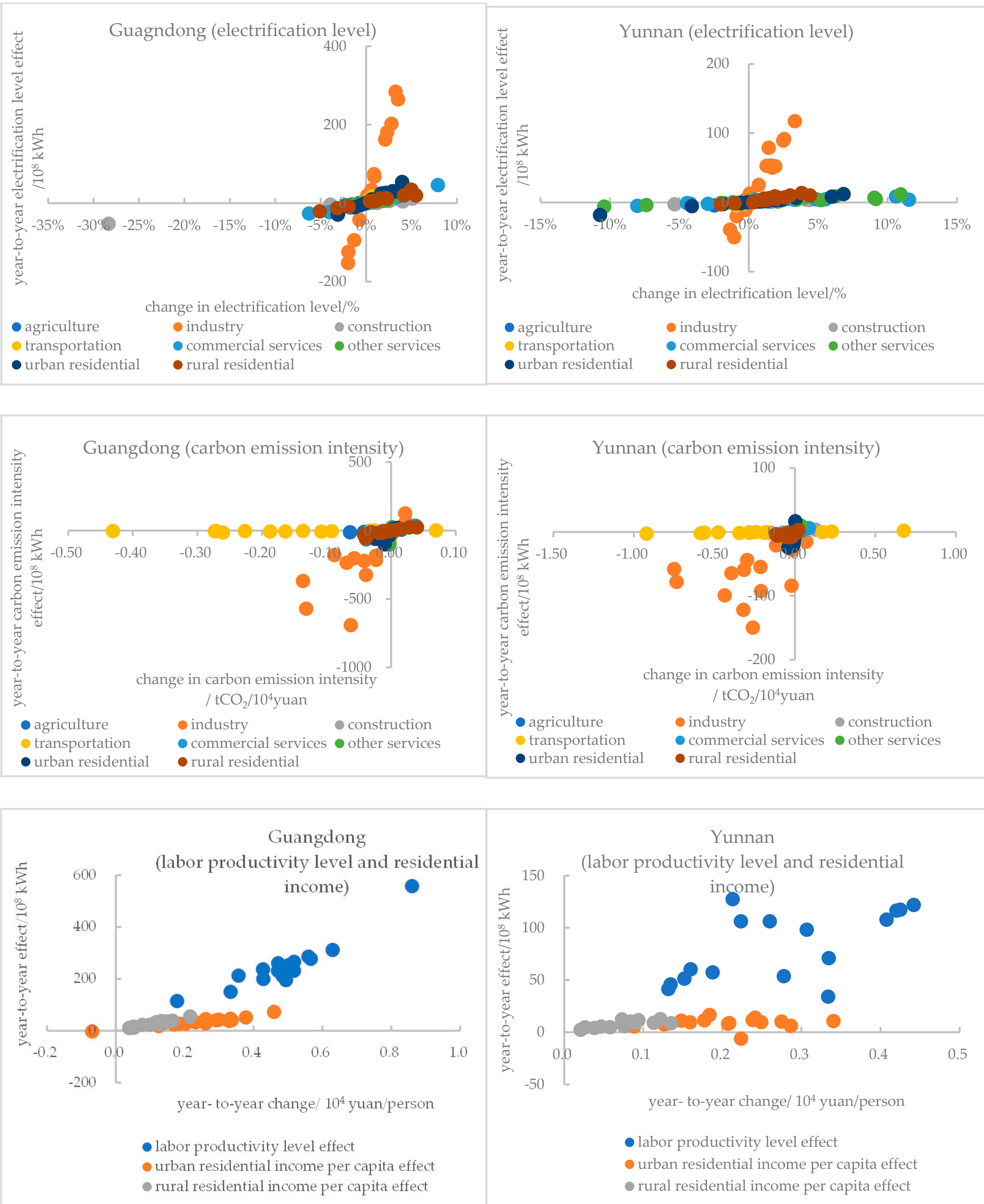

Figure 5. Scatterplot of changes in drivers and corresponding year-to-year effects from 2005 to 2021.

Table 4. Cumulative effects of each driver by subsector during the period of 2005–2021.

Effect	Province	Agriculture	Industry	Construction	Transportation	Commercial Services	Other Services	Urban Residential	Rural Residential	Total
ELE	Guangdong	57	914	−25	93	51	54	174	91	1409
	Yunnan	22	508	13	4	29	37	10	88	713
CEE	Guangdong	35	987	81	4	64	271	88	59	1589
	Yunnan	−3.3	195	7	0.3	7	43	10	6	265
CIE	Guangdong	−64	−3181	−45	−69	−144	−326	−489	−134	−4452
	Yunnan	−14	−995	−28	−16	0.8	−40	−135	−74	−1300
ISE1	Guangdong	−77	62	−23	−4	−8	63			14
	Yunnan	−11	117	12	−1.1	6	−12			112
RIE2	Guangdong							572	430	1002
	Yunnan							141	122	263
UPE2	Guangdong							90	−121	−31
	Yunnan							48	−23	25

Note: The unit is 10^8 kWh.

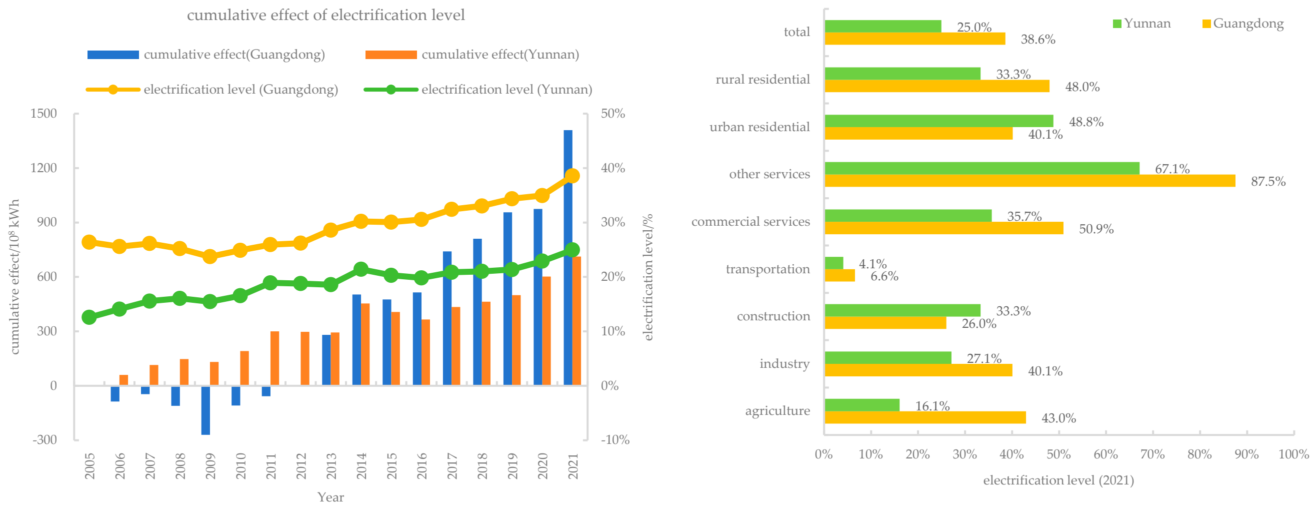

Figure 6. Cumulative electrification level effect and electrification level.

4.4.3. Energy Consumption Intensity Effect

What needs to be clarified is that energy consumption intensity denotes the average final energy consumption per unit of carbon emissions in this study. In Table 4, it is worth noting that the cumulative energy consumption intensity effect in Yunnan's agriculture sector was -3.3×10^8 kWh due to the decrease in energy consumption intensity during this period. The top three subsectors in terms of cumulative energy consumption intensity effect were industry (987×10^8 kWh, 62.1%), other services (271×10^8 kWh, 17.0%), urban residential (88×10^8 kWh, 5.6%) in Guangdong, and industry (195×10^8 kWh, 73.6%), other services (43×10^8 kWh, 17.0%), urban residential (10×10^8 kWh, 4.0%) in Yunnan. As shown in Figure 7, during 2005–2021, energy consumption intensity fluctuated upwards both in Guangdong and Yunnan, and the corresponding effects changed in the same direction as energy consumption intensity. Guangdong's energy consumption intensity rose from 0.623 tce/tCO_2 to 0.808 tce/tCO_2, while Yunnan's rose from 0.481 tce/tCO_2 to 0.592 tce/tCO_2. In this study, higher energy consumption intensity indicates higher decarbonization of energy consumption. Compared to Guangdong, Yunnan's energy decarbonization has some room for improvement to increase electricity consumption in the agriculture industry, construction, and other services. The energy consumption intensity of transportation in both provinces is low, so transportation is a key sector for the low-carbon transformation of energy.

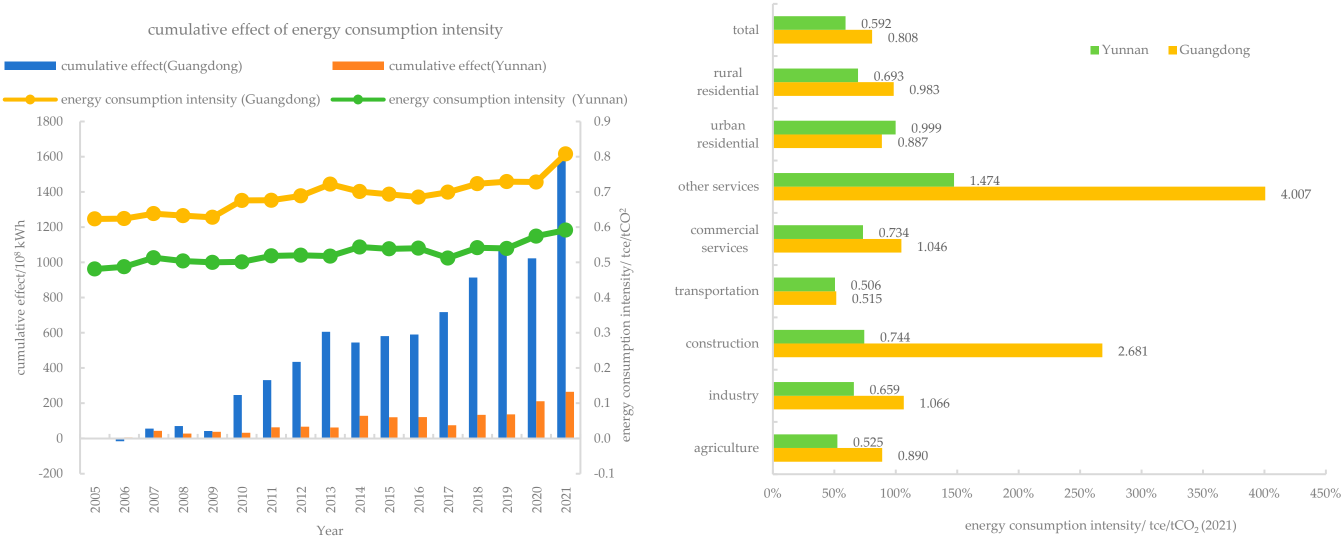

Figure 7. Cumulative energy consumption intensity effect and energy consumption intensity.

4.4.4. Carbon Emission Intensity Effect

The top three subsectors in terms of cumulative carbon emission intensity effect were industry (−3181 × 10^8 kWh, 71.5%), urban residential (−489 × 10^8 kWh, 11.0%), other services (−326 × 10^8 kWh, 7.3%) in Guangdong, and industry (−995 × 10^8 kWh, 76.5%), urban residential (−135 × 10^8 kWh, 11.0%), rural residential (−74 × 10^8 kWh, 5.7%) in Yunnan (Table 4). From 2005 to 2021, the cumulative carbon emission intensity effect in Guangdong and Yunnan decreased with the decrease of carbon emission intensity (Figure 8). The total cumulative contribution of carbon emission intensity to final electricity consumption in Guangdong and Yunnan was from −30 × 10^8 kWh and −74 × 10^8 kWh in 2006 to −4452 × 10^8 kWh and −1300 × 10^8 kWh in 2021, respectively. Guangdong's carbon emission intensity declined from 0.753 $tCO_2/10^4$ yuan to 0.289 $tCO_2/10^4$ yuan, while Yunnan's declined from 2.510 $tCO_2/10^4$ yuan to 0.896 $tCO_2/10^4$ yuan. Compared to Guangdong, Yunnan's carbon emission intensity has a lot of room to decline in industry and transportation, implying that it has a great potential to reduce electricity consumption.

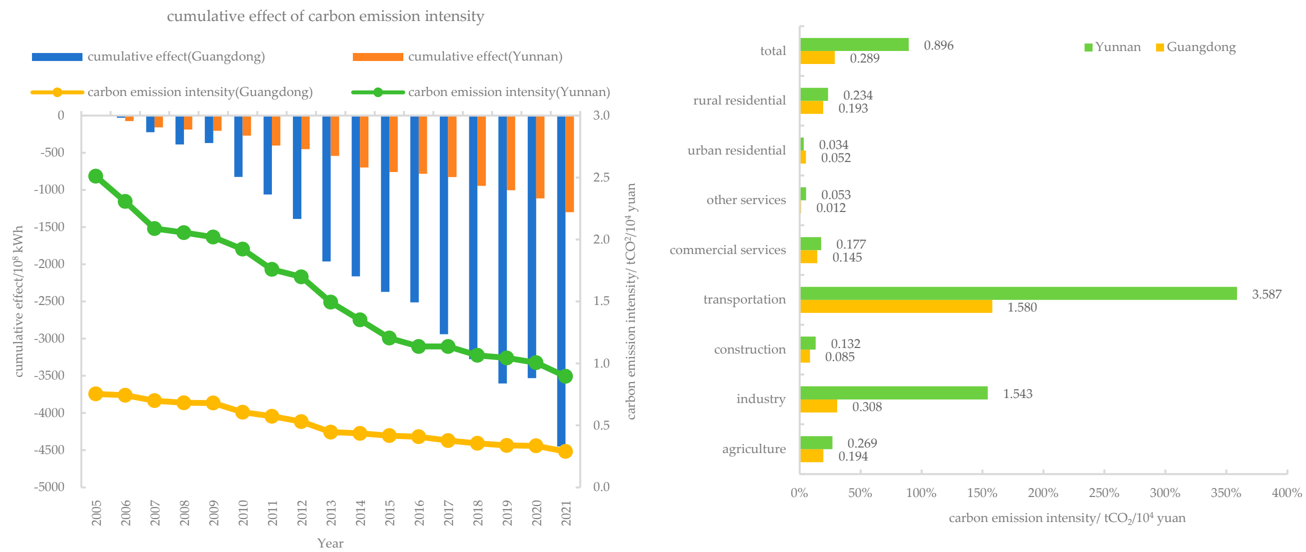

Figure 8. Cumulative carbon emission intensity effect and carbon emission intensity.

4.4.5. Industrial Structure Effect

Changes in the share of value added of industrial subsectors reflect changes in industrial structure. As shown in Figure 9, during the period of 2005–2021, the industrial structure effect of each industrial subsector varied in the same direction with the change in value-added share. Both in Guangdong and Yunnan, the change in the value-added share of the industry subsector had the most obvious impact on the total industrial structure effect. The cumulative industrial structure effects of industry were 62 $\times$ 10^8 kWh in Guangdong and 117 $\times$ 10^8 kWh in Yunnan. The decrease in value-added share of agriculture led to a negative cumulative effect (-77×10^8 kWh in Guangdong and -11×10^8 kWh in Yunnan). In addition, the increase in value-added share of other services in Guangdong increased electricity consumption by 63 $\times$ 10^8 kWh, while the decrease in Yunnan decreased electricity consumption by -12×10^8 kWh.

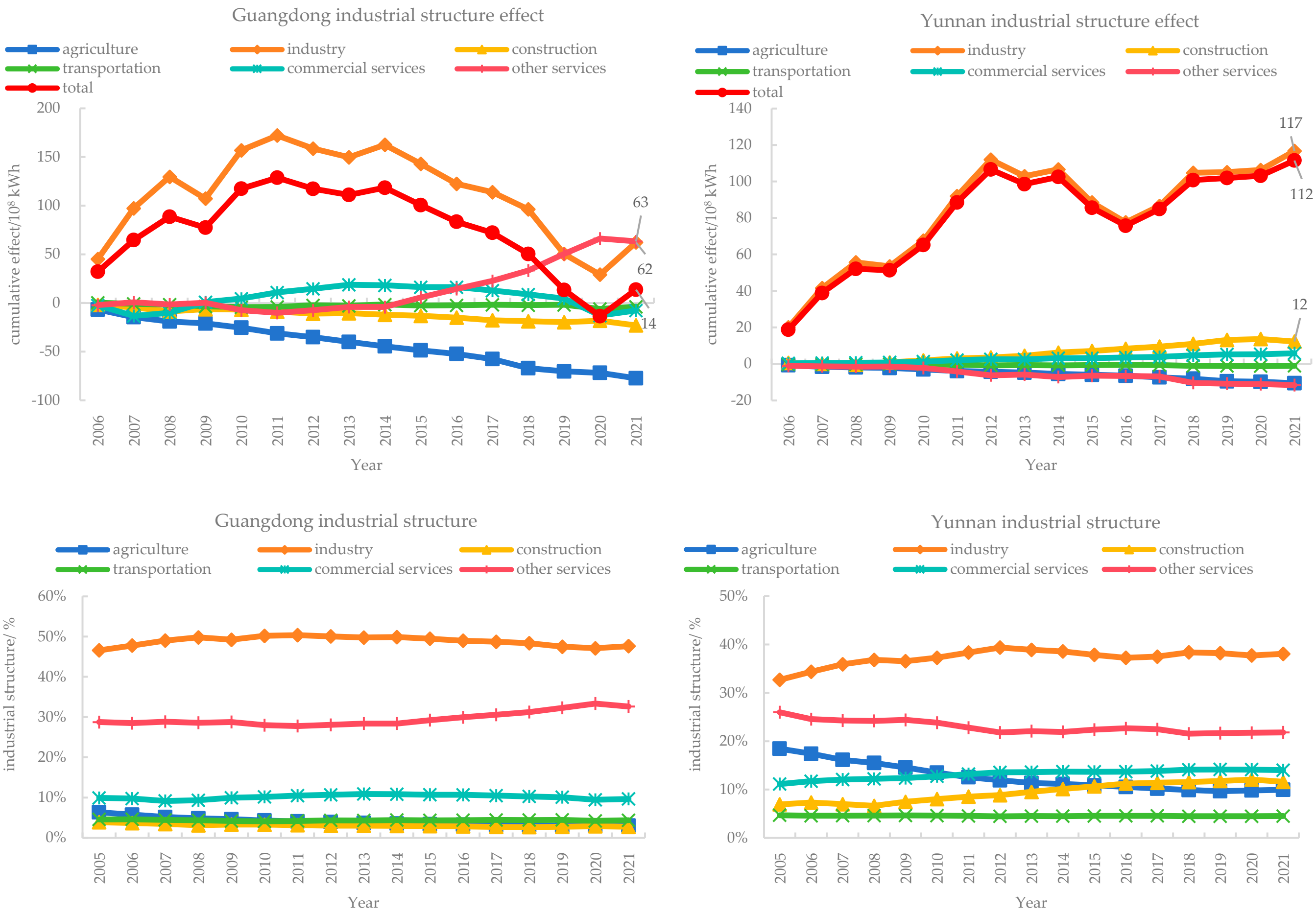

Figure 9. Cumulative industrial structure effect by subsector.

4.4.6. Labor Productivity Level Effect and Residential Income Per Capita Effect

As shown in Figure 10, during 2005–2021, labor productivity level, urban residential income per capita, and rural residential income per capita in Guangdong and Yunnan increased year by year, resulting in the corresponding cumulative effects overall year by year. The cumulative labor productivity level effects in Guangdong and Yunnan were 3988 $\times$ 10^8 kWh and 1315 $\times$ 10^8 kWh, respectively. That was due to the fact that the labor productivity level in Guangdong and Yunnan increased from 4.37 $\times$ 10^4 yuan/person and 1.42 $\times$ 10^4 yuan/person in 2005 to 12.17 $\times$ 10^4 yuan/person and 5.82 $\times$ 10^4 yuan/person in 2021, respectively. Labor productivity level not only represents the economic output per laborer but also reflects technological progress to a certain extent. The increase in labor productivity level was the primary driver for the growth of electricity consumption in Guangdong and Yunnan during the 2005–2021 period. In addition, Yunnan's labor productivity level is much lower than Guangdong's, and as it grows, it will contribute significantly to the growth of Yunnan's electricity consumption.

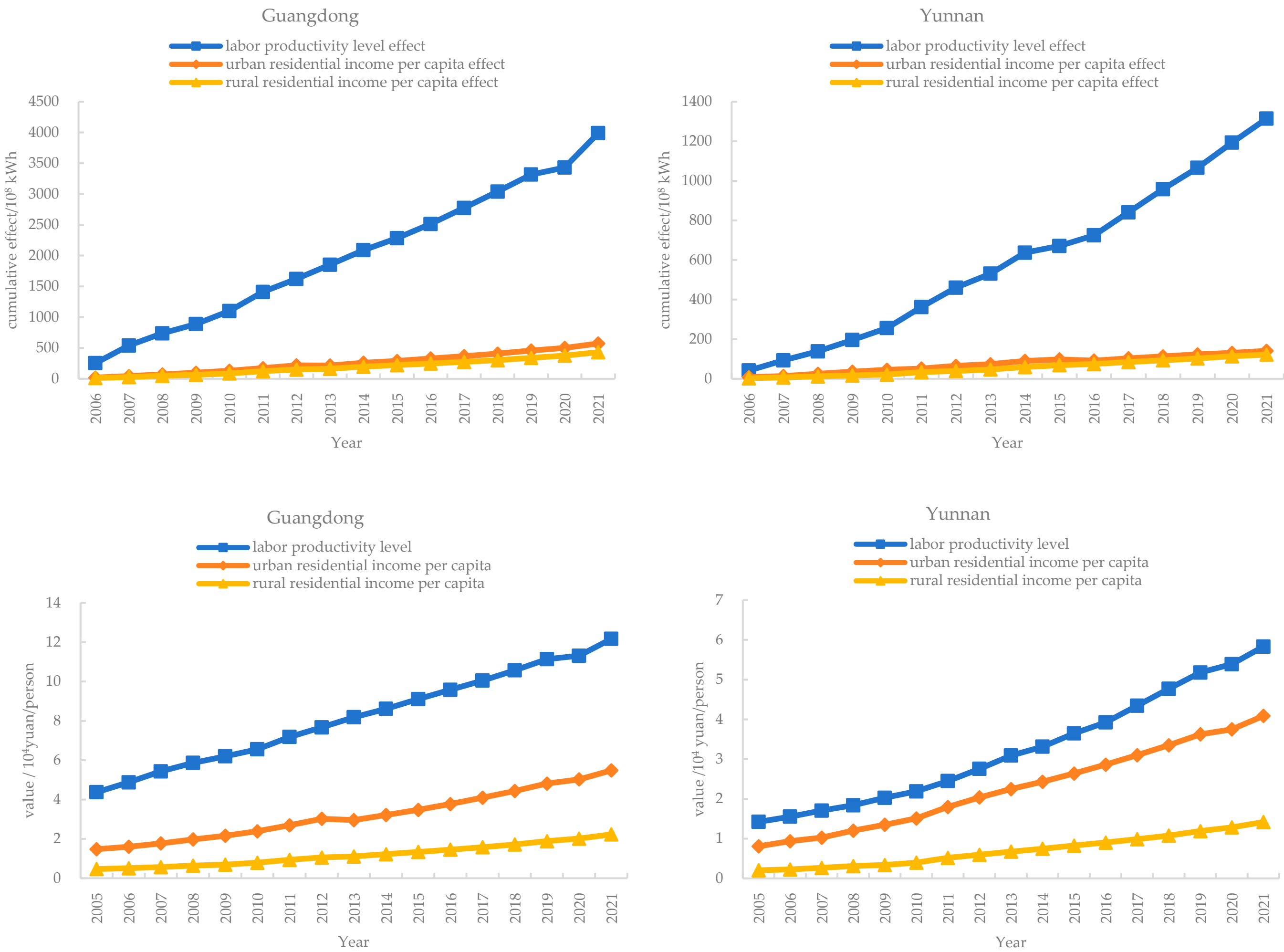

Figure 10. Cumulative labor productivity level effect and residential income per capita effect.

Residential income per capita is an important indicator representing the living standard of residents, and the larger it is, the higher the living standard of residents. As shown in Figure 10, during the period of 2005–2021, the cumulative urban residential income per capita effect and rural residential income per capita effect in Guangdong were 572×10^8 kWh and 430×10^8 kWh, respectively, and that in Yunnan were 141×10^8 kWh and 122×10^8 kWh, respectively. The per capita income of urban and rural residents in Yunnan is slightly lower than that in Guangdong, but both have increased significantly from 2005 to 2021, playing a positive role in increasing residential electricity consumption. With the future economy's expected growth, the per capita income of urban and rural residents will increase, contributing to an increase in residential electricity consumption.

4.4.7. Population-Related Effects

As shown in Figure 11, during the period of 2005–2021, Growth in the employed population size and the permanent population size increased electricity consumption. Guangdong's cumulative employment-population size effect was 1333×10^8 kWh, much larger than Yunnan's 111×10^8 kWh. Similarly, Guangdong's cumulative permanent population size effect was 229×10^8 kWh, much larger than Yunnan's 8×10^8 kWh. This is mainly attributable to the faster growth of Guangdong's employed and permanent population. As population growth slows or even declines across China and as employment decreases due to the aging population, this will lead to a reduction in electricity consumption.

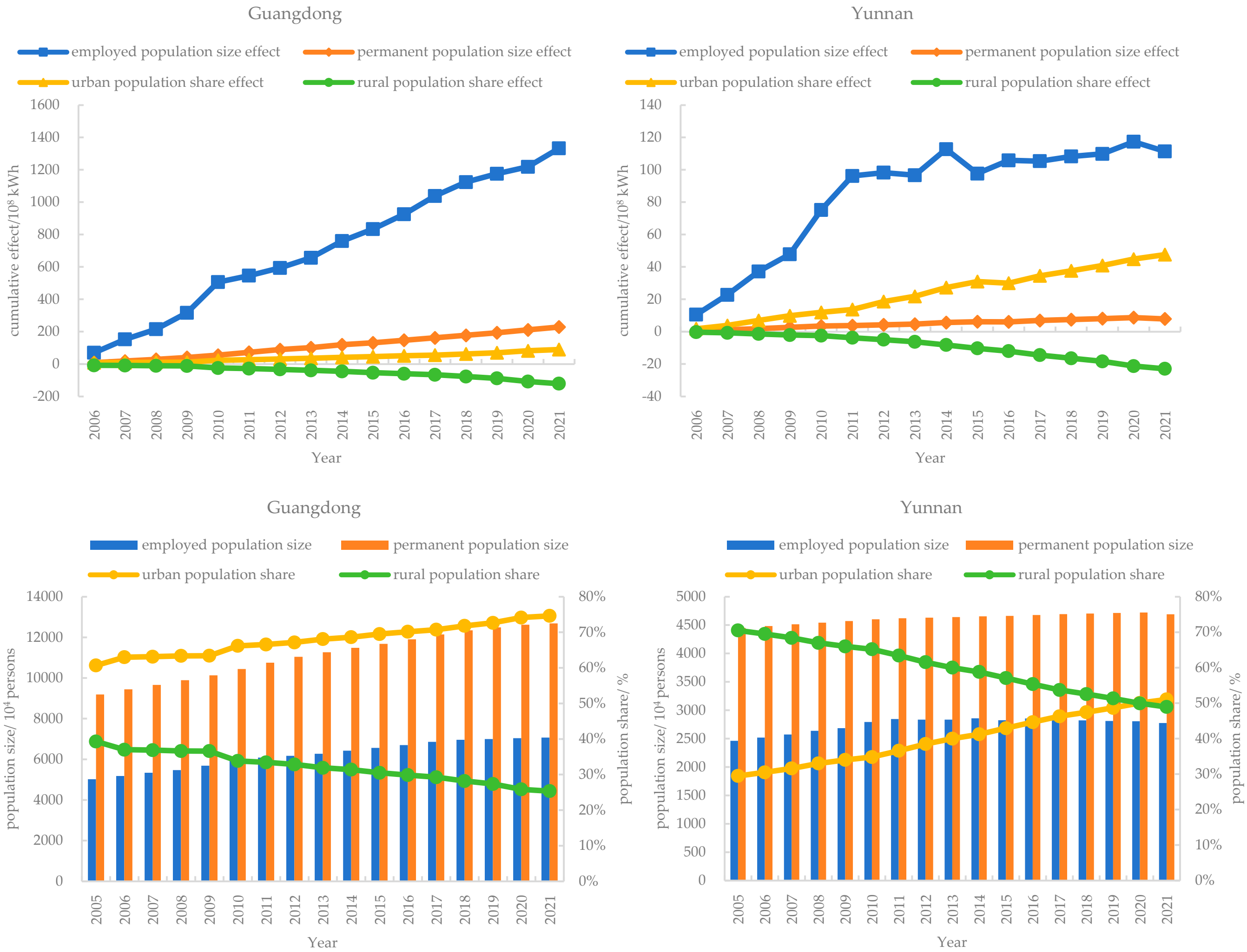

Figure 11. Cumulative population-related effects.

With continued urbanization, the urban population share increased and promoted electricity consumption, while the rural population share decreased and inhibited electricity consumption. Nevertheless, during 2005–2021, Guangdong's cumulative urban–rural population structure effect was negative (-31×10^8 kWh), while Yunnan's was positive (25×10^8 kWh). This is due to the large difference in the urbanization process between Guangdong and Yunnan during the period.

4.4.8. Spatial Difference in Effect by Subsector

Spatial difference is expressed in terms of subtraction of corresponding cumulative effects between Guangdong and Yunnan. Taking 2021 as the year for comparison, Figure 12 shows the differences in effect between the two provinces at the provincial, sectoral, and subsectoral levels. The total difference in effect was 3571×10^8 kWh, of which 2784×10^8 kWh (78.0%) for the industrial sector and 787×10^8 kWh (22.0%) for the residential sector. It indicates that industrial electricity is the main source of the total electricity consumption gap between Guangdong and Yunnan.

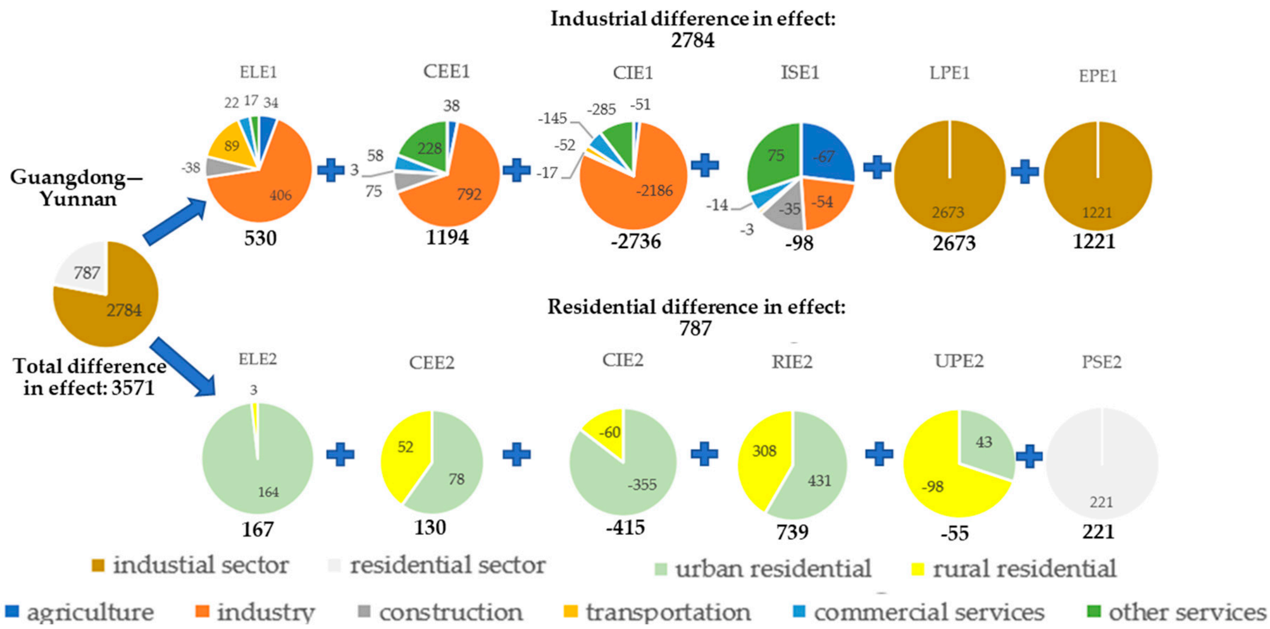

Figure 12. Decomposition of spatial difference of total final electricity consumption between Guangdong and Yunnan (2021).

The industrial labor productivity level effect (LPE_1) is the main driver in promoting the total electricity consumption in Guangdong to be higher than that in Yunnan, which expands the electricity consumption gap between Guangdong and Yunnan to 2673×10^8 kWh. It is mainly attributed to the fact that the labor productivity level in Guangdong increased by 7.8×10^4 yuan/person, much higher than the increase of 4.4×10^4 yuan/person in Yunnan during the period of 2005–2021. However, the industrial carbon emission intensity effect (CIE_1), which is the main driver in inhibiting the total electricity consumption, has narrowed the electricity consumption gap between Guangdong and Yunnan by -2737×10^8 kWh, mainly caused by the industry subsector (-2186×10^8 kWh). The employed population size effect (EPE_1) has widened the electricity consumption gap between Guangdong and Yunnan by 1221×10^8 kWh.

In the residential sector, the residential income per capita effect (RIE_2), which is the main driver in promoting residential electricity consumption, has expanded the electricity consumption gap between Guangdong and Yunnan by 739×10^8 kWh, caused by urban residential sector (431×10^8 kWh) and rural residential sector (308×10^8 kWh). Nevertheless, the residential carbon emission intensity effect (CIE_2), which is the main driver in inhibiting residential electricity consumption, has narrowed the electricity consumption gap between Guangdong and Yunnan by -415×10^8 kWh, mainly caused by the urban industrial sector (-355×10^8 kWh). The permanent population size effect (PSE_2) has widened the electricity consumption gap between Guangdong and Yunnan by 221×10^8 kWh.

The average effect of change in drivers during 2005–2021 is listed in Table 5. It indicates that the average effects vary considerably across different subsectors. For example, when the electrification level of each subsector in Guangdong increases by 1%, the average electrification level effects range from 2.1×10^8 kWh (construction) to 83.1×10^8 kWh (industry). In addition, the average effect in Guangdong is larger than the corresponding average effect in Yunnan. This can be explained by the fact that the effect is related to the change in the corresponding driver and the change in subsector electricity consumption. The change in subsector electricity consumption in Guangdong is often larger than that in Yunnan, resulting in a large average effect.

Table 5. Average effect of change in driver during 2005–2021.

Driver	Change	Province	Agriculture	Industry	Construction	Transportation	Commercial Services	Other Services	Urban Residential	Rural Residential	Total
electrification level	+1%	Guangdong	3.2	83.1	2.1	20.5	6.4	6.0	13.2	6.7	
		Yunnan	1.9	38.9	0.9	7.2	1.2	1.3	1.9	3.5	
energy consumption intensity	+0.1 tc/tCO_2	Guangdong	13.8	316.2	4.3	15.7	31.7	16.1	54.3	31.1	
		Yunnan	3.0	132.4	3.7	5.4	4.0	6.1	9.2	9.5	
carbon emission intensity	−0.1 tCO_2/10^4 yuan	Guangdong	−39.1	−502.2	−54.5	−3.1	−160.2	−2953.5	−452.4	−110.9	
		Yunnan	−4.2	−24.5	−9.5	−0.6	−14.7	−90.7	−106.3	−14.2	
industrial structure	+1%	Guangdong	23.3	60.5	20.3	17.8	30.5	16.3			
		Yunnan	1.2	21.8	2.6	5.9	2.0	2.8			
labor productivity level	+10^4 yuan/person	Guangdong									511.4
		Yunnan									298.1
residential income per capita	+10^4 yuan/person	Guangdong							142.6	244.2	
		Yunnan							42.9	100.2	
urban–rural population structure	+1%	Guangdong							6.5	8.7	
		Yunnan							2.2	1.1	
employed population size	+10^4 persons	Guangdong									0.65
		Yunnan									0.36
permanent population	+10^4 persons	Guangdong									0.07
		Yunnan									0.03

Note: The unit is 10^8 kWh; + indicates an increase in the value of the driver, − indicates a decrease in the value of the driver.

5. Conclusions and Policy Implications

5.1. Conclusions

Taking carbon emissions constraint factor into account, this study constructs the Kaya extended model of electricity consumption, analyzes the decomposition of the drivers of electricity consumption in the industrial sector and residential sector using the LMDI method, and empirically explores the temporal and spatial differences in the driving effects on provincial, sectoral and subsectoral electricity consumption, respectively. The main findings are as follows:

(1) During the period of 2005–2021, the total final electricity consumption growth in Guangdong (5093 $\times$ 10^8 kWh) is much higher than that in Yunnan (1510 $\times$ 10^8 kWh), but the average annual growth rate in Guangdong (7.1%) is lower than Yunnan (9.0%). The industrial sector accounted for a primary share of total final electricity consumption relative to the residential sector, and the share of industrial electricity consumption went down slowly in Guangdong and fluctuated in Yunnan. In addition, the growth of industry subsector electricity consumption is the main contributor to growth in total final electricity consumption, but the share of industry subsector electricity consumption went down slowly both in Guangdong and Yunnan;

(2) Except for the carbon emission intensity effect and urban–rural population structure effect, all other cumulative effects contributed to the growth of total final electricity consumption in Guangdong and Yunnan during 2005–2021. The industrial labor productivity level effect is the primary driver that increases total final electricity consumption (Guangdong: 3988 $\times$ 10^8 kWh or 78.5%, Yunnan: 1315 $\times$ 10^8 kWh or 87.1%), and industrial carbon emission intensity effect is the primary driver that decreases total final electricity consumption (Guangdong: -3828 $\times$ 10^8 or -75.3%, Yunnan: -1092 $\times$ 10^8 kWh or -72.3%). The industrial energy consumption intensity effect and employed population size effect are the second and third drivers that increase industrial electricity consumption in Guangdong, while the industrial electrification level effect and industrial energy consumption intensity effect are the second and third drivers that increase industrial electricity consumption in Yunnan. The industrial structure effect in Guangdong shows an upward and then a downward trend, while in Yunnan, it shows an upward trend during 2005–2021;

(3) In the residential sector, the residential income per capita effect and residential electrification level effect are the primary and secondary drivers that increase residential electricity consumption during 2005–2021, while the residential carbon emission intensity effect is the primary driver that reduces residential electricity consumption both in Guangdong and Yunnan. The urban–rural population structure effect was a negative contribution of -30.7 $\times$ 10^8 kWh (-0.6%) in Guangdong, while a positive contribution of 24.7 $\times$ 10^8 kWh (1.6%) in Yunnan. This is mainly caused by the differences in the urbanization process and urban–rural electricity consumption between the two provinces;

(4) As the drivers change, the year-to-year effects of each driver fluctuate up and down both in Guangdong and Yunnan from 2005 to 2021. The year-to-year effect of each driver by subsector is overall positively correlated with the year-to-year change in the corresponding driver, i.e., the increase in driver promotes electricity consumption, while the decrease in driver inhibits electricity consumption. Carbon emission intensity and rural population share generally decrease from year to year, with the corresponding effect being a decrease in electricity consumption, while other effects generally increase electricity consumption;

(5) The total difference in effect between Guangdong and Yunnan was 3571 $\times$ 10^8 kWh, of which 2784 $\times$ 10^8 kWh (78.0%) for the industrial sector and 787 $\times$ 10^8 kWh (22.0%) for the residential sector and the industrial labor productivity level effect. The largest positive difference lies in the industrial labor productivity level effect, which widens

the gap in electricity consumption by 2673 $\times$ 10^8. The largest negative difference lies in the industrial carbon emission intensity effect, which narrows the gap in electricity consumption by -2737×10^8 kWh, mainly caused by the industry subsector (-2186×10^8 kWh). The difference in each effect between the two provinces is mainly determined by change in the corresponding driver and change in subsectoral electricity consumption. The average effect of change in driver varies considerably across different subsectors, helping to understand the difference in effect between Guangdong and Yunnan.

5.2. Policy Implications

Based on the analysis of the results, we propose the following policy implications:

(1) A high share of industrial electricity consumption in Guangdong and Yunnan needs to be rationalized. With further industrialization, urbanization, and intelligence development, electricity consumption will still increase significantly. The expected continued improvement in the living standards of the residents foretells that there is little room for a reduction in electricity consumption in the residential sector. Therefore, controlling industrial electricity consumption is a priority, such as using more efficient electrical equipment, optimizing production processes, and upgrading production technology. The residential sector also needs to implement locally adapted tariff policies to scientifically manage electricity consumption to avoid wastage;

(2) Increasing the electrification level in sectors with a high share of fossil energy consumption is urgent. Guangdong is the largest province in terms of energy consumption and carbon emissions. Yunnan's end-use energy consumption has a high proportion of fossil energy consumption, and its overall electrification level is much lower than Guangdong's. In the context of the carbon-neutral strategy, both provinces are under tremendous pressure to control energy consumption and reduce carbon emissions. Further promoting the implementation of an electricity substitution policy can be less effective for final fossil energy consumption and improve the electrification level in industry, transportation, construction, and other sectors. The electrification rate has more room for improvement in Yunnan;

(3) Improving technology and reducing carbon emission intensity is fundamental. The improvement of labor productivity will increase economic output and electricity consumption. However, improving technology can optimize energy management and economic structure and control energy-intensive industries to lower energy consumption and electricity consumption intensity. Compared to Guangdong, Yunnan's carbon emission intensity has a lot of room to decline in industry and transportation. Guangdong should rely on its strong economic strength and talent advantage to strengthen the research investment and the application of advanced technologies and further optimize the structure of energy production and consumption to increase the share of low-carbon electricity. In addition, it is necessary to enhance public awareness of energy saving, low carbon, and environmental protection.

5.3. Limitation and Future Research

This study also has some limitations. In analyzing the factors related to final carbon emissions, the estimation of carbon emissions only includes direct carbon emissions from the combustion of fossil fuels, and the indirect carbon emissions from electricity consumption are not included. In further studies, we will consider this point and also consider the potential impacts of cross-regional electricity transmission. In addition, this study only uses Guangdong and Yunnan provinces as comparisons, and future studies will expand the regional scope to explore different electricity consumption characteristics in more regions.

Author Contributions: H.C.: conceptualization, investigation, methodology, project administration, supervision, visualization, writing–original draft, writing—review and editing. S.L.: investigation, data curation, formal analysis, visualization. Y.K.: methodology, data curation, formal analysis, validation, writing—review and editing. J.S.: validation, data curation, formal analysis. Z.M.: validation, formal analysis. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix A

Table A1. Final CO_2 emissions by subsector in Guangdong.

Year	Agriculture	Industry	Construction	Transportation	Commercial Services	Other Services	Urban Residential	Rural Residential
2005	500.54	9634.34	142.11	3762.60	510.18	145.30	1321.26	532.12
2006	427.87	11,656.03	153.02	3868.02	567.85	145.69	1419.48	502.02
2007	378.59	12,505.43	168.24	4263.49	649.77	165.47	1629.72	542.05
2008	390.58	13,675.78	154.53	4596.10	616.60	150.95	1673.24	618.73
2009	392.07	15,202.03	177.85	4816.74	818.48	161.08	1736.97	665.07
2010	405.68	14,721.58	192.68	5309.77	846.40	173.47	1664.64	732.72
2011	419.28	14,783.01	203.93	5448.02	885.17	183.77	2132.86	1021.13
2012	428.96	14,539.45	210.25	5664.91	969.85	184.76	2073.19	1014.46
2013	439.69	12,330.90	218.25	5488.15	1285.49	217.52	2013.23	890.03
2014	452.30	13,258.39	223.31	5747.96	1177.93	224.30	2081.99	928.02
2015	469.58	12,963.01	190.43	6279.50	1225.16	247.83	2424.00	1138.65
2016	517.40	13,041.44	219.34	6703.92	1350.63	298.09	2765.70	1308.50
2017	497.14	12,620.13	225.51	6794.97	1398.82	309.54	2808.11	1319.89
2018	493.06	12,534.06	227.81	6924.76	1391.27	317.68	2877.04	1352.05
2019	477.02	12,884.86	207.44	7015.23	1144.25	286.25	2834.72	1452.36
2020	528.92	13,890.87	205.10	6150.76	1173.96	290.52	2910.48	1527.46
2021	507.82	12,633.79	199.34	5903.57	1201.28	336.77	2708.40	1387.22

Note: The unit of CO_2 emissions is 10^4 t.

Table A2. Final CO_2 emissions by subsector in Yunnan.

Year	Agriculture	Industry	Construction	Transportation	Commercial Services	Other Services	Urban Residential	Rural Residential
2005	385.71	6418.54	102.97	1064.14	66.82	88.75	170.37	482.79
2006	396.77	6528.10	114.04	1203.21	66.88	90.88	170.32	446.34
2007	409.11	6500.91	113.16	1303.71	83.05	67.69	210.86	474.29
2008	408.38	7163.88	160.86	1339.62	120.37	120.12	212.13	449.01
2009	430.41	8038.40	175.81	1374.26	159.98	113.28	227.93	470.55
2010	442.24	8306.95	201.64	1724.90	188.51	127.95	268.81	485.28
2011	405.87	8574.91	256.14	1844.25	225.51	128.51	218.45	588.59
2012	412.50	9222.86	240.67	1970.62	307.35	171.36	284.80	653.28
2013	407.52	9143.48	240.14	1867.05	344.49	184.88	275.44	622.74
2014	440.27	8635.20	236.11	2111.80	253.72	215.98	261.72	641.27
2015	495.13	8061.62	247.58	2043.91	399.11	229.99	259.89	659.06
2016	451.30	8256.18	261.33	2138.98	382.47	178.25	312.07	754.53
2017	462.84	9454.23	270.41	2184.95	380.15	180.15	324.64	721.24
2018	459.55	9506.62	269.73	2454.90	394.98	198.74	327.18	721.60
2019	449.77	10,151.85	273.91	2672.77	399.01	200.85	340.66	708.06
2020	457.23	10,297.63	253.46	2538.50	343.55	222.21	318.75	776.29
2021	433.00	9507.47	247.52	2618.45	401.07	187.99	333.15	761.46

Note: The unit of CO_2 emissions is 10^4 t.

Table A3. Year-to-year effects of each driver on final electricity consumption in Guangdong.

Year	Industrial Sector						
	ELE_1	**CEE_1**	**CIE_1**	**ISE_1**	**LPE_1**	**EPE_1**	**YEC_1**
2005–2006	−105.16	−27.28	−0.98	32.10	252.10	70.17	220.96
2006–2007	41.16	67.43	−188.70	32.51	285.50	81.99	319.90
2007–2008	−77.88	9.70	−134.70	24.01	199.16	62.90	83.19
2008–2009	−181.53	−37.28	47.38	−11.27	149.72	101.50	68.51
2009–2010	139.21	200.13	−396.40	40.06	212.04	189.17	384.22
2010–2011	97.53	103.30	−275.91	11.32	311.20	40.08	287.53
2011–2012	18.70	83.48	−244.43	−11.45	210.35	48.02	104.68
2012–2013	241.31	156.47	−523.98	−6.25	230.93	62.37	160.85
2013–2014	183.70	−84.31	−140.92	7.35	236.42	103.36	305.60
2014–2015	15.19	59.87	−247.15	−17.84	195.04	73.90	79.01
2015–2016	58.38	21.93	−149.45	−17.11	231.41	91.62	236.78
2016–2017	212.69	120.23	−371.87	−11.29	260.17	112.97	322.91
2017–2018	55.82	189.10	−284.48	−21.73	265.49	85.42	289.61
2018–2019	116.18	136.48	−261.11	−37.03	277.15	51.75	283.41
2019–2020	−17.67	−57.40	106.19	−26.93	114.23	42.86	161.28
2020–2021	346.70	500.15	−761.99	27.24	557.45	114.73	784.29
Year	**Residential Sector**						
	ELE_2	**CEE_2**	**CIE_2**	**RIE_2**	**UPE_2**	**PSE_2**	**YEC_2**
2005–2006	18.42	11.04	−29.42	27.93	0.20	9.24	37.39
2006–2007	−0.58	4.29	−4.97	38.90	−0.04	8.99	46.59
2007–2008	13.76	5.29	−30.84	49.42	−0.63	10.39	47.39
2008–2009	21.47	9.48	−27.83	42.48	−0.01	11.67	57.26
2009–2010	22.14	4.02	−59.79	54.78	−0.95	14.47	34.67
2010–2011	−46.51	−19.05	41.12	78.42	−0.46	17.43	70.95
2011–2012	42.24	20.02	−85.89	74.03	−0.42	16.97	66.95
2012–2013	35.92	14.71	−48.03	8.32	−1.11	11.73	21.55
2013–2014	39.04	23.36	−57.39	77.47	−1.09	18.07	99.47
2014–2015	−42.58	−23.43	36.39	56.47	−3.54	11.82	35.12
2015–2016	−19.74	−12.73	9.59	66.25	−1.33	16.26	58.29
2016–2017	13.72	6.71	−57.49	63.36	−1.92	15.00	39.37
2017–2018	14.09	7.46	−51.12	68.77	−3.45	15.26	51.01
2018–2019	29.01	18.40	−64.34	88.94	−3.90	15.89	83.99
2019–2020	36.19	11.02	−35.83	79.22	−7.54	17.80	100.85
2020–2021	87.93	66.40	−157.25	127.14	−4.48	18.03	137.77

Note: The unit is 10^8 kWh.

Table A4. Year-to-year effects of each driver on final electricity consumption in Yunnan.

Year	Industrial Sector						
	ELE_1	**CEE_1**	**CIE_1**	**ISE_1**	**LPE_1**	**EPE_1**	**YEC_1**
2005–2006	55.70	5.30	−60.28	18.77	41.34	10.54	71.38
2006–2007	57.28	37.97	−87.48	20.09	51.20	12.17	91.23
2007–2008	14.06	−17.30	−8.85	13.26	45.69	14.48	61.35
2008–2009	−21.65	−5.08	−5.82	−0.81	57.30	10.62	34.56
2009–2010	56.40	6.90	−63.04	13.86	60.12	27.31	101.55
2010–2011	104.60	32.72	−103.27	23.31	106.17	21.04	184.58
2011–2012	1.34	7.70	−49.83	18.10	98.14	2.07	77.51
2012–2013	−14.54	−8.83	−68.31	−8.04	70.80	−1.61	−30.53
2013–2014	135.14	52.50	−126.63	3.91	106.11	16.09	187.14
2014–2015	−55.50	−11.48	−43.87	−16.89	34.03	−15.10	−108.80
2015–2016	−21.03	18.33	−41.96	−9.84	53.52	8.20	7.23
2016–2017	56.59	−50.84	−25.71	9.15	116.44	−0.52	105.10

Table A4. *Cont.*

Year	Industrial Sector						
	ELE_1	CEE_1	CIE_1	ISE_1	LPE_1	EPE_1	YEC_1
2017–2018	21.13	56.01	−100.33	15.85	117.21	2.91	112.77
2018–2019	30.54	−0.01	−43.20	1.16	107.69	1.60	97.78
2019–2020	87.13	71.90	−92.17	1.24	127.34	7.49	202.92
2020–2021	107.33	52.45	−171.00	8.41	121.79	−5.92	113.06
Year	**Residential Sector**						
	ELE_2	CEE_2	CIE_2	RIE_2	UPE_2	PSE_2	YEC_2
2005–2006	4.15	0.86	−13.72	9.96	1.43	0.55	3.23
2006–2007	−2.36	−0.98	1.53	9.43	1.66	0.58	9.87
2007–2008	18.03	1.87	−19.56	16.54	2.44	0.70	20.01
2008–2009	5.74	14.97	−10.85	15.55	2.19	0.87	28.47
2009–2010	3.88	−12.62	−2.94	14.09	1.74	0.74	4.89
2010–2011	4.31	−1.44	−29.28	18.48	0.49	0.27	−7.17
2011–2012	−3.80	−3.77	0.35	19.51	3.67	0.51	16.47
2012–2013	10.44	3.70	−21.20	16.31	1.89	0.41	11.55
2013–2014	25.32	14.27	−29.67	28.66	3.49	1.00	43.08
2014–2015	8.55	2.77	−17.24	17.31	1.64	0.48	13.51
2015–2016	−21.12	−17.40	19.16	−0.44	−2.73	−0.07	−22.60
2016–2017	12.34	4.84	−19.70	21.59	2.06	0.83	21.97
2017–2018	8.43	3.34	−17.01	18.64	1.17	0.56	15.13
2018–2019	5.95	2.26	−16.33	19.00	1.38	0.57	12.83
2019–2020	14.98	2.48	−17.01	18.98	1.03	0.65	21.11
2020–2021	3.22	1.63	−14.88	19.03	1.10	−0.83	9.27

Note: The unit is 10^8 kWh.

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