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What Drove Changes in the Embodied Energy Consumption of Guangdong's Exports from 2007–2012?

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Abstract: China's economy has been highly reliant on exports in recent years, with Guangdong its biggest province in export trade volume. Despite the global financial crisis of 2008, exports from Guangdong continued to increase significantly; however, the energy consumption embodied in exports is unknown. In this study, we investigate the changes of energy embodied in exports from 2007 to 2012 in Guangdong Province. We use EIO (Environmental Input-Output) and LMDI (Logarithmic Mean Divisia Index) method to find out the drivers of such changes embodied in total exports and export of each sector. Our results show: Firstly, from 2007 to 2012, the export structure in Guangdong has changed, reflecting in low energy intensity industry experiencing faster growth in exports than high energy intensity industry. Secondly, the growth rate of embodied energy consumption in Guangdong's exports is slowing, with average annual growth from 2007 to 2012 of 6.8%. Thirdly, though Guangdong's exports grew significantly, the energy consumption embodied therein decreased by 23% from 2007 to 2012, representing a drop of 50.51 Mtce. Finally, the most prominent change driver differed across sectors: For low value-added industries, such as metal smelting and rolling, the main contributor was export structure change, whereas for high value-added industries, such as communications, computers, and other electronic equipment, the main contributor was technical change. Guangdong is playing a leading role in industrial upgrading in China, and this has made the embodied energy consumption decreased obviously in Guangdong. It will be interesting to further investigate the trends of embodied energy consumption of other provinces in China, as this would give us deeper understanding of Chinese resource and environment problems.

Keywords: Guangdong; exports' embodied energy consumption; input-output model; logarithmic mean Divisia index

1. Introduction

China's energy consumption is unrivalled. In 2011, its primary energy consumption accounted for 21.3% of the world's total—replacing the United States as the world's largest energy consumer, contributing 71% of the global energy consumption increment. As China is still undergoing rapid development in urbanization and industrialization, it is expected that its future energy demands will continue to increase. In BP's 2017 "Energy Outlook" report, China's energy consumption is forecast to constitute 1/4 of the world's total by 2035 [1]. Meanwhile, China's export trade is also expanding. Exports are closely related to energy consumption, including their accompanying domestic consumption. Chinese government has noticed the heavily embodied energy consumption embodied in trade and made some policies to alleviate the energy problem such as control the export of some products with high energy consumption [2]. Guangdong Province, located in South China, is one of the country's most developed provinces, with the greatest GDP at provincial level for 29 consecutive years [3]. Its economic development is characterized by high carbon emissions [4]. With such extensive production and export activities, Guangdong has a strong and invariant demand for energy; consequently, carbon emissions in the province have become a prominent problem. It is important to identify the trend of energy consumption embodied in Guangdong's exports, as well as the main factors contributing to changes therein.

With the rapid development of international trade, the relationship between trade and energy consumption has attracted growing attention. Early studies focused mainly on the impact of trade on the environment in host countries [5]. In recent years, however, researchers have shifted their attention to the environmental pollution inherent in the production of goods for trade, namely the issues of embodied energy in trade. Embodied energy refers to the total energy consumed throughout a product's production process, including the direct consumption in final processing and the indirect consumption of intermediate inputs [6]. Wyckoff et al. [7] conducted the first study of the energy consumption and environmental pollution in production and foreign trade. They used input-output analysis to measure the embodied carbon emissions of products imported by the six largest OECD countries (Canada, France, Japan, Germany, the United Kingdom, and the United States). Their results showed that the embodied carbon emissions of imported products accounted for 13% of these countries' total carbon emissions. Wiedmann [8] built a multi-regional input-output model to measure the trade energy footprint of the United Kingdom in 2002. It demonstrated that the energy footprint of imports was greater than that of exports. Since the reform and opening-up in China, energy consumption has increased quickly and continues to rise—for example, energy consumption increased from 1549 Mtce in 2001 to 4260 Mtce in 2014 [9]. Meanwhile, China's trade is growing rapidly, which has driven the country to become the world's largest exporter. The embodied energy and pollution of China has received much focus in academia. Li et al. [10] used the energy footprint method to estimate embodied energy in international trade flow from China during 1996–2004, based on sub-sectoral level of economy and detailed traded items. They found that the embodied energy of China's exports has been increasing continuously, as has the proportion of export embodied energy to total energy consumption. However, with the transformation of its economy and upgrading of industrial structure, China has witnessed declining energy intensity, which may bring about new changes to export embodied energy. Mi et al. [11] found that China's export embodied carbon emissions peaked in 2008. The subsequent decline in CO_2 emissions was mainly due to the changing structure of Chinese production.

To investigate the reasons for these changes in export embodied energy, we employ a decomposition technique to analyze the influential factors. Currently, structural decomposition analysis (SDA) and index decomposition analysis (IDA) are the most-used decomposition techniques for energy consumption. SDA is based on the input-output table, while IDA uses the aggregated number of industry sector and the data. SDA takes more advantages than IDA, since its input-output model can be used to analyze both the technical effect and final demand effect. Direct and indirect effects can also be analyzed using SDA [12]. In four separate studies, researchers used SDA to analyze energy consumption changes in Brazil, US, Korea, and Italy, respectively [13–16]. They found that structural changes contribute most to reducing energy consumption. Scholars have paid much attention to the reasons for growing energy consumption in China. SDA has been used to analyze the main factors contributing to changes in China's energy consumption in different stages [12,17–22]; the researchers found that increases in end-use drive growth in energy consumption. Other scholars have analyzed energy consumption changes at the provincial level [23]. In addition, SDA has been extensively used to analyze the changing factors of export embodied energy and embodied pollution [24,25].

The principal disadvantage of SDA is the interaction problem that arises in the decomposition process, resulting in inconsistent calculation results, poor comparability among factor weights, and an indecomposable interaction effect. Although many methods have been proposed to resolve these problems—including the polar decomposition method, neutral point decomposition method, and weighted average decomposition method—none can completely decompose the interaction, resulting in the following problems. Firstly, there is error term between the decomposed results and the actual results. Secondly, the decomposed results are different because the ways of attaching interactive items to non-interactive items are different. Compared to the SDA method, the IDA method has lower data requirements—specifically, it does not need input-output data. Furthermore, in calculating decomposition, LMDI (Logarithmic Mean Divisia Index) can completely decompose the remainder with non-explainable remainders. LMDI is widely used in the quantitative study of the contributors to changes in energy consumption and carbon emissions, as its data requirements are not high and there is no unexplained residual. Regarding spatial scale, LMDI can be used at country level. For example, it has been used to study energy consumption and carbon emissions in China, the European Union 27, and in other regions [26–30]. Many studies of energy consumption and carbon emissions have been conducted at provincial level [31–36] and city level [37]. Research has also been conducted at sector level—for example, Choi and Oh [38] studied the energy consumption and carbon emissions associated with Korea's manufacturing industry, while Zhang et al. [39] investigated the energy consumption of transportation services in China.

As described above, the LMDI has many advantages. However, it does not consider intermediate inputs, and thus ignores the structure-driven changes in energy consumption between sectors [40]. Treating energy consumption as a variable to decompose, this paper uses a method that incorporates the advantages of both LMDI and input–output methods. It allows full decomposition and explains how the energy consumption structure affects changes in consumption. It, thereby, avoids the shortcomings of classical MDI (Mean Divisia Index) (which does not consider indirect effects on carbon emissions, and the non-uniqueness problem of SDA [41]) this method has been widely used in analyzing the drivers of environmental problems change in national level [14,42,43] Provincial-level changes in the energy consumption embodied in exports have rarely been studied. Therefore, we chose Guangdong Province as a case study in this paper, aiming to develop better understanding of the changing trend of energy consumption embodied in trade in China.

The remainder of this article is organized as follows. Section 2 presents the hybrid approach and the environmental input–output approach for calculating the provincial embodied energy consumption in Guangdong. It also details the decomposition approach, which combines the input-output technique and the LMDI to analyze the drivers of change in embodied energy consumption. Section 3 presents the trends in export structure and energy consumption in Guangdong Province. Section 4 then explores the effects of different factors on the changes in energy consumption embodied in Guangdong's exports, based on LMDI. Finally, Section 5 presents conclusions and discusses several policy implications.

2. Method and Data Preparation

2.1. Embodied Energy Accounting Method

Comprehensive analysis of energy consumption in an industry supply chain must consider the energy use in intermediate production processes by other industrial sectors in the chain [44]. One appropriate method to capture energy consumption flows in the economy is the environmental input–output (EIO) model, which is extended from the standard Leontief input–output model [45,46]. This tool allows the calculation of direct energy consumption from a sector's final demand, as well as the indirect energy consumptions from other sectors in the supply chain. The EIO model can be expressed as:

$$E = e(I - A)^{-1}Y = e \times C \times Y, \quad (1)$$

where E is the embodied energy resulting from the final demand, such as export; e is the row vector of direct energy consumption of unit total output; I is the unit matrix; A is the direct consumption coefficient matrix; C is the Leontief inverse matrix; and Y is the column vector of final demand. Introducing the export structure into Equation (1) transforms it into:

$$E = e(I - A)^{-1}Y = e \times C \times s \times y, \tag{2}$$

where s is the column vector of export structure, and y is total exports. We can obtain the total amount of embodied energy resulting from exports through Equation (2).

2.2. Decomposition Method

To decompose the variation in energy consumption by sector, we need to comprehensively calculate the energy consumption in each sector. We used the provincial input–output model to undertake decomposition analysis of the factors influencing embodied energy in Guangdong. According to Ang's research [47], the LMDI approach is preferable to other index composition methods. Ang [48] provided a practical guide for the LMDI method, while Ang and Liu [49] proposed a technique for handling zero values when using LMDI. Therefore, we conducted decomposition analysis by combining the input–output model and the LMDI approach.

According to Equation (2), the change in E between time points t_0 and t_1 can be decomposed as:

$$\Delta E = E^{t_1} - E^{t_0} = f(\Delta e^T) + f(\Delta C) + f(\Delta s) + f(\Delta y), \tag{3}$$

where ΔE represents the embodied energy change, E^{t_0} and E^{t_1} represent embodied energy in t_0 and t_1, $f(\Delta \mathbf{e^T})$, $f(\Delta \mathbf{C})$, $f(\Delta \mathbf{s})$, and $f(\Delta \mathbf{y})$ respectively represent variation in technical, input structural, export structural, and scale effects in the embodied energy of Guangdong's exports from t_0 to t_1.

To apply the LMDI approach to sector i and j, we can rewrite Equation (2) as:

$$E = \sum_j \sum_i (e_i^T C_{ij}) s_j y. \tag{4}$$

According to Equation (4), and following Ang [49] and Ang and Liu [50], the components of Equation (3) can be expressed as

$$f(\Delta e^T) = \sum_j L_j \sum_i (w_{ij}/w_j) \cdot \ln(e_j^{t_1}/e_j^{t_0}), \tag{5}$$

$$f(\Delta C) = \sum_j L_j \sum_i (w_{ij}/w_j) \cdot \ln(C_{ij}^{t_1}/C_{ij}^{t_0}), \tag{6}$$

$$f(\Delta s) = \sum_j L_j \ln(s_j^{t_1}/s_j^{t_0}) \text{ and} \tag{7}$$

$$f(\Delta y) = \sum_j L_j \ln(y_j^{t_1}/y_j^{t_0}), \tag{8}$$

In Equations (5)–(8), L_j represents the energy change function from t_0 to t_1, w_{ij} represents the function of change of the total energy embodied in sector i input to sector j, w_j is the sum of w_{ij} of all sector i, these terms can be expressed as follows:

$$L_j = (E_j^{t_1} - E_j^{t_0})/(\ln E_j^{t_1} - \ln E_j^{t_0}), \tag{9}$$

$$w_{ij} = (g_{ij}^{t_1} - g_{ij}^{t_0})/(\ln g_{ij}^{t_1} - \ln g_{ij}^{t_0}) \tag{10}$$

$$w_j = (g_j^{t_1} - g_j^{t_0})/(\ln g_j^{t_1} - \ln g_j^{t_0}), \tag{11}$$

where

$$g_{ij} = e_i C_{ij} \tag{12}$$

and

$$g_j = \sum_i g_{ij} \tag{13}$$

g_{ij} represents the total energy embodied in sector i input to sector j, g_j represents the total energy consumption of sector j.

Through Equations (3)–(13), we obtained the variation in energy consumption in Guangdong resulting from four factors, each of which were further analyzed.

2.3. Data Preparation

This study uses the 2007 and 2012 input–output tables of Guangdong Province [50,51]. It also uses the HS (Harmonized System) data of China Customs and the accounting department of the National Bureau of Statistics to verify the data quality of those input-output tables through non-competitive import standard processing. To maintain consistency with the energy consumption indicators of different industries in the Guangdong Statistical Yearbook for 2008 and 2013 [52,53], from which all the energy data were sourced, we merged the original 42 sectors into 27 sectors (see Table 1) and adjusted the 2012 price to be comparable to that in 2007.

Table 1. Sector number according to its denomination of national economy of Guangdong (2007–2012).

Sector Code	Sector Description
S1	Agriculture
S2	Coal mining
S3	Oil and gas mining
S4	Metal mining
S5	Nonmetal mining
S6	Tobacco, food, and beverages
S7	Textiles
S8	Wearing apparel, dressing, and fur dyeing
S9	Wood and wood products
S10	Paper and products for culture, education, and sports
S11	Refined petroleum products, coking products, and nuclear fuel products
S12	Chemicals and chemical products
S13	Nonmetallic mineral products
S14	Metal smelting and rolling
S15	Manufacture of fabricated metal products
S16	Common and special equipment
S17	Transport equipment
S18	Electrical machinery and apparatuses
S19	Communications, computers, and other electronic equipment and apparatuses
S20	Instruments, meters, and cultural and office machinery
S21	Other industrial activities
S22	Production and distribution of electricity and heat
S23	Steam and water supply
S24	Construction
S25	Transportation, warehouse, and post
S26	Wholesale, retail, accommodation, eating, and drinking services
S27	Other service activities

3. Guangdong's Trade and Energy Consumption

3.1. Guangdong's Exports in 2007 and 2012

As noted earlier, Guangdong Province is one of China's most important trade provinces and, in economic terms, is highly reliant on exports. As Figure 1 shows, in 2012, the value of exports from Guangdong was USD 574 billion, accounting for 28.0% of China's total exports, representing a small decline on the 2007 level of 30.2%. In terms of export volume change, the total export volume of

Guangdong in 2012 increased by USD 272 billion from 2007, though experienced the global financial crisis in 2008–2009.

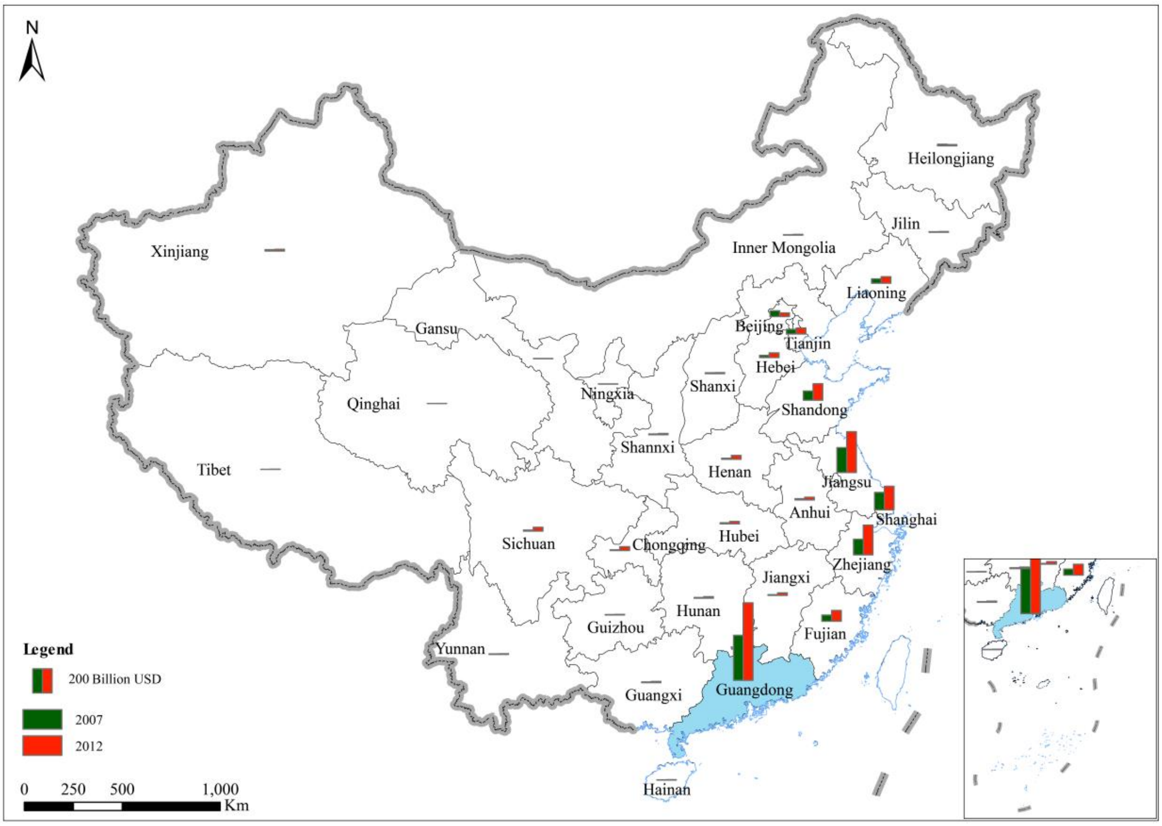

Figure 1. Exports of each province of China in 2007 and 2012.

Figure 2 shows that, despite the global financial crisis, exports from Guangdong still grew significantly in most sectors. S19 (communications, computers, and other electronic equipment and apparatuses) is the most exported growth sector, rising from CNY 881 billion in 2007 to CNY 1322.77 billion in 2012, respectively representing 29.03% and 33.08% of Guangdong's total exports in those years. Besides, S8 (wearing apparel, dressing, and fur dyeing), S10 (paper and products for culture, education, and sports), S16 (Common and special equipment), and S18 (Electrical machinery and apparatuses) each exceeded CNY 200 billion in export value in 2012. Across all sectors, S10 and S27 had the greatest percentage increase in exports from 2007 to 2012.

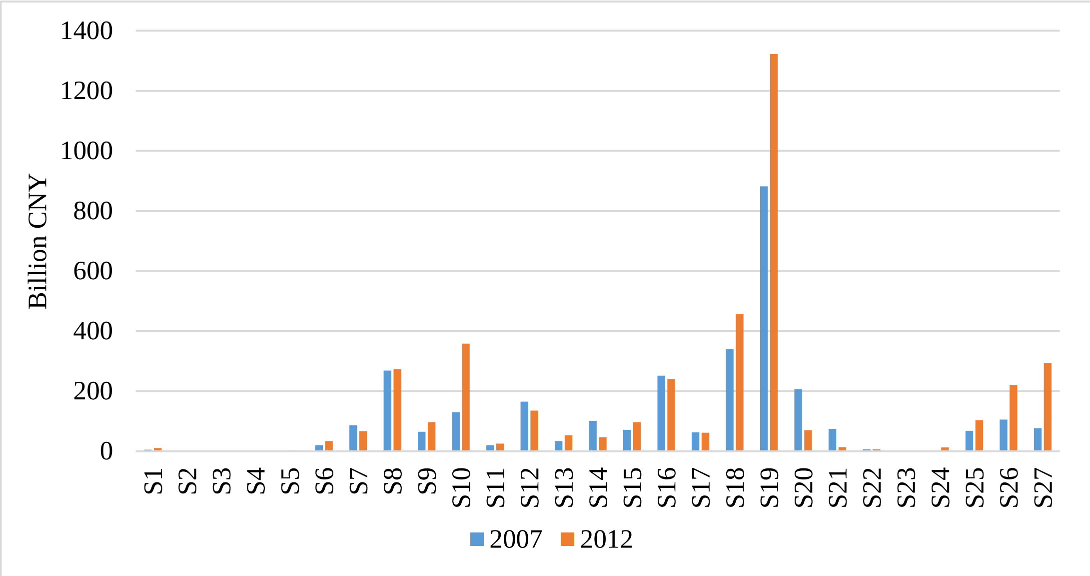

Figure 2. Export volumes by industry for Guangdong in 2007 and 2012.

3.2. Trend of Guangdong's Energy Consumption

As Figure 3 shows, the growth rate of energy consumption in Guangdong is slowing down. Between 2007 and 2012, total energy consumption in Guangdong rose from 173.4 Mtce in 2007 to 237.9 Mtce in 2012, respectively accounting for 6.57% and 6.78% of national total energy consumption. From 2007 to 2012, the average annual growth rate of energy consumption was 6.5%, which is far less than the province's annual GDP growth rate. The energy consumption structure also changed slightly, with the proportion of total energy consumption attributed to coal decreasing very steadily from 52.0% in 2007 to 46.4% in 2012. Meanwhile, the proportion of consumption attributed to natural gas grew fastest, from 3.5% in 2007 to 6.4% in 2012. The findings on energy consumption and its structure show that Guangdong has made progress in reducing energy intensity and using cleaner energy to reduce pollution.

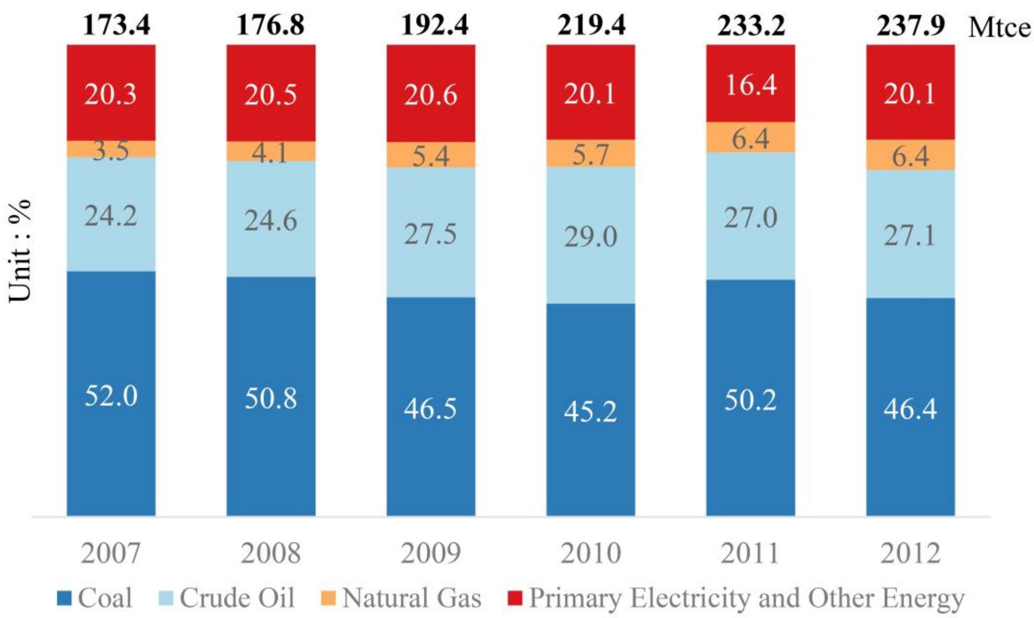

Figure 3. Structure of energy consumption in Guangdong from 2007 to 2012.

The province's energy consumption increased in most sectors between 2007 and 2012, though the highest increases were seen in S13 (nonmetallic mineral products), S25 (transportation, warehouse, and post), and S27 (other service activities). However, in most sectors, energy intensity decreased, especially in S11 (refined petroleum products, coking products, and nuclear fuel products) and S14 (metal smelting and rolling), which dropped from 6.06 tce/CNY 10,000 and 3.65 tce/CNY 10,000 to 1.80 tce/CNY 10,000 and 2.09 tce/CNY 10,000, respectively (Figure 4). The energy intensity of the manufacturing sectors (mostly above 0.5 tce/CNY 10,000) is clearly higher than that of the service sectors (mostly less than 0.5 tce/CNY 10,000).

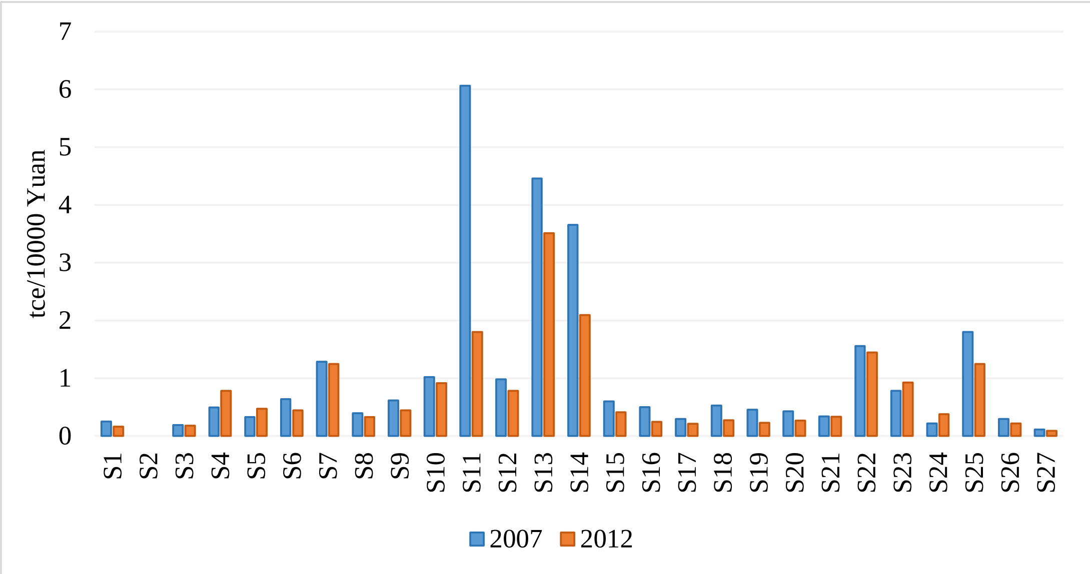

Figure 4. Energy intensity of each sector in Guangdong in 2007 and 2012.

4. Results

4.1. Energy Consumption Change in Each Sector from 2007–2012

Focusing on changes in the embodied energy consumption of Guangdong's exports, we find that although export volumes substantially increased, the total embodied energy decreased by 50.5 Mtce from 2007 to 2012. As Figure 5 shows, embodied energy consumption decreased in most sectors from 2007 to 2012; the exceptions, in which consumption increased, were S10 (paper and products for culture, education, and sports), which witnessed a significant increase of 18.5 Mtce, together with S13 (nonmetallic mineral products), S26 (wholesale, retail, accommodation, eating, and drinking services), and S27 (other service activities), in which the increases were relatively small. S14 (metal smelting and rolling) had the biggest decrease (26 Mtce), while a further six sectors showed decreases of more than 5 Mtce: S11 (refined petroleum products, coking products, and nuclear fuel products), S12 (chemicals and chemical products), S16 (common and special equipment), S18 (electrical machinery and apparatuses), S19 (communications, computers, and other electronic equipment and apparatuses), and S20 (instruments, meters, and cultural and office machinery).

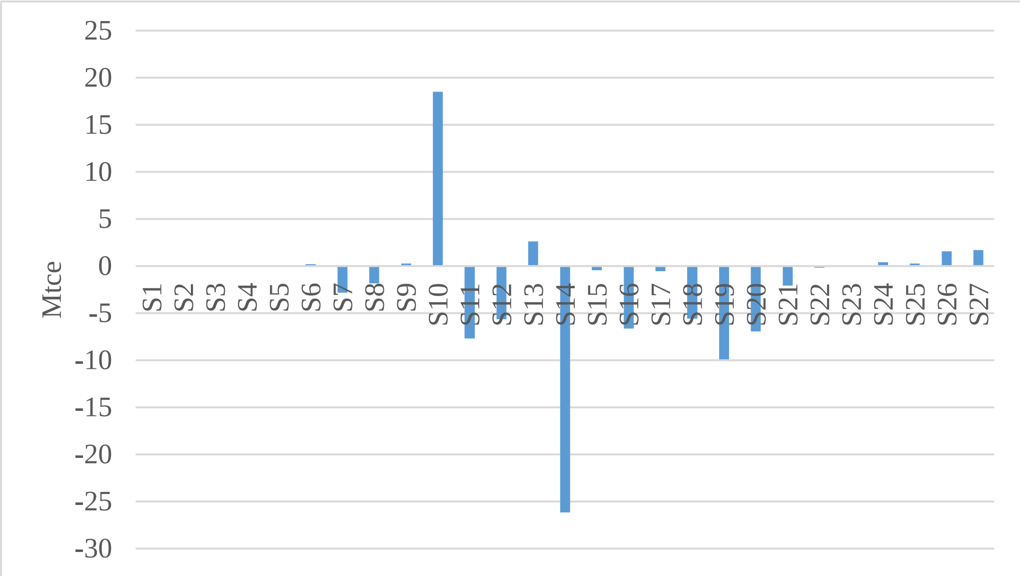

Figure 5. Sector-level change in energy consumption embodied in Guangdong's exports (2007–2012).

4.2. Contributors to Change in Energy Consumption Embodied in Guangdong's Exports

Figure 6 illustrates the results of the LMDI comparing the forces driving the increase in energy consumption embodied in Guangdong's exports from 2007 to 2012. Overall, energy consumption embodied in exports decreased by 50.5 Mtce. The change in energy intensity, the first term in Equation (2), is the largest contributor, reducing embodied energy consumption by 74.60 Mtce. Changes in economic export structure and input structure, the third and second terms in Equation (2), reduced embodied energy consumption by 16.43 and 10.75 Mtce, respectively. However, the export scale, the last term in Equation (2), increased embodied energy consumption by 51.26 Mtce, reflecting the significant increase in exports from Guangdong over the studied period.

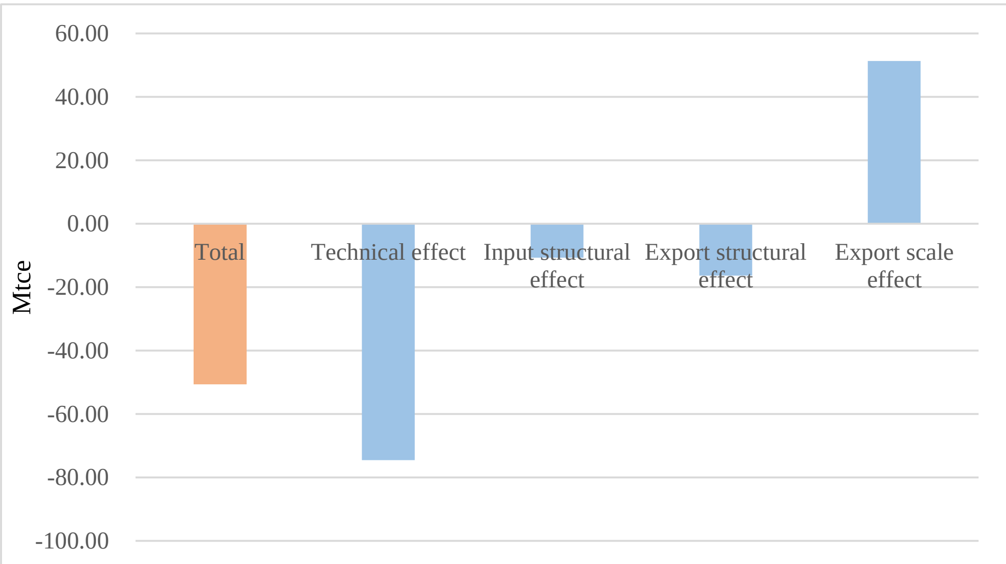

Figure 6. Contributors driving changes in energy consumption embodied in Guangdong's exports (2007–2012).

4.3. Contributors to Change in Embodied Energy Consumption in Each Sector

Results of the decomposition of energy consumption embodied in Guangdong's exports (2007–2012) are presented in Tables 2 and 3. For reducing embodied energy consumption, the technical effect was found to be most important. The three sectors with the largest reduction in embodied energy consumption attributable to energy intensity were S19 (communications, computers, and other electronic equipment and apparatuses), S14 (metal smelting and rolling), and S18 (electrical machinery and apparatuses), which respectively reduced their exports' embodied energy consumption by 23.6 Mtce, 10.7 Mtce, and 9.6 Mtce. Input structural effects led to decreases in embodied energy consumption in most sectors, producing the largest reductions in S19 (communications, computers, and other electronic equipment and apparatuses), S11 (refined petroleum products, coking products, and nuclear fuel products), and S14 (metal smelting and rolling), mainly due to lower energy consumption embodied in these industries' inputs. Export scale increased substantially in most sectors, resulting in increased demand for embodied energy consumption. The three sectors in which export scale brought the largest increases in embodied energy consumption were S19 (communications, computers, and other electronic equipment and apparatuses), S10 (paper and products for culture, education, and sports), and S14 (Metal smelting and rolling), which experienced respective increases of 9.44, 5.69, and 5.29 Mtce.

Table 2. Decomposition factors affecting change in energy consumption embodied in Guangdong's exports from 2007 to 2012 (unit: Mtce).

Sector	Technical Effect (Δd)	Input Structural Effect (ΔC)	Export Structural Effect (Δs)	Export Scale Effect (Δy)	Total Energy Consumption Change
S1	−0.06	0.00	0.08	0.04	0.06
S2	0.00	0.00	0.00	0.00	0.00
S3	0.00	0.00	0.02	0.00	0.02
S4	0.00	0.00	0.00	0.00	0.00
S5	0.02	0.00	0.03	0.02	0.08
S6	−0.44	−0.05	0.35	0.38	0.23
S7	−0.78	0.29	−4.85	2.52	−2.82
S8	−2.79	0.82	−2.48	2.62	−1.82
S9	−1.15	−0.24	0.55	1.11	0.26
S10	−2.81	0.20	15.44	5.69	18.52
S11	−7.22	−2.00	−0.53	2.08	−7.67
S12	−3.00	−0.07	−6.09	3.52	−5.65
S13	−3.44	−0.51	2.46	4.13	2.63
S14	−9.56	−1.63	−20.26	5.29	−26.16
S15	−1.43	−0.19	0.12	1.08	−0.42
S16	−6.07	−0.16	−2.74	2.36	−6.61
S17	−0.33	−0.17	−0.46	0.42	−0.55
S18	−8.45	−1.43	0.34	3.98	−5.56
S19	−18.88	−4.95	4.50	9.44	−9.89
S20	−1.36	−0.80	−5.98	1.21	−6.94
S21	−0.17	0.13	−2.35	0.32	−2.07
S22	0.01	−0.26	−0.10	0.18	−0.17
S23	0.00	0.00	0.00	0.00	0.00
S24	0.00	0.00	0.42	0.00	0.43
S25	−4.88	0.09	1.68	3.39	0.28
S26	−1.41	0.17	1.77	1.05	1.59
S27	−0.41	0.04	1.66	0.43	1.73

Table 3. Four factors contributing to the change in energy consumption embodied in Guangdong's exports from 2007–2012 (unit: %).

Sector	Technical Effect (Δd)	Input Structural Effect (ΔC)	Export Structural Effect (Δs)	Export Scale Effect (Δy)	Total Embodied Energy Consumption Change	Total Energy Consumption Embodied in Exports in 2007 (Mtce)
S1	−50	−3	70	34	51	0.11
S2	0	0	0	0	0	0.00
S3	0	0	0	0	0	0.00
S4	49	3	−37	34	48	0.01
S5	59	2	84	50	195	0.04
S6	−35	−4	27	30	18	1.26
S7	−7	3	−45	24	−26	10.67
S8	−27	8	−24	25	−17	10.49
S9	−29	−6	14	28	7	3.91
S10	−22	2	121	44	145	12.80
S11	−60	−17	−4	17	−64	12.06
S12	−19	0	−38	22	−36	15.83
S13	−25	−4	18	30	19	13.74
S14	−27	−5	−58	15	−74	35.21
S15	−34	−5	3	26	−10	4.16
S16	−49	−1	−22	19	−54	12.30
S17	−19	−10	−25	23	−30	1.81
S18	−48	−8	2	23	−32	17.45
S19	−48	−13	11	24	−25	39.56
S20	−16	−9	−68	14	−79	8.75
S21	−7	5	−94	13	−83	2.50
S22	1	−34	−13	24	−22	0.76
S23	0	0	0	0	0	0.00
S24	0	0	0	0	0	0.00
S25	−40	1	14	28	2	12.21
S26	−45	6	57	34	51	3.09
S27	−48	5	195	50	203	0.85

Of those sectors that experienced an increase in energy consumption embodied in exports between 2007 and 2012, the largest increases were in S27 (other service activities), S5 (nonmetal mining), and S10 (paper and products for culture, education, and sports), with the latter experiencing an increase exceeding 200%. In 20 of the 27 sectors, energy intensity declined, which means that the majority made technical improvements to reduce energy consumption. By contrast, the input structural effect increased embodied energy consumption in 14 of the 27 sectors, with increases exceeding 10% in S22 (production and distribution of electricity and heat), S11 (refined petroleum products, coking products, and nuclear fuel products), and S19 (communications, computers, and other electronic equipment and apparatuses). The export structural effect decreased embodied energy consumption in 11 of the 27 sectors, with the drop exceeding 50% in S21 (other industrial activities), S20 (instruments, meters, and cultural and office machinery), and S14 (metal smelting and rolling). However, it increased embodied energy consumption in 12 sectors, with the rise exceeding 100% in S10 (paper and products for culture, education, and sports) and S27(other service activities). The export scale increased embodied energy consumption in 23 of the 27 sectors, with the largest impact (a 50% rise) in S5 (nonmetal mining) and S27 (other service activities). The sectors that contributed most to energy consumption embodied in exports were S19 (communications, computers, and other electronic equipment and apparatuses) and S14 (metal smelting and rolling). Both achieved significant reductions in their exports' embodied energy consumption, though with different principal drivers: The technical effect for S19 and the export structural effect for S14.

5. Conclusions and Policy Implications

This study focused on the energy consumption embodied in Guangdong's exports during and in the aftermath of the global financial crisis. We constructed a method to calculate the energy consumption embodied in exports and the contributors to changes therein from 2007 to 2012. The main conclusions from our findings are as follows:

(1) From 2007 to 2012, despite the global financial crisis, growth in exports from Guangdong remained fast. Changes to the export structure in Guangdong are reflected in low energy intensity industry experiencing faster growth in exports than high energy intensity industry.
(2) The growth rate of embodied energy consumption in Guangdong's exports is slowing, with average annual growth from 2007 to 2016 of 5.1%. The energy structure is also becoming cleaner. Through technical change, the energy intensity of most industries has decreased sharply, especially for high energy intensity industries such as metal smelting and rolling.
(3) Though Guangdong's exports grew significantly, the energy consumption embodied therein decreased by 23% from 2007 to 2012, representing a drop of 50.51 Mtce. The most important driver was technical change, which contributed 146% of the reduction in total embodied energy consumption.
(4) In terms of sector-level changes, the largest increase in energy consumption embodied in exports from 2007 to 2012 was in metal smelting and rolling. The most prominent change driver differed across sectors. For low value-added industries, such as metal smelting and rolling, the main contributor was export structure change, while for high value-added industries, such as communications, computers, and other electronic equipment, the main contributor was technical change.

Energy consumption embodied in exports attracts much attention with regard to environmental equity in trade. The energy consumption embodied in exports have decreased considerably in Guangdong in recent years because of changing patterns of regional productions and the changing role in global supply chains. Guangdong is playing a leading role in industrial upgrading in China, and this has made the embodied energy consumption decreased obviously in Guangdong, it will be interesting to further investigate the trends of embodied energy consumption of other provinces in China, this would give us deeper understanding of Chinese resource and environment problems. Going forwards, Guangdong should maintain focus on transforming and upgrading traditional industries, which could promote the upgrading of exports and further change the export structure, thereby continuing to reduce embodied energy consumption.

The calculation of embodied energy is an important topic in regional environmental studies. In this paper, we combine the input-output table to comprehensively calculate the embodied energy consumption in export. This method could also be adopted in researching other environmental problems like the calculation of ecological footprint and embodied pollutions. Because of its comprehensiveness, we are able to make a real understanding of the environmental problems brought along with economic development, and set significant guidance for future policy making. However, our calculating method still investigates change on a macro level. It will be better to combine the investigation methods on both a macro and micro level, in order to have more accurate results of embodied energy consumption. Therefore, related topics still worth developing in the future.

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