Analysis of Deconstructing and Decoupling Carbon Emissions Embodied in the Industrial Chain: the Case of Guangdong Province

Genglin Dong[a,b,c], Ying Huang[b,c], Daiqing Zhao[a,b,c], Cuiping Liao[a,b,c,*]

[a]School of Energy Science and Engineering, University of Science and Technology of China, Hefei, 230026, Anhui, China
[b]Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou, 510640, Guangdong, China
[c]University of Science and Technology of China, Hefei, 230026, Anhui, China

*Corresponding author. Email address: liaocp@ms.giec.ac.cn (C.-P. Liao)

Abstract. The design of effective and scientifically grounded policies for carbon mitigation relies on a thorough understanding of carbon emission sources and their relationship with economic growth. However, this relationship is rarely analyzed from an industrial chain perspective, particularly over long-term periods. This study compiled time-series carbon emission inventories and input-output tables for 127 industrial sectors, employed multi-temporal structural path analysis to trace carbon emissions and economic benefits embodied in the industrial chain, and introduced the decoupling theory to examine the relationship between carbon emissions and economic growth in Guangdong. The results show that: 1) A few industrial chains dominate the carbon emissions and economic benefits of the entire industrial system, with chains such as *cement → construction* and *electricity and heat production → electricity and heat production* emerging as major carbon emission pathways. 2) The carbon footprint hotspot has shifted significantly within the industrial chain system, with carbon emissions from chain activities such as *electricity and heat production → real estate* increasing dramatically. 3) Nearly 10% of carbon emissions remain insufficiently decoupled from economic growth in key chain activities. These findings are expected to guide the formulation of carbon abatement policies and the allocation of carbon abatement responsibilities from an industrial chain perspective, thereby supporting the achievement of regional dual-carbon targets.

Keywords: Industrial chains; Carbon emissions decoupling; Sustainable development; Structural path analysis.

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1 Introduction

As the world's largest carbon emitter, China has implemented a series of policies aimed at controlling carbon emissions from energy-intensive industries. However, various industries are interconnected. Energy-intensive industries emit substantial amounts of carbon in producing intermediate inputs essential for downstream sectors. Despite the relentless efforts by these industries to achieve low-carbon development, uncontrolled downstream demand continues to drive significant carbon emissions [1]. Additionally, China's energy-intensive production model generates substantial emissions that are often economically inefficient in the industrial chain, creating a significant gap between environmental degradation and economic growth. This imbalance in China maintains high levels of energy and carbon intensities globally, with only slow declines [2,3]. To effectively address the practical challenges of reconciling carbon reduction with economic growth, it is necessary to study the sources of carbon emissions and their relationship with economic growth within industrial chains [4].

Embodied carbon emissions (ECE), based on the consumption accounting principle, capture carbon emissions across the supply chain, including raw material extraction, intermediate processing, merchandising, and final consumption [1,5,6]. Similarly, embodied value added (EVA) measures the economic benefits embedded in production and consumption within the supply chain [2,7]. Recent studies have used input-output (IO) models to estimate ECE at national, regional, and sectoral levels to guide the allocation of carbon reduction responsibilities [5,6]. Others have assessed the sustainability of sectoral production and the decoupling of carbon emissions from consumption-side economic growth [8-10]. However, few studies have examined the process of ECE release or its dynamic relationship with economic growth within the industrial chain.

Intermediate producers within the chain significantly influence ECE and EVA through their production characteristics [11]. Managers need to understand this information about key stakeholders such as producers and buyers to design targeted carbon reduction measures. Structural path analysis (SPA) provides a practical framework for analyzing ECE and EVA within specific industrial chains, enabling more informed production chain management [4,12]. However, computational limitations previously constrained its application. With recent advances in computational software, SPA has increasingly been used to study the carbon, energy, and other atmospheric emission characteristics of industrial chains [2,13,14]. Despite this progress, many studies neglect the differences in carbon emissions and economic benefits of various inputs or industrial chains, as well as the decoupling relationship between them. Existing studies indicate that restructuring inputs and reducing emissions from energy-intensive industrial chains are effective measures to narrow the gap between environmental degradation and economic development [15,16]. However, achieving this requires a comprehensive understanding of carbon emissions and economic benefits within the chain. Policies based solely on emissions may inadvertently push downstream consumers to adopt low-emission, low-value-added inputs, potentially threatening the economy's overall sustainability.

Furthermore, existing studies often focus on single time points, overlooking the significant impact of China's evolving supply chain and demand patterns on industrial chain characteristics and carbon emissions [7,17]. Current approaches also frequently rely on aggregated input-output models to match carbon emission inventories across broad industrial sectors, which can lose critical information within the industrial chain network and reduce the accuracy of results [17,18]. In sum, the inadequate disclosure of environmental-economic impacts in industrial chains leaves a critical knowledge gap for assessing and improving regional sustainability.

To address these gaps, this study employs a multi-temporal SPA model to trace carbon emissions and economic benefits embodied in Guangdong's industrial chain and introduces the decoupling theory to analyze the relationship between carbon emissions and economic growth within the chain. The study aims to identify efficient and refined carbon mitigation pathways, allocate mitigation responsibilities more effectively, and guide the region in achieving its carbon mitigation targets while promoting sustainable economic growth.

This research advances the current literature in several ways: 1) It traces industrial carbon emission sources and their relationship with economic growth across a multi-sectoral system within the industrial chain from a multi-temporal perspective. 2) It compiles detailed time-series carbon emission inventories and environmental-economic input-output framework for 127 industrial sectors, preserving the complex information within the chain and improving result accuracy.

Guangdong was chosen for the study for the following reasons. First, achieving national carbon mitigation targets heavily depends on regional contributions. Guangdong, as China's largest emitter, with the highest GDP and largest population, plays a pivotal role in meeting national reduction goals. Second, Guangdong's advanced manufacturing and export-oriented economy, combined with its role as a policy demonstration area, makes it highly representative for interpreting the implications of relevant carbon mitigation policies. The study's results will provide valuable lessons for other regions facing similar carbon reduction challenges.

2 Methods and Materials

2.1 Environmental-economic Extension of Input-output Analysis

Input-output models can quantify relationships between inputs and outputs of different activities in an economic system. It has been extended to many areas such as energy use, resource footprints, and other issues. The basic model is given as follows:

$$X = AX + Y \tag{1}$$

Where X is the total output vector; A is the technology coefficient matrix; and Y is the final demand vector. The original input-output tables follow the competitive import hypothesis for Guangdong. That is, the technical matrix and final demand include both domestically-produced and imported input. As the research focuses on the distribution and flow of emissions and economic benefits in domestic production, following previous studies [3,18], we eliminated the impact of imports on domestic production. The domestic input matrix can be derived as:

$$A^d = \left(I - diag(\frac{X^m}{X+X^m-f^e})\right) A \quad (2)$$

Where I is the unit matrix; X^m is the import vector; and f^e is the export vector. Then, the basic equations of the Leontief model including only domestic supply chains can be derived as:

$$X = (I - A^d)^{-1} Y^d = L^d Y^d \quad (3)$$

$$Y^d = \left(I - diag(\frac{X^m}{X+X^m-f^e})\right) Y \quad (4)$$

Where $L^d = (I - A^d)^{-1}$ is the Leontief inverse matrix; Y^d is the domestic final demand after removing imports. The environmental and economic extension input-output model is obtained by treating emissions and value-added as exogenous transactions of sectoral activities [18]. It can be used to calculate the embodied emissions and value-added in the production process from intermediate inputs in supply chains. Thus, the ECE and EVA can be calculated as follows:

$$ECE = f(I - A^d)^{-1} Y^d \quad (5)$$

$$EVA = v(I - A^d)^{-1} Y^d \quad (6)$$

Where f direct emissions coefficient vector and v is the direct value-added coefficient vector.

2.2 Structural Path Analysis

SPA allows clear tracking of production information along the chain in an industrial network. To investigate the carbon emissions and economic benefits of industrial chains, we invoked SPA. Based on the Taylor series expansion of the Leontief inverse matrix, ECE and EVA can be assigned to different production layers and production chains. The model is constructed as follows:

$$ECE = f(I + A^d + {A^d}^2 + {A^d}^3 + \cdots)^{-1} \widehat{Y^d} = \underbrace{f\widehat{Y^d}}_{layer1} + \underbrace{fA^d\widehat{Y^d}}_{layer2} + \underbrace{fA^2\widehat{Y^d}}_{layer3} + \cdots \quad (7)$$

$$EVA = v(I + A^d + {A^d}^2 + {A^d}^3 + \cdots)^{-1} \widehat{Y^d} = \underbrace{v\widehat{Y^d}}_{layer1} + \underbrace{vA^d\widehat{Y^d}}_{layer2} + \underbrace{v{A^d}^2\widehat{Y^d}}_{layer3} + \cdots \quad (8)$$

Where $f{A^d}^t\widehat{Y^d}$ and $v{A^d}^t\widehat{Y^d}$ denote the ECE and EVA generated in production layer $t+1$, respectively [4], and internal element denotes the industrial chain path. Taking $f_i a_{ik}^d a_{kj}^d y_j^d$ and $v_i a_{ik}^d a_{kj}^d y_j^d$ in the second layer as examples, they denote the ECE and EVA generated by specific sector i in producing intermediate inputs, induced by final demand of sector j through specific intermediate sector k, respectively. It is denoted as the industrial chain path of "*Si*→*Sk*→*Sj*". The direction of the arrow is the flow direction of ECE and EVA along a specific production chain. The number of paths increases dramatically with production layers [13,18], eventually approaching infinity; while the path value decreases with increasing path length [18]. The truncation method is commonly applied to determine the number of production layers to be studied [12]. We examined paths up to production layer 3 and used coverage greater than 0.01% of total ECE and EVA to distinguish critical industrial chain paths [2,14]. We identified the most critical industrial chain paths during the study period by the rule of (Paths2007 > 0.01%)∩(Paths2012 > 0.01%)∩(Paths2017 > 0.01%).

2.3 Decoupling Analysis of the Relationship Between Carbon Emissions and Economic Growth in the Industrial Chain

Decoupling analysis helps to study the dynamic relationship between environmental factors and economic growth. It excels in quantifying the coupling between energy consumption, carbon and pollutant emissions and economic growth by calculating the elasticity coefficients [9,10]. In the study, it allows to classification the coupling relationship between ECE and EVA into 8 states by calculating decoupling index (TDI) [19]. The TDI can be calculated as:

$$TDI_* = \frac{\%\Delta ECE_*}{\%\Delta EVA_*} = \frac{ECE_*^t - ECE_*^0}{ECE_*^0} / \frac{EVA_*^t - EVA_*^0}{EVA_*^0} \tag{9}$$

Here TDI_* is the decoupling index of ECE and EVA in production activities at different levels. ΔECE_* and ΔEVA_* is the change in ECE and EVA in the target year relative to the base year, respectively. Table 1 gives the detailed decoupling state divisions and associated abbreviations.

Table 1. Division of the decoupling state.

%ΔECE	%ΔEVA	TDI	States	Abbre.
>0	>0	0≤TDI≤0.8	Weak decoupling	WD
>0	>0	0.8<TDI<1.2	Expansive coupling	EC
>0	>0	1.2≤TDI	Expansive negative decoupling	END
<0	>0	TDI<0	Strong decoupling	SD
<0	<0	1.2≤TDI	Recessive decoupling	RD
<0	<0	0.8<TDI<1.2	Recessive coupling	RC
<0	<0	0≤TDI≤0.8	Weak negative decoupling	WND
>0	<0	TDI<0	Strong negative decoupling	SND

2.4 Data Sources

Five types of data from 2007, 2012, and 2017 were used in this study: input-output tables, price indexes, carbon emission inventories, final demand inventories, and value added inventories. Guangdong publishes the input-output tables every five years, and the latest data is based on 2017. Therefore, the study period of this paper is limited to

2007-2017. The time series input-output tables were from the Guangdong Provincial Bureau of Statistics [20]. Since the sectoral classifications were not consistent across time points, we harmonized the sectoral classifications in input-output tables into 127 subsectors based on the International Classification for National Economic Activities [21]. Price indices that are used for the compilation of the constant price input-output tables were collected from the National Bureau of Statistics [22]. Sectoral final demand inventories and value-added inventories can be extracted from the recompiled constant price input–output tables based on non-competitive assumptions. Sectoral carbon accounting includes fossil fuel combustion and industrial process emissions. Sectoral energy consumption data for 2007-2017 were collected from the China Emission Accounts and Datasets [23]. As the initial energy data are only applicable to 47 aggregated sectors, we created a mapping between input-output sectors and energy sectors. We aggregated the subsector output from input-output tables to the sectoral classifications used in the energy data, then calculated the carbon emissions coefficients of aggregated sector. We further assume that subsector that map to the one aggregated sector have the same carbon emissions coefficient to recalculate the carbon emissions based 127 subsectors [3].

3 Results and Discussion

3.1 Carbon Emissions Embodied in the Industrial Chain

We tracked the footprints of carbon emissions and economic benefits along the industrial chain paths in Guangdong. Table 2 presents the statistical analysis results of the critical paths with a coverage of 0.01% as the threshold. The results show that no more than 130 (50) industrial chain paths can account for nearly 50% of the total carbon emissions (economic benefits). As the coverage increases, the number of critical paths increase significantly. This implies that a small number of industrial chain paths dominate the carbon emissions and economic benefits of the entire industrial system, and it is worthwhile to focus on the carbon footprints within these critical paths for effective ECE management [4,12]. Notably, economic structural changes seem to contribute to the divergence of carbon emissions hotspots during 2007-2012. During this period, the number of critical paths identified by the threshold increased significantly from 632 to 682. Meanwhile, although the number of critical chain paths increases significantly for the constant ECE coverage, the paths contributing to economic growth instead have become increasingly concentrated.

Table 2. Structural path analysis results of ECE and EVA in Guangdong, 2007-2017.

	Year	Total	Coverage	Number of paths contributing a percentage of total ECE and EVA						
				30%	40%	50%	60%	70%	80%	90%
ECE	2007	632	70.4%	16	36	78	182	596	>632	
	2012	682	66.0%	27	60	130	326	>682		
	2017	617	73.5%	11	26	57	134	373	>617	

	2007	648	79.0%	10	20	40	82	201	>648	
EVA	2012	642	79.6%	11	20	36	73	185	>642	
	2017	608	82.8%	11	18	33	63	130	399	>608

This demonstrates significant changes in the characteristics of the industrial chain system. The critical industrial chain path extracted based on a single time set does not effectively meet the needs of carbon mitigation policymaking [17]. Thus, we identified 328 critical industrial chain paths for reducing industrial carbon from a multi-temporal perspective, responsible for 245-333 Mt of carbon emissions and 2.1-4.9 trillion RMB of economic benefits in Guangdong, corresponding to 56-65% of total emissions and 55-57% of total economic growth. Overall, these chains commonly originate from energy-intensive industries such as *Ceramic products(S54)*, *Steel rolled products(S58)*, and *Electricity and heat(S90)*. This analysis reveals the flow of carbon emissions from energy-intensive industries through the industrial chain, thus providing more valuable information for carbon reduction strategies.

We observed significant shifts in carbon hotspots within the industrial chain system. The ECE coverage and rankings of certain paths changed markedly during the study period. For example, the ECE coverage of *Electricity and heat(S90)→Real estate(S108)* increased dramatically from 0.04% in 2007 to 1.2% in 2017, with its ranking rising from 203rd to 11th. Conversely, the ECE coverage of *Electricity and heat(S90)→Construction(S93)* decreased significantly, from 7% in 2007 to 2% in 2017. Overall, the carbon coverage of 148 critical industrial chain paths collectively increased by 23%, while the carbon coverage of the remaining 180 paths collectively declined by 21% during 2007-2017. This calls for a trade-off between effectiveness and urgency in chain-related carbon regulation [13,14]. Table 3 further lists 20 carbon emission paths that deserve strict regulation, as their carbon emissions grown rapidly and the corresponding carbon coverage increased from 12% in 2007 to 30% in 2017. Among them, carbon emissions increased significantly by 56 Mt from industrial chain activities related to internal production in the e *Electricity and heat(S90)* during 2007-2012, warranting focused attention.

Table 3. Top 20 ranked crucial paths for ECE in Guangdong, 2007–2017.

	Industrial chain path	ECE-2017 (Mt)	Change (%)
1	*Electricity and heat(S90)*	54.4	5.64
2	*Electricity and heat(S90)→Electricity and heat(S90)*	21.8	2.45
3	*Road transportation(S96)*	11.8	1.43
4	*Ceramic products(S54)*	12.7	1.39
5	*Electricity and heat(S90)→Real estate(S108)*	6.2	1.15
6	*Electricity and heat(S90)→Electricity and heat(S90)→Electricity and heat(S90)*	8.7	1.05
7	*Wholesale and retail(S94)*	6.6	0.54
8	*Electricity and heat(S90)→Electricity and heat(S90)→Real estate(S108)*	2.5	0.46
9	*Steel rolled products(S58)→Metal Products(S62)*	2.4	0.43

10	*Road transportation(S96)→Construction(S93)*	4.5	0.42
11	*Electricity and heat(S90)→Education(S119)*	2.4	0.39
12	*Ceramic products(S54)→Electronic components(S85)*	2.1	0.38
13	*Electricity and heat(S90)→Wholesale and retail(S94)*	2.2	0.35
14	*Ceramic products(S54)→Construction(S93)*	3.3	0.3
15	*Electricity and heat(S90)→Electronic components(S85)*	2.6	0.28
16	*Road transportation(S96)→Wholesale and retail(S94)*	2.3	0.28
17	*Steel rolled products(S58)→Automobile manufacturing(S72)*	1.5	0.27
18	*Gypsum, cement products(S51)*	1.6	0.26
19	*Rail transport(S95)*	1.9	0.23
20	*Electricity and heat(S90)→Ceramic products(S54)*	1.9	0.2

3.2 Decoupling of carbon Emissions Embodied in the Industrial Chain

For overall industrial system, the decoupling status is classified as weak decoupling, attributed to Guangdong's shift from crude to intensive economic growth, which has gradually reduced reliance on carbon emissions. Fig. 1 presents the statistical results of the decoupling status of carbon emissions and economic growth for 328 critical industrial chain paths during 2007-2017. Among these, 50 paths achieved the optimal strong decoupling, with their carbon emissions decreasing from 24 to 14 Mt CO_2. These chains consistently traded lower environmental costs for high economic effects, achieving 13% of total EVA with 3% of total ECE in 2017. Meanwhile, 138 industrial chain paths exhibited weak decoupling, with their carbon emissions increasing from 110 to 237 Mt CO_2. During the study period, these chains achieved a 3.4-fold expansion in economic value-added, while emissions grew by only 1.2 times. Technological advancements have enabled these chains to achieve economic growth while controlling emissions. This also is a fundamental reason for Guangdong's overall weak decoupling status.

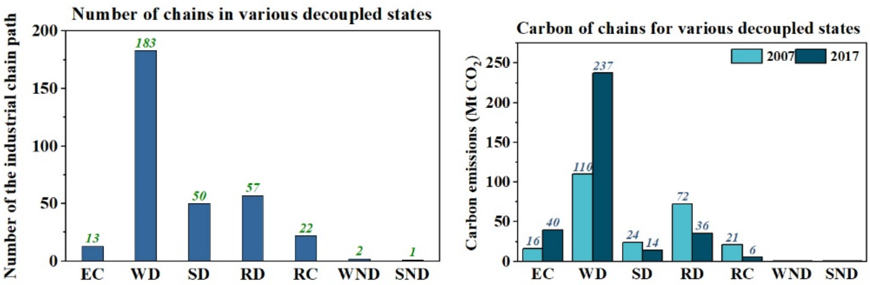

Fig. 1. Decoupling status of ECE and EVA for industrial chain path in Guangdong, 2007-2017.

However, 38 industrial chain paths failed to achieve effective decoupling, emitting 46 Mt CO2 in 2017, representing 10% of total carbon emissions. Among these, 13 chains exhibited expansive coupling, as shown in Table 4. This indicates that economic growth still costs high emissions growth in these chains. For example, the *Wholesale and retail(S94)→Construction(S93)* chain experienced faster emissions growth than economic value-added. Targeted reduction measures should be implemented for such production chains.

Table 4. The industrial chain path of the expansive coupling state of carbon emissions in Guangdong, 2007-2017.

Industrial chain path	ECE-2017 (Mt)	TDI	DS
Ceramic products(S54)	12.74	0.83	EC
Gypsum, cement products(S51)→Construction(S93)	6.99	0.89	EC
Wholesale and retail(S94)	6.62	1.12	EC
Ceramic products(S54)→Construction(S93)	3.31	0.81	EC
Construction(S93)	2.19	0.91	EC
Ceramic products(S54)→Electronic components(S85)	2.07	0.87	EC
Agricultural products(S1)	1.66	1.06	EC
Gypsum, cement products(S51)	1.58	0.95	EC
Ceramic products(S54)→Ceramic products(S54)	1.40	0.84	EC
Accommodation(S102)	0.40	1.10	EC
Wholesale and retail(S94)→Construction(S93)	0.39	1.08	EC
Ceramic products(S54)→Ceramic products(S54)→Construction(S93)	0.36	0.83	EC
Wholesale and retail(S94)→Household appliances(S79)	0.10	1.11	EC

4 Conclusion

This study compiled a time-series carbon emissions inventory for 127 industries, applied multi-temporal structural path analysis to deeply trace the carbon emissions and economic benefits embodied in Guangdong's industrial chain, and employed decoupling theory to investigate the decoupling of carbon emissions from economic growth embodied in the industrial chain. The results will help to develop more precise and effective carbon abatement policies and responsibility allocation from an industrial chain perspective, while the methodology will provide a reference for addressing similar issues in other regions. The primary conclusions are as follows:

1) A small number of industrial chains dominate the carbon emissions and economic benefits of the entire industrial system. Fewer than 130 (50) industrial chain paths account for over 50% of total carbon emissions (economic growth), highlighting the need to focus on the critical industrial chain for carbon reduction.

2) The carbon hotspots have shifted significantly within the industrial chain system. Carbon emissions from key industrial chain paths such as *electricity and heat → construction* have declined, whereas emissions from chains such as *electricity and heat → real estate* have increased considerably. The carbon regulation within the industrial chain requires balancing urgency and efficiency, with particular attention needed for internal industrial chain activities related to electricity and heat production.

3) Although aggregate industrial carbon emissions and economic growth exhibit signs of decoupling, nearly 10% of carbon emissions remain insufficiently decoupled

from economic growth in key industrial chain activities. The economic growth of industrial chain activities such as *gypsum and ceramic products → construction* and *ceramic products → electronic components* are still paid for by high growth in carbon emissions. Targeted carbon management measures are essential for these segments to ensure Guangdong's sustainable development.

The SPA based on the input-output model is a powerful tool for analyzing carbon reduction within industrial chains. As economic globalization progresses, the transnational flow of resources and factors has become increasingly prevalent, making cross-regional industrial chain management and collaborative carbon reduction critical for achieving climate stability. Future research will aim to extend this framework to the multi-regional input-output model for examining cross-regional carbon emissions. Future research can also apply this framework to study the impact of economic development on carbon decoupling during and after the new crown epidemic. Finally, further IO tables and carbon emission inventories at successive points in time could be developed to exhaustively track the evolution of carbon decoupling in the chain.

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