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Demand-driven air pollutant emissions for a fast-developing region in China

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HIGHLIGHTS

- Consumption-based emissions for 7 air pollutants in Guangdong in 2007 and 2012 were estimated.
- Consumption-based emission patterns varied from production-based ones.
- Half of the air pollutant emissions were related to export.
- Production-end control, industrial structures and final demands explained emission trends.
- Guangdong was moving towards a cleaner production and consumption pathway.

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ABSTRACT

Guangdong is one of many fast-developing regions in China that are confronting the challenges of air pollution mitigation and sustainable economic development. Previous studies have focused on the characterization of production-based emissions to formulate control strategies, but the drivers of emission growth and pattern changes from the consumption side have rarely been explored. In this study, we used environmentally extended input-output analysis with well-established production-based emission inventories to develop a consumption-based emission inventory for seven pollutants in the years 2007 and 2012. The results showed that the demands of construction, transport and other services dominated the emissions from the consumption perspective, followed by electric power and some machinery and light industries. The varying trends of air pollutants from 2007 to 2012 were associated with production-based control measures and changes in economic structure and trading patterns. From the consumption perspective, due to the stringent control of SO_2 in power plants and key industries, the SO_2 emissions underwent substantial declines, while the less controlled PM_{10}, $PM_{2.5}$, VOC and CO emissions continued to grow. The contributions of the cleaner (that is, with lower emission intensity) service sectors (third-sector industries, excluding transport, storage and post) to all seven pollutants increased. This increase could be a consequence of the expansion of the service sector in Guangdong; in this five-year period, the service sector grew by 41% in terms of its contributions to Guangdong's gross domestic product. Meanwhile, exports accounted for more than half of the emissions, but their share had started to decrease for most pollutants except VOC and CO. The results suggest that Guangdong moved towards a cleaner production and consumption pathway. The transformation of the industrial structure and increase in of urban demand should help to further reduce emissions while maintaining economic development.

1. Introduction

The air pollution problem in China, characterized by a high concentration of $PM_{2.5}$ (particulate matter with an aerodynamic

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diameter of less than 2.5 μm) and persistent haze, has raised extensive concerns domestically and internationally. The origins of air pollution are closely related to the rapid urbanization and industrialization processes in China, especially in the fast-developing regions along the coastline [1]. The economic growth in these regions has been accompanied by severe air pollution, and these areas are now confronting the challenge of pollution mitigation and earnestly exploring new approaches to sustainable development.

Guangdong province is a microcosm of China's fast-developing regions. Located on the coast of southern China, the province occupies approximately 1.9% of China's land coverage but contributed 6.6% and 10.6% of the national population and gross domestic product (GDP), respectively, in 2015 [2]. From 2007 to 2015, the GDP of Guangdong grew at an annual rate of 11% [2]. The highly dense population and intensive industrial activities have led to notable air pollution and deteriorating air quality in recent decades.

To address the air pollution problem, Guangdong, along with adjacent Hong Kong, is taking a lead role in China in emission reduction and air quality improvement measures [3]. Dating back to 2003, the governments of Guangdong and Hong Kong signed the Pearl River Delta Regional Air Quality Management Plan to pursue regional reductions in sulphur dioxide (SO_2), nitrogen oxide (NOx), PM_{10} (particulate matter with an aerodynamic diameter of less than 10 μm) and volatile organic compound (VOC) emissions [4]. By 2010, the reduction targets for SO_2, NOx and PM_{10} had been fulfilled compared to the reference level of 1997, but reductions in VOC emissions failed to meet the goal. Nevertheless, the air quality in Guangdong was under control, largely due to these efforts. Compared with the levels in 2007, the SO_2, NO_2 and PM_{10} concentrations in 2015 decreased by 63%, 16% and 29%, respectively, while ozone (O_3) increased by 6% [5]. In 2012, the two governments endorsed a succeeding emission reduction plan that would further reduce the air pollutant emissions up to 2020 [4]. Determining how to meet the emission reduction target and improve regional air quality while maintaining economic growth and the local living standard is a challenge for Guangdong and a key task of policy-makers.

In the past few decades, many studies conducted in Guangdong have endeavoured to clarify the causes of air pollution. In terms of bottom-up emission accounting, following the localization of emission factors [6–8], chemical source profiles [7,9,10], the spatial allocation method [6,11–13] and an emission processing system [7], a series of highly temporal and spatially resolved emission inventories for SO_2, NOx, carbon monoxide (CO), PM_{10}, $PM_{2.5}$, VOC, black carbon (BC), organic carbon (OC), ammonia (NH_3), mercury and others have been developed [6,8,10,14–18]. These inventories serve as fundamental data to understand the emission contributors from the production end and to support air quality simulations and forecasts [19–22]. In addition, ambient concentrations of multipollutants were monitored, and a top-down receptor model was applied to characterize the emission sources [23–27]. These studies laid the groundwork for emission reduction and air pollution control in Guangdong province and contributed to air quality improvement in recent years [3]. However, such efforts generally focused on production-based emissions, while the causes from the consumption perspective and the economic and social drivers remain largely unknown. Because Guangdong is an important exporting province in China, further reduction of air pollutants will require not only production-based measures but also consumption-end measures and stimulations. These measures should be built on a thorough understanding of air pollutant emissions from the consumption perspective.

Consumption-based accounting allows the tracking of emissions along production supply chains and associates the emissions with different final demands [28–33], yet the advantages and benefits of this method are not fully manifested in the understanding of air pollution causes, especially at the regional- and city-level scales. There is a wealth of literature on the consumption-based accounting of greenhouse gas emissions [34–38]. For example, Feng et al. (2013) [39] studied the carbon emissions embodied in products in Chinese cities, and Mi et al. (2016) [40] calculated the consumption-based CO_2 emissions for 13 cities in China and examined the relationship between trading patterns and carbon emissions. In terms of air pollutants, the body of literature is much thinner, and most studies are focused on the broader global or national scales. Concerning international trade, Zhang et al. (2017) [41] linked global air pollution and related mortality to the production and consumption of goods and services in different world regions, combining input-output (IO) analysis and other models. At the national scale, Huo et al. (2014) [42] examined production- and consumption-based air pollution in China and found substantial differences between the two accounting approaches. Guan et al. (2014) [43] decomposed the socioeconomic drivers of China's primary $PM_{2.5}$ emissions based on environmentally extended input-output (EEIO) analysis and found that exports was the only final demand category that drove China's emission growth between 1997 and 2010. Zhao et al. (2015) [44] assessed the air pollution embodied in interprovincial trade in China, providing a valuable understanding of how the pollutants were triggered and transferred through economic and trade activities. These studies demonstrated the advantages and effectiveness of consumption-based accounting in understanding the socioeconomic causes and impacts of air pollutions. To support bottom-up air pollution regulation and control from a local perspective, however, more regional- and city-level investigations are required. This is especially true for fast-developing regions such as Guangdong province, where the emission reduction potentials of end-of-pipe treatments and other production-end measures are becoming exhausted due to the stringent control measures in recent years [18,45].

Therefore, this study examines the air pollutant emissions in Guangdong province in 2007 and 2012 from the consumption perspective to obtain a proper understanding of the demand-driven emissions in this province and to determine how they evolved over half a decade, with the aim of supporting further air pollution controls.

2. Methods and data

In this study, consumption-based emissions driven by different final demands for seven air pollutants (SO_2, NOx, CO, PM_{10}, $PM_{2.5}$, VOC and NH_3) in Guangdong province in 2007 and 2012 were calculated and compared to the production perspective. The methods and data sources are described below.

2.1. Environmentally extended input-output model for consumption-based accounting

EEIO analysis has increasingly been used to study the drivers and causes of regional and global environmental changes associated with air pollutant emissions [41–44]. This method was used to calculate the consumption-based emissions in this study.

The methodological framework of IO is built upon the delineation of sectoral outputs with interindustry flows and final demands. The total outputs of sectors in a given economy can be defined as

$$\boldsymbol{X} = \boldsymbol{Z} + \boldsymbol{F} = \boldsymbol{AX} + \boldsymbol{F} \tag{1}$$

where $\boldsymbol{X}$ is the total output of n sectors; $\boldsymbol{Z}$ is the direct requirement matrix between sectors; $\boldsymbol{F}$ represents the matrix of final demands;

and $\boldsymbol{A}$ is the IO coefficient matrix, representing the ratios of sector inputs to sectoral outputs.

The above framework is for noncompetitive single-regional input-output tables (IOTs), which do not consider the influence of imports. Most IOTs, however, are competitive ones with import columns. Therefore, adjustments were made to exclude the interference of imports. Following previous studies [42,43,46,47], it was assumed that import products were used proportionally in the direct requirement matrix $\boldsymbol{Z}$ and final demand $\boldsymbol{F}$, which can be adjusted with a reduction ratio of s_i and k_i:

$$s_i = \frac{f_{import(i)}}{x_i + f_{import(i)} + f_{inflow(i)}} \tag{2}$$

$$k_i = \frac{f_{inflow(i)}}{x_i + f_{import(i)} + f_{inflow(i)}} \tag{3}$$

$$\boldsymbol{Z_d} = (\boldsymbol{I} - \boldsymbol{S}^{\wedge} - \boldsymbol{K}^{\wedge}) \times \boldsymbol{Z} \tag{4}$$

$$\boldsymbol{A_d} = (\boldsymbol{I} - \boldsymbol{S}^{\wedge} - \boldsymbol{K}^{\wedge}) \times \boldsymbol{A} \tag{5}$$

$$\boldsymbol{F_d} = (\boldsymbol{I} - \boldsymbol{S}^{\wedge} - \boldsymbol{K}^{\wedge}) \times \boldsymbol{F} \tag{6}$$

where $\boldsymbol{x_i}$ is the output of sector i; $\boldsymbol{f}_{import(i)}$ and $\boldsymbol{f}_{inflow(i)}$ are the imports (international) and inflow (interprovincial) of sector i in the final demand matrix, respectively; $\boldsymbol{I}$ is the identity matrix; $\boldsymbol{S}^{\wedge}$ and $\boldsymbol{K}^{\wedge}$ are the diagonal matrixes of $[s_1, \ldots s_i, \ldots, s_n]$ and $[k_1, \ldots k_i, \ldots k_n]$, respectively; and $\boldsymbol{Z_d}$, $\boldsymbol{A_d}$ and $\boldsymbol{F_d}$ are the adjusted values of the direct requirement matrix, IO coefficient matrix and final demand matrix, respectively.

Then, an environmental indicator was incorporated into the analysis. The production-based emission intensity, $\boldsymbol{\epsilon} = [\epsilon_1 \ldots \epsilon_i \ldots \epsilon_n]$, which is the air pollutant emissions per unit of monetary output of a sector, was used to calculate the total amount of emissions caused by final demands:

$$\boldsymbol{E} = \boldsymbol{\epsilon}^{\wedge} (\boldsymbol{I} - \boldsymbol{A_d})^{-1} \boldsymbol{F_d} \tag{7}$$

where $\boldsymbol{E}$ is the matrix of emissions driven by final demands for n sectors and $\boldsymbol{\epsilon}^{\wedge}$ is the diagonal matrix with elements of $\boldsymbol{\epsilon}$ on its main diagonal and other elements equal to 0. The emissions caused by different final demands and by different IO sectors were generated in this way. Thus, the embodied emission intensity of IO sectors can be calculated by dividing the sectoral emissions from rural consumption, urban consumption, government consumption, capital formation and exports by sectoral GDP.

In this study, the EEIO analysis is built upon the single-region IO model with the intent of providing detailed accounting of demand-driven emissions from the consumption end, including those embodied in imports and exports. However, the exact provinces or countries from which these embodied emissions come or into which they flow cannot be identified.

2.2. Data sources

IOTs, production-based emission inventories of air pollutants, and proxies for emission mapping were the key data demands in this study. The IOTs for the years 2007 and 2012 were provided by the Bureau of Statistics in Guangdong province [48]. These tables include final demands from rural consumption, urban consumption, government consumption, fixed capital investment, capital inventory change, exports, imports and inflow. Fixed capital investment generally refers to the investments on the addition of new tools and equipment and real estates that require to create and house the products. Capital inventory change stands for the changed value on the prices of fixed capital within a certain time. In the final demand matrix, we grouped the fixed capital investment and capital inventory changes into one category, "capital formation", for further analysis.

The production-based emission inventories for SO_2, NOx, CO, PM_{10}, $PM_{2.5}$, VOC and NH_3 for the years 2007 and 2012 for Guangdong province were developed using the established frameworks and methodologies by Zheng et al. (2009) [12], Lu et al. (2013) [18], Pan et al. (2014) [49], Ou et al. (2015) [10], Yin et al. (2015) [6], and others [50] with activity-level data from statistical

Table 1
Category of the 18 sectors.

No.	Sector	Sectors in IOT[a]
1	Agriculture	(1) Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy
2	Food Processing	(6) Food Processing, Food Production, Beverage Production, Tobacco Processing
3	Garments	(8) Garments and Other Fibre Products, Leather, Furs, Down and Related Products
4	Timber Processing	(9) Timber Processing, Bamboo, Cane, Palm and Straw Products, Furniture Manufacturing
5	Paper Products	(10) Papermaking and Paper Products, Printing and Record Medium Reproduction
6	Chemical Products	(12) Raw Chemical Materials and Chemical Products, Medical and Pharmaceutical Products, Chemical Fibre, Rubber Products, Plastic Products
7	Non Metallic Mineral Products	(13) Non Metallic Mineral Products
8	Smelting and Pressing of Metal	(14) Smelting and Pressing of Ferrous and Nonferrous Metals
9	Transportation Equipment	(18) Transportation Equipment
10	Electric Equipment	(19) Electric Equipment and Machinery
11	Telecommunications Equipment	(20) Electronic and Telecommunications Equipment
12	Electric Power	(25) Electric Power and Heat; (26) Steam and (27) Water Production and Supply
13	Construction	(28) Construction Industry
14	Transport and Storage	(30) Transport, Storage and Post
15	Other Services	(29) Wholesale and Retail Trade; (31) Hotels, Catering Service; (32) Information Transmission, Computer services and Software; (33) Finances; (34) Real state; (35) Leasing and commercial services; (36) Research and Experimental Development; (37) Water conservancy, Environment and Public Facilities Management; (38) Service to Households and Other Service; (39) Education; (40) Health, Social Security and Social Welfare; (41) Culture, Sports and Entertainment; (42) Public Management and Social Organization
16	Others	(2) Coal Mining and Dressing; (3) Petroleum and Natural Gas Extraction; (4) Ferrous and Nonferrous Metals Mining and Dressing; (5) Non-metal and Other Minerals Mining and Dressing; (7) Textile Industry; (11) Petroleum Processing and Coking, (16) Ordinary Machinery; (17) Equipment for Special Purpose; (21) Instruments, Meters Cultural and Office Machinery; (22) Artworks and other manufactures; (23) Waste; (24) Metal Products and Maintenance;
17	Rural direct emission	Fossil fuel combustion for rural residents; wood burning; straw burning; rural household solvent usage
18	Urban direct emission	Fossil fuel combustion for urban residents; urban household solvent usage

[a] Number in the blanket was the order of sector in the input-output tables.

yearbooks at the provincial and city levels [2,51] and local environmental statistical data. The frameworks and methodologies have been used to develop a set of highly temporal and spatially resolved bottom-up emission inventories in the Pearl River Delta region and Guangdong province that are used as recognized data input for air quality simulations in this region [20–22].

To match the production-based emission inventories with IOTs, the 42 production sectors in Guangdong's IOTs were aggregated into 26 sectors (see Supporting Information Table S-1). In Section 3, the 26 sectors are further grouped into 16 sectors in which some less significant sectors are aggregated as "Others" (see Table 1). In addition, some production-based emissions, e.g., fossil fuel combustion for residential usage, wood burning, straw burning and household solvent usage, do not involve intersectoral flow and are relevant to the urban and rural direct demand [42,47]. Therefore, in addition to the 16 sectors, 2 more categories – rural and urban direct emissions – are included for analysis and discussion. During the mapping process, the energy data from the Guangdong energy balance table [2], the Guangdong census [2], and the China Emission Accounts and Datasets (CEADs, http://www.ceads.net/) [52] were used as proxies to allocate the aggregated emissions to residential and service sectors and household solvents.

The uncertainty of this work is introduced mainly by the input data, especially from the production-based emission inventory and IOT. The uncertainty of production-based emissions varies based on the pollutants. Generally, the uncertainty is lowest for SO_2 emissions, followed by NOx. Compared to these two pollutants, the accounting of PM_{10}, $PM_{2.5}$, CO and VOC is associated with higher uncertainties. The development of an IOT also involves uncertainty in data collection and in national accounting and statistics systems. Despite the inherent uncertainty of the input data, we believe that the analysis provided in this study is robust and is the best available approach since the reliability of the production-based inventory has been demonstrated by air quality models and since the IOT is the only official data available for IO analysis.

3. Results and discussion

3.1. Comparison of sectoral contribution patterns from the production and consumption perspectives

Fig. 1 compares the contribution patterns of the 16 IO sectors from the production (outer pie) and consumption (inner pie) perspectives in 2012. Production-based emissions are an estimate of the emissions from all production activities within the target sector. Consumption-based emissions, on the other hand, account for the emissions embodied in all the supporting sectors throughout the national economy that are caused by the demand of a certain sector. For the purposes of the following discussion, the demand of a certain sector specifically includes the demand from rural consumption, urban consumption, government consumption, capital formation and exports. As shown in Fig. 1, the production-based source contributions varied based on the pollutants, but most pollutants, except NH_3, shared similar source contribution patterns from the perspective of consumption.

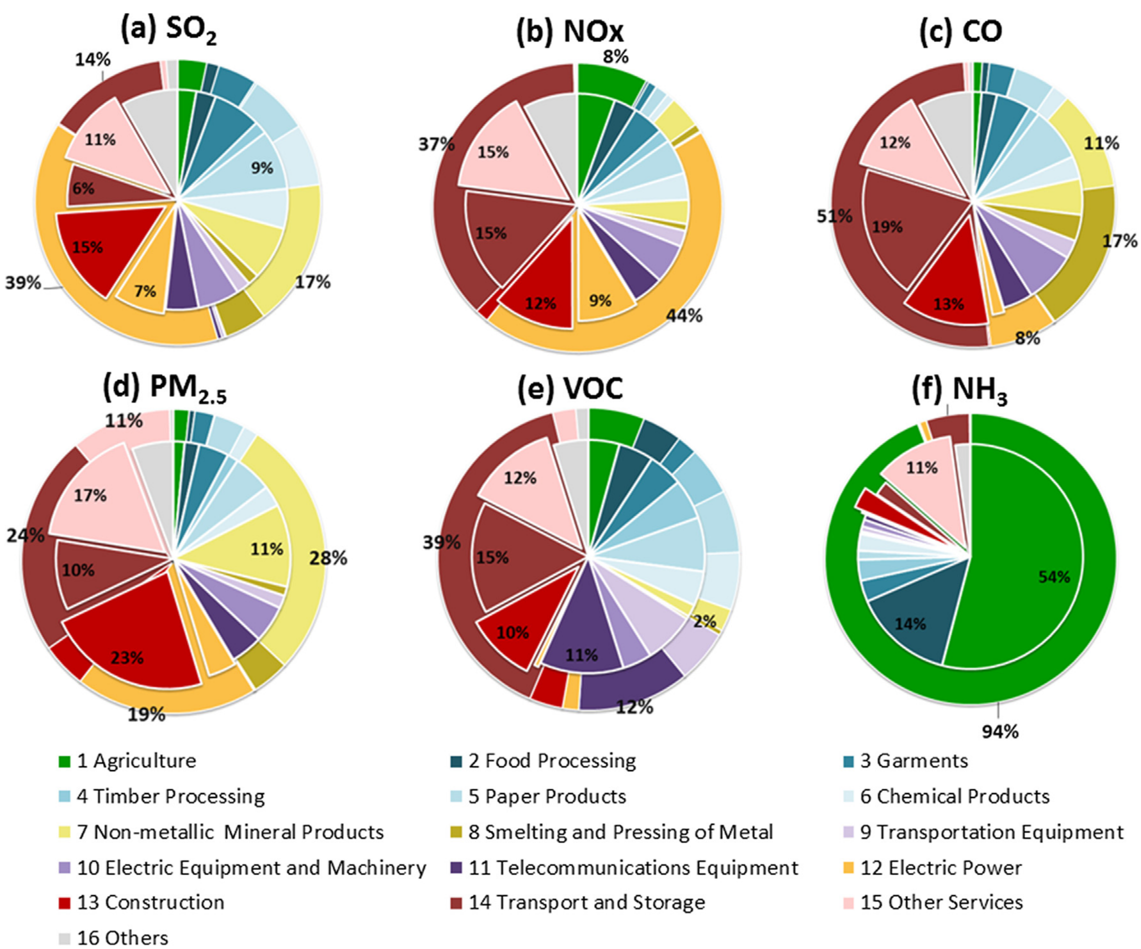

Fig. 1. Source contributions from production (outer pie) and consumption (inner pie) perspectives for SO_2, NOx, CO, $PM_{2.5}$, VOC and NH_3 in Guangdong in 2012.

For SO_2, electric power, non metallic mineral products and transport were the three dominant contributors in production, constituting 39, 17 and 14% of the production-based emissions from the IO production sectors (excluding rural and urban direct emissions), respectively. The electric power sector includes electric power, heat generation, and steam and water production and supply, as shown in Table 1. The large emissions from non metallic mineral products were attributed mainly to the production of cement, arising from the combustion of fossil fuel as well as industrial processes. From the perspective of consumption, however, the contributions of these three sources decreased to 7, 8 and 6%. Instead, construction and other services were the largest contributors, responsible for 15 and 11% of the emissions, respectively. Similar characteristics were observed for NOx, CO, PM_{10} and $PM_{2.5}$. According to the production-based accounting, electric power, transport, non metallic mineral products, and the smelting and pressing of metal accounted for over 60% of NOx, CO, PM_{10} and $PM_{2.5}$ emissions. Their subtotal of contributions decreased to less than 30% from the consumption perspective, while the proportions of construction, other services and transport were highest.

With respect to VOC, its production-based emissions are related more to vehicles and industrial processes that involve the extensive use of VOC-containing products such as paints and adhesives. Consequently, its production-based emissions relied greatly upon transport (39%) and light industries such as telecommunication equipment (12%). From the consumption perspective, light industries were still important contributors, but the proportion of transport decreased to 15%. Other services and construction accounted for 12 and 10% of emissions, respectively. For NH_3, agriculture dominated its production-based emissions with a 94% contribution. The contribution of agriculture declined to 54% on the consumption side, accompanied by increased proportions of food processing (14%) and other services (11%). Specifically, the consumption-based NH_3 emissions from agriculture were related to the emissions from direct agricultural product consumption and the indirect emissions embodied in other sectors such as fertilizers in chemical production sectors. The high consumption-based emissions of agriculture were mainly associated with its high self-demand on agricultural products.

The differences between the consumption and production perspectives were associated with the emission flows between IO sectors. Large amounts of SO_2, NOx, CO, PM_{10} and $PM_{2.5}$ production-based emissions caused by fossil fuel combustion from electric power, non metallic mineral products and transport were indeed caused by the demands of other IO sectors such as construction and services. The production-based NH_3 emissions from agriculture were related to agriculture's own demands as well as those from the food processing and other service sectors.

3.2. Sectoral emissions from production and consumption in 2007 and 2012

The seven pollutants showed different emission trends over the half decade from 2007 to 2012. Emissions of SO_2 (including urban and rural direct emissions) underwent a decline of 28%, while NOx, CO, PM_{10}, $PM_{2.5}$, VOC and NH_3 grew by 1.4%, 26%, 8.6%, 8.5%, 31% and 10%, respectively. Changes in sectoral emissions from the consumption and production perspectives are shown in Fig. 2 and discussed below. Note that the numbers at the top of Fig. 2 correspond to the sectors in Table 1.

From a production perspective, the decrease in SO_2 emissions was attributed to the substantial emission reductions in the three largest sources – electric power (Sector 12), transport (Sector 14) and non metallic mineral products (Sector 7), which decreased by 38%, 19% and 9%, respectively. This decrease resulted from the stringent SO_2 control measures that were implemented during the 11th and 12th five-year plans (2006–2010 and 2011–2015) and led to an increase in the penetration rates of desulphurization treatments and usage of low-sulphur coal in power plants and large industrial boilers. In terms of consumption, the largest contributor – construction (Sector 13) – showed a decline of 42%. Other important contributors, such as transport, non metallic mineral products, and telecommunication equipment (Sector 11), also declined by varying degrees. The emissions of paper products (Sector 5) and other services (Sector 15), however, rose by 37% and 6.4%, respectively.

Regarding NOx, the production-based emissions from power plants generally remained loosely controlled until 2010, when denitrification processes such as selective catalytic reduction (SCR) were required for electric sectors and large industrial sources. Thanks to these measures, the NOx emissions from the electric sector were curbed and decreased by 1.3% from 2007 to 2012. This decrease suggests that the NOx control measures were effective, but more time is still required to further increase the penetration rate of NOx treatments and achieve substantial NOx emission reduction. Meanwhile, emissions from transport increased by 7%. From the consumption viewpoint, emissions from construction and telecommunication equipment decreased by 32% and 41%, respectively. However, emissions from other major contributors – other services, transport and electric power – increased by 59%, 10% and 27%, respectively.

The production-based emissions of $PM_{2.5}$ were mainly composed of non metallic mineral products, transport, electric power and rural direct emissions from the burning of wood and straw (Sector 17). From 2007 to 2012, emissions from the electric sector and rural direct emissions decreased by 5.2% and 12%, respectively, while those from non metallic mineral products and transport increased by 19% and 27%, respectively. Viewed from the perspective of consumption, most major contributors experienced an increasing trend except non metallic mineral products (−1.7%). Construction, transport and other services rose by 15%, 28% and 39%, respectively. PM_{10} exhibited a trend similar to that of $PM_{2.5}$.

VOC exhibited a 31% increase over the five years. The production-based emissions of transport and telecommunication increased by 41% and 250%, respectively, accompanied by varying increases from other light industries. Similar increasing trends were observed for consumption-based emissions. Emissions from transport, construction, other services and telecommunication were 38%, 35%, 68% and 70% higher, respectively, in 2012. From the production view, the increase for CO was attributed mainly to transport, while construction, transport and other services explained the growth from the consumption perspective. Regarding NH_3, agriculture explained the emission growth from both perspectives.

The changes in emissions were attributable to different sources based on the points of view of production and consumption. Viewed from the production side, the emissions from power plants displayed a decreasing trend for SO_2 and generally remained stable for other pollutants, such as NOx and $PM_{2.5}$. Most pollutants, except SO_2, from transport, non metallic mineral production and other light industries continued growing, serving as the drivers of the increasing emissions of NOx, PM_{10}, $PM_{2.5}$, VOC and CO. From the consumption perspective, construction, electric power, transport, other services, non metallic mineral productions and some light industries contributed to varying trends in pollutants. The SO_2 and NOx emissions from construction decreased noticeably, but that sector's emissions of $PM_{2.5}$ and VOC rose. With the exception of SO_2, the emissions from transport increased. The emissions of all the pollutants from other services continued growing over the years.

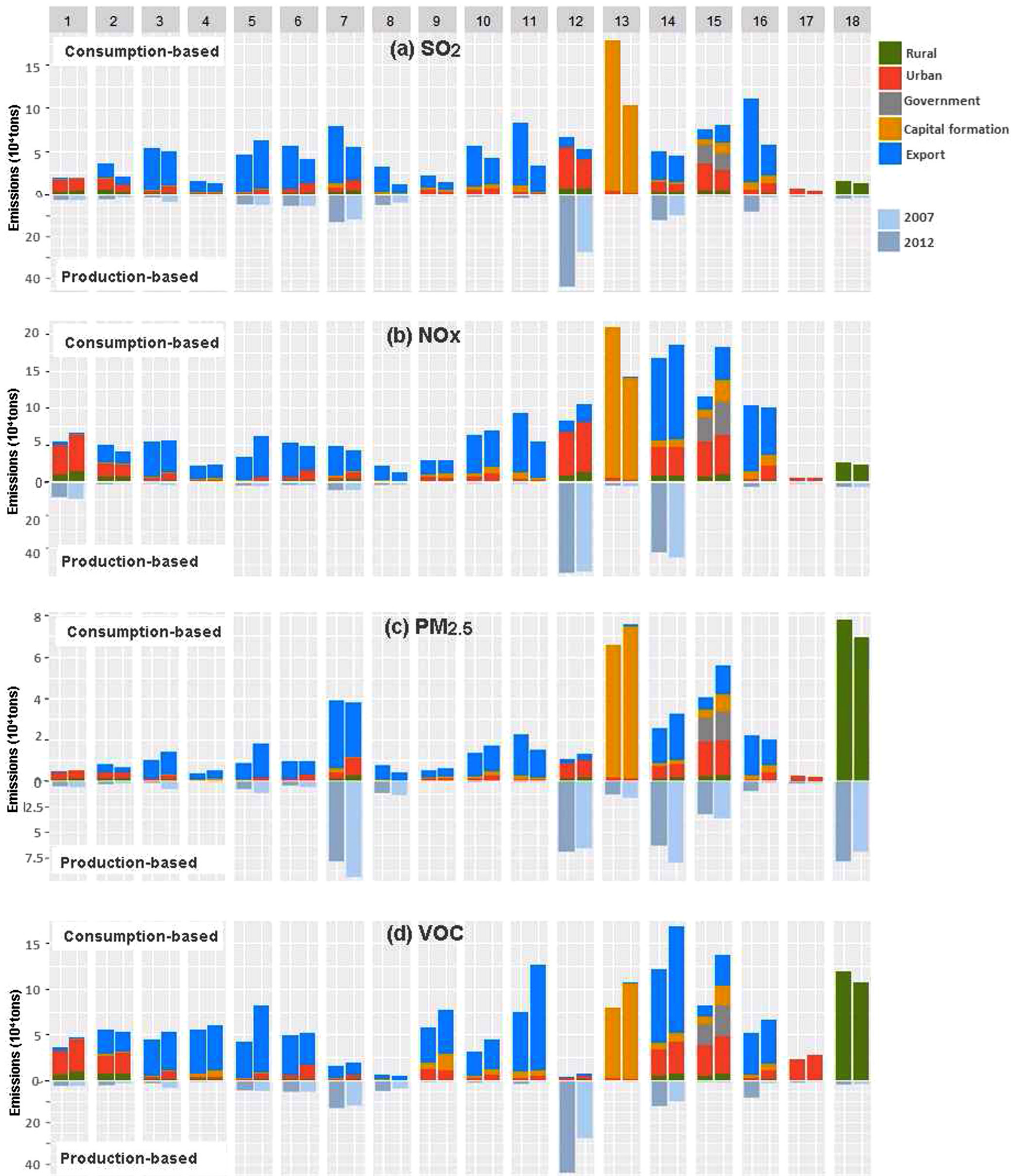

Fig. 2. Consumption-based and production-based emissions of (a) SO_2, (b) NOx, (c) $PM_{2.5}$ and (d) VOC in 2007 and 2012.

3.3. Changes in sectoral sources of contributions and emission intensities

As discussed above, production-based emissions from the electric sector generally displayed a downward trend, while the emissions from transport, non metallic mineral products and some light industries grew at different levels. As a consequence, the source of contribution patterns from the production perspective changed from 2007 to 2012. The contribution of electric power decreased slightly or remained stable, accompanied by increasing

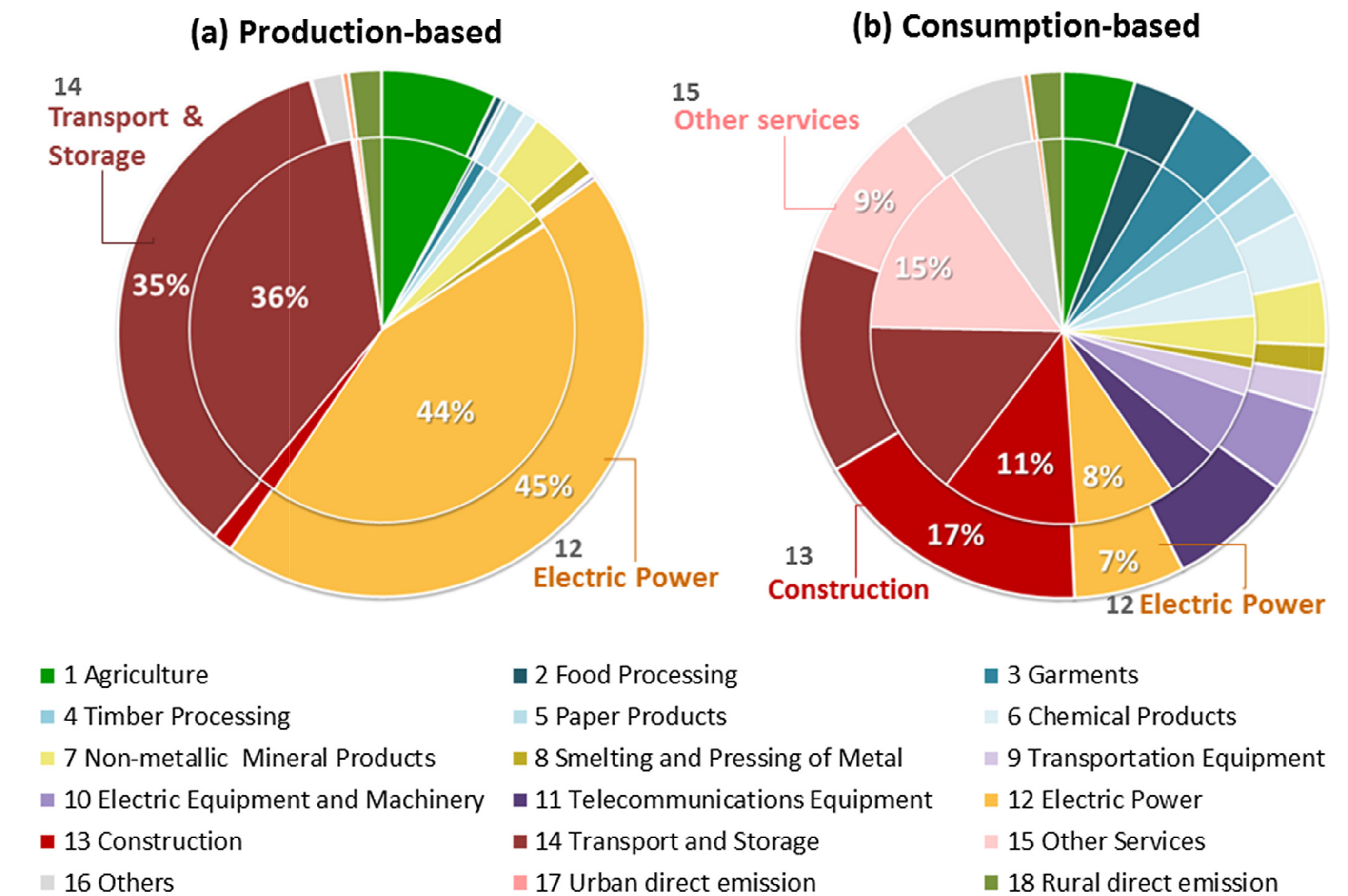

Fig. 3. Changes in NOx source contributions from 2007 (outer pie) to 2012 (inner pie) from (a) production and (b) consumption perspectives.

proportions from transport, non metallic mineral products and light industries, as shown in Fig. 3a.

From the consumption perspective, the change in the source of contribution seems to be more notable than the change in production. Due to the noticeable decreases in absolute emissions (Fig. 2), the relative contributions of construction to SO_2 and NOx emissions decreased noticeably from 18% and 17% in 2007 to 14% and 11% in 2012, respectively. Meanwhile, the proportion of other services played a more prominent role for nearly all the pollutants. This sector's contribution to SO_2, NOx, PM_{10}, $PM_{2.5}$ and VOC from the consumption perspective increased from 8%, 9%, 8%, 11% and 9% to 11%, 15%, 12%, 14% and 11% over the five years, as illustrated in Fig. 3b with NOx as an example.

Concerning the emission intensities by IO sector, both the direct and embodied emission intensities showed a decreasing trend for most sources. Here, the sectoral embodied emission intensities are discussed in detail.

Fig. 4 shows that for SO_2 and NOx, the emission intensity of the power sector (Sector 12) was the highest, followed by that of transport (Sector 14), non metallic mineral products (Sector 7) and construction (Sector 13). All four high emission-loading sectors exhibited a substantial decline, especially for SO_2, from 2007 to 2012. The SO_2 emission intensity of electric power decreased by 56%, and the rates of decrease for the other three sectors were in the range of 54–65%. For NOx, the intensity declined by 30% for the power sector and by 42–59% for other sectors.

Regarding PM_{10} and $PM_{2.5}$, non metallic mineral products and transport showed the highest emission intensities, but those decreased by 35–41% during the half decade. Electric power also had high particulate emission loadings, which declined by approximately 30%. With respect to VOC, the intensity of transport and timber processing (Sector 4) was prominent, showing decreases of 35% and 36%, respectively. The intensities of CO were quite similar for most IO sectors, but they decreased by a much lower rate than those of other pollutants; some intensities even increased. For NH_3, the emission intensities of agriculture and the food processing industry were prominent, with declines of 11% and 40%, respectively. Detailed emission intensities by sectors can be found in Supporting Information Table S-2.

Notably, the sectors with high emission intensities were generally the same as those with high absolute emissions, except other services. This sector constituted 10–20% of the emissions from the consumption perspective, but its emission intensity (Sector 15) was relatively low, as shown in Fig. 4. Taking SO_2 intensity in 2012 as an example, the intensity of electric power was 19 times that of other services. Combined with the fact that other services took a more prominent role in emissions on the consumption side, this finding suggests that Guangdong is moving towards a greener consumption pathway. This movement might benefit from the efforts in emission reductions from the production end and the growing weight of other service industries in Guangdong, which increased from 17% to 24% of the provincial GDP from 2007 to 2012.

3.4. Contributions by final demands

Emissions from the consumption perspective are driven by different final demands. As shown in Fig. 2, with the exception of

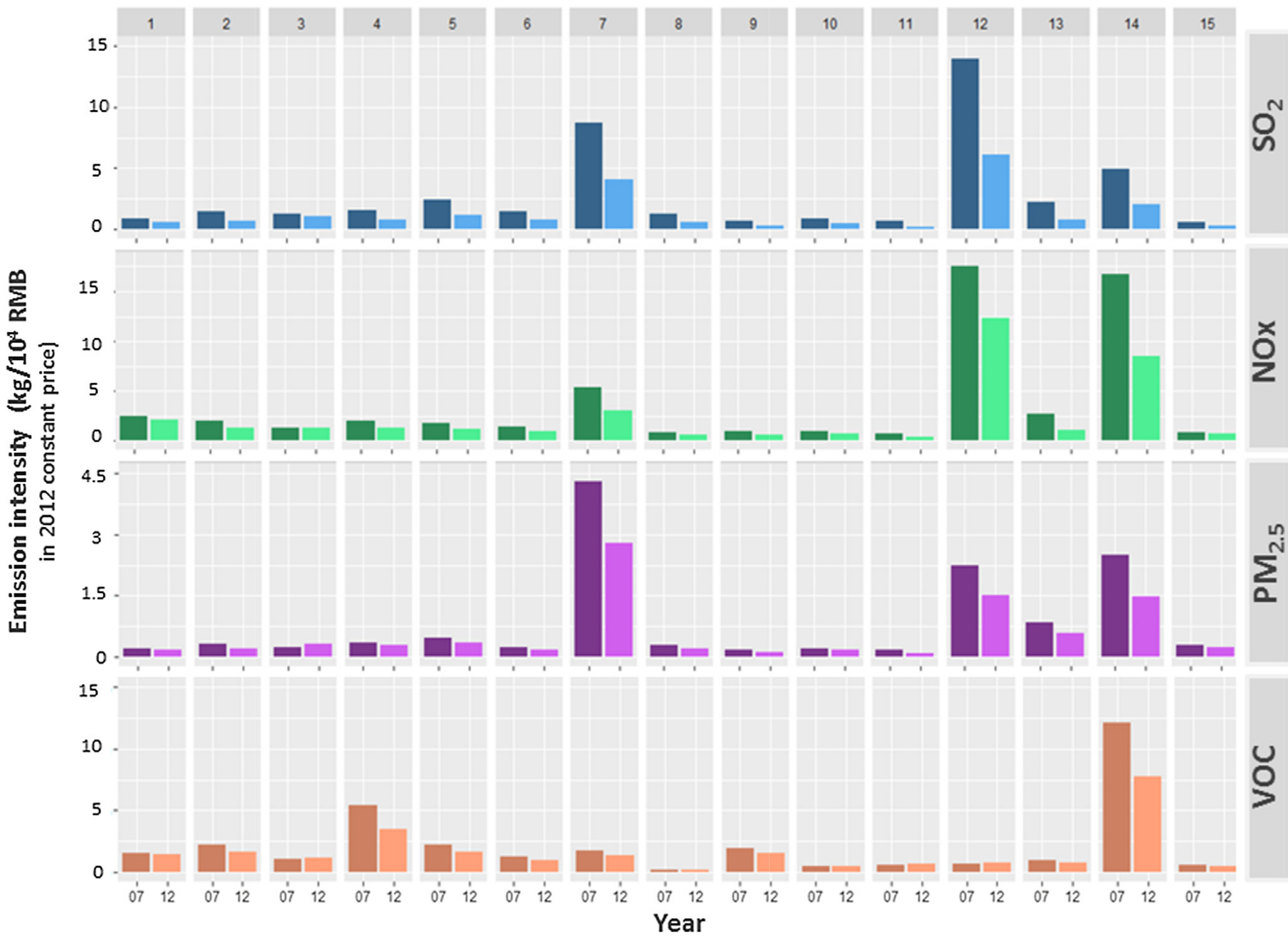

Fig. 4. Embodied emission intensities of SO_2, NOx, $PM_{2.5}$ and VOC in 2007 and 2012.

construction, which was constituted mainly by capital formation, other IO sectors were related to exports and urban consumption. Indeed, exports (including international export and interprovincial outflow) were the most important driver for the emissions of SO_2 (Fig. 5a), NOx, PM_{10}, $PM_{2.5}$ and VOC (Fig. 5c) in Guangdong, accounting for 50% or more of emissions from the consumption perspective. Contributions by final demands for all the pollutants are shown in Supporting Information Table S-3. From 2007 to 2012, the proportion of exports decreased for SO_2, NOx, PM_{10} and $PM_{2.5}$. As Fig. 5c illustrates, the contribution of exports declined from 56% to 50% for SO_2. However, for VOC and CO, the percentages of exports were stable or increased slightly. For all the pollutants, urban consumption made increasing contributions; e.g., its contribution to SO_2 and VOC increased from 16% and 18% to 21% and 19%, respectively, over the five years. This increase is largely due to the urbanization process in Guangdong. From 2007 to 2012, the proportion of the urban population grew from 63.1% to 67.4%, reaching 71.4 million in 2012.

In terms of emission intensities, capital formation and exports had high emission rates of SO_2 (Fig. 5b), NOx, CO, PM_{10} and $PM_{2.5}$. For VOC, the intensities embodied in exports, rural and urban consumptions were high, while those of capital formation and government consumption were low (Fig. 5d). For NH_3, rural consumption was associated with the highest emission intensity, followed by urban consumption. (Emission intensities by final demands for all the pollutants can be found in Supporting Information Table S-4.) During the half decade, the emission intensities of the five final demands generally showed a decreasing trend of varying degrees for different pollutants. Again, SO_2 exhibited the most notable decline, with intensities from capital formation and exports falling by 68% and 57%, respectively. In addition to SO_2, notable declines were observed for NOx, PM_{10} and $PM_{2.5}$. VOC and CO exhibited the lowest degree of decline. For VOC, the emission intensities for exports, rural consumption and urban consumption fell by 24%, 26% and 26%, respectively, declining by only half the amount of SO_2 emission intensities for the same sectors.

Compared to the national average, exports account for an unusually high share of Guangdong's consumption-based emissions, suggesting that Guangdong bears an even higher cost of air pollution and related health problems than the rest of the country due to the embodied emissions in export. As the "world factory", China is recognized as the largest embodied emission exporter in the world [41,53]. According to Huo et al. (2014) [42], exports accounted for 24%, 24%, 15% and 19% of SO_2, NOx, $PM_{2.5}$ and VOC emissions, respectively, in China in 2010. Exports accounted for half of Guangdong's emissions, a proportion that is double the national average. A recent study linking embodied emissions with health impacts showed that the level of premature mortality due to international trade may be higher than that caused by long-distance atmospheric pollution transport [41]. This finding indicates that a very large external cost is probably borne by the people of Guangdong in producing various products for export.

Intriguingly, Guangdong also had high emissions embodied in imports (including international imports and interprovincial

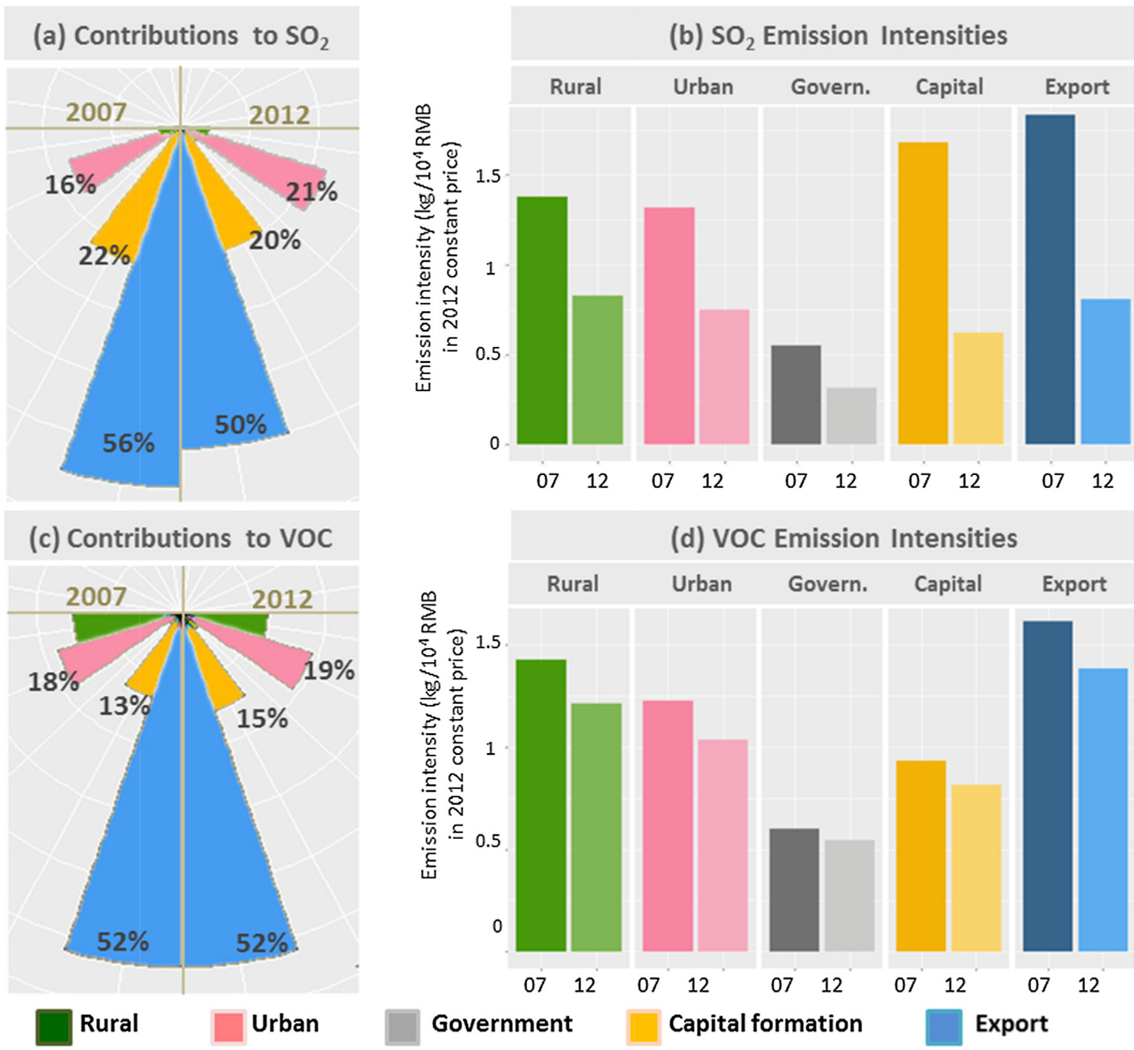

Fig. 5. Contributions and emission intensities by final demands of (a, b) SO_2 and (c, d) VOC in 2007 and 2012.

inflow). As shown in Fig. 6, the embodied emissions of imports were close to those of exports for SO_2, NOx, CO, PM_{10} and $PM_{2.5}$. For NH_3, the emissions from imports surpassed those from exports at 1.55 and 2.04 times the level of export emissions in 2007 and 2012. With respect to VOC, a large proportion of production-based emissions (nearly 45%) were emitted from light industries for export commodities; the embodied emissions of exports remained higher than those of imports, but the gap had narrowed. The embodied emissions of imports were 59% and 72% of those of exports in 2007 and 2012, respectively.

The embodied emissions of imports were generally associated with electric power, construction, agriculture, chemical products, the smelting and pressing of metal, telecommunication equipment and transport. Meanwhile, substantial emissions were embodied in export commodities from telecommunication equipment, transport and several key light industries in Guangdong, e.g., paper products, timber processing, garments and chemical products. The differences between the sectors contributing to embodied import and export emissions reflected the trade characteristics of Guangdong, which relies on electricity, raw materials for manufacturing and agricultural products from other areas to support local production and living demands while exporting large quantities of electrical equipment and machinery, wood furniture, paper products, ceramics, garments and other items for interprovincial or international trade.

4. Conclusions

From 2007 to 2012, the GDP of Guangdong increased dramatically by more than 60%. Meanwhile, Guangdong underwent a 28% decrease in SO_2 emissions, accompanied by stabilized NOx emissions and 26%, 8.6%, 8.5%, 31% and 10% increases in CO, PM_{10}, $PM_{2.5}$, VOC and NH_3, respectively. Using EEIO analysis, we aimed to examine the final demand drivers of the air pollutant emissions of this fast-developing region to gain a better understanding of air pollution causes and their evolution.

First, the traditional major emitters from the production perspective were electric power, transport, non metallic mineral products, and some equipment machinery and light industries. These sources are the targets of the current control measures that track emissions from the production end. From the consumption perspective, however, the contributions from construction, transport and other services were the highest. Substantial emissions from the large production-based emitters were indeed caused by the demands of these sources, which should generate more concern because of their hidden responsibilities for local air pollution.

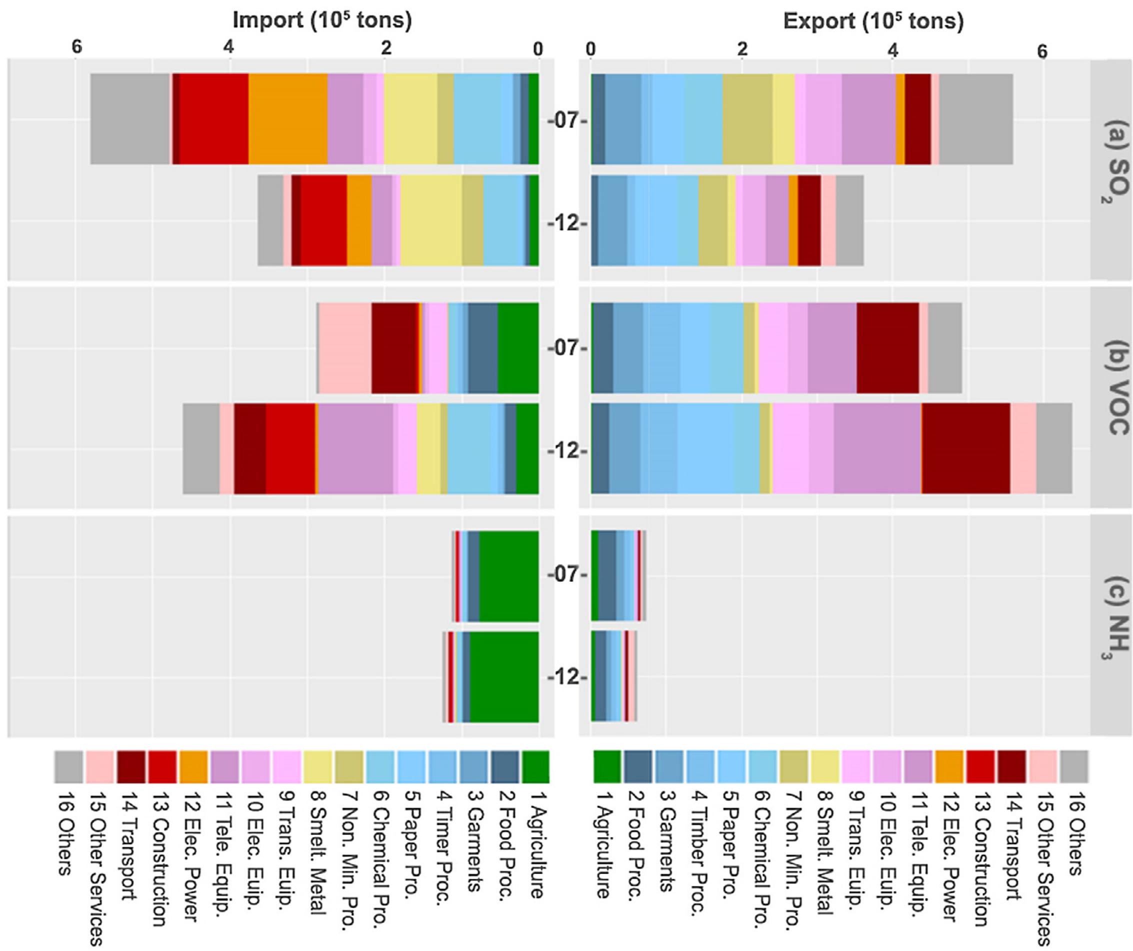

Fig. 6. Air pollutant emissions embodied in import and export in 2007 and 2012.

The trends in the sectors' emission intensities and their contributions to total emissions revealed that Guangdong was making progress in industrial transformation and greener production and consumption. From 2007 to 2012, most of the abovementioned production- and consumption-based emitters saw a decrease of more than 30% in their emission intensities, although their emissions generally displayed an increasing trend (with the exceptions of SO_2 and NOx emissions from electric power and construction) due largely to the dramatic growth of the local population and economy. In sharp contrast to other major emitters, the other services sector had very low emission intensity. In addition, this less emission-intensive sector was taking a more prominent role in the industrial structure with an increasing share in the local GDP (from 17% to 24% over the five years), while the proportion of construction contributions to both emissions and GDP had decreased, suggesting the shaping of a greener industrial structure.

Guangdong had a delicate balance between export- and import-embodied emissions. On the one hand, because Guangdong is the major exporting province in China, more than half of its air pollutant emissions were driven by exports. This figure was twice the national average. Telecommunication equipment, transport and several key light industries in Guangdong, e.g., paper products, timber processing, garments and chemical products, were the major industrial sectors responsible for the large amount of export-embodied emissions. On the other hand, Guangdong also relied heavily on the importing of agricultural products, raw materials, electricity and other items from other areas. Indeed, the embodied emissions of imports for SO_2, NOx, CO, PM_{10} and $PM_{2.5}$ were close to those of exports. The embodied emissions of imports for NH_3 were nearly twice those of exports. However, for VOC, whose emissions were related largely to machinery and light industries of export commodities, the embodied emissions of exports still outweighed those of imports. Notably, the emission intensity of exports was generally the highest among the five final demand categories. Fortunately, the share of export contributions to SO_2, NOx, PM_{10} and $PM_{2.5}$ had started to decrease, accompanied by the growth of less emission-intensive urban consumption. This finding is another positive sign of greener consumption in this region.

In summary, the changes in air pollutant emissions can be explained by the control measures from the production end, the evolution of industrial structures and the final demands. Based upon the results, a few policy implications are provided. In general, consumption accounting should complement the production-based emission inventory to support policy formulation. While the long-standing control measures generally target the pollution producers, the contribution and responsibility of the pollution demander and consumer should be disclosed and considered. This approach is the foundation for the regulator in adjusting and leading consumer behaviour and demand in the less emission-intensive industries. As the relative contribution of urban consumption to air pollutant emissions will continue to grow, more attention should be devoted to guiding urban consumer behaviour towards more energy-economic and environmentally friendly practices. In addition, a high load of air pollutant emissions was embodied in export commodities. While reducing exports might depress the local economy, more stringent measures for emission control, especially for VOC and CO emissions, should be implemented to further reduce emission intensity. Efforts should be continued to transform the industrial structure from an export-reliant industry to a high-value-added, less polluted industry. Finally, the flow of export- and import-embodied emissions also underlines the importance of interprovincial collaboration in combating air pollution, given that both local production and consumption are related to the behaviours of other regions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.06.112.

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