Carbon emissions and their drivers for a typical urban economy from multiple perspectives: a case analysis for Beijing City

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Abstract: Understanding carbon emission profile of cities from multiple perspectives is a prerequisite to design just and effective carbon reduction policies. Previous studies on CO_2 emissions by cities are usually confined to production or consumption-based perspective, while income-based perspective has been neglected. To fill the gap, direct emissions (a.k.a. production-based emissions), upstream emissions driven by final demand (a.k.a. consumption-based emissions) and downstream emissions enabled by primary input (a.k.a. income-based emissions) in an urban economy are comprehensively explored and compared for the first time, taking Beijing as a case. In the period of 2005~2012, *Manufacture of Nonmetallic Mineral Products*/*Construction*/*Processing of Petroleum, Coking, Processing of Nuclear Fuel* is identified as the key contributor to carbon emission by Beijing from the production/consumption/income-based perspective, respectively, indicating each perspective can unveil important information which the other methods fail to discover. Moreover, driving forces of CO_2 emissions change in Beijing are uncovered using the structural decomposition analysis (SDA) from both the demand and supply sides. Emission intensity, production input and output structure change contribute to CO_2 emission decrease in Beijing, which are largely offset by population, final demand/primary input level and final demand/primary input structure change, resulting in a net 3.9 Mt reduction during 2005~2012. While current policies continue to highlight end-of-pipe measures in cities, more attention should be paid to demand (e.g., encouraging low-carbon consumption) and supply side (e.g., controlling capital investment in enterprises with large income-based CO_2 emissions).

Keywords: urban CO_2 emissions; multiple accounting principles; structural decomposition analysis; Beijing

1. Introduction

As the center for population, transportation, energy consumption and business activities, cities are the major contributors to global CO_2 emissions. According to International Energy Agency, 71% of CO_2 emissions come from cities worldwide in 2006 and this share will increase to 76% in 2030 [1]. Among the important CO_2

sources, cities are responsible for 69% and 80% of EU and USA's carbon emissions [2, 3], respectively. As the world's largest energy consumer, cities are responsible for 85% of China's total CO_2 emissions [4]. Regarding the vital role in global CO_2 emissions, cities are considered as key areas in strategies formulated for fighting against global climate change.

The first and fundamental step for proper mitigation policy design is to accurately quantify cities' carbon emissions. Currently, there are three different accounting principles that are widely used: production, consumption and income-based accounting [5-7]. ~~However, a~~Although each of the aforementioned accounting frameworks has its own merits, they have inherent blind spots (detailed reviews of each accounting principle are presented in Section 2.1). ~~In other words, there is no best carbon emission accounting method.~~ Under this circumstance, Steininger et al. [8] argued that carbon emissions accounting under ~~different~~ multiple perspectives are suggested to support fair and effective mitigation strategies and identify some underlying reduction potentials. Moreover, the carbon emissions accounting under different perspectives can be combined as cornerstone for a shared-responsibility [9]. Notably, to the best of our knowledge, ~~this kind of research~~carbon emission accounting at urban scale from three different perspectives ~~on cities~~ ~~have~~ has not been found yet, as our reviews in Section 2.1 suggest that current studies on carbon emission accounting of cities are usually confined to one or two perspectives.

Beside the comprehensive perspectives on carbon emissions, the knowledge about how the carbon emissions change and their underlying drivers also have important policy implications. A prerequisite to meet the carbon mitigation targets without ~~damaging~~ harming domestic competitiveness is to successfully identify the main drivers of the carbon emissions [10]. ~~A considerable amount of studies has been performed to elaborate the driving factors of carbon emissions change by using decomposition analysis, including index decomposition analysis (IDA) [47, 48], structural decomposition analysis (SDA) [49, 50] and production-theoretical decomposition analysis (PDA) [51, 52]. SDA is coupled with input-output analysis,~~

~~enabling it to take the effect of production structure into consideration [53]. Currently, SDA studies have been widely conducted to identify the driving factors of carbon emission change at global [54], national [55, 56], subnational [57], city [49, 58] and even sectoral level [59].~~ That is to say, a robust decomposition analysis on carbon emission driving factors will lead to appropriate policy design. Structural decomposition analysis (SDA) is usually coupled with input-output analysis, enabling it to take the effect of production structure into consideration [11]. As our review in section 2.2 shows, h~~H~~owever~~, these~~, most previous SDA studies are ~~also~~ confined in ~~one~~ demand-side perspective, little is known about the driving factors and their contributions from supply-side ~~multiple~~ perspectives, especially those at city scale. ~~(i.e., both the supply and demand sides). Moreover, the driving factors from the the supply-side perspective which is helpful for identifying new critical emission contributors is left unknown at city scale.~~

Hence, this study aims to fill the knowledge gaps by evaluating the production, consumption and income-based carbon emissions simultaneously ~~–~~and ~~their~~ the major driving forces from ~~multiple~~ supply and demand-side perspectives, using the case of the capital city of China, Beijing. After the United States' withdrawal from the 2015 Paris Agreement, many researchers stated that China, the world's largest direct carbon emitter, can and will lead on climate change [12]. In order to reach emission peak before 2030, China has taken low-carbon cities a priority in mitigating climate change, which has been emphasized in many national plans, such as *National Plan on Climate Change (2014-2020)* and *Work Plan for Controlling Greenhouse Gas Emission during the 13th Five-Year Plan Period (2016-2020)*. Many Chinese cities, including Beijing, have promised to reach the carbon emissions peak around 2020. In order to build a low carbon urban economy as well as play a leading exemplary role for the whole nation, the Municipal Government of Beijing has promised to reach the carbon emissions peak in 2020 or even earlier [13]. As Beijing's carbon mitigation has entered a new stage, it is urgent to draw a holistic picture of Beijing's carbon emissions and furthermore, to identify the driving factors from different perspectives, based on the latest data. It is expected that the study will bring new insights for carbon emissions mitigation actions as well as enlarging the possibilities for future climate policies for Beijing, or even other global cities fighting against the climate change.

The rest of this study is organized as follows: Section 2 reviews the recent advances in multiple accounting principles and structural decomposition analysis at city level; methodology and data adopted in this paper are elaborated in Section ~~2~~3; Section ~~3~~ 4 presents the detailed results; some discussions and policy implications are illustrated in Section ~~4~~5; finally, conclusions are drawn in Section ~~5~~6.

2. Literature review

2.1 Multiple accounting principles

Multiple accounting principles in this study include production, consumption and income-based accounting. The production-based accounting focuses on the carbon emissions emitted within the administrative boundaries, including those caused by exports production [5]. This approach is widely used in global climate change agreements, including the Kyoto Protocol and Paris Agreement. Though most of the previous production-based researches are developed at national scale, city-level emission inventory has attracted ever-increasing attentions [14-16]. Kennedy et al. [17] constructed the greenhouse gas inventories for 22 global cities and investigated the underlying characteristics. Hoornweg et al. [18] reviewed per capita emissions of 100 cities to identify the hotspots for effective mitigation efforts. Besides, emission inventory for many Chinese cities has also been compiled. Sugar et al. [19] provided a comprehensive and detailed emission inventory for Beijing, Tianjin and Shanghai, which are among the highest per-capita emissions in global cities. Yu et al. [20] has drawn the similar conclusion that highly urbanized Chinese cities generated higher per-capita emissions than their European counterparts. Wang et al. [21] and Shan et al.[22] compiled 12 and 20 Chinese cities, respectively. Fang et al. [23] investigated the relationship between urban form and carbon emissions in 30 provincial capital cities. All these studies provide preliminary information for understanding the role of cities in global climate change. However, the adequacy of production-based perspective has also been questioned for it causes carbon leakages which lead to the serious issue of policy efficiency [24, 25]. For example, household in cities consumes a huge amount of electricity produced in the power plants that may not locate in the city boundary, while the production-based perspective neglects the upstream carbon emissions caused by electricity generation [26].

Given the insufficiency of production-based accounting, many researchers argue that besides the direct emissions, carbon emissions embodied in goods and services consumed by the economy but produced in other places should also be taken into consideration [5, 27]. Consequently, the consumption-based perspective, which is able to cover the upstream carbon emissions, is suggested as a supplementary for the production-based perspective for benchmarking cities' carbon emission inventory [28, 29]. For example, Minx et al. [30] evaluated the carbon footprint of citied in UK, which was proved to be determined by socio-economic rather than geographic and infrastructural factors. Long et al. [31] used a multi-regional input-output model to estimate the indirect emissions induced by Tokyo, Japan. Many attentions have also been paid to Chinese cities, among which Beijing, Tianjin, Shanghai and Chongqing are always on the list [32, 33]. A most updated and comprehensive consumption-based accounting database for 13 Chinese cities was constructed by Mi et al. [34]. Besides, more advanced models are developed to assess the consumption-based emissions of cities by taking the domestic and foreign supply chains into consideration, such as multi-scale input-output model [35, 36], city-centric global multi-regional input-output model [37]. A consistent conclusion reached in most of these studies is that cities, especially those heavily rely on service industries, have higher consumption-based carbon emissions than their production-based emissions, indicating that final consumption in cities can displace carbon emissions in other regions. Peters and Hertwich [38] as well as many other researches [39, 40] have highlighted the advantages of consumption-based accounting over production-based accounting in addressing carbon leakage, increasing reduction potential and improving policy fairness. Jacob and Marschinski [41], however, argued that consumption-based accounting maybe misleading for policy makers, as the potential consequences of the trade restriction or adjustment are hard to evaluate.

It should be pointed out that before purchasing goods and services, final consumers should first earn income as suppliers. The supply of primary inputs such as wages and taxes would enable carbon emissions by downstream users via product sale chain, which are usually named as income-based emissions [7]. The accounting for income-based emissions can provide important information for carbon emission reduction policymaking from the supply side. Compared to the large amount of production and consumption-based literature, there has been very limited reports of income-based carbon emissions. For example, Marques et al. [42] found that 18% of global carbon emissions are enabled by the primary inputs abroad. Liang et al. [43] have shown that income-based accounting could provide additional information for emission allocation. Yet no income-based emissions accounting has been carried out at city level. It should also be noted that the there are some debates on the interpretation of the supply-driven input-output model which is used for income-based accounting [44-46].

In summary, each accounting principle has its own pros and cons, making multiple carbon accounting of cities necessary for just and effective mitigation policy design.

2.2 Structural decomposition analysis

A considerable amount of studies has been performed to elaborate the driving factors of energy consumption and carbon emissions change by using decomposition analysis, including index decomposition analysis (IDA) [47, 48], structural decomposition analysis (SDA) [49, 50] and production-theoretical decomposition analysis (PDA) [51, 52]. SDA has its unique strength that it can take the production structure change into consideration, which has been widely conducted to identify the driving factors of carbon emission change at various economic scales.

At global scale, Wang et al. [53] applied SDA to investigate the driving factors of global and national carbon emissions intensity change and found that sectoral emission efficiency improvement was the dominant driving factors of global emission intensity decrease during 2000-2009. By using the SDA, Jiang and Guan [54] found that infrastructure built contributed significantly to emission increase in developing countries during 1995-2009. Moreover, Xu and Dietzenbacher [55] presented a SDA for the emissions embodied in trade. The results have shown that trade structure changes caused uneven growth in embodied emissions in trade between developed and developing economies. SDA has also been conducted at national scale, such as China [56, 57], Singapore [58] and USA [59]. Besides, driving factors of China's regional carbon emissions growth have also been identified by using spatial SDA [60-62].

At city scale, Tian et al. [63], Wang et al. [64]and Wei et al. [65] all focused on the driving forces of carbon emissions in Beijing during 1997-2007, 1997-2010 and 2000-2010, respectively, by applying the SDA. A consistent finding was that carbon emission intensity decrease significantly hampered the emission growth, while the production structure change contributed to the emission increase in Beijing. Besides, Hu et al. [66] explored the determinants behind the GHG emissions change in Chongqing and found that emission intensity and input-output structure drove GHG emission reduction, while the increasing final demand contributed the most to the emission growth.

Notably, most previous SDA studies have been conducted under demand-side perspective (i.e., consumption-based perspective). A few of them have paid attentions to the driving factors from supply-side perspective (i.e., income-based perspective), but only at national scale . For example, Zhang et al. [67] carried out a supply-side SDA to show that supply-side structure, defined as sectoral shares in value added, was the main drivers of carbon emission increase in China during 1992-2002. Liang et al. [59] also argued that supply-side SDA could provide new driving forces for emission change. Yet no efforts have been made to uncover the impacts of supply-side factors (i.e., income-based perspective) on carbon emissions at city scale.

3. Methodology and data

3.1 ~~Multiple~~ Production, consumption and income-based accounting ~~principles~~

Production-based CO_2 emission inventories (*E*) can be compiled by multiplying the amount of different fossil fuel consumption (M) and the corresponding emission factors (EF), as expressed by:

$$E=\sum_{i}^{n} e_i=\sum_{i}^{n} M_i \times EF_i \tag{1}$$

Then, the environmentally-extended input-output analysis (EEIOA) is applied to calculate the consumption-based and income-based CO_2 emissions of sectors. The consumption-based CO_2 emissions of a sector is the direct and indirect upstream emissions caused by the final demand of the sector, while the income-based CO_2 emissions of a sector is the direct and indirect downstream emissions enabled by the primary input of the sector [8, 43]. To trace the upstream and downstream emissions, Leontief inverse matrix ($\boldsymbol{L}$) and Ghosh inverse matrix ($\boldsymbol{G}$) are used. They can be expressed as Eq. 2 and Eq. 3, respectively.

$$\boldsymbol{L}=(\boldsymbol{I}-\boldsymbol{A})^{-1} \tag{2}$$

$$\boldsymbol{G}=(\boldsymbol{I}-\boldsymbol{H})^{-1} \tag{3}$$

where $\boldsymbol{A}$ is the direct input coefficient matrix whose elements represent the direct input needed from other sectors or itself to satisfy unitary production of one particular sector; $\boldsymbol{H}$ is the direct output coefficient matrix whose elements represent the direct output of one particular sector enabled by unitary input from other sectors or itself; $\boldsymbol{I}$ is the identity matrix.

It should be noted that the imports and exports are included in the primary input and final demand, respectively, based on previous studies [59]. Given these, sectoral consumption-based and income-based CO_2 emissions can be calculated by:

$$\boldsymbol{U}=\boldsymbol{f}(\boldsymbol{I}-\boldsymbol{A})^{-1}\hat{\boldsymbol{Y}}=\boldsymbol{f}\boldsymbol{L}\hat{\boldsymbol{Y}} \tag{4}$$

$$\boldsymbol{D}=\hat{\boldsymbol{V}}(\boldsymbol{I}-\boldsymbol{H})^{-1}\boldsymbol{f}'=\hat{\boldsymbol{V}}\boldsymbol{G}\boldsymbol{f}' \tag{5}$$

Say that the economy contains n sectors, then $\boldsymbol{U}$ is a ~~n~~1×~~1~~ n vector, whose elements U_j is the consumption-based CO_2 emissions of sector j. $\boldsymbol{Y}$ is a n×1 vector, which represents the final demand of different sectors; $\boldsymbol{D}$ is a ~~1~~n×~~n~~ 1 vector, whose elements D_j is the income-based CO_2 emissions of sector j; $\boldsymbol{V}$ is a 1×n vector, which represents the primary input of different sectors; $\boldsymbol{f}$ is a ~~n~~1×~~1~~ n vector, whose elements f_j is the

CO_2 emission intensity of sector *j*, defined as the CO_2 emission accompanied with unitary output of sector *j*. The superscript ' is a symbol for transposition and the ︿ means diagonalization of the vector. In this study, final demand includes household consumption, government consumption, gross capital formation, foreign export and domestic export, while primary inputs consist of value added, foreign import and domestic import.

3.2 ~~Structure~~ Structural decomposition analysis

Structurale decomposition analysis (SDA) is a well-acknowledged method to quantify the relative contributions of different socio-economic factors to the total energy consumption and pollutant emissions change [49, 59, 68]. Here we conduct the SDA from consumption-based and income-based perspectives to investigate the relative contributions of both supply-side and consumption-side socio-economic factors to the overall fossil-fuel-related CO_2 emissions in Beijing.

Despite the different distribution of CO_2 emissions among all economic sectors, the total CO_2 emission remains the same.

$$E=\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}\,p=p\boldsymbol{v_l}V_s\boldsymbol{G}\boldsymbol{f}' \qquad (6)$$

where the final demand ($\boldsymbol{Y}$) is viewed as a product of population (p), the final demand structure ($\boldsymbol{Y_s}$) and per-capita demand volume (y_l) and the primary input vector($\boldsymbol{V}$) is viewed as a product of population(p), the primary input structure($\boldsymbol{V_s}$) and per-capita input volume(v_l).

Then a total difference of Eq. 6 generates the decomposition form:

$$\varDelta E=\varDelta\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}p+\boldsymbol{f}\varDelta\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}p+\boldsymbol{f}\boldsymbol{L}\varDelta\boldsymbol{Y_s}\boldsymbol{y_l}p+\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\varDelta\boldsymbol{y_l}p+\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}\varDelta p \qquad (7)$$

$$\varDelta E=\varDelta p\boldsymbol{v_l}V_s\boldsymbol{G}\boldsymbol{f}'+p\varDelta\boldsymbol{v_l}V_s\boldsymbol{G}\boldsymbol{f}'+p\boldsymbol{v_l}\varDelta V_s\boldsymbol{G}\boldsymbol{f}'+p\boldsymbol{v_l}V_s\varDelta\boldsymbol{G}\boldsymbol{f}'+p\boldsymbol{v_l}V_s\boldsymbol{G}\varDelta\boldsymbol{f}' \qquad (8)$$

The item in the left side of these equations ($\varDelta E$) is the change of total CO_2 emissions during a specific period and every item in the right represents the contributions to the total change of one particular socio-economic factor change while others remain constant. For instance, the first item in the right side of Eq. 7 represents the change of CO_2 emissions due to emission intensity ($\boldsymbol{f}$) changes while Leontief inverse matrix ($\boldsymbol{L}$), final demand structure ($\boldsymbol{Y_s}$), per-capita demand level ($\boldsymbol{y_l}$) and population remain constant. It's noted that there are *n*! types of decomposition forms when decomposing the total change into n factors and no one of them is proved to be the best. In this study, we use the average of two polar decompositions and it provides relatively accurate results without complicated calculations [69].

3.3 Data sources

This Energy consumption data are derived from Beijing Statistical Yearbooks [70], which provides detailed information on 8 different types of fossil fuels. The updated emission factor for coal in China is adopted from Liu's study [71], which is assumed to be more accurate than the IPCC default values. In this study, coal samples of 4243 state-owned coal mines (36% of Chinese coal production in 2011) are evaluated while IPCC's default value ignore the differences of fuel contents between regions and countries. Emission factors of other fuels are default values recommended by the Intergovernmental Panel on Climate Change (IPCC) [72]. Detailed emission factors for various fuels are presented in Appendix Table A1.

The monetary input-output tables for Beijing are derived from the website provided by Beijing Municipal Bureau of Statistics. The sector classification of energy consumption in the Beijing Statistical Yearbooks and the Input-Output Tables is different. Therefore, we have made a compatible classification according to GB/4754-2011. The sectors and their codes are presented in Table. 1. To conduct the SDA, a time-series of constant-price input-output tables has been constructed using the double-deflation method [73]. The price indices of all sectors needed for double-deflation method are collected from various sourced, as presented in Appendix Table A2.

4. Results

4.1 Total CO_2 emissions of Beijing

Figure 1(a) shows the variation trend of fossil-fuel related CO_2 emissions (hereinafter referred to as CO_2 emissions) in Beijing during 2005-2012. CO_2

emissions in Beijing have fluctuated within a narrow range between 81.4 and 89.5 Mt, with a slight growing trend during 2005-2007 and a declining trend during 2007-2012. The general trend is consistent with previous studies [4, 22]. Coal use, mainly used for coal-fired power generation, dominates Beijing's CO_2 emissions during the accounting period, accounting for 45-60% of total CO_2 emissions. Benefitting from the energy structure optimization in Beijing [74], coal-related CO_2 emissions has saw annual decreases from 51.9 Mt in 2005 to 36.6 Mt in 2012. Meanwhile, emissions due to coke consumption have been slashed to less than 1.0 Mt. On the other hand, emissions from natural gases increase more than 3 times during 2005-2012 (from 5.0 Mt to 15.4 Mt).

Though CO_2 emissions stagnated during 2005-2012, Beijing's gross domestic production and population has increased by 155% and 35%, respectively. As described in Figure 1(b), emission intensity declines significantly from 122.4 t/million CNY in 2005 to 45.5 t/million CNY in 2012, with an average annual decrease rate of 28%. With regard to per-capita emissions, a continual decrease from 5.5 t/capita in 2005 to 3.9 t/capita in 2012 is identified. Given this, Beijing has made considerable progress in tackling climate change from a production-based perspective.

4.2 Multiple CO_2 emissions accounting of sectors

Figure 2 depicts the sectoral CO_2 emissions of Beijing in 2012 under multiple accounting principles, namely income, production and consumption-based accounting. The PSE directly emits 28.9 Mt CO_2 emissions in 2012, most of which comes from coal consumption. Production-based emissions of PSE are responsible for 35.5% of total emissions, while its income and consumption-based emissions only account for 29.8% and 28.2% of the total, respectively. This result highlights PSE's more important role as producer directly emitting CO_2 emissions than primary supplier enabling downstream emissions and final consumer driving upstream emissions. The similar pattern can also be identified for TSP, MNM (*Manufacture of Nonmetallic Mineral Products*) and PDG (*Production and Distribution of Gas*). Furthermore, some sectors, such as MWC (*Mining and Washing of Coal*), EPN (*Extraction of Petroleum* *and Natural Gas*), SRM (*Smelting and Pressing of Metals*) and FIN (*Finance*), are more important as primary suppliers enabling downstream emissions than producers and final consumers. For example, income-based emissions of SRM are 390% and 310% larger than its production and consumption-based emissions, respectively. What's more, income-based emissions of EPN are even 100 times larger than its production and consumption-based emissions. Besides, MTE (*Manufacture of Transport Equipment*), MCE (*Manufacture of Communication Equipment, Computer and Other Electronic Equipment*), CON (*Construction*) and OSS (*Other Services*) have larger consumption-based emissions than income and production-based emissions, indicating its more important role as final consumer driving upstream emissions than primary supplier and producer.

In brief, Sectors like PSE (*Production and Supply of Electric Power and Heat Power*), TSP (*Transportation, Storage, Posts and Telecommunications*) and OSS (*Other services*) are always at the forefront of different measures, indicating that these sectors play important roles in the CO_2 supply chain in Beijing. However, their relative contributions to total CO_2 emissions under different accounting principles are varied. It will provide multidimensional information on the effects of the sector exert on the total CO_2 emissions in Beijing, making multiple accounting necessary for comprehensively understanding the emission profile of a city.

The temporal change of sectoral income, production and consumption-based emissions is described in Figure 3. From a production perspective, CO_2 emissions of *Production and Supply of Electric Power and Heat Power* gradually increases from 24.7 Mt in 2005 to 28.9 Mt in 2012. The direct CO_2 emissions of *Transportation, Storage, Posts and Telecommunications* nearly doubled during 2005-2012. It should be noted that CO_2 emissions of *Smelting and Pressing of Metals* has witnessed a dramatic decrease from 17.7 Mt in 2007 to 0.3 Mt in 2010, potentially due to the reallocation project of the Capital Steel Company. The project started in 2005 and was not completely finished until the end of 2010 [75]. There is a slight decreasing trend for CO_2 emissions directly emitted by *Manufacture of Nonmetallic Mineral Products* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel*. Moreover, CO_2

emissions of *Other Services* remain relatively stable during 2005-2012. From a consumption perspective, *Production and Supply of Electric Power and Heat Power* has witnessed a sudden increase from 2.4 Mt in 2010 to 23.0 Mt in 2012. Consumption-based CO_2 emissions of *Other Services* increase from 21.2 Mt in 2005 to 25.4 Mt in 2010, followed by a large decrease to 11.7 Mt in 2012. The *Construction* drives less and less upstream emissions during the period. It's consumption-based CO_2 emissions in 2012 are 5.1 Mt, less than one quarter of that in 2005. The upstream CO_2 emissions driven by *Transportation, Storage, Posts and Telecommunications* show ups and downs during 2005-2012. Consumption-based CO_2 emissions of *Smelting and Pressing of Metals* also show a large drop from 5.0 Mt 2007 to 1.1 Mt in 2010. From a income-based perspective, CO_2 emissions of *Production and Supply of Electric Power and Heat Power* grow from 15.8 Mt in 2005 to 24.3 Mt in 2012 with a drop from 20.4 Mt in 2007 to 15.0 Mt in 2010. Similar to the variation identified by production and consumption-based perspective, downstream CO_2 emissions enabled by the primary inputs of *Smelting and Pressing of Metals* encounter a sudden steep decline from 15.9 Mt in 2007 to 1.4 Mt in 2010. Moreover, income-based CO_2 emissions of *Transportation, Storage, Posts and Telecommunications* show a general tendency towards rising, while that of *Other Services*, *Manufacture of Nonmetallic Mineral Products* and *Finance* fluctuate with a relative small range during 2005-2012.

In general, different accounting principles also reveal new variation trend of sectoral CO_2 emissions, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications* and *Other Services*. Besides, a few consistent change patterns can also be identified by different accounting principles, such as the sudden drop of *Smelting and Pressing of Metals* from 2007 to 2010.

4.3 CO_2 emissions allocation by final demand and primary inputs

Figure 4 (a) and (b), from another point of view, show the allocation of Beijing's production-based CO_2 emissions to different primary supply and final demand categories in 2012, respectively. In terms of final demand, domestic export is the dominant contributor, accounting for 67% of total emissions in 2012. Domestic export of CO_2 emissions are mainly through *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications* and *Other Services* (excluding the aggregated *Others*). Gross capital formation ranks second of total emissions embodied in final demand. Of the 8.4 Mt CO_2 induced by Gross capital formation, more than half are contributed by *Construction Industry*. Household consumption is responsible for 6.6 Mt CO_2 emissions in 2012, with relative even distribution in various sectors. In terms of primary inputs, domestic import enables 49.3 Mt CO_2 emissions along the downstream supply chains, accounting for 61% of the total emissions in 2012. *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel* are the three leading sectors. Value added occupies the second position by causing 21.1 Mt CO_2 emissions, which are mainly contributed by *Production and Supply of Electric Power and Heat Power*, *Other Services* and *Transportation, Storage, Posts and Telecommunications*. Foreign import only leads to 13.5% of total emissions.

Moreover, structure variation of the overall CO_2 emissions by final demand and primary input categories during 2005-2012 is demonstrated in Figure 5. From the demand side, there is a distinct trend that Beijing's dominant driver of carbon emissions by final demand is sifting from gross capital formation and household consumption towards domestic export. In a sense, Beijing has transferred from a invest and consumption-driven economy to a export-driven economy. In specific, domestic export takes up an increasing share of the overall emissions driven by final demand, from a proportion of 29% in 2005 to 67% in 2012. Therefore, special attention should be paid to CO_2 emissions of upstream suppliers of these sectors. Gross capital formation has progressively lowered its influences on total CO_2 emissions, whose share of total emissions decreases from 30% to 10% in this period. The same is true of household consumption, as its share of total emissions in 2012 is less than half of that in 2005. Foreign export and government consumption play relative small roles in final demand, leading to 7-16% and 5-12% of Beijing's CO_2

emissions during 2005-2012, respectively. From the supply side, domestic import and value-added are responsible for most of the emissions in Beijing during 2005-2012. They contribute comparably (around 43-44%) to total CO_2 emissions in 2005 and 2007. However, domestic import's share of total emissions decreases to 30% in 2010, followed by a huge increase to 61% in 2012.

4.4 Key drivers of CO_2 emissions from demand and supply sides

The overall CO_2 emissions are determined by many socio-economic factors, such as the population expansion, production structure change and technology improvement. To reveal the relative contributions of different socio-economic factors, the changes of overall CO_2 emissions of Beijing during 2005-2012 are decomposed from both demand and supply sides, as shown in Figure 6.

From the demand side, the largest factor curbing CO_2 emissions during 2005-2012 is emission intensity, which has decreased 62% between 2005 and 2012 (Figure 1). The decline of emission intensity has avoided 140.0 Mt (-164%) CO_2 emissions if other factors had remained constant. Another vital factor in reducing CO_2 emissions is production input structure, whose improvement leads to 49.6 Mt (58%) CO_2 emissions reduction. These efforts have been tempered by per-capita demand growth, population growth and final demand structure change. The per-capita demand level is the largest driver causing the growth of CO_2 emissions during 2005-2012. In this period, it has increased by 4 times at the constant price based on 2010, which could have led to another 132.1 Mt (155%) CO_2 emissions if other factors had remained constant. The population growth and final demand structure change have smaller effects on emissions change, contributing to 26.1 Mt (31%) and 27.5 Mt (32%) CO_2 emissions growth, respectively. From the supply side, increasing per-capita primary input, growing population and final demand together contribute to CO_2 emissions increase by 214% (156%, 31% and 27%, respectively). When integrated with the decreasing emission intensity (-164%) and improving production output structure (-54%), the net effect is a 5% reduction in CO_2 emissions during 2005-2012 in Beijing.

Although all factors' aggregated effects on overall emissions during 2005-2012 have been discussed, their relative contributions in shorter periods are not known. Therefore, this study further investigates the contributions of different factors to CO_2 emissions during 2005-2007, 2007-2010 and 2010-2012 in Beijing, respectively.

Between 2005 and 2007, increasing per-capita final demand, growing population have prompted CO_2 emissions up by a combined 42.1 Mt (34.6 and 7.5 Mt, respectively), which are largely offset by emissions intensity decrease (-21.9 Mt) and production input structure improvement (-15.2 Mt) and final demand structure change (-0.7 Mt), resulting in a rise of CO_2 emissions by 4.2 Mt. From the supply side, per-capita input level (27.7 Mt) and population growth (7.5 Mt) are the major factors increasing the CO_2 emissions, while emission intensity reduction (-21.9 Mt), primary input structure (-7.2 Mt) and production output structure change (-1.9 Mt) are key factors reducing CO_2 emissions. Notably, the primary input structure in this period contributes to CO_2 emissions reduction, contrary to the effects during 2007-2010 and 2010-2012.

Between 2007 and 2010, production input structure becomes the largest driver leading to CO_2 emissions increase (24.5 Mt), while it contributes to the CO_2 emissions reduction during 2005-2007 and 2007-2010. Per-capita demand level has a smaller effect on CO_2 emissions than that of the previous period but also drives another 17.2 Mt CO_2 emissions increase if all other factors had remained constant. Population growth plays an increasing important role in increasing CO_2 emissions in this period (14.1 Mt). Emission intensity is still the major force reducing CO_2 emissions (-51.9 Mt), followed by final demand structure (-4.6 Mt). From the supply side, emission intensity becomes the only factor restraining CO_2 emissions. It is worth noting that the effect of primary input structure on CO_2 emissions has changed from positive during 2005-2007 to negative in this period. Moreover, only in this period its counter part from the demand side (final demand structure) has different effects on CO_2 emissions.

Between 2010 and 2012, per-capita demand level becomes the major force increasing the emissions again, contributing to 80.3 Mt CO_2 emissions if other factors had remained constant. The effect of final demand structure has shifted from negative during 2005-2007 and 2007-2010 to positive during 2010-2012 (32.8 Mt). Luckily, the positive influences are overwhelmed by the negative influences of emission intensity decrease (-66.3 Mt) and production input structure change (-58.8 Mt), leading to a reduction of 7.4 Mt CO_2 emissions during 2010-2012. From the supply side, per-capita input level (79.6 Mt), primary input structure (28.9 Mt) and population growth (4.5 Mt) are the major factors increasing the CO_2 emissions, while emission intensity reduction (-66.3 Mt) and production output structure change (-54.0 Mt) are dominant factors reducing CO_2 emissions.

In general, SDA from both the demand and supply sides have shown that population /emission intensity change contributes to CO_2 emissions increase/decrease with the same quantity in each time period. The relative contributions of per-capita demand and per-capita input level to CO_2 emission have similar variation trend during 2005-2012 as they are both highly related to economic growth. However, structural factors like final demand structure, primary input structure, production output structure and production input structure don't exert same effect on CO_2 emissions all the time.

5. Discussions and policy implications

~~After the United States' withdrawal from the 2015 Paris Agreement, many researchers stated that China, the world's largest direct carbon emitter, can and will lead on climate change. In order to reach emission peak before 2030, China has taken low-carbon cities a priority in mitigating climate change, which has been emphasized in many national plans, such as *National Plan on Climate Change (2014-2020)* and *Work Plan for Controlling Greenhouse Gas Emission during the 13th Five-Year Plan Period (2016-2020)*. Many Chinese cities, including Beijing, have promised to reach the carbon emissions peak around 2020. To this end, Beijing specifically formulated *The 12th/13th Five-Year Plan for Energy Conservation and Climate Change Mitigation of Beijing*, in which reduction targets are set. Multiple emission emission accounting and the underlying driving forces identification in this study could further~~

~~support more comprehensive carbon emissions reduction policies with both equality and efficiency.~~

The SDA results have revealed that emission intensity change is the largest factor reducing CO_2 emissions (Figure 6). Therefore, lowering emission intensity should be put in the top position to reduce CO_2 emissions in Beijing, as. Emissions intensity is determined by fuel mix and energy efficiency [76]. Measures related to optimize fuel mix and improve energy efficiency should be introduced, especially for those critical sectors with large production-based CO_2 emissions in Beijing, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications*, *Other Services* and *Manufacture of Nonmetallic Mineral Products* (Figure 2). On one hand, Beijing has made great progress in upgrading the fuel mix, such as prohibiting the new coal combustion projects, replacing coal-fired boilers with gas-fired boilers for electricity generating, heating and industrial production and importing electricity from other other provinces (i.e., Inner Mongolia, Shanxi and Hebei) [77]. As a result, coal consumption in Beijing has been substantially reduced from 30.7 Mt in 2005 to 22.7 Mt in 2012, while natural gas consumption has increased from 3.2 billion m^3 in 2005 to 9.2 m^3 in 2012 [78]. In 2016, the last coal-fired power plant in Beijing was shut down (http://news.xinhuanet.com/2017-03/20/c_1120655036.htm). On the other hand, developing high energy efficiency technology to reduce energy consumption per unit GDP is also favored. During 2005-2012, Beijing has halved the energy intensity to 44 tonnes standard coal equivalent/million RMB of GDP [70]. It should be noted that these suggestions are consistent with *Beijing Clean Air Action Plan 2013–2017*. Therefore, further optimizing fuel mix and enhancing energy efficiency in Beijing could not only contribute to more CO_2 emission reduction, but also bring co-benefits in terms of controlling air pollutants (i.e., $PM_{2.5,}$ black carbon and atmospheric mercury emissions) [79-81]. When designing carbon reduction policies, urban energy-water nexus issue should also be considered as the adoption of a specific energy-related policy may have the potential to exert adverse effect on water resources [82, 83].

The consumption-based accounting identifies critical sectors whose final demand causes large upstream CO_2 emissions, such as *Production and Supply of Electric Power and Heat Power, Transportation, Storage, Posts and Telecommunications, Other Services* and *Construction* (Figure 3). Beijing government should establish an incentive mechanism for low carbon consumption. For example, measures such as carbon footprint label certification and carbon tax could be adopted to promote low carbon consumption culture in Beijing. Besides, major enterprises in those critical sectors are encouraged to report CO_2 emissions generated in their production activities and upstream supply chains. It's verified that integrating carbon footprint into supply chain management to develop a green supply chain will obtain more profits [84]. The SDA from the demand-side also highlights production input structure as the second major curbing factor to CO_2 emissions (Figure 6a). Thus, optimizing production input structure by using inputs from low carbon upstream suppliers is advocated.

The income-based accounting identifies critical sectors whose primary input induces large downstream CO_2 emissions, such as *Production and Supply of Electric Power and Heat Power, Transportation, Storage, Posts and Telecommunications, Other Services* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel* (Figure 3). Measures related to subsidies decrease, revenue tax increase, product prices regulation and loan supply restriction in these sectors could be adopted [67]. China is now carrying out the Supply Side Reform, in which correction of the distortion in the composition and size of capital investment is a key aspect [85]. Therefore, the government could encourage investors to pour more capital into sectors with less income-based CO_2 emissions during the reform. Moreover, banks should also restrict loans to the enterprises with large CO_2 emissions in their downstream supply chains [7]. The SDA from the supply-side also identifies production output structure as a key factor reducing CO_2 emissions (Figure 6b). Thus, enterprises in these sectors are encouraged to sell their products to less carbon-intensive downstream users.

Besides, Beijing's population is projected to maintain its growth trend [86], which is a driving force to increase CO_2 emissions (Figure 6). Beijing has stressed in *The 13th Five-Year Plan For Economic And Social Development Of Beijing* to take targeted measures to properly control the excessive growth of population. For example, the Xiong'an New Area in Hebei province has been established to accelerate the removal of non-capital functions out of Beijing city. Then, considerable population would move from Beijing city to Xiong'an New Area in future, restraining the contribution of population growth to CO_2 emission increase.

Moreover, imports and exports are playing ever-increasing important roles in enabling downstream CO_2 emissions and driving upstream CO_2 emissions, respectively (Figure 4). Numerous studies have highlighted the importance of trade in redistributing environmental impacts [87-92]. Low-carbon city planning for Beijing should not only focus on the local reduction, but also take the domestic and foreign supply chains into consideration. On one hand, Beijing will deepen its connection with Tianjin and Hebei according to *The Outline of the Plan for Coordinated Development for the Beijing-Tianjin-Hebei Region*. On the other hand, Beijing is encouraged to build or intensify commercial intercourses with economies along the Belt and Road. Therefore, when regionalizing and globalizing Beijing city, multi-scale co-governance covering Beijing's entire domestic and foreign supply chains should be considered as an efficient way to coordinate and cooperate in reducing income, production and consumption-based CO_2 emissions simultaneously.

6. Concluding remarks

This study investigates the production, consumption and income-based fuel-related CO_2 emissions of sectors in Beijing from 2005 to 2012. CO_2 emissions in Beijing have increase from 85.3 Mt in 2005 to 89.5 Mt in 2007, followed by a continuous decline to 81.4 Mt in 2012. Some key sectors, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications* and *Other services*, always stand out based on different measures. However, different accounting principle also identifies unique critical sectors which the others could not identify. For example, in addition to the abovementioned three sectors, production, consumption and income-based accounting also identify *Manufacture of Nonmetallic Mineral Products*, *Construction* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel* as critical sectors, respectively. These accountings will provide different information about the impacts of the sector's actions on total CO_2 emissions in Beijing, which is useful to support just and effective carbon reduction policies.

Furthermore, ~~SDA~~ structural decomposition analysis from both the demand and supply sides is conducted to investigate the socioeconomic driving forces of CO_2 emissions change in Beijing during 2005-2012. In general, population growth, per-capital final demand/primary input level surge and final demand/primary input structure change contribute to CO_2 emission increase in Beijing. These effects are offset by emission intensity and production input/output structure change, leading to a net 3.9 Mt CO_2 emissions decrease during 2005-2012. Given these, targeted policies from both demand and supply sides are suggested.

Beijing has been prepared to meet the challenge of mitigating climate change. For example, Beijing Municipality has announced *The 12th/13th Five-Year Plan for Energy Conservation and Climate Change Mitigation of Beijing* that emphasizes the phasing out of coal-fired boilers, greening energy structure and industrial structure, enhancing regulations and removal of non-capital functions. These measures mainly aim at reducing production-based CO_2 emissions rather than rectifying the underlining driving forces that result in emission increases through the domestic and foreign supply chains. For example, simply outsourcing the carbon-intensive industries (e.g., shifting iron and steel industry to Hebei) and replacing local coal-fired electricity by importing electricity from other provinces (e.g., Shanxi) has a potential for overall CO_2 emissions rise, due to the weaker regulation and poor technology in these regions. While new policies continue in strengthening end-of-pipe measures, more efforts are required based on demand (e.g., facilitating low-carbon consumption) and supply side (e.g., controlling capital investment in enterprises with large income-based CO_2 emissions).

It's noted that exports and imports contribute significantly to downstream and upstream CO_2 emissions in Beijing, respectively. However, only local supply chains of Beijing (i.e., single-regional input-output model) are considered in this study. Thus, it is an interesting future work to investigate socioeconomic drivers of Beijing's CO_2 emissions by taking the domestic and foreign supply chains into consideration (i.e., a multi-scale input–output analysis [36], a nested Chinese multi-regional input-output (MRIO) model [93], a city-centric global MRIO model [37] or multi-scale MRIO model [94]). Moreover, the price variability [95], carbon emission inventory [71] and sector aggregation [96] all contribute to the uncertainties of the results.

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Carbon emissions and their drivers for a typical urban economy from multiple perspectives: a case analysis for Beijing City

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Abstract: Understanding carbon emission profile of cities from multiple perspectives is a prerequisite to design just and effective carbon reduction policies. Previous studies on CO_2 emissions by cities are usually confined to production or consumption-based perspective, while income-based perspective has been neglected. To fill the gap, direct emissions (a.k.a. production-based emissions), upstream emissions driven by final demand (a.k.a. consumption-based emissions) and downstream emissions enabled by primary input (a.k.a. income-based emissions) in an urban economy are comprehensively explored and compared for the first time, taking Beijing as a case. In the period of 2005~2012, *Manufacture of Nonmetallic Mineral Products*/*Construction*/*Processing of Petroleum, Coking, Processing of Nuclear Fuel* is identified as the key contributor to carbon emission by Beijing from the production/consumption/income-based perspective, respectively, indicating each perspective can unveil important information which the other methods fail to discover. Moreover, driving forces of CO_2 emissions change in Beijing are uncovered using the structural decomposition analysis (SDA) from both the demand and supply sides. Emission intensity, production input and output structure change contribute to CO_2 emission decrease in Beijing, which are largely offset by population, final demand/primary input level and final demand/primary input structure change, resulting in a net 3.9 Mt reduction during 2005~2012. While current policies continue to highlight end-of-pipe measures in cities, more attention should be paid to demand (e.g., encouraging low-carbon consumption) and supply side (e.g., controlling capital investment in enterprises with large income-based CO_2 emissions).

Keywords: urban CO_2 emissions; multiple accounting principles; structural decomposition analysis; Beijing

1. Introduction

As the center for population, transportation, energy consumption and business activities, cities are the major contributors to global CO_2 emissions. According to International Energy Agency, 71% of CO_2 emissions come from cities worldwide in 2006 and this share will increase to 76% in 2030 [1]. Among the important CO_2

sources, cities are responsible for 69% and 80% of EU and USA's carbon emissions [2, 3], respectively. As the world's largest energy consumer, cities are responsible for 85% of China's total CO_2 emissions [4]. Regarding the vital role in global CO_2 emissions, cities are considered as key areas in strategies formulated for fighting against global climate change.

The first and fundamental step for proper mitigation policy design is to accurately quantify cities' carbon emissions. Currently, there are three different accounting principles that are widely used: production, consumption and income-based accounting [5-7]. Although each of the aforementioned accounting frameworks has its own merits, they have inherent blind spots (detailed reviews of each accounting principle are presented in Section 2.1). Under this circumstance, Steininger et al. [8] argued that carbon emissions accounting under multiple perspectives are suggested to support fair and effective mitigation strategies and identify some underlying reduction potentials. Moreover, the carbon emissions accounting under different perspectives can be combined as cornerstone for a shared-responsibility [9]. Notably, to the best of our knowledge, carbon emission accounting at urban scale from three different perspectives has not been found yet, as our reviews in Section 2.1 suggest that current studies on carbon emission accounting of cities are usually confined to one or two perspectives.

Beside the comprehensive perspectives on carbon emissions, the knowledge about how the carbon emissions change and their underlying drivers also have important policy implications. A prerequisite to meet the carbon mitigation targets without harming domestic competitiveness is to successfully identify the main drivers of the carbon emissions [10]. That is to say, a robust decomposition analysis on carbon emission driving factors will lead to appropriate policy design. Structural decomposition analysis (SDA) is usually coupled with input-output analysis, enabling it to take the effect of production structure into consideration [11]. As our review in section 2.2 shows, however, most previous SDA studies are confined in demand-side perspective, little is known about the driving factors and their contributions from supply-side perspectives, especially those at city scale.

Hence, this study aims to fill the knowledge gaps by evaluating the production, consumption and income-based carbon emissions simultaneously and the major driving forces from supply and demand-side perspectives, using the case of the capital city of China, Beijing. After the United States' withdrawal from the 2015 Paris Agreement, many researchers stated that China, the world's largest direct carbon emitter, can and will lead on climate change [12]. In order to reach emission peak before 2030, China has taken low-carbon cities a priority in mitigating climate change, which has been emphasized in many national plans, such as *National Plan on Climate Change (2014-2020)* and *Work Plan for Controlling Greenhouse Gas Emission during the 13th Five-Year Plan Period (2016-2020)*. Many Chinese cities, including Beijing, have promised to reach the carbon emissions peak around 2020. In order to build a low carbon urban economy as well as play a leading exemplary role for the whole nation, the Municipal Government of Beijing has promised to reach the carbon emissions peak in 2020 or even earlier [13]. As Beijing's carbon mitigation has entered a new stage, it is urgent to draw a holistic picture of Beijing's carbon emissions and furthermore, to identify the driving factors from different perspectives, based on the latest data. It is expected that the study will bring new insights for carbon emissions mitigation actions as well as enlarging the possibilities for future climate policies for Beijing, or even other global cities fighting against the climate change.

The rest of this study is organized as follows: Section 2 reviews the recent advances in multiple accounting principles and structural decomposition analysis at city level; methodology and data adopted in this paper are elaborated in Section 3; Section 4 presents the detailed results; some discussions and policy implications are illustrated in Section 5; finally, conclusions are drawn in Section 6.

2. Literature review

2.1 Multiple accounting principles

Multiple accounting principles in this study include production, consumption and income-based accounting. The production-based accounting focuses on the carbon emissions emitted within the administrative boundaries, including those caused by exports production [5]. This approach is widely used in global climate change agreements, including the Kyoto Protocol and Paris Agreement. Though most of the previous production-based researches are developed at national scale, city-level emission inventory has attracted ever-increasing attentions [14-16]. Kennedy et al. [17] constructed the greenhouse gas inventories for 22 global cities and investigated the underlying characteristics. Hoornweg et al. [18] reviewed per capita emissions of 100 cities to identify the hotspots for effective mitigation efforts. Besides, emission inventory for many Chinese cities has also been compiled. Sugar et al. [19] provided a comprehensive and detailed emission inventory for Beijing, Tianjin and Shanghai, which are among the highest per-capita emissions in global cities. Yu et al. [20] has drawn the similar conclusion that highly urbanized Chinese cities generated higher per-capita emissions than their European counterparts. Wang et al. [21] and Shan et al.[22] compiled 12 and 20 Chinese cities, respectively. Fang et al. [23] investigated the relationship between urban form and carbon emissions in 30 provincial capital cities. All these studies provide preliminary information for understanding the role of cities in global climate change. However, the adequacy of production-based perspective has also been questioned for it causes carbon leakages which lead to the serious issue of policy efficiency [24, 25]. For example, household in cities consumes a huge amount of electricity produced in the power plants that may not locate in the city boundary, while the production-based perspective neglects the upstream carbon emissions caused by electricity generation [26].

Given the insufficiency of production-based accounting, many researchers argue that besides the direct emissions, carbon emissions embodied in goods and services consumed by the economy but produced in other places should also be taken into consideration [5, 27]. Consequently, the consumption-based perspective, which is able to cover the upstream carbon emissions, is suggested as a supplementary for the production-based perspective for benchmarking cities’ carbon emission inventory [28, 29]. For example, Minx et al. [30] evaluated the carbon footprint of citied in UK, which was proved to be determined by socio-economic rather than geographic and infrastructural factors. Long et al. [31] used a multi-regional input-output model to estimate the indirect emissions induced by Tokyo, Japan. Many attentions have also been paid to Chinese cities, among which Beijing, Tianjin, Shanghai and Chongqing are always on the list [32, 33]. A most updated and comprehensive consumption-based accounting database for 13 Chinese cities was constructed by Mi et al. [34]. Besides, more advanced models are developed to assess the consumption-based emissions of cities by taking the domestic and foreign supply chains into consideration, such as multi-scale input-output model [35, 36], city-centric global multi-regional input-output model [37]. A consistent conclusion reached in most of these studies is that cities, especially those heavily rely on service industries, have higher consumption-based carbon emissions than their production-based emissions, indicating that final consumption in cities can displace carbon emissions in other regions. Peters and Hertwich [38] as well as many other researches [39, 40] have highlighted the advantages of consumption-based accounting over production-based accounting in addressing carbon leakage, increasing reduction potential and improving policy fairness. Jacob and Marschinski [41], however, argued that consumption-based accounting maybe misleading for policy makers, as the potential consequences of the trade restriction or adjustment are hard to evaluate.

It should be pointed out that before purchasing goods and services, final consumers should first earn income as suppliers. The supply of primary inputs such as wages and taxes would enable carbon emissions by downstream users via product sale chain, which are usually named as income-based emissions [7]. The accounting for income-based emissions can provide important information for carbon emission reduction policymaking from the supply side. Compared to the large amount of production and consumption-based literature, there has been very limited reports of income-based carbon emissions. For example, Marques et al. [42] found that 18% of global carbon emissions are enabled by the primary inputs abroad. Liang et al. [43] have shown that income-based accounting could provide additional information for emission allocation. Yet no income-based emissions accounting has been carried out at city level. It should also be noted that the there are some debates on the interpretation of the supply-driven input-output model which is used for income-based accounting [44-46].

In summary, each accounting principle has its own pros and cons, making multiple carbon accounting of cities necessary for just and effective mitigation policy design.

2.2 Structural decomposition analysis

A considerable amount of studies has been performed to elaborate the driving factors of energy consumption and carbon emissions change by using decomposition analysis, including index decomposition analysis (IDA) [47, 48], structural decomposition analysis (SDA) [49, 50] and production-theoretical decomposition analysis (PDA) [51, 52]. SDA has its unique strength that it can take the production structure change into consideration, which has been widely conducted to identify the driving factors of carbon emission change at various economic scales.

At global scale, Wang et al. [53] applied SDA to investigate the driving factors of global and national carbon emissions intensity change and found that sectoral emission efficiency improvement was the dominant driving factors of global emission intensity decrease during 2000-2009. By using the SDA, Jiang and Guan [54] found that infrastructure built contributed significantly to emission increase in developing countries during 1995-2009. Moreover, Xu and Dietzenbacher [55] presented a SDA for the emissions embodied in trade. The results have shown that trade structure changes caused uneven growth in embodied emissions in trade between developed and developing economies. SDA has also been conducted at national scale, such as China [56, 57], Singapore [58] and USA [59]. Besides, driving factors of China’s regional carbon emissions growth have also been identified by using spatial SDA [60-62].

At city scale, Tian et al. [63], Wang et al. [64]and Wei et al. [65] all focused on the driving forces of carbon emissions in Beijing during 1997-2007, 1997-2010 and 2000-2010, respectively, by applying the SDA. A consistent finding was that carbon emission intensity decrease significantly hampered the emission growth, while the production structure change contributed to the emission increase in Beijing. Besides, Hu et al. [66] explored the determinants behind the GHG emissions change in Chongqing and found that emission intensity and input-output structure drove GHG emission reduction, while the increasing final demand contributed the most to the emission growth.

Notably, most previous SDA studies have been conducted under demand-side perspective (i.e., consumption-based perspective). A few of them have paid attentions to the driving factors from supply-side perspective (i.e., income-based perspective), but only at national scale . For example, Zhang et al. [67] carried out a supply-side SDA to show that supply-side structure, defined as sectoral shares in value added, was the main drivers of carbon emission increase in China during 1992-2002. Liang et al. [59] also argued that supply-side SDA could provide new driving forces for emission change. Yet no efforts have been made to uncover the impacts of supply-side factors (i.e., income-based perspective) on carbon emissions at city scale.

3. Methodology and data

3.1 Production, consumption and income-based accounting

Production-based CO_2 emission inventories (E) can be compiled by multiplying the amount of different fossil fuel consumption (M) and the corresponding emission factors (EF), as expressed by:

$$E=\sum_{i}^{n} e_i = \sum_{i}^{n} M_i \times EF_i \tag{1}$$

Then, the environmentally-extended input-output analysis (EEIOA) is applied to calculate the consumption-based and income-based CO_2 emissions of sectors. The consumption-based CO_2 emissions of a sector is the direct and indirect upstream emissions caused by the final demand of the sector, while the income-based CO_2 emissions of a sector is the direct and indirect downstream emissions enabled by the primary input of the sector [8, 43]. To trace the upstream and downstream emissions, Leontief inverse matrix (***L***) and Ghosh inverse matrix (***G***) are used. They can be expressed as Eq. 2 and Eq. 3, respectively.

$$\boldsymbol{L=(I-A)^{-1}} \tag{2}$$

$$\boldsymbol{G=(I-H)^{-1}} \tag{3}$$

where $\boldsymbol{A}$ is the direct input coefficient matrix whose elements represent the direct input needed from other sectors or itself to satisfy unitary production of one particular sector; $\boldsymbol{H}$ is the direct output coefficient matrix whose elements represent the direct output of one particular sector enabled by unitary input from other sectors or itself; $\boldsymbol{I}$ is the identity matrix.

It should be noted that the imports and exports are included in the primary input and final demand, respectively, based on previous studies [59]. Given these, sectoral consumption-based and income-based CO_2 emissions can be calculated by:

$$\boldsymbol{U=f(I-A)^{-1}\hat{Y}=fL\hat{Y}} \tag{4}$$

$$\boldsymbol{D=\hat{V}(I-H)^{-1}f'=\hat{V}Gf'} \tag{5}$$

Say that the economy contains n sectors, then $\boldsymbol{U}$ is a $1\times n$ vector, whose elements U_j is the consumption-based CO_2 emissions of sector j. $\boldsymbol{Y}$ is a $n\times 1$ vector, which represents the final demand of different sectors; $\boldsymbol{D}$ is a $n\times 1$ vector, whose elements D_j is the income-based CO_2 emissions of sector j; $\boldsymbol{V}$ is a $1\times n$ vector, which represents the primary input of different sectors; $\boldsymbol{f}$ is a $1\times n$ vector, whose elements f_j is the CO_2 emission intensity of sector j, defined as the CO_2 emission accompanied with unitary output of sector j. The superscript $'$ is a symbol for transposition and the $\hat{}$ means diagonalization of the vector. In this study, final demand includes household consumption, government consumption, gross capital formation, foreign export and domestic export, while primary inputs consist of value added, foreign import and domestic import.

3.2 Structural decomposition analysis

Structural decomposition analysis (SDA) is a well-acknowledged method to quantify the relative contributions of different socio-economic factors to the total energy consumption and pollutant emissions change [49, 59, 68]. Here we conduct the SDA from consumption-based and income-based perspectives to investigate the relative contributions of both supply-side and consumption-side socio-economic factors to the overall fossil-fuel-related CO_2 emissions in Beijing.

Despite the different distribution of CO_2 emissions among all economic sectors, the total CO_2 emission remains the same.

$$E=\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}\,p=p\boldsymbol{v_l}\boldsymbol{V_s}\boldsymbol{G}\boldsymbol{f'} \tag{6}$$

where the final demand ($\boldsymbol{Y}$) is viewed as a product of population (p), the final demand structure ($\boldsymbol{Y_s}$) and per-capita demand volume (y_l) and the primary input vector($\boldsymbol{V}$) is viewed as a product of population(p), the primary input structure($\boldsymbol{V_s}$) and per-capita input volume(v_l).

Then a total difference of Eq. 6 generates the decomposition form:

$$\Delta E=\Delta\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}p+\boldsymbol{f}\Delta\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}p+\boldsymbol{f}\boldsymbol{L}\Delta\boldsymbol{Y_s}\boldsymbol{y_l}p+\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\Delta\boldsymbol{y_l}p+\boldsymbol{f}\boldsymbol{L}\boldsymbol{Y_s}\boldsymbol{y_l}\Delta p \tag{7}$$

$$\Delta E=\Delta p\boldsymbol{v_l}\boldsymbol{V_s}\boldsymbol{G}\boldsymbol{f'}+p\Delta\boldsymbol{v_l}\boldsymbol{V_s}\boldsymbol{G}\boldsymbol{f'}+p\boldsymbol{v_l}\Delta\boldsymbol{V_s}\boldsymbol{G}\boldsymbol{f'}+p\boldsymbol{v_l}\boldsymbol{V_s}\Delta\boldsymbol{G}\boldsymbol{f'}+p\boldsymbol{v_l}\boldsymbol{V_s}\boldsymbol{G}\Delta\boldsymbol{f'} \tag{8}$$

The item in the left side of these equations (ΔE) is the change of total CO_2 emissions during a specific period and every item in the right represents the contributions to the total change of one particular socio-economic factor change while others remain constant. For instance, the first item in the right side of Eq. 7 represents the change of CO_2 emissions due to emission intensity ($\boldsymbol{f}$) changes while Leontief inverse matrix ($\boldsymbol{L}$), final demand structure ($\boldsymbol{Y_s}$), per-capita demand level ($\boldsymbol{y_l}$) and population remain constant. It's noted that there are *n*! types of decomposition forms when decomposing the total change into n factors and no one of them is proved to be the best. In this study, we use the average of two polar decompositions and it provides relatively accurate results without complicated calculations [69].

3.3 Data sources

This Energy consumption data are derived from Beijing Statistical Yearbooks [70], which provides detailed information on 8 different types of fossil fuels. The updated emission factor for coal in China is adopted from Liu's study [71], which is assumed to be more accurate than the IPCC default values. In this study, coal samples of 4243 state-owned coal mines (36% of Chinese coal production in 2011) are evaluated while

IPCC's default value ignore the differences of fuel contents between regions and countries. Emission factors of other fuels are default values recommended by the Intergovernmental Panel on Climate Change (IPCC) [72]. Detailed emission factors for various fuels are presented in Appendix Table A1.

The monetary input-output tables for Beijing are derived from the website provided by Beijing Municipal Bureau of Statistics. The sector classification of energy consumption in the Beijing Statistical Yearbooks and the Input-Output Tables is different. Therefore, we have made a compatible classification according to GB/4754-2011. The sectors and their codes are presented in Table. 1. To conduct the SDA, a time-series of constant-price input-output tables has been constructed using the double-deflation method [73]. The price indices of all sectors needed for double-deflation method are collected from various sourced, as presented in Appendix Table A2.

4. Results

4.1 Total CO_2 emissions of Beijing

Figure 1(a) shows the variation trend of fossil-fuel related CO_2 emissions (hereinafter referred to as CO_2 emissions) in Beijing during 2005-2012. CO_2 emissions in Beijing have fluctuated within a narrow range between 81.4 and 89.5 Mt, with a slight growing trend during 2005-2007 and a declining trend during 2007-2012. The general trend is consistent with previous studies [4, 22]. Coal use, mainly used for coal-fired power generation, dominates Beijing's CO_2 emissions during the accounting period, accounting for 45-60% of total CO_2 emissions. Benefitting from the energy structure optimization in Beijing [74], coal-related CO_2 emissions has saw annual decreases from 51.9 Mt in 2005 to 36.6 Mt in 2012. Meanwhile, emissions due to coke consumption have been slashed to less than 1.0 Mt. On the other hand, emissions from natural gases increase more than 3 times during 2005-2012 (from 5.0 Mt to 15.4 Mt).

Though CO_2 emissions stagnated during 2005-2012, Beijing's gross domestic production and population has increased by 155% and 35%, respectively. As described in Figure 1(b), emission intensity declines significantly from 122.4 t/million CNY in 2005 to 45.5 t/million CNY in 2012, with an average annual decrease rate of 28%. With regard to per-capita emissions, a continual decrease from 5.5 t/capita in 2005 to 3.9 t/capita in 2012 is identified. Given this, Beijing has made considerable progress in tackling climate change from a production-based perspective.

4.2 Multiple CO_2 emissions accounting of sectors

Figure 2 depicts the sectoral CO_2 emissions of Beijing in 2012 under multiple accounting principles, namely income, production and consumption-based accounting. The PSE directly emits 28.9 Mt CO_2 emissions in 2012, most of which comes from coal consumption. Production-based emissions of PSE are responsible for 35.5% of total emissions, while its income and consumption-based emissions only account for 29.8% and 28.2% of the total, respectively. This result highlights PSE's more important role as producer directly emitting CO_2 emissions than primary supplier enabling downstream emissions and final consumer driving upstream emissions. The similar pattern can also be identified for TSP, MNM (*Manufacture of Nonmetallic Mineral Products*) and PDG (*Production and Distribution of Gas*). Furthermore, some sectors, such as MWC (*Mining and Washing of Coal*), EPN (*Extraction of Petroleum and Natural Gas*), SRM (*Smelting and Pressing of Metals*) and FIN (*Finance*), are more important as primary suppliers enabling downstream emissions than producers and final consumers. For example, income-based emissions of SRM are 390% and 310% larger than its production and consumption-based emissions, respectively. What's more, income-based emissions of EPN are even 100 times larger than its production and consumption-based emissions. Besides, MTE (*Manufacture of Transport Equipment*), MCE (*Manufacture of Communication Equipment, Computer and Other Electronic Equipment*), CON (*Construction*) and OSS (*Other Services*) have larger consumption-based emissions than income and production-based emissions, indicating its more important role as final consumer driving upstream emissions than primary supplier and producer.

In brief, Sectors like PSE (*Production and Supply of Electric Power and Heat*

Power), TSP (*Transportation, Storage, Posts and Telecommunications*) and OSS (*Other services*) are always at the forefront of different measures, indicating that these sectors play important roles in the CO_2 supply chain in Beijing. However, their relative contributions to total CO_2 emissions under different accounting principles are varied. It will provide multidimensional information on the effects of the sector exert on the total CO_2 emissions in Beijing, making multiple accounting necessary for comprehensively understanding the emission profile of a city.

The temporal change of sectoral income, production and consumption-based emissions is described in Figure 3. From a production perspective, CO_2 emissions of *Production and Supply of Electric Power and Heat Power* gradually increases from 24.7 Mt in 2005 to 28.9 Mt in 2012. The direct CO_2 emissions of *Transportation, Storage, Posts and Telecommunications* nearly doubled during 2005-2012. It should be noted that CO_2 emissions of *Smelting and Pressing of Metals* has witnessed a dramatic decrease from 17.7 Mt in 2007 to 0.3 Mt in 2010, potentially due to the reallocation project of the Capital Steel Company. The project started in 2005 and was not completely finished until the end of 2010 [75]. There is a slight decreasing trend for CO_2 emissions directly emitted by *Manufacture of Nonmetallic Mineral Products* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel*. Moreover, CO_2 emissions of *Other Services* remain relatively stable during 2005-2012. From a consumption perspective, *Production and Supply of Electric Power and Heat Power* has witnessed a sudden increase from 2.4 Mt in 2010 to 23.0 Mt in 2012. Consumption-based CO_2 emissions of *Other Services* increase from 21.2 Mt in 2005 to 25.4 Mt in 2010, followed by a large decrease to 11.7 Mt in 2012. The *Construction* drives less and less upstream emissions during the period. It's consumption-based CO_2 emissions in 2012 are 5.1 Mt, less than one quarter of that in 2005. The upstream CO_2 emissions driven by *Transportation, Storage, Posts and Telecommunications* show ups and downs during 2005-2012. Consumption-based CO_2 emissions of *Smelting and Pressing of Metals* also show a large drop from 5.0 Mt 2007 to 1.1 Mt in 2010. From a income-based perspective, CO_2 emissions of *Production and Supply of Electric Power and Heat Power* grow from 15.8 Mt in 2005 to 24.3 Mt in 2012 with a drop from 20.4 Mt in 2007 to 15.0 Mt in 2010. Similar to the variation identified by production and consumption-based perspective, downstream CO_2 emissions enabled by the primary inputs of *Smelting and Pressing of Metals* encounter a sudden steep decline from 15.9 Mt in 2007 to 1.4 Mt in 2010. Moreover, income-based CO_2 emissions of *Transportation, Storage, Posts and Telecommunications* show a general tendency towards rising, while that of *Other Services*, *Manufacture of Nonmetallic Mineral Products* and *Finance* fluctuate with a relative small range during 2005-2012.

In general, different accounting principles also reveal new variation trend of sectoral CO_2 emissions, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications* and *Other Services*. Besides, a few consistent change patterns can also be identified by different accounting principles, such as the sudden drop of *Smelting and Pressing of Metals* from 2007 to 2010.

4.3 CO_2 emissions allocation by final demand and primary inputs

Figure 4 (a) and (b), from another point of view, show the allocation of Beijing's production-based CO_2 emissions to different primary supply and final demand categories in 2012, respectively. In terms of final demand, domestic export is the dominant contributor, accounting for 67% of total emissions in 2012. Domestic export of CO_2 emissions are mainly through *Production and Supply of Electric Power and Heat Power, Transportation, Storage, Posts and Telecommunications* and *Other Services* (excluding the aggregated *Others*). Gross capital formation ranks second of total emissions embodied in final demand. Of the 8.4 Mt CO_2 induced by Gross capital formation, more than half are contributed by *Construction Industry*. Household consumption is responsible for 6.6 Mt CO_2 emissions in 2012, with relative even distribution in various sectors. In terms of primary inputs, domestic import enables 49.3 Mt CO_2 emissions along the downstream supply chains, accounting for 61% of the total emissions in 2012. *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel* are the three leading sectors. Value added occupies the second position by causing 21.1 Mt CO_2 emissions, which are mainly contributed by *Production and Supply of Electric Power and Heat Power*, *Other Services* and *Transportation, Storage, Posts and Telecommunications*. Foreign import only leads to 13.5% of total emissions.

Moreover, structure variation of the overall CO_2 emissions by final demand and primary input categories during 2005-2012 is demonstrated in Figure 5. From the demand side, there is a distinct trend that Beijing's dominant driver of carbon emissions by final demand is sifting from gross capital formation and household consumption towards domestic export. In a sense, Beijing has transferred from a invest and consumption-driven economy to a export-driven economy. In specific, domestic export takes up an increasing share of the overall emissions driven by final demand, from a proportion of 29% in 2005 to 67% in 2012. Therefore, special attention should be paid to CO_2 emissions of upstream suppliers of these sectors. Gross capital formation has progressively lowered its influences on total CO_2 emissions, whose share of total emissions decreases from 30% to 10% in this period. The same is true of household consumption, as its share of total emissions in 2012 is less than half of that in 2005. Foreign export and government consumption play relative small roles in final demand, leading to 7-16% and 5-12% of Beijing's CO_2 emissions during 2005-2012, respectively. From the supply side, domestic import and value-added are responsible for most of the emissions in Beijing during 2005-2012. They contribute comparably (around 43-44%) to total CO_2 emissions in 2005 and 2007. However, domestic import's share of total emissions decreases to 30% in 2010, followed by a huge increase to 61% in 2012.

4.4 Key drivers of CO_2 emissions from demand and supply sides

The overall CO_2 emissions are determined by many socio-economic factors, such as the population expansion, production structure change and technology improvement. To reveal the relative contributions of different socio-economic factors, the changes of overall CO_2 emissions of Beijing during 2005-2012 are decomposed from both demand and supply sides, as shown in Figure 6.

From the demand side, the largest factor curbing CO_2 emissions during 2005-2012 is emission intensity, which has decreased 62% between 2005 and 2012 (Figure 1). The decline of emission intensity has avoided 140.0 Mt (-164%) CO_2 emissions if other factors had remained constant. Another vital factor in reducing CO_2 emissions is production input structure, whose improvement leads to 49.6 Mt (58%) CO_2 emissions reduction. These efforts have been tempered by per-capita demand growth, population growth and final demand structure change. The per-capita demand level is the largest driver causing the growth of CO_2 emissions during 2005-2012. In this period, it has increased by 4 times at the constant price based on 2010, which could have led to another 132.1 Mt (155%) CO_2 emissions if other factors had remained constant. The population growth and final demand structure change have smaller effects on emissions change, contributing to 26.1 Mt (31%) and 27.5 Mt (32%) CO_2 emissions growth, respectively. From the supply side, increasing per-capita primary input, growing population and final demand together contribute to CO_2 emissions increase by 214% (156%, 31% and 27%, respectively). When integrated with the decreasing emission intensity (-164%) and improving production output structure (-54%), the net effect is a 5% reduction in CO_2 emissions during 2005-2012 in Beijing.

Although all factors' aggregated effects on overall emissions during 2005-2012 have been discussed, their relative contributions in shorter periods are not known. Therefore, this study further investigates the contributions of different factors to CO_2 emissions during 2005-2007, 2007-2010 and 2010-2012 in Beijing, respectively.

Between 2005 and 2007, increasing per-capita final demand, growing population have prompted CO_2 emissions up by a combined 42.1 Mt (34.6 and 7.5 Mt, respectively), which are largely offset by emissions intensity decrease (-21.9 Mt) and production input structure improvement (-15.2 Mt) and final demand structure change (-0.7 Mt), resulting in a rise of CO_2 emissions by 4.2 Mt. From the supply side, per-capita input level (27.7 Mt) and population growth (7.5 Mt) are the major factors increasing the CO_2 emissions, while emission intensity reduction (-21.9 Mt), primary input structure (-7.2 Mt) and production output structure change (-1.9 Mt) are key factors reducing CO_2 emissions. Notably, the primary input structure in this period contributes to CO_2 emissions reduction, contrary to the effects during 2007-2010 and 2010-2012.

Between 2007 and 2010, production input structure becomes the largest driver leading to CO_2 emissions increase (24.5 Mt), while it contributes to the CO_2 emissions reduction during 2005-2007 and 2007-2010. Per-capita demand level has a smaller effect on CO_2 emissions than that of the previous period but also drives another 17.2 Mt CO_2 emissions increase if all other factors had remained constant. Population growth plays an increasing important role in increasing CO_2 emissions in this period (14.1 Mt). Emission intensity is still the major force reducing CO_2 emissions (-51.9 Mt), followed by final demand structure (-4.6 Mt). From the supply side, emission intensity becomes the only factor restraining CO_2 emissions. It is worth noting that the effect of primary input structure on CO_2 emissions has changed from positive during 2005-2007 to negative in this period. Moreover, only in this period its counter part from the demand side (final demand structure) has different effects on CO_2 emissions.

Between 2010 and 2012, per-capita demand level becomes the major force increasing the emissions again, contributing to 80.3 Mt CO_2 emissions if other factors had remained constant. The effect of final demand structure has shifted from negative during 2005-2007 and 2007-2010 to positive during 2010-2012 (32.8 Mt). Luckily, the positive influences are overwhelmed by the negative influences of emission intensity decrease (-66.3 Mt) and production input structure change (-58.8 Mt), leading to a reduction of 7.4 Mt CO_2 emissions during 2010-2012. From the supply side, per-capita input level (79.6 Mt), primary input structure (28.9 Mt) and population growth (4.5 Mt) are the major factors increasing the CO_2 emissions, while emission intensity reduction (-66.3 Mt) and production output structure change (-54.0 Mt) are dominant factors reducing CO_2 emissions.

In general, SDA from both the demand and supply sides have shown that population /emission intensity change contributes to CO_2 emissions increase/decrease with the same quantity in each time period. The relative contributions of per-capita demand and per-capita input level to CO_2 emission have similar variation trend during 2005-2012 as they are both highly related to economic growth. However, structural factors like final demand structure, primary input structure, production output structure and production input structure don't exert same effect on CO_2 emissions all the time.

5. Discussions and policy implications

The SDA results have revealed that emission intensity change is the largest factor reducing CO_2 emissions (Figure 6). Therefore, lowering emission intensity should be put in the top position to reduce CO_2 emissions in Beijing, as. Emissions intensity is determined by fuel mix and energy efficiency [76]. Measures related to optimize fuel mix and improve energy efficiency should be introduced, especially for those critical sectors with large production-based CO_2 emissions in Beijing, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications*, *Other Services* and *Manufacture of Nonmetallic Mineral Products* (Figure 2). On one hand, Beijing has made great progress in upgrading the fuel mix, such as prohibiting the new coal combustion projects, replacing coal-fired boilers with gas-fired boilers for electricity generating, heating and industrial production and importing electricity from other other provinces (i.e., Inner Mongolia, Shanxi and Hebei) [77]. As a result, coal consumption in Beijing has been substantially reduced from 30.7 Mt in 2005 to 22.7 Mt in 2012, while natural gas consumption has increased from 3.2 billion m^3 in 2005 to 9.2 m^3 in 2012 [78]. In 2016, the last coal-fired power plant in Beijing was shut down (http://news.xinhuanet.com/2017-03/20/c_1120655036.htm). On the other hand, developing high energy efficiency technology to reduce energy consumption per unit GDP is also favored. During 2005-2012, Beijing has halved the energy intensity to 44 tonnes standard coal equivalent/million RMB of GDP [70]. It should be noted that these suggestions are consistent with *Beijing Clean Air Action Plan 2013–2017*. Therefore, further optimizing fuel mix and enhancing energy efficiency in Beijing could not only contribute to more CO_2 emission reduction, but also bring co-benefits in terms of controlling air pollutants (i.e., $PM_{2.5,}$ black carbon and atmospheric mercury emissions) [79-81]. When designing carbon reduction policies, urban energy-water nexus issue should also be considered as the adoption of a specific energy-related policy may have the potential to exert adverse effect on water resources [82, 83].

The consumption-based accounting identifies critical sectors whose final demand causes large upstream CO_2 emissions, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications*, *Other Services* and *Construction* (Figure 3). Beijing government should establish an incentive mechanism for low carbon consumption. For example, measures such as carbon footprint label certification and carbon tax could be adopted to promote low carbon consumption culture in Beijing. Besides, major enterprises in those critical sectors are encouraged to report CO_2 emissions generated in their production activities and upstream supply chains. It’s verified that integrating carbon footprint into supply chain management to develop a green supply chain will obtain more profits [84]. The SDA from the demand-side also highlights production input structure as the second major curbing factor to CO_2 emissions (Figure 6a). Thus, optimizing production input structure by using inputs from low carbon upstream suppliers is advocated.

The income-based accounting identifies critical sectors whose primary input induces large downstream CO_2 emissions, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications*, *Other Services* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel* (Figure 3). Measures related to subsidies decrease, revenue tax increase, product prices regulation and loan supply restriction in these sectors could be adopted [67]. China is now carrying out the Supply Side Reform, in which correction of the distortion in the composition and size of capital investment is a key aspect [85]. Therefore, the government could encourage investors to pour more capital into sectors with less income-based CO_2 emissions during the reform. Moreover, banks should also restrict loans to the enterprises with large CO_2 emissions in their downstream supply chains [7]. The SDA from the supply-side also identifies production output structure as a key factor reducing CO_2 emissions (Figure 6b). Thus, enterprises in these sectors are encouraged to sell their products to less carbon-intensive downstream users.

Besides, Beijing's population is projected to maintain its growth trend [86], which is a driving force to increase CO_2 emissions (Figure 6). Beijing has stressed in *The 13th Five-Year Plan For Economic And Social Development Of Beijing* to take targeted measures to properly control the excessive growth of population. For example, the Xiong'an New Area in Hebei province has been established to accelerate the removal of non-capital functions out of Beijing city. Then, considerable population would move from Beijing city to Xiong'an New Area in future, restraining the contribution of population growth to CO_2 emission increase.

Moreover, imports and exports are playing ever-increasing important roles in enabling downstream CO_2 emissions and driving upstream CO_2 emissions, respectively (Figure 4). Numerous studies have highlighted the importance of trade in redistributing environmental impacts [87-92]. Low-carbon city planning for Beijing should not only focus on the local reduction, but also take the domestic and foreign supply chains into consideration. On one hand, Beijing will deepen its connection with Tianjin and Hebei according to *The Outline of the Plan for Coordinated Development for the Beijing-Tianjin-Hebei Region*. On the other hand, Beijing is encouraged to build or intensify commercial intercourses with economies along the Belt and Road. Therefore, when regionalizing and globalizing Beijing city, multi-scale co-governance covering Beijing's entire domestic and foreign supply chains should be considered as an efficient way to coordinate and cooperate in reducing income, production and consumption-based CO_2 emissions simultaneously.

6. Concluding remarks

This study investigates the production, consumption and income-based fuel-related CO_2 emissions of sectors in Beijing from 2005 to 2012. CO_2 emissions in

Beijing have increase from 85.3 Mt in 2005 to 89.5 Mt in 2007, followed by a continuous decline to 81.4 Mt in 2012. Some key sectors, such as *Production and Supply of Electric Power and Heat Power*, *Transportation, Storage, Posts and Telecommunications* and *Other services*, always stand out based on different measures. However, different accounting principle also identifies unique critical sectors which the others could not identify. For example, in addition to the abovementioned three sectors, production, consumption and income-based accounting also identify *Manufacture of Nonmetallic Mineral Products*, *Construction* and *Processing of Petroleum, Coking, Processing of Nuclear Fuel* as critical sectors, respectively. These accountings will provide different information about the impacts of the sector's actions on total CO_2 emissions in Beijing, which is useful to support just and effective carbon reduction policies.

Furthermore, structural decomposition analysis from both the demand and supply sides is conducted to investigate the socioeconomic driving forces of CO_2 emissions change in Beijing during 2005-2012. In general, population growth, per-capital final demand/primary input level surge and final demand/primary input structure change contribute to CO_2 emission increase in Beijing. These effects are offset by emission intensity and production input/output structure change, leading to a net 3.9 Mt CO_2 emissions decrease during 2005-2012. Given these, targeted policies from both demand and supply sides are suggested.

Beijing has been prepared to meet the challenge of mitigating climate change. For example, Beijing Municipality has announced *The 12th/13th Five-Year Plan for Energy Conservation and Climate Change Mitigation of Beijing* that emphasizes the phasing out of coal-fired boilers, greening energy structure and industrial structure, enhancing regulations and removal of non-capital functions. These measures mainly aim at reducing production-based CO_2 emissions rather than rectifying the underlining driving forces that result in emission increases through the domestic and foreign supply chains. For example, simply outsourcing the carbon-intensive industries (e.g., shifting iron and steel industry to Hebei) and replacing local coal-fired electricity by importing electricity from other provinces (e.g., Shanxi) has a potential for overall

CO_2 emissions rise, due to the weaker regulation and poor technology in these regions. While new policies continue in strengthening end-of-pipe measures, more efforts are required based on demand (e.g., facilitating low-carbon consumption) and supply side (e.g., controlling capital investment in enterprises with large income-based CO_2 emissions).

It’s noted that exports and imports contribute significantly to downstream and upstream CO_2 emissions in Beijing, respectively. However, only local supply chains of Beijing (i.e., single-regional input-output model) are considered in this study. Thus, it is an interesting future work to investigate socioeconomic drivers of Beijing’s CO_2 emissions by taking the domestic and foreign supply chains into consideration (i.e., a multi-scale input–output analysis [36], a nested Chinese multi-regional input-output (MRIO) model [93], a city-centric global MRIO model [37] or multi-scale MRIO model [94]). Moreover, the price variability [95], carbon emission inventory [71] and sector aggregation [96] all contribute to the uncertainties of the results.

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Figure

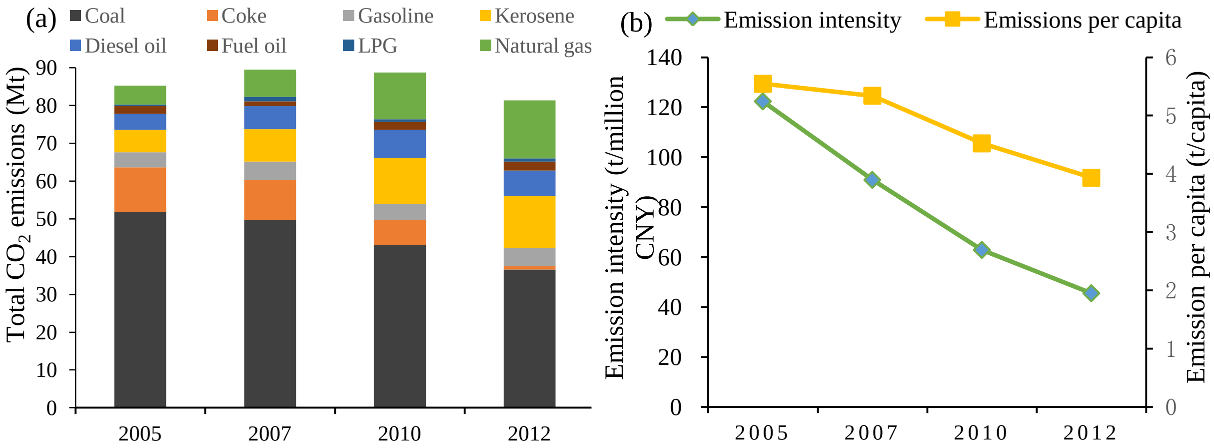

Fig. 1 Fossil fuel induced CO_2 emissions of Beijing by fuel type (a) and emissions intensity and emissions per capita (b) from 2005 to 2012

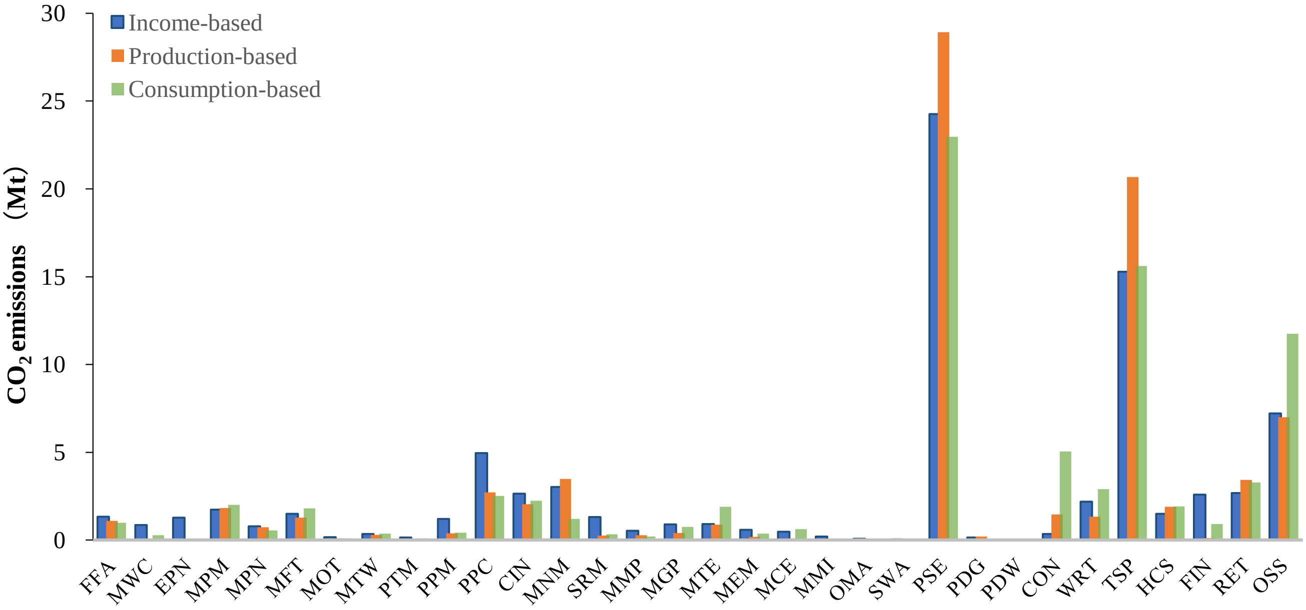

Fig. 2 Sectoral income-based, production-based and consumption-based CO_2 emissions of Beijing in 2012

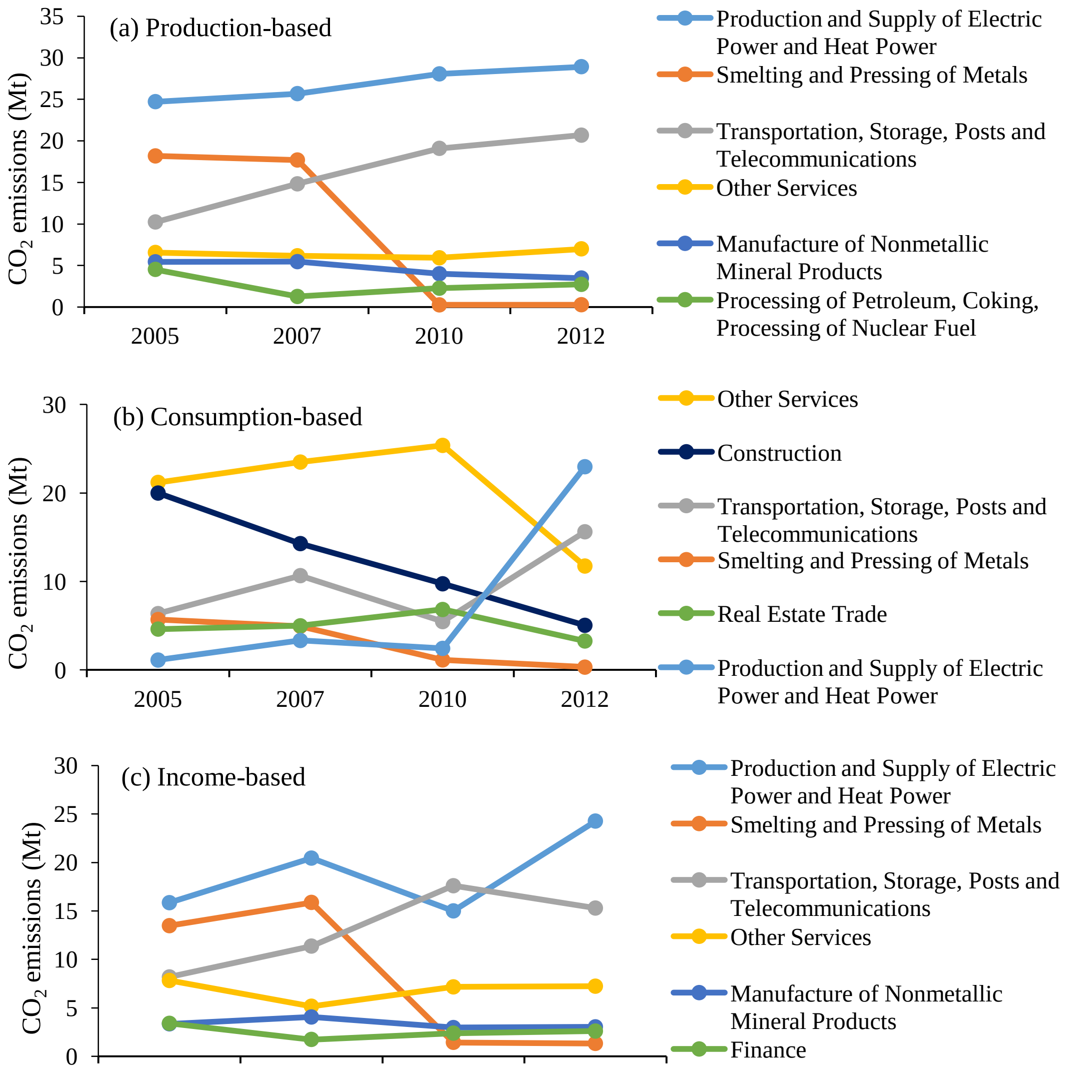

Fig. 3 Evolution of sectoral production (a), consumption (b) and income-based (c) CO_2 emissions of sectors in Beijing during 2005-2012. (Full sectoral data can be found in Appendix Table A3-A5)

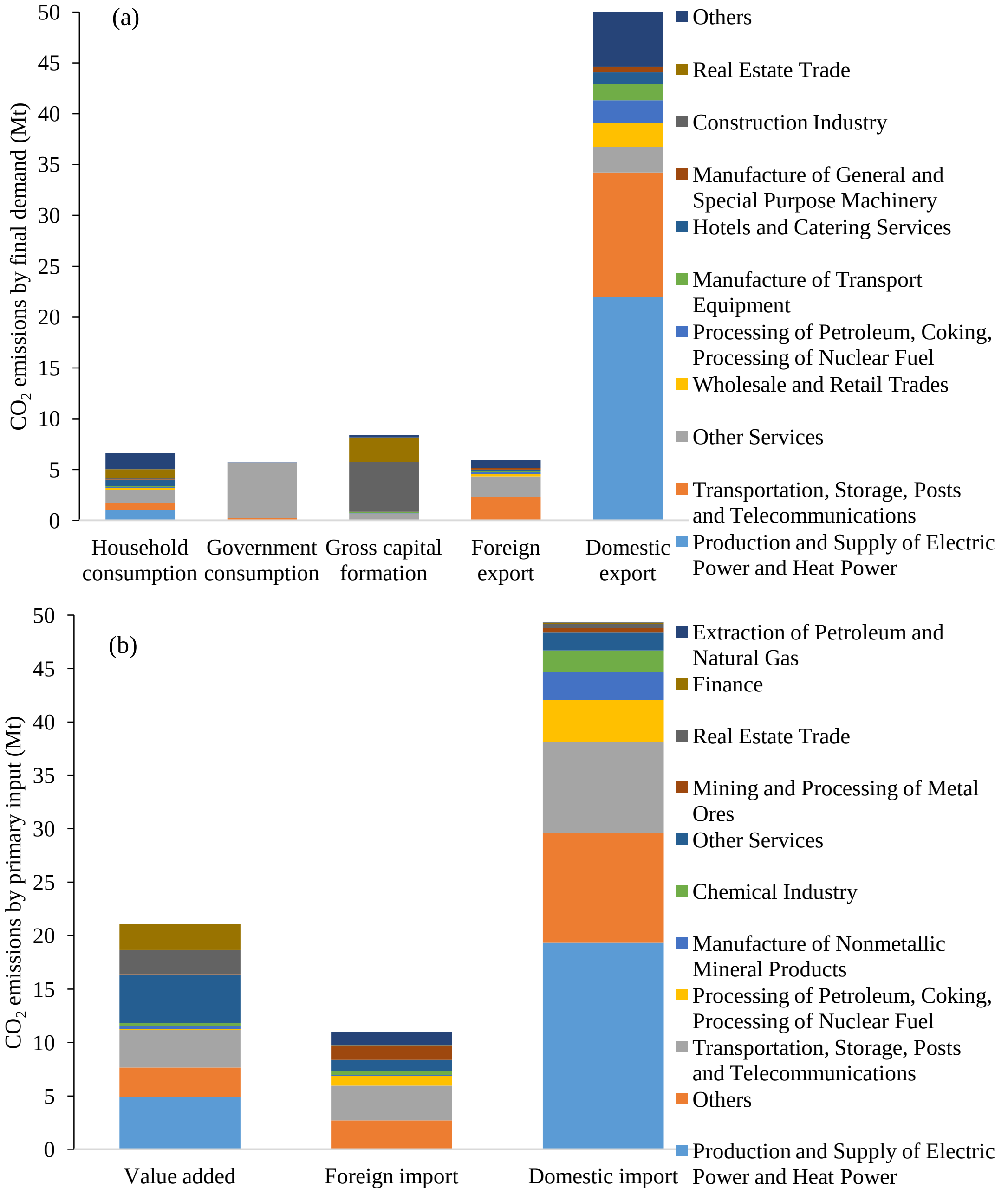

Fig. 4 CO$_2$ emissions of Beijing by final demand (a) and primary input (b) categories in 2012 (Beside the top 10 components, rest of the sectors are aggregated to “Others” for better illustration)

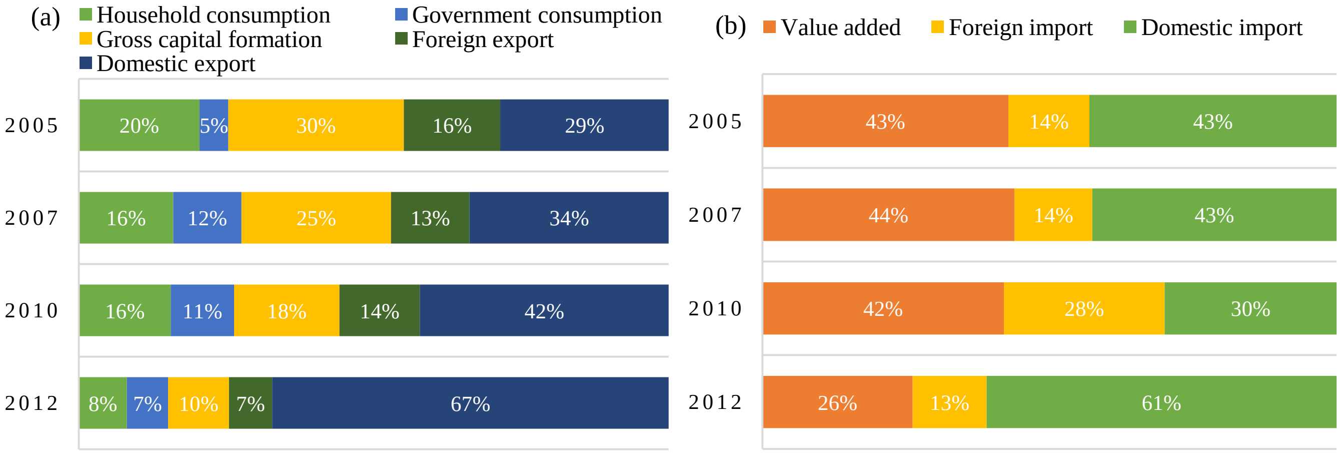

Fig. 5 Structure variation of the overall CO_2 emissions by final demand (a) and primary input (b) categories during 2005-2012.

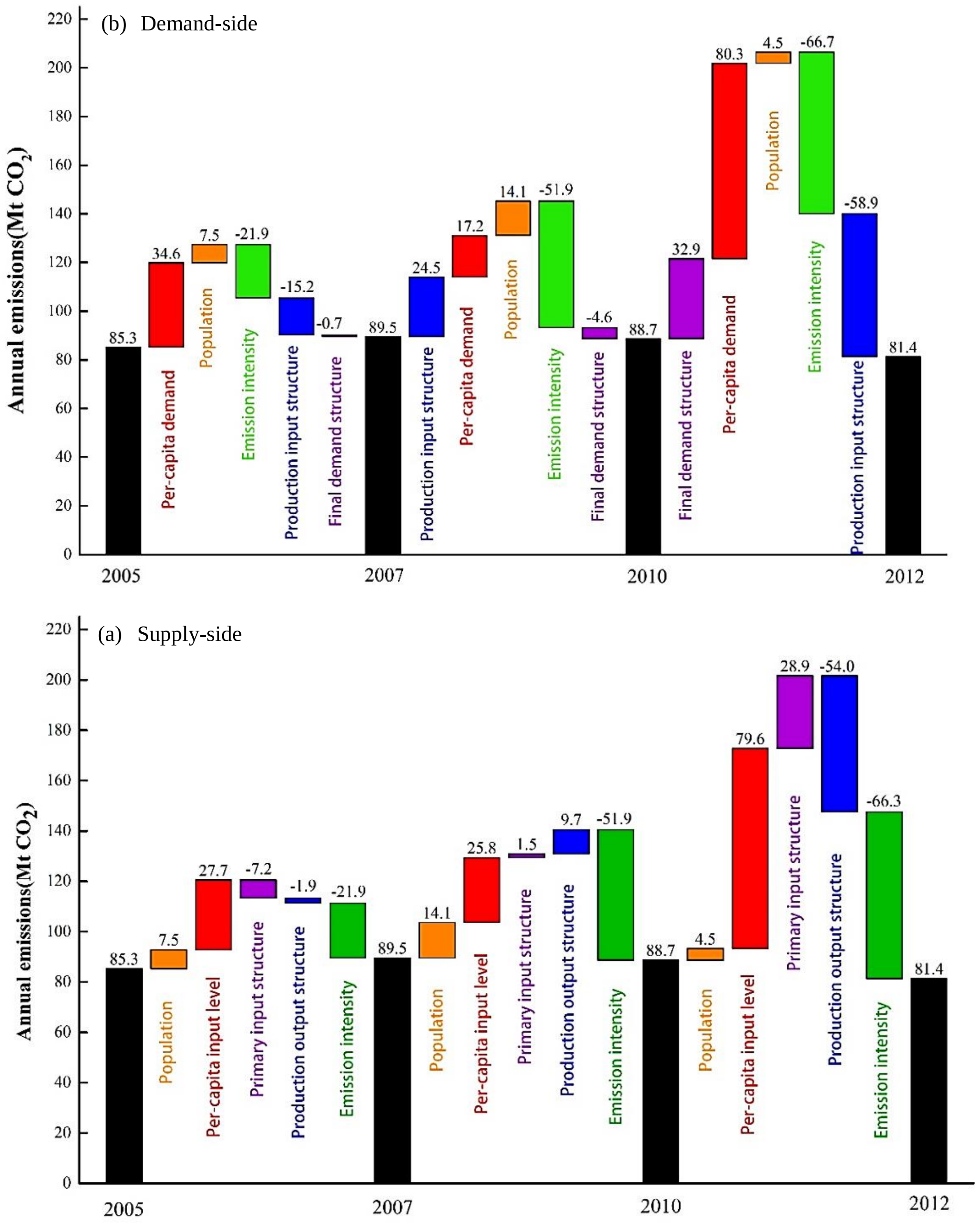

Fig. 6 Contributions of socio-economic factors to Beijing's CO_2 emission changes during 2005-2012 from the demand (a) and supply side (b).

Table

Table. 1. Sector classification

Code	Sector	Abbreviation
1	Farming, Forestry, Animal Husbandry and Fishery	FFA
2	Mining and Washing of Coal	MWC
3	Extraction of Petroleum and Natural Gas	EPN
4	Mining and Processing of Metal Ores	MPM
5	Mining and Processing of Nonmetal Ores and Other Ores	MPN
6	Manufacture of Foods and Tobacco	MFT
7	Manufacture of Textile	MOT
8	Manufacture of Textile Wearing Apparel, Footwear, Caps, Leather, Fur, Feather(Down) and Its products	MTW
9	Processing of Timbers and Manufacture of Furniture	PTM
10	Papermaking, Printing and Manufacture of Articles for Culture, Education and Sports Activities	PPM
11	Processing of Petroleum, Coking, Processing of Nuclear Fuel	PPC
12	Chemical Industry	CIN
13	Manufacture of Nonmetallic Mineral Products	MNM
14	Smelting and Pressing of Metals	SRM
15	Manufacture of Metal Products	MMP
16	Manufacture of General and Special Purpose Machinery	MGP
17	Manufacture of Transport Equipment	MTE
18	Manufacture of Electrical Machinery and Equipment	MEM
19	Manufacture of Communication Equipment, Computer and Other Electronic Equipment	MCE
20	Manufacture of measuring instrument and meter	MMI
21	Other manufacturing	OMA
22	Scrap and Waste	SWA
23	Production and Supply of Electric Power and Heat Power	PSE
24	Production and Distribution of Gas	PDG
25	Production and Distribution of Water	PDW
26	Construction	CON
27	Wholesale and Retail Trades	WRT
28	Transportation, Storage, Posts and Telecommunications	TSP
29	Hotels and Catering Services	HCS
30	Finance	FIN
31	Real Estate Trade	RET
32	Other services	OSS

Appendix

Table A1

Emission factors for various fuels

Fossil fuel	**Emission factors**	**Fossil fuel**	**Emission factors**
Coal	0.499	Diesel Oil	0.860
Coke	0.807	Fuel Oil	0.844
Gasoline	0.831	LPG	0.805
Kerosene	0.846	Natural Gas	0.521

Table A2

Price indices of sectors

Sector	Price indices	Resources
1	Producer price indices for agricultural products	Beijing Statistical Yearbook
2~25	Producer price indices for industrial products	Beijing Statistical Yearbook
26	The build-in project price indices	China Statistical Yearbook
27	Retail Price Indices	Beijing Statistical Yearbook
28	Traffic and Telecommunications price indices	Beijing Statistical Yearbook
29	Consumer price indices	Beijing Statistical Yearbook
30	The average of fixed-asset investment prices indices and consumer price indices	Beijing Statistical Yearbook
31	The average of Price Indices of Real Estate Sales, Real estate rent and leasing price indices and Property management price indices	Database of macroeconomic and social development in Beijing
32	Consumer price indices	Beijing Statistical Yearbook

Table A3

Sectoral income-based emissions during 2005-2012 (Unit: Mt)

Sector	2005	2007	2010	2012
1	1.1	1.7	1.3	1.3
2	2.2	1.7	1.9	0.9
3	3.1	1.3	2.1	1.3
4	3.1	1.2	8.9	1.7
5	0.2	0.7	0.7	0.8
6	1.5	1.3	1.3	1.5
7	0.3	0.3	0.3	0.2
8	0.4	0.3	0.4	0.3
9	0.2	0.2	0.2	0.2
10	1.1	0.9	0.9	1.2
11	2.3	3.1	4.3	5.0
12	2.7	3.5	2.9	2.6
13	3.3	4.0	3.0	3.0
14	13.5	15.9	1.4	1.3
15	0.8	0.6	0.7	0.5
16	1.9	1.2	0.9	0.9
17	2.3	1.3	1.8	0.9
18	1.0	0.6	0.9	0.6
19	0.8	0.9	1.0	0.5
20	0.8	0.2	0.2	0.2
21	0.3	0.2	0.2	0.1
22	0.5	0.2	0.1	0.0
23	15.8	20.4	15.0	24.3
24	0.3	1.2	1.7	0.2
25	0.1	0.0	0.0	0.0
26	0.6	0.7	1.3	0.4
27	1.8	2.6	4.6	2.2
28	8.2	11.4	17.6	15.3
29	1.6	2.0	1.4	1.5
30	3.4	1.7	2.4	2.6
31	2.3	2.7	2.3	2.7
32	7.8	5.2	7.2	7.2

Table A4

Sectoral production-based emissions during 2005-2012 (Unit: Mt)

Sector	2005	2007	2010	2012
1	1.2	1.3	1.2	1.1
2	0.1	0.1	0.0	0.0
3	0.0	0.0	0.6	0.0
4	0.2	0.1	12.1	1.8
5	0.1	0.2	0.1	0.7
6	1.4	1.5	1.4	1.3
7	0.2	0.2	0.2	0.1
8	0.3	0.3	0.2	0.3
9	0.1	0.1	0.1	0.1
10	0.4	0.4	0.4	0.4
11	4.5	1.3	2.3	2.7
12	2.0	2.8	2.3	2.0
13	5.4	5.5	4.0	3.5
14	18.2	17.7	0.3	0.3
15	0.2	0.2	0.2	0.3
16	0.6	0.8	0.6	0.4
17	0.9	0.9	0.9	0.9
18	0.1	0.1	0.2	0.2
19	0.1	0.1	0.1	0.1
20	0.0	0.0	0.0	0.0
21	0.3	0.2	0.1	0.0
22	0.0	0.0	0.0	0.0
23	24.7	25.7	28.1	28.9
24	0.0	0.1	0.2	0.2
25	0.0	0.0	0.0	0.0
26	1.2	1.2	2.0	1.5
27	1.0	1.8	1.2	1.3
28	10.2	14.8	19.1	20.7
29	1.6	2.5	1.8	1.9
30	0.1	0.1	0.1	0.1
31	3.4	3.2	3.3	3.4
32	6.6	6.2	5.9	7.0

Table A5

Sectoral consumption-based emissions during 2005-2012 (Unit: Mt)

Sector	2005	2007	2010	2012
1	1.7	0.9	1.3	1.0
2	0.0	0.1	0.4	0.3
3	0.0	0.0	0.8	0.0
4	0.0	0.0	9.4	2.0
5	0.0	0.0	0.0	0.5
6	2.0	2.7	2.3	1.8
7	0.3	0.3	0.2	0.1
8	0.7	0.4	0.3	0.4
9	0.2	0.2	0.1	0.1
10	0.3	0.2	0.1	0.4
11	1.6	1.2	1.8	2.5
12	2.5	2.8	2.7	2.2
13	0.2	1.7	1.2	1.2
14	5.7	5.0	1.1	0.3
15	0.3	0.3	0.2	0.2
16	2.5	2.6	1.9	0.8
17	1.9	2.6	2.5	1.9
18	0.5	0.6	0.6	0.4
19	3.6	2.6	1.4	0.6
20	0.2	0.2	0.1	0.1
21	0.5	0.5	0.3	0.1
22	0.0	0.0	0.0	0.0
23	1.1	3.3	2.4	23.0
24	0.1	0.0	0.1	0.1
25	0.2	0.1	0.2	0.0
26	20.0	14.3	9.7	5.1
27	4.3	2.6	2.8	2.9
28	6.4	10.7	5.5	15.6
29	1.9	2.8	2.6	1.9
30	0.8	2.4	4.2	0.9
31	4.6	5.0	6.8	3.3
32	21.2	23.5	25.4	11.7