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CO₂ Emissions in Beijing: Sectoral Linkages and Demand Drivers

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Abstract: Cities contribute to most of the CO₂ emissions. And the economic system at city level is much complex due to various linked sectors. This paper aims to analyze the economy-wide contribution of sectors and households to CO₂ emissions in Beijing (China) by utilizing a semi-closed input-output model integrated with a modified hypothetical extraction method. Results show that, compared with 2005, in 2012 (1) within the entire economic system, interprovincial export caused the largest amount of CO₂ emissions [135.50 million tons (Mt)] with the main contributions arising from manufacturing (42.12 Mt); transportation, storage, and post (TSP in short, 29.13 Mt); and urban households (23.57 Mt); (2) across the intermediate input-output system, real estate activities accounted for the largest amount of embodied CO₂ intensity (0.07 kg per yuan) and more sectors outsourced CO₂; (3) tracing the integrated sector network, CO₂ linkages pointed to manufacturing and TSP dominating the internal linkages, manufacturing prominent in mixed linkages, secondary industry leading the net forward linkages, and tertiary industry dominant in terms of net backward linkages, helping control CO₂ according to its origin; (4) CO₂ emissions induced by household strikingly affected total CO₂ emissions in Beijing, mainly coming from income-oriented affects, with a large rural-urban disparity and a similar sectoral distribution pattern. Finally, we propose suggestions on carbon reduction in terms of technological interlinkages, final demand and household participation.

Keywords: CO₂ emissions; Semi-closed input-output model; Modified hypothetical extraction method; City; Beijing

1. Introduction

During industrialization, urbanization, and modernization, CO₂ emissions at the city level have become not only a main contributor to climate change (Chen et al., 2016b; Wiedmann et al., 2015), but also a vital cause of poor health (Bell et al., 2007; Jacobson, 2009), leading to a crucial academic concern with multidisciplinary involvements. Consequently, to reduce CO₂ emissions at the city level, there are wide-ranging considerations, such as its calculation methods (Feng et al., 2014; Shan et al., 2016), factors (Gudipudi et al., 2016; Wang et al., 2012), forecasts (Mohareb and Kennedy, 2014; Singh and Kennedy, 2015), and control technologies and strategies (Kumar et al., 2015; Masson et al., 2014; Mi et al., 2015). These studies indicate that a healthy city environment is a complex system full of closer inter-linkages among varied participants.

However, concerning the coupling effects among sectoral linkages, demand drivers and household participation in city-level CO₂ reduction efforts, there are two obvious problems: (1) details are lacking quantitatively in depicting how each of the above-mentioned factors influences CO₂ reduction and (2) these factors are investigated without an integrated research framework.

Regarding the relationship between sectoral linkages and CO₂, related studies have mainly focused on the country-level performance, with four methods involving the classical multiplier method (Lenzen, 2003; Zhang, 2010), sensitivity analysis (Morán and del Río González, 2007; Tarancon and Del Rio, 2007), hypothetical extraction method (Schultz, 1977), and modified hypothetical extraction method (Duarte et al., 2002; Wang et al., 2013a), to reflect the role of each sector in CO₂ emissions within the economic system. However, CO₂ mitigation approaches are further explored for a single sector or all sectors independent with one another, without more concerns about sectoral linkages. Related methods include decomposition methods (Hoekstra and Van den Bergh, 2003; Kopidou et al., 2016; Su and Ang, 2012), input-output model (Tian et al., 2015; Tian et al., 2014), and econometrics models (Talukdar and Meisner, 2001; Zhou et al., 2013).

Despite the growing significance of consumption to CO₂ reduction, the relationship between detailed final demand categories and CO₂ is not a main concern at the city level (Tian et al., 2013; Wang et al., 2013b). Given the emphasis on the relationship between the country-level demand drivers and CO₂ emissions, relevant researches are conducted not only in each final demand category, such as trade (Dong et al., 2010), household consumption (Perobelli et al., 2015), government consumption (Zhang et al., 2017) and capital formation (Talukdar and Meisner, 2001), but also in all demand drivers like (Cansino et al., 2016; Kucukvar et al., 2014). Correspondingly, the involved methods fall into three categories: (1) econometrics models (Talukdar and Meisner, 2001; Zhang et al., 2017); (2) input-output methods (Kucukvar et al., 2014); and (3) input-output model joint with decomposition analysis (Cansino et al., 2016; Dong et al., 2010).

Referring to household participation and CO₂, relevant studies can be characterized as follows: first, some micro-level studies stress the differences among households in terms of income, age, educational level, size, location, gender composition, and rebound effects, which is depicted by Ref.(Zhang et al., 2015); second, some explore rural-urban disparities and related CO₂ at different levels, covering multi-region level (Jacobson, 2009; Nejat et al., 2015; Zhou et al., 2015), bilateral-region level (Krey et al., 2012) and single-region level (Fan et al., 2015; Fan et al., 2013; Fan et al., 2016; Liu et al., 2011), by using literature review method (Krey et al., 2012; Nejat et al., 2015), the stochastic impacts by regression on population, affluence and technology (STIRPAT) model (Zhou et al., 2015), input-output analysis (Fan et al., 2016), end-use analysis

(Fan et al., 2015), divisia index decomposition (Fan et al., 2013), and Consumer Life Cycle Analysis (Liu et al., 2011). However, most studies give priorities to the ratio of the urban population to total population as the representative of household impacts; furthermore, the endogenous impact of household income and expenditure within the intermediate input-output system on CO₂ is ignored during urbanization.

Beijing, characterized by a complex multilayer society involving economy, policy, and culture, has formed a stable service-oriented economic structure (Mi et al., 2015; Wang et al., 2014) and experienced increasing urban population, rising incomes, and changing lifestyle (Wang et al., 2012), with continuing urban expansion and associated growing car use (Feng et al., 2013). Meanwhile, these changes also mean reducing energy consumption and mitigating climate change continue to need great efforts (Mi et al., 2015; Wang et al., 2014). Apart from that, with closer sectoral connections and developing scale effects, it is worthwhile to explore underlying challenges in CO₂ reduction in Beijing in the long run, such as (1) lag effects or the imbalance between its economic development and sectoral convergence, (2) its unique features and structure of final demand, and (3) impacts of household participation involving income and expenditure on CO₂ emissions.

Based on the above analysis, the contribution of this paper includes the expansion of a semi-closed input-output (IO) model with a (modified) hypothetical extraction method (HEM) as another approach to study city-level CO₂, with regard to coupling effects among sectoral linkage, demand drivers, and household participation. The semi-closed IO model, pioneered in 1987 (Batey et al., 1987), emphasizes endogenous impacts of household income and consumption on the intermediate input-output system and regards households as both producers and consumers. This model is common in economic, policy, and impact analysis in the fields of energy (Behrens, 1984), agriculture (Cardenete et al., 2014), and water (Zou and Liu, 2016) instead of CO₂. The modified HEM, a method used to explore sectoral linkages under input-output analysis was initially proposed in 2002 (Duarte et al., 2002) based on HEM (Paelinck et al., 1965). Just as mentioned in the relationship between sectoral linkage and CO₂ emissions, there remain diverse methods, such as the classical multiplier method (Chen et al., 2016a), sensitivity analysis (Liu et al., 2016), and HEM (Schultz, 1977). Different from these approaches, modified HEM could illustrate the impacts of one sector on the remaining sectors considering the combination of technological levels for each sector with components of vertical integrated consumption. It has been utilized on the domain of CO₂ (Duarte et al., 2002; Perobelli et al., 2015; Wang et al., 2013a; Zhao et al., 2015).

Therefore, this paper integrates the semi-closed IO model with the modified HEM to explore the economy-wide contribution of 17 sectors and households to CO₂ emissions in Beijing in 2005 and 2012. The remainder of the paper is structured as follows: section 2 explains method and data, the results analysis is depicted in section 3, and section 4 provides conclusions and policy implications.

2 Materials and methodology

2.1 Research Framework

According to Fig.1, sectoral CO₂ emissions and relevant economic drivers in Beijing in 2005 and 2012 are explored by employing the semi-closed input-output (IO) model. Corresponding to

the sectoral specification in economic activities, the sectoral distribution of CO₂ emissions is based on a modified hypothetical extraction method (HEM), which includes internal linkage, mixed linkage, net forward linkage, and net backward linkage. Then endogenous effects of household income and consumption on CO₂ emissions are discussed by using HEM.

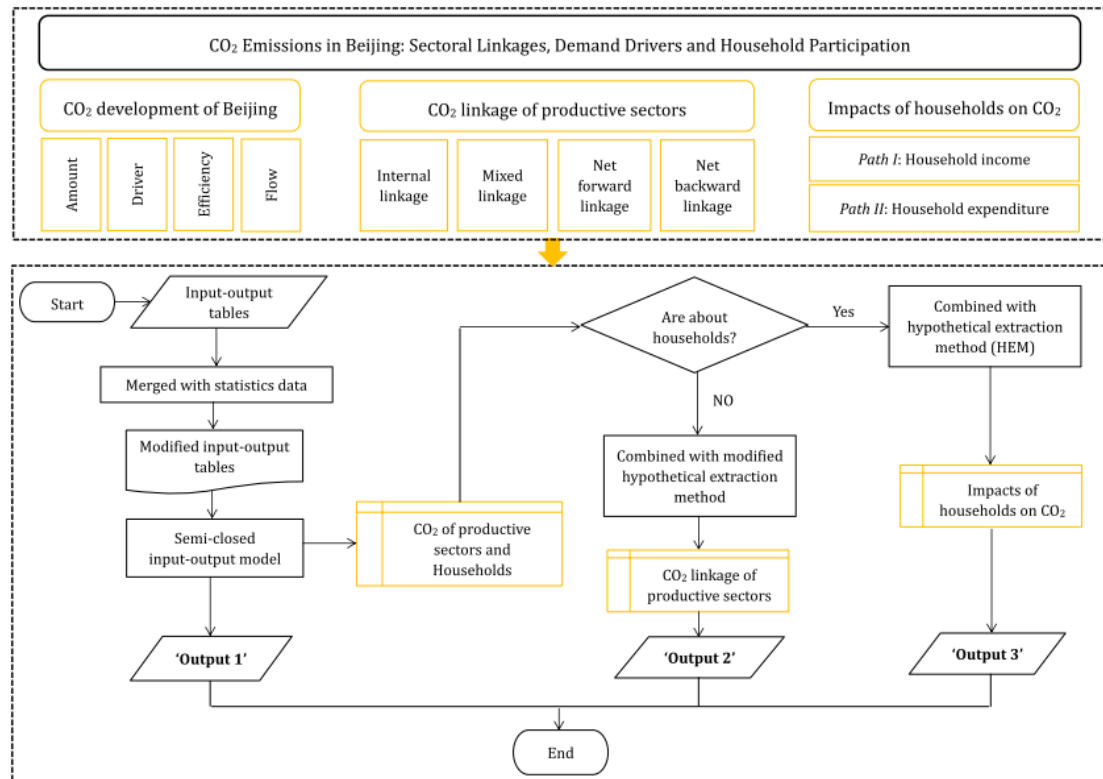


Fig.1. Framework for CO₂ calculation and evaluation

2.2 Data source and data processing

Beijing’s input-output tables for 2005 and 2012 from Beijing Municipal Bureau of Statistics are used, and other data for 2005 and 2012 come from Beijing Statistics Yearbook. Data processing can be divided into three steps as follows: (1) Adjusting IO table according to semi-closed IO model: first, regard “household consumption” (including urban and rural household consumption), originally in the “final demand” column, as a new column in “intermediate demand”. Second, divide the “value added” row into “household income” row (including urban and rural household income) and “other value added” row, and then remove the “household income” row into the “intermediate supply” (see Table A1 in the Appendix). (2) Integrating the 42 sectors of IO table and the 57 sectors consuming energy: according to Industrial Classification for Economic Activities in China, 42 sectors in the original IO table and 57 sectors consuming energy are classified and then 17 sectors, urban household and rural household are formed (see Tables A2 and A3 in the Appendix). (3) Changing competitive IO table into non-competitive IO table: competitive IO table, such as Beijing’s IO table, could not reflect the products origin, which could be changed into non-competitive IO table by deducting the import matrix from the competitive IO table. Meantime, followed by the basic structure of semi-closed IO model in (Miyazawa, 1976), import is not involved along the supply chain. So the formula (1) is used to change competitive IO table into the non-competitive one:

$$\varphi_i = (x_i - e_i)/(x_i + m_i - e_i) \quad (1)$$

where φ_i is the proportion of domestic product to the total domestic demand of sector i , x_i is the gross output of sector i ; m_i is imports of sector i ; and e_i is exports of sector i . Then the competitive IO table could be changed into the non-competitive IO table, by multiplying each supply row of sector i in competitive IO table by φ_i .

2.3 Indexes for CO₂ development based on semi-closed input-output Model

To figure out the general development of the city-level CO₂ emissions, several aspects of CO₂ emissions are analysed, with regard to its amount, demand drivers, efficiency and flows induced by import. Particularly, its amount and demand drivers are calculated directly based on the semi-closed IO model, its efficiencies are represented by three indexes, namely, direct CO₂ intensity, total CO₂ intensity and embodied CO₂ intensity, and its flows caused by import are gained according to the modified total CO₂ consumption coefficient.

The basic traditional IO model based on the non-competitive imports assumption that imported products are identified corresponding to the origin of import products is:

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \quad (2)$$

where \mathbf{X} is the vector of total output; \mathbf{A} is the technological coefficient matrix, representing the consumption of sector j relying on the production of sector i ; $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix; \mathbf{Y} is the final demand including household consumption \mathbf{H}^{con} , government consumption \mathbf{G} , capital formation \mathbf{CA} , and net export $(\mathbf{EX} - \mathbf{IM})$.

Nevertheless, the basic IO model ignores the endogenous impacts of household income-expenditure relations on the intermediate demand and supply. The semi-closed IO model could avoid it when taking into consideration household income and consumption within the intermediate IO system. More specifically, driven by increasing income induced by growing total output, households could increase their consumption of goods, which in turn spurs the production sectors to produce more. Thus, the increased production will improve household incomes through the income distribution.

The following steps detail how the basic IO model is modified into the semi-closed IO model:

First, change the technological coefficient as follows:

$$\mathbf{A}^* = \begin{bmatrix} \mathbf{A} & \mathbf{H}^{\text{con}} \\ \mathbf{H}^{\text{inc}} & \mathbf{0} \end{bmatrix} \quad (3)$$

where \mathbf{A}^* is the technological coefficient matrix of the semi-closed IO model, and \mathbf{A}^* includes \mathbf{A} , the technological coefficient matrix of the basic IO model, \mathbf{H}^{con} , the ratio of household consumption to total output for each sector, and \mathbf{H}^{inc} , the ratio of household income to total income for each sector.

Next, change final demand, \mathbf{Y}^* , without household consumption compared to \mathbf{Y} :

$$\mathbf{Y}^* = \mathbf{G} + \mathbf{CA} + (\mathbf{EX} - \mathbf{IM}) \quad (4)$$

Then obtain the corresponding total output, \mathbf{X}^* :

$$\mathbf{X}^* = (\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{Y}^* \quad (5)$$

Therefore, CO₂ calculations based on the semi-closed IO model are as follows:

$$\mathbf{C} = \mathbf{e}(\mathbf{I} - \mathbf{A}^*)^{-1}\mathbf{Y}^* \quad (6)$$

where \mathbf{C} is CO₂ emissions based on the semi-closed IO model, \mathbf{e} is the CO₂ direct intensity, i.e., the ratio of one sector's CO₂ emissions to its total output.

After calculating CO₂ emissions, \mathbf{e} , and total output, the other two CO₂ intensities are:

$$\mathbf{e}^{\text{total}} = \mathbf{e}(\mathbf{I} - \mathbf{A}^*)^{-1} \quad (7)$$

$$e^{embodied} = e^{total} - e \quad (8)$$

where e^{total} is the total CO₂ intensity representing the direct and indirect CO₂ generated by per unit of total output, $e^{embodied}$ is the embodied CO₂ intensity equalling the gap between total CO₂ intensity and direct CO₂ intensity, meaning the CO₂ intensity embodied in the intermediate IO system.

Unlike the multiple-region IO analysis, the basic single-region IO one fails to track the import-induced CO₂ flow between regions. The total CO₂ consumption coefficient could be employed to interpret the outsourced CO₂ emissions via import, which helps identify the sectors impacted most dramatically by imports in terms of CO₂ emissions. This is because it is calculated through by the direct CO₂ intensity multiplying the total consumption coefficient based on formula (1):

$$e^{import} = e[(I - A^*)^{-1} - I] \quad (9)$$

where e^{import} is the modified total CO₂ consumption coefficient to reflect the influence of import on city-level CO₂ caused by per unit of output.

2.4 CO₂ Linkages based on Modified Hypothetical Extraction Method

● Hypothetical Extraction Method (HEM)

As a method to study sectoral linkages, the HEM is used to evaluate one sector's economy-wide contributions to remaining sectors by comparing the real economic system including this sector with a hypothetical economic system excluding this sector.

First, the sectoral system of the city, \mathbf{M} , is divided into two sectoral clusters, \mathbf{M}_s and \mathbf{M}_{-s} . \mathbf{M}_s represents the sectoral cluster with sectors sharing the same characteristics, and \mathbf{M}_{-s} the cluster comprising the remaining sectors. Then, the total sectors of the city can be grouped as follows:

$$\mathbf{I} = \begin{bmatrix} \mathbf{M}_{s,s} & \mathbf{M}_{s,-s} \\ \mathbf{M}_{-s,s} & \mathbf{M}_{-s,-s} \end{bmatrix} \quad (6)$$

Next, set two scenarios: scenario 1 represents the real economic system and scenario 2 represents the hypothetical economic system where a certain sector is extracted.

Under scenario 1, CO₂ levels are calculated as follows:

$$\begin{bmatrix} \mathbf{C}_s \\ \mathbf{C}_{-s} \end{bmatrix} = \begin{bmatrix} \mathbf{e}_s & \mathbf{0} \\ \mathbf{0} & \mathbf{e}_{-s} \end{bmatrix} \begin{bmatrix} \mathbf{B}_{s,s} & \mathbf{B}_{s,-s} \\ \mathbf{B}_{-s,s} & \mathbf{B}_{-s,-s} \end{bmatrix} \begin{bmatrix} \mathbf{Y}_s^* \\ \mathbf{Y}_{-s}^* \end{bmatrix} \quad (7)$$

where $(\mathbf{I} - \mathbf{A}^*)^{-1} = \begin{bmatrix} \mathbf{B}_{s,s} & \mathbf{B}_{s,-s} \\ \mathbf{B}_{-s,s} & \mathbf{B}_{-s,-s} \end{bmatrix}$.

Under scenario 2, when sector s is extracted, CO₂ levels are calculated using

$$\begin{bmatrix} \mathbf{C}_s \\ \mathbf{C}_{-s} \end{bmatrix} = \begin{bmatrix} \mathbf{e}_s & \mathbf{0} \\ \mathbf{0} & \mathbf{e}_{-s} \end{bmatrix} \begin{bmatrix} (\mathbf{I} - \mathbf{A}_{s,s}^*)^{-1} & \mathbf{0} \\ \mathbf{0} & (\mathbf{I} - \mathbf{A}_{-s,-s}^*)^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{Y}_s^* \\ \mathbf{Y}_{-s}^* \end{bmatrix} \quad (8)$$

The difference between scenario 1 and scenario 2 is explained in equations (9) and(10).

$$\mathbf{C}^{bef} - \mathbf{C}^{aft} = \begin{bmatrix} \mathbf{e}_s & \mathbf{0} \\ \mathbf{0} & \mathbf{e}_{-s} \end{bmatrix} \begin{bmatrix} \mathbf{C}_s^{bef} - \mathbf{C}_s^{aft} \\ \mathbf{C}_{-s}^{bef} - \mathbf{C}_{-s}^{aft} \end{bmatrix} \quad (9)$$

$$\mathbf{C}^{bef} - \mathbf{C}^{aft} = \begin{bmatrix} \mathbf{B}_{s,s} - (\mathbf{I} - \mathbf{A}_{s,s}^*)^{-1} & \mathbf{B}_{s,-s} \\ \mathbf{B}_{-s,s} & \mathbf{B}_{-s,-s} - (\mathbf{I} - \mathbf{A}_{-s,-s}^*)^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{Y}_s^* \\ \mathbf{Y}_{-s}^* \end{bmatrix}, \quad (10)$$

where \mathbf{C}^{bef} is calculated under scenario 1 and \mathbf{C}^{aft} under scenario 2.

● Modified HEM

Based on the modified HEM(Duarte et al., 2002), CO₂ linkages among sectors could be decomposed into four elements, that is, internal linkage (IL), mixed linkage(ML), net forward linkage (NFL), and net backward linkage (NBL):

$$\mathbf{IL} = \mathbf{u}'_s \mathbf{e}_s (\mathbf{I} - \mathbf{A}_{s,s}^*)^{-1} \mathbf{Y}_s^* \quad (11)$$

where \mathbf{IL} refers to the CO₂ generated by the products and services created by \mathbf{M}_s itself to satisfy the final demand of \mathbf{M}_s

$$\mathbf{ML} = \mathbf{u}'_s \mathbf{e}_s [\mathbf{B}_{s,s} - (\mathbf{I} - \mathbf{A}_{s,s}^*)^{-1}] \mathbf{Y}_s^* \quad (12)$$

where \mathbf{ML} is the CO₂ generated by the products and services created by \mathbf{M}_s firstly but then used by another sector (cluster), \mathbf{M}_{-s} , and repurchased and reprocessed by \mathbf{M}_s , aiming at meeting the final demand of \mathbf{M}_s

$$\mathbf{NFL} = \mathbf{u}'_s \mathbf{e}_s \mathbf{B}_{s,-s} \mathbf{Y}_{-s}^* \quad (13)$$

where, to meet the final demand of another sector (cluster), \mathbf{Y}_{-s}^* , there would be CO₂ (\mathbf{NFL}) generated during the direct and indirect production of \mathbf{M}_s

$$\mathbf{NBL} = \mathbf{u}'_{-s} \mathbf{e}_{-s} \mathbf{B}_{-s,s} \mathbf{Y}_s^* \quad (14)$$

where, to satisfy the final demand of \mathbf{M}_s , \mathbf{Y}_s^* , CO₂ (\mathbf{NBL}) would be generated during the direct and indirect production of another sector (cluster), \mathbf{M}_{-s} .

2.5 Impacts of household income and expenditure on CO₂ emissions

Based on the semi-closed IO model and HEM described above, impacts of household income and expenditure on CO₂ levels within the economic system could be gained by extracting the “income row” and “consumption column” of households, respectively from the whole economic system. Furthermore, the impacts could be studied at three levels: urban (rural) households, 17 sectors, and rural (urban) counterparts.

3 Result analysis and discussion

3.1 Historical variation and characteristics of CO₂ emissions in Beijing

3.1.1 CO₂ emissions caused by energy consumption

Affected by energy consumption directly, total CO₂ emissions in Beijing increased from 135.66 Mt in 2005 to 171.85 Mt in 2012, with main concentrations arising from manufacturing (S3), transportation, storage and post (S14), and urban households (S19) (see Fig. 2). This indicates that a shift in economic structure from industrialized to service-driven activities could not achieve the expected low carbonization. Furthermore, households have an increasingly important impact on CO₂ levels, partly due to urbanization causing population migration, changing lifestyles, increasing motor vehicle utilization, and so on.

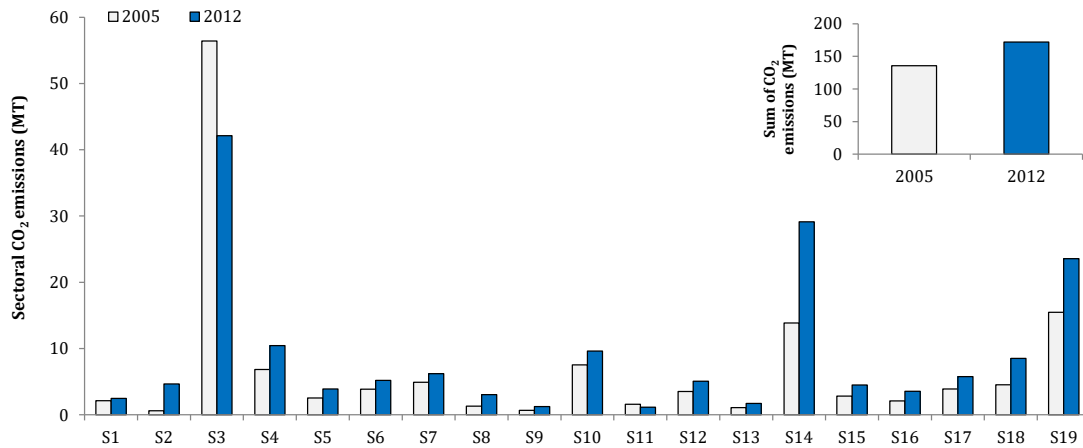


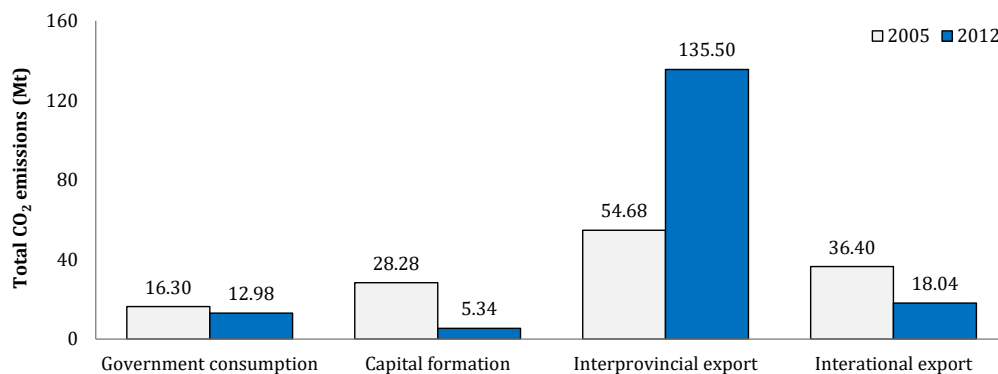
Fig.2. Total CO₂ emissions and its sectoral shares in Beijing in 2005 and 2012. Note. Sectors include 17 sectors from S1 to S17, in addition, S18 represents rural household and S19 urban household (see Table A2 in the Appendix).

3.1.2 CO₂ emissions driven by final demand

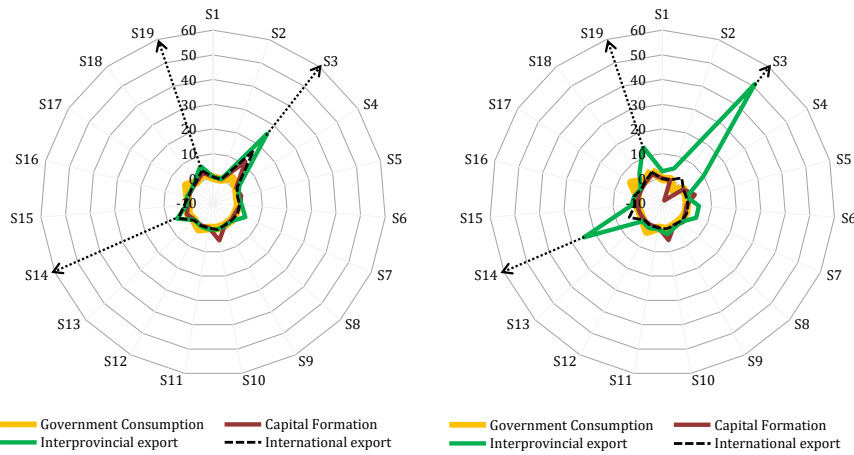
In line with the semi-closed IO model, household income-expenditure relationship is among the intermediate IO system and then imposes the endogenous effects on this system. Therefore, there is one difference between other precious studies where household in Beijing is interpreted as the consumer (Feng et al., 2014; Guo et al., 2012; Wang et al., 2013b) and the section where household are considered as both the producer and consumer.

Accompanying closer trade links between Beijing and its surrounding regions, the increasing total CO₂ emissions were driven mostly by Beijing's interprovincial export (Fig. 3a). By contrast, CO₂ emissions induced by other final demand categories grew at a shrinking small scale (Fig. 3a). Therefore, Beijing should adjust the structure of final demand to reduce CO₂ emissions with the prerequisite of maintaining healthy operation of sectoral economies.

To determine the sectoral shares of CO₂ driven by each final demand category, results in 2012 are as follows (Figs. 3b and c): (1) manufacturing (S3), transportation, storage, and post (S14), and urban households (S19) generated most CO₂ by Beijing's interprovincial export; and (2) manufacturing (S3) caused the largest amount of CO₂ leakage because its government consumption and capital formation were imported-dependent. These findings indicate the significance of import and export to CO₂ reductions in the manufacturing (S3) sector, along with reductions in Beijing's interprovincial export of the transportation, storage, and post (S14) and urban household (S19) in Beijing.



(a) Total CO₂ emissions driven by final demand



(b) Sectoral CO₂ in 2005

(c) Sectoral CO₂ in 2012

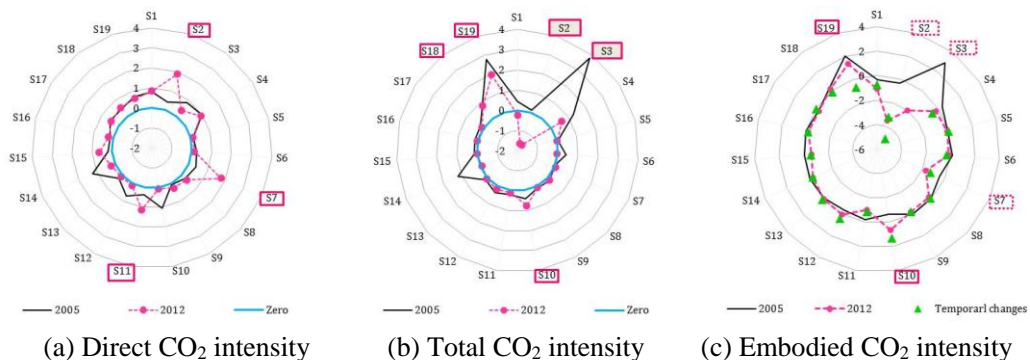
Fig.3. Sectoral CO₂ emissions driven by final demand in Beijing in 2005 and 2012 (unit: MtCO₂e)

3.1.3 CO₂ emissions embodied in the intermediate input-output system

Whether “intensity targets” could be effective for CO₂ reduction, along with how to achieve “intensity targets” effectively, still generates some debates in academia (Chong et al., 2012; Mi et al., 2015). In this section, by comparing differing CO₂ intensities, “intensity targets” would be examined as well. Each sector, *i*, should have its CO₂ intensity considered both directly and indirectly: the direct CO₂ intensity represents direct CO₂ from unitary total output; and total CO₂ intensity refers to direct and indirect CO₂ from unitary output. Therefore, if sector *i*’s total CO₂ intensity is more than its direct CO₂ intensity, the extra CO₂ produced by sector *i* is embodied in the intermediate input-output system and if not, the CO₂ generated by sector *i* is transferred outside the intermediate system.

Differences exist between direct CO₂ intensity and total CO₂ intensity across sectors. Specifically, in 2012, direct CO₂ intensity in Beijing was in a stage of flux, with mining (S2), hotels and restaurants (S7), and resident and other services (S11) in the top three sectors (see Fig. 4a). Its total CO₂ intensity also changed substantially, with manufacturing (S3) and mining (S2) being characterized by lowest intensities due to their imports, and urban households (S19), rural households (S18), and real estate activities (S10) the top three (see Fig. 4b).

In terms of embodied CO₂ intensity, which refers to embodied CO₂ per unit of output in the intermediate input-output system, Fig. 4c indicates that (1) urban households (S19) and real estate activities (S10) ranked as the top two sectors; (2) manufacturing (S2), mining (S3), and hotels and restaurants (S7) ranked in the bottom three sectors due to their imports; and (3) most sectors, especially among secondary industries, reduced CO₂ arising from the intermediate input-output system, according to their negative value of embodied CO₂ intensity (see Fig. 4c).



(a) Direct CO₂ intensity

(b) Total CO₂ intensity

(c) Embodied CO₂ intensity

Fig.4. Direct CO₂ intensity, total CO₂ intensity and embodied CO₂ intensity in Beijing in 2005 and 2012 (unit: tCO₂e per ten thousand yuan in constant 2005 price)

3.1.4 CO₂ emissions outsourced via import

Beijing's economy being impacted largely by import in 2012, the number of sectors outsourcing their CO₂ increased, meaning import-dependent economy in Beijing was beneficial to its CO₂ reduction. Precious studies also advocated the positive impacts of domestic and foreign import on CO₂ emissions in Beijing (Feng et al., 2014; Ling et al., 2016) using the Multi-Region Input-Output Model.

According to Table 1, after deducting the import matrix from the total CO₂ consumption coefficients, the modified total CO₂ consumption coefficients of hotels and restaurants (S7) allocated to all sectors (excluding itself) became negative in 2005, meaning S7's production for the consumption of other sectors encouraged CO₂ leakage. On the contrary, in 2012, four sectors had CO₂ leakage along their supply chains and they are agriculture (S1), manufacturing (S3), wholesale and retail trade (S6), and transport, storage and post (S14). Nevertheless, only the sum of the modified total consumption coefficient of S3 was negative (-3.2872 kg/ten yuan), which means that when serving as producers, sectors including S1, S6, and S14 cannot benefit from their import trade as much as other sectors did (see stars in Table 1).

Table 1

Modified total CO₂ consumption coefficient in Beijing at sector level (Unit: kg/ten yuan)

Year	2005		2012			
Producer	S7	S1	S3	S6	S14	
Consumer						
S1	-0.0068	0.8934*	-0.2154	-0.0087	-0.0019	
S2	-0.0048	-0.0002	-0.0155	-0.0019	-0.0005	
S3	-0.0071	-0.0069	0.5745*	-0.0168	-0.0008	
S4	-0.0047	-0.0007	-0.0614	-0.0030	-0.0003	
S5	-0.0073	0.0001	-0.4608	-0.0058	-0.0013	
S6	-0.0086	-0.0051	-0.1134	0.9723*	-0.0042	
S7	0.9957	-0.0477	-0.2789	-0.0140	-0.0011	
S8	-0.0051	-0.0041	-0.2648	-0.0092	-0.0011	
S9	-0.0029	-0.0047	-0.1162	-0.0051	-0.0015	
S10	-0.0030	-0.0041	-0.1228	-0.0048	-0.0010	
S11	-0.0060	-0.0242	-0.2979	-0.0116	-0.0019	
S12	-0.0063	-0.0096	-0.2291	-0.0094	-0.0034	
S13	-0.0062	-0.0056	-0.2672	-0.0088	-0.0031	
S14	-0.0064	-0.0014	-0.2436	-0.0055	0.9848*	
S15	-0.0058	-0.0099	-0.2255	-0.0098	-0.0031	
S16	-0.0056	-0.0043	-0.2808	-0.0145	-0.0034	
S17	-0.0072	-0.0123	-0.3087	-0.0101	-0.0027	
S18	-0.0024	-0.0024	-0.0503	-0.0022	-0.0002	
S19	-0.0124	-0.0249	-0.3093	-0.0158	-0.0016	
Sum	0.8871	0.7256	-3.2872	0.8153	0.9518	

Note: * are sectors that cannot benefit from their import as much as other sectors do when serving as producers.

3.2 CO₂ linkages among sectors in Beijing

In terms of impacts of industry structure on CO₂ emissions in Beijing, most studies have advocated its significances. For instance, Beijing is supposed to act as a reminder to other Chinese cities with regard to the development of its industrial structure (Tian et al., 2013). In addition, it is worth examining the potential impacts of industrial structure on energy-related CO₂ in Beijing (Mi et al., 2015), to mitigate climate change. For CO₂ decomposition along supply and demand chains in this section, based on the modified hypothetical extraction method, CO₂ flows were decomposed corresponding to sectoral specifications, consisting of internal linkage (IL), mixed linkage (ML), net forward linkage (NFL) and net backward linkage (NBL).

3.2.1 Overview of CO₂ linkages among sectoral clusters

As shown in Fig. 5, in Beijing, sectoral convergence has not progressed smoothly, leading to further CO₂ emissions accumulating in the closed circuits of sectoral supply and demand (i.e., IL). By contrast, with industrial structure upgrading and import development, CO₂ emission reductions were induced along the NFL of secondary sectors and NBL of both secondary and tertiary industry. In addition, tertiary industry continued to generate CO₂ in each segment of the supply and demand chains, owing to its wide-ranging contributions to Beijing's GDP. In particular, for a certain industry, its CO₂ levels in 2012 compared to those in 2005: (1) more CO₂ emissions were induced by its increasing IL; (2) few CO₂ emissions were caused by ML; (3) for secondary industry, its imports started encouraging the largest CO₂ leakages in light of negative NFL and NBL; and (4) for tertiary industry, CO₂ emissions caused by NBL remained the highest and those from NFL continued to be positive.

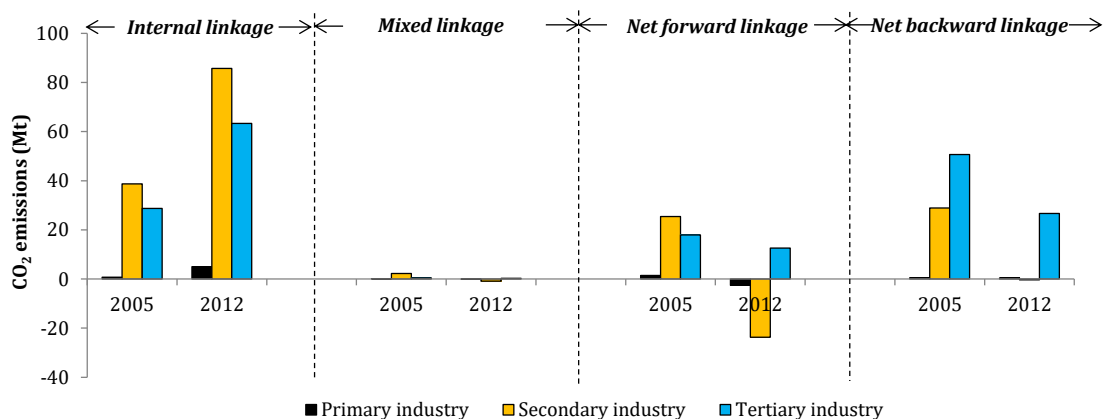


Fig.5. Overview of CO₂ linkage among sector clusters in Beijing

3.2.2 Sectoral shares of CO₂ linkages

CO₂ emissions caused by self-sufficient production in Beijing increased substantially. Among sectors, manufacturing (S3), and transportation, storage and post (S14) contributed the most. Specifically, the sectoral IL of CO₂ levelled out at the range of 0 to 10 Mt CO₂ with an increasing trend (see Fig. 6a). Besides, the IL of the top two sectors including manufacturing (S3), and transportation, storage, and post (S14) had different causes: S3 was driven by its larger final demand while S14 by its higher direct CO₂ intensity. In this regard, figuring out the detailed drivers of sectoral IL is also important for CO₂ reduction and needs more in-depth analysis of sectoral characteristics.

Overall, the ML of CO₂ contributed the least to the increased CO₂ emissions in Beijing, compared to other types of sectoral linkages. Furthermore, when it comes to sectoral shares of ML,

manufacturing (S3) played the paramount role in ML: the ML of manufacturing (S3) was greatest in 2005 but by 2012, it had fallen to the least (see Fig. 6b).

Following NFL of CO₂ within the sectoral network, obvious changes existed in the NFL of secondary industry, rather than that of other industries. This is largely because in secondary industry, manufacturing (S3) presented the most evident changes in NFL (see Fig. 6c).

Tertiary industry experienced an upward trend in the positive net NBL of CO₂. Typically, along NBL, some sectors clearly increased their CO₂ emissions and they were wholesale and retail trade (S6), information transformation, computer services and software (S8), and finance (S9). At the same time, CO₂ reductions were encouraged by import-dependent consumption, with a declining inter-sector difference. In particular, manufacturing (S3) and construction (S5) had obvious CO₂ leakages due to their producers' import and the large amount of Beijing's interprovincial export for their consumption (Fig. 6d).

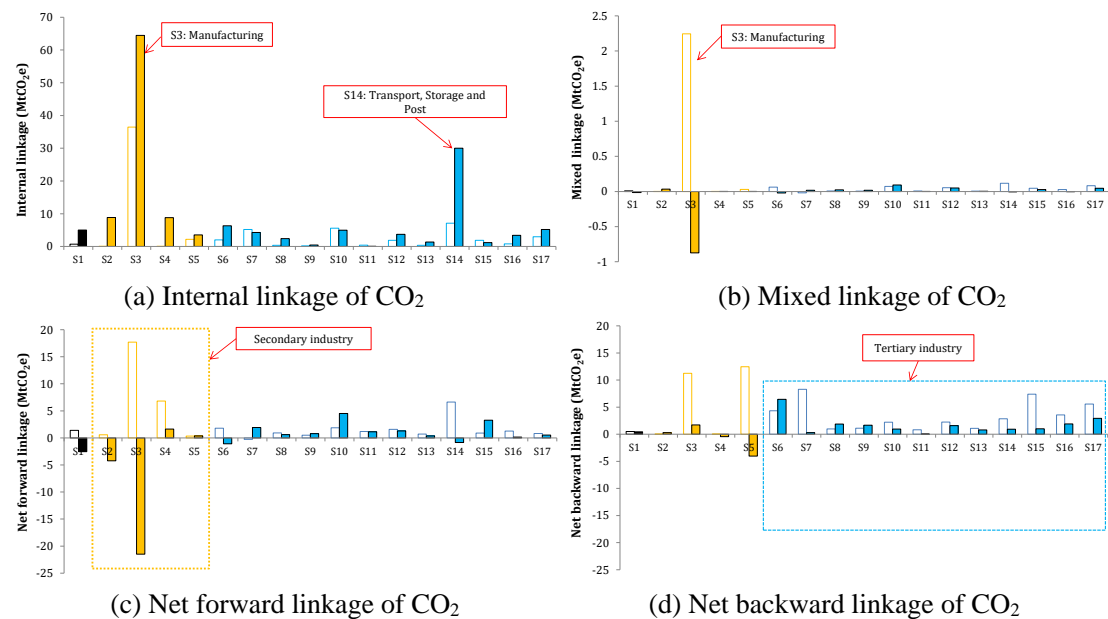


Fig.6. Sectoral shares of CO₂ linkages in Beijing. Note. In Figs. 6a, b, c and d, the bars without any colour correspond to sectoral CO₂ linkages in 2005, while the bars containing a colour correspond to sectoral CO₂ linkages in 2012.

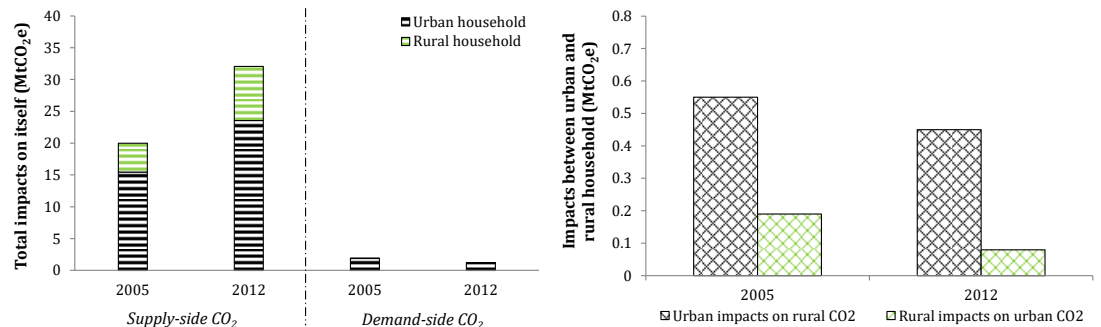
3.3 Impacts of household income and expenditure on CO₂ emissions

In the field of impacts of household consumption on CO₂ emissions, situations where households serve as consumers have been considered in depth at the country level (Wiedenhofer et al., 2017) or at the city level (He et al., 2016; Wang and Yang, 2016). Different from this thinking, endogenous effects of household on intermediate input-output system are taken into account through household income-expenditure relation. Household income-oriented impacts on their own CO₂ emissions intended to be more than household expenditure-oriented impacts in Beijing (see Fig. 7a), but they all exceeded household impacts on sectoral CO₂ as well as CO₂ emission of households excluding itself (see Figs. 7a–d). Residential sectors preferred saving money to consuming at present in order to avoid future risks, although household income increased thanks to the country's overall economic development. Meantime, for each household, the imbalanced results among its own CO₂, sectoral CO₂, and CO₂ of households excluding themselves showed

that individual households were not the main participant of economic activities of sectors and other households.

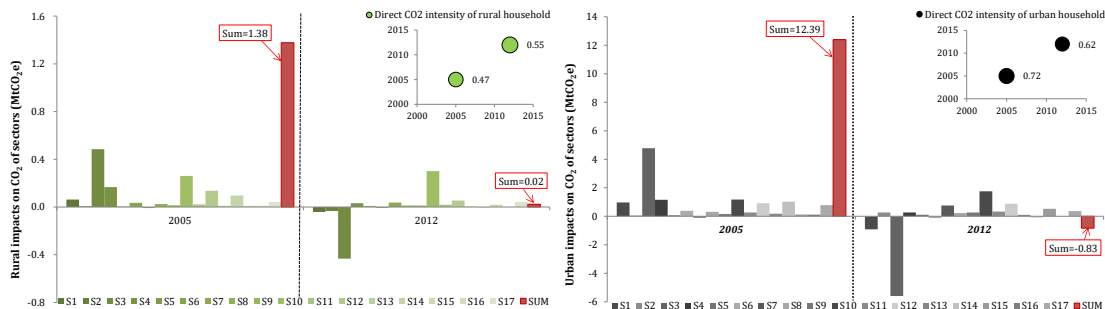
Rural–urban disparities in both supply-side and demand-side CO₂ were widening while those in sectoral CO₂ were narrowing (Figs. 7c-f). However, the reasons behind such changes were similar but different in the impact direction. Accompanying the limits on the household registration system and rural-urban disparities in income in the context of rapid urbanization, differing household participation levels in economic activities have been stimulated in Beijing. Consequently, through incomes and expenditures, urban households could influence supply-side and demand-side CO₂, as well as sectoral CO₂ emissions more than rural households. Additionally, sectoral CO₂ emissions were not only influenced by households but also by import and final demand within the economic system (as mentioned before, the whole system was greatly influenced by import), so they were not mainly responsible for the impacts of household on total emissions. Nonetheless, despite the fact above, the direct CO₂ intensity of urban households decreased but that of rural households increased in 2012 (see Fig. 7c and d). Therefore, both amount and intensity of CO₂ emissions caused by households should be considered when designing environmental policies or rules.

However, urban and rural households had some features in common (see Fig. 7c and d): (1) impacted by households, CO₂ leakages existed in some sectors like agriculture (S1), manufacturing (S3), wholesale and retail trade (S6), and transport, storage, and post (S14); (2) affected by households, tertiary sectors like hotels and restaurants (S7), real estate activities (S10), and education (S15) generated more CO₂. These similarities suggest the necessity of considering linkages between households and typical sectors for designing environmental policies or adopting related countermeasures.



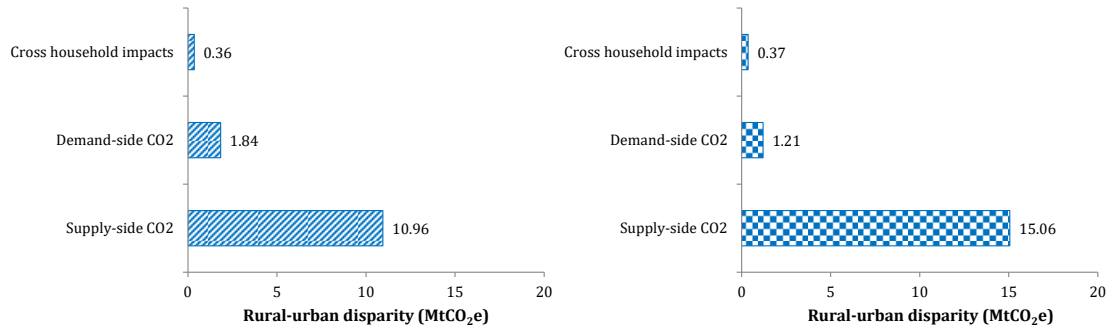
(a) Urban (rural) impacts on urban (rural) CO₂

(b) Urban (rural) impacts on rural (urban) CO₂



(c) Rural Impacts on sectoral CO₂

(d) Urban impacts on sectoral CO₂



(e) Categories of rural-urban disparity in 2005 (f) Categories of rural-urban disparity in 2012
 Fig.7. Rural and urban impacts on CO₂ of households including urban and rural household and traditional sectors involving from sector 1 to sector 17. Note. In Figs. 7c and d, the unit of the direct CO₂ intensity is tCO₂e per ten thousand yuan in constant 2005 price.

4 Conclusions and policy implications

Comprehensive understanding of CO₂ emissions in Beijing could boost the effectiveness of CO₂ mitigation measures. This paper evaluated total CO₂ in Beijing in 2005 and 2012 in terms of three aspects: Aspect 1 considers the amount, drivers, efficiency, and flow of CO₂; Aspect 2 focuses on allocation of CO₂ according to sectoral linkages; and Aspect 3 points to household impacts on CO₂. Then, corresponding policy implications were considered. All results were gained by integrating a semi-closed input-output model with a hypothetical extraction thinking.

4.1 Conclusions

● Aspect 1

First, a shift in economic structure from industrialized to service-driven activities in Beijing did not aid a lot in low carbonization. It is because the total CO₂ emissions experienced an increase trend mainly coming from manufacturing; transportation, storage, and post; and urban households. Secondly, accompanying closer trade connection between Beijing and its surrounding regions or areas, the increases in total CO₂ were driven mostly by Beijing's interprovincial export while less driven by other final demand categories. Thirdly, there were obvious differences between the direct and total CO₂ intensity in light of sum and sectoral distribution, indicating that evident changes came to CO₂ embodied in the intermediate IO system correspondingly. Both economy and CO₂ reduction could benefit from import in Beijing, with regard to the sectoral distribution of total CO₂ consumption coefficients of agriculture; manufacturing; wholesale and retail trade; and transport, storage, and post in 2012.

● Aspect 2

Sectoral convergence in Beijing has not progressed smoothly, causing more CO₂ emissions accumulated in closed circuits of sectoral supply and demand. Among the sectors, manufacturing; and transportation, storage, and post contributed the most. But more CO₂ reductions came from the NFL and NBL of secondary sectors particularly for manufacturing. This phenomenon was partly driven by both industrial structure upgrading and import developments in Beijing. Few CO₂ emissions were caused by ML across all sectors, among which manufacturing played the leading role. In addition, tertiary industry continued to generate CO₂ in each part of the supply and demand chains with the related smaller inter-sector differences, owing to its wide-ranging contribution to Beijing's GDP.

● Aspect 3

Households' income-oriented impacts on their own CO₂ were greater than household expenditure-oriented impacts in Beijing, but they all exceeded household impacts on sectoral CO₂ and CO₂ emission of households excluding themselves. Besides, rural–urban disparities in both supply-side and demand-side CO₂ were widening while that in sectoral CO₂ was narrowing. Despite these divergences, urban and rural impacts on sectoral CO₂ have something in common: (1) some tertiary sectors (e.g., hotels and restaurants; real estate activities; and education) generated the increased CO₂ emissions with household effects; (2) some sectors (e.g., agriculture, manufacturing; wholesale and retail trade; and transport, storage, and post) had the obvious carbon leakage due to the household participation. Additionally, the direct CO₂ intensity of urban households decreased whereas that of rural households increased in 2012.

4.2 Policy Implications

In terms of aspect 1, Beijing could focus on mitigating CO₂ emissions from manufacturing; transportation, storage, and post; and urban household sectors. For economic drivers, adjusting the structure of final demand to reduce CO₂ emissions is also crucial with the prerequisite of the healthy operation of sectoral economies. More importantly, it is worthwhile to combine the consideration of sectoral characteristics with sectoral final demand categories in the field of CO₂ alleviation. For instance, these findings support the significance of CO₂ reduction in both import and export of Manufacturing, along with the interprovincial export of transportation, storage and post and urban household. Given that sectoral CO₂ intensities varied sustainably in the intermediate input-output system, final demand side, and the entire economic system, if environmental policies only consider direct CO₂ intensity, measures will not be implemented efficiently and effectively. Besides, although the continuing encouragement of imports improved both the economy and environment in Beijing, attention could be paid to how to select feasible sectors that could achieve environmental and economic benefits.

In light of aspect 2, it is necessary to decompose sectoral CO₂ emissions according to sectoral specifications along supply and demand chains. Inefficiency of environmental policies and regulations could also arise if they are only implemented in some certain sectors which would generate further direct CO₂ emissions, particularly when differing sectoral contributions to CO₂ emissions are considered in Beijing. For example, CO₂ emissions from manufacturing were caused mainly by its internal linkage among sectors (as were those from the transport, storage, and post sector), but its net forward and net backward linkages could aid in mitigating CO₂ emissions. Therefore, different activities of the manufacturing sector along its supply and demand chain allow for CO₂ emissions to be decomposed.

With respect to aspect 3 indicating household CO₂ emissions have greatly contributed to the increased CO₂ in Beijing, results suggest that CO₂ reductions be increased more evidently by decreases in household income-oriented impacts than expenditure-oriented impacts. In addition, both the amount and intensity of CO₂ emissions caused by households could be considered together, along with the emphasis on thinking of the CO₂ linkages between households and typical sectors for designing environmental policies or rules. Furthermore, aiming at exploring future potentials for CO₂ reduction, urban-rural integration in Beijing deserves further promotions.

Last but not least, based on sectoral economy-wide effects in the field of CO₂, related incentive-based measures such as the emissions trading scheme (ETS) and the carbon tax for CO₂

reduction could be reconsidered. As we know, the fundamental step of the two main mechanisms concerns the calculation of carbon emissions. In practice, according to the current accounting principle in Beijing's ETS, the direct CO₂ emissions are calculated through multiplying the amount of fossil fuel consumption of selected energy-intensive sectors by direct CO₂ emission factor which will be replaced by the indirect CO₂ emission factor of electricity consumption when the indirect CO₂ emissions are measured. Nonetheless, out of the empirical results gained from the semi-closed IO model integrated with HEM in this paper, CO₂ emissions from energy consumption are the integrated outcomes in terms of direct CO₂ emission factor, the Leontief inverse (i.e., total requirements matrix) and final demand categories. Therefore, the reassessments of CO₂ emission could be required, ensuring the equality of its implementation for ETS.

4.3 Future studies

Based on the analysis presented in this paper, information collected on CO₂ emissions was considered to determine policy implications on sectoral CO₂ in terms of how each sector influences (1) the overall economic system, and (2) the intermediate input-output system. However, in the field of CO₂, identifying the key sector would pinpoint which sector has the largest potential to trigger CO₂ throughout the economy, thus helping understand the exact origins of CO₂ flows and aiding in evaluating industrial policy efficiency and ensuring adoption of feasible policies. Therefore, based on identifying the key sector, improved understanding of embodied CO₂ flow and carbon balance among sectors is a recommended avenue for future researches.

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Appendix

Table A1 Semi-closed Input-Output table

Input \ Output		Intermediate demand			Final demand			Import	Total output	
		Sector(1...17)	Household consumption		Government consumption	Investment	Export			
			Urban	Rural						
Intermediate supply	Sector(1...17)	<i>I</i>			<i>II</i>					
	Income									Urban
										Rural
Value added	Other value added	<i>III</i>								
Total input										

Table A2 The classification of 42 sectors into 17 sectors

Code	17 sectors	42 sectors of IOT
S1	Agriculture	Farming, Forestry, Animal Husbandry and Fishery
S2	Mining	Mining and Wasting of Coal
		Extraction of Petroleum and Natural Gas
		Mining of Metal Ores
		Mining and Processing of Nonmetal Ores
S3	Manufacturing	Manufacture of Foods and Tobacco
		Manufacture of Textile
		Manufacture of Textile Wearing Apparel, Footwear, Caps, Leather, Fur, Feather(Down) and Its products
		Processing of Timbers and Manufacture of Furniture
		Papermaking, Printing and Manufacture of Articles of Culture, Education and Sports Activities
		Processing of Petroleum, Coking, Processing of Nuclear Fuel
		Chemical Industry
		Manufacture of Nonmetallic Mineral Products
		Smelting and Rolling of Metals Products
		Manufacture of Metal Products
		Manufacture of General Purpose Machinery
		Manufacture of Special Purpose Machinery
		Manufacture of Transport Equipment
		Manufacture of Electrical Machinery and Equipment
		Manufacture of Communication Equipment, Computer and Other Electronic Equipment
		Manufacture of Measuring Instrument and Machinery for Cultural Activity, Office Work and Artwork
		Other Manufacture
		Scrap and Waste
S4	Production and Supply of Electric Power and Heat Power	Production and Supply of Electric Power and Heat Power
		Production and Distribution of Gas
		Production and Distribution of Water
S5	Construction	Construction
S6	Wholesale and retail Trade	Wholesale and retail Trade

Continued Table A2

Code	17 sectors	42 sectors of IOT
S7	Hotel and Restaurants	Hotel and Restaurants
S8	Information Transmission, Computer Service and Software	Information Transmission, Computer Service and Software
S9	Finance	Finance
S10	Real Estate Trade	Real Estate Trade
S11	Resident Services and Other Services	Resident Services and Other Services
S12	Education	Education
S13	Culture, Art, Sports and Recreation	Culture, Art, Sports and Recreation
S14	Transportation, Storage and Post	Transportation, Storage and Post
S15	Tenancy and Commercial Service	Tenancy and Commercial Service
S16	Compositive Technical Service	Compositive Technical Service
S17	Public and social management	Water, Environment and Municipal Engineering Conservancy
		Health Care, Social Security and Social Welfare
		Publish Manage and Social Organization

Table A3 The classification of 57 sectors into 17 sectors and households

Code	17 sectors and households	57 sectors consuming energy
S1	Agriculture	Agriculture, forestry, animal husbandry and fishing
S2	Mining	Mining and washing of coal
		Extraction of petroleum and natural gas
		Mining and processing of Ferrous metal ores
		Mining and processing of Non-ferrous metal ores
		Mining and dressing of nonmetal ores
		Mining of other ores
S3	Manufacturing	Procession of food from agriculture products
		Manufacture of foods
		Manufacture of beverage
		Manufacture of tobacco
		Manufacture of textile
		Manufacture of textile wearing apparel, footwear and caps
		Manufacture of leather, furs, feather(down) and related products
		Processing of timber, manufacture of wood, bamboo, rattan, palm and straw products
		Manufacture of furniture
		Manufacture of paper and paper products
		Printing, reproduction of recording media
		Manufacture of articles for culture, education and sports activity
		Processing of petroleum, coking, processing of nuclear fuel
		Manufacture of raw chemical materials and chemical products
		Manufacture of medicines
		Manufacture of chemical fibers
		Manufacture of rubber
		Manufacture of plastics
		Manufacture of non-metallic mineral products
		Smelting and pressing of ferrous metals
		Smelting and processing of nonferrous metals
		Manufacture of Metal products
		Manufacture of general purpose machinery
Manufacture of Special purpose machinery		
Manufacture of Transportation equipment		
Manufacture of Electrical machinery and equipment		
Manufacture of communication equipment, computers and other electronic equipment		

Continued Table A3

Code	17 sectors and households	57 sectors consuming energy
S3	Manufacturing	Manufacture of measuring instruments and machinery for culture activity and office work
		Machinery of artwork and other manufacturing
		Recycling and disposal of waste
S4	Production and distribution of electricity, gas and water	Production and distribution of electric power and heat power
		Production and distribution of gas
		Production and distribution of water
S5	Construction	Construction
S6	Wholesale and retail trade	Wholesale and retail trade
S7	Hotel and restaurants	Hotel and restaurants
S8	Information transmission, computer services and software	Information transmission, computer services and software
S9	Finance	Finance
S10	Real estate trade	Real estate trade
S11	Resident services and other services	Resident services and other services
S12	Education	Education
S13	Culture, art, sports and recreation	Culture, art, sports and recreation
S14	Transportation, storage, and post	Transportation, storage, post and telecommunications
S15	Tenancy and commercial services	Tenancy and commercial services
S16	Compositive Technical Service	Scientific studied, technical services and geological prospecting
S17	Public and social management	Public manage and social organization
		Water, environment and municipal engineering conservancy
		Health care, social security and social welfare
S18	Rural Household	Rural consumption
S19	Urban Household	Urban consumption