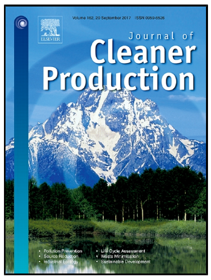
Accepted Manuscript



CO_2 Emissions in Beijing: Sectoral Linkages and Demand Drivers

Hua Liao, Celio Andraded, Julio Lumbreras, Jing Tian

PII:	S0959-6526(17)31749-3
DOI:	10.1016/j.jclepro.2017.08.033
Reference:	JCLP 10291
To appear in:	*Journal of Cleaner Production*
Received Date:	21 January 2017
Revised Date:	17 July 2017
Accepted Date:	05 August 2017

Please cite this article as: Hua Liao, Celio Andraded, Julio Lumbreras, Jing Tian, CO_2 Emissions in Beijing: Sectoral Linkages and Demand Drivers, *Journal of Cleaner Production* (2017), doi: 10.1016 /j.jclepro.2017.08.033

CO_2 Emissions in Beijing: Sectoral Linkages and Demand Drivers

Hua Liao[a, b, c, d], Celio Andraded[f], Julio Lumbreras[e], and Jing Tian[a,b,c,d,e]

a. School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China.
b. Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China.
c. Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing 100081, China.
d. Sustainable Development Research Institute for Economy and Society of Beijing, Beijing 100081, China.
e. Environmental Modelling Laboratory, Department of Chemical and Environmental Engineering, Technical University of Madrid (UPM), c/ José Gutiérrez Abascal 2, 28006 Madrid, Spain.
f. School of Management, Federal University of Bahia (UFBA), 40210-630 Salvador, Bahia, Brazil.

Abstract: Cities coutribute to most of the CO_2 emissions. And the economic system at city level is much complex due to various linkaged sectors. This paper aims to analyze the sectors and households to CO_2 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) interprovincial export caused the largest amount of CO_2 emissions [135.5 Mt] with the main contributions arising from manufacturing (42.1 Mt); transportation, storage, and post (TSP in short, 29.1 Mt); and households (23.6 Mt); (2) across the intermediate input-output system, real estate activities accounted for the largest amount of embodied CO_2 intensity (0.07 kg per yuan) and more sectors outsourced CO_2; (3) tracing the integrated sector network, CO_2 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 CO_2 according to its origin; (4) CO_2 emissions induced by household strikingly affected total CO_2 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: CO_2 emissions; Semi-closed input-output model; Modified hypothetical extraction method; City; Beijing

1. Introduction

During industrialization, urbanization, and modernization, CO_2 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 CO_2 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 CO_2 reduction efforts, there are two obvious problems: (1) details are lacking quantitatively in depicting how each of the above-mentioned factors influences CO_2 reduction and (2) these factors are investigated without an integrated research framework.

Regarding the relationship between sectoral linkages and CO_2, 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 CO_2 emissions within the economic system. However, CO_2 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 CO_2 reduction, the relationship between detailed final demand categories and CO_2 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 CO_2 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 CO_2, 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 Zhang et al. (2015); second, some explore rural-urban disparities and related CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2, regarding 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 CO_2. 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 CO_2 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 CO_2 (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 CO_2 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 CO_2 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 CO_2 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 CO_2 emissions are discussed by using HEM.

Fig.1. Framework for CO_2 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:

$$\varphi_i = {(x_i - e_i)}/{(x_i + m_i - e_i)} \tag{1}$$

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 CO_2 development based on semi-closed input-output Model

To figure out the general development of the city-level CO_2 emissions, several aspects of CO_2 emissions are analysed, regarding 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 CO_2 intensity, total CO_2 intensity and embodied CO_2 intensity, and its flows caused by import are gained according to the modified total CO_2 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:

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

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 $(\mathbf{EX} - \mathbf{IM})$. Here we define the final demand excluding the import.

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:

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

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, $\mathbf{H}^{\mathbf{con}}$, the ratio of household consumption to total output for each sector, and $\mathbf{H}^{\mathbf{inc}}$, 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, CO_2 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 CO_2 emissions based on the semi-closed IO model, $\mathbf{e}$ is the CO_2 direct intensity, i.e., the ratio of one sector's CO_2 emissions to its total output.

After calculating CO_2 emissions, $\mathbf{e}$, and total output, the other two CO_2 intensities are:

$$\boldsymbol{e}^{\boldsymbol{total}} = \boldsymbol{e}\left(\boldsymbol{I} - \boldsymbol{A}^*\right)^{-1} \quad (7)$$

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

where $\boldsymbol{e}^{\boldsymbol{total}}$ is the total CO_2 intensity representing the direct and indirect CO_2 generated by per unit of total output, $\boldsymbol{e}^{\boldsymbol{embodied}}$ is the embodied CO_2 intensity equalling the gap between total CO_2 intensity and direct CO_2 intensity, meaning the CO_2 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 CO_2 flow between regions. The total CO_2 consumption coefficient could be employed to interpret the outsourced CO_2 emissions via import, which helps identify the sectors impacted most dramatically by imports in terms of CO_2 emissions. This is because it is calculated through by the direct CO_2 intensity multiplying the total consumption coefficient based on formula (1):

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

where $\boldsymbol{e}^{\boldsymbol{import}}$ is the modified total CO_2 consumption coefficient to reflect the influence of import on city-level CO_2 caused by per unit of output.

2.4 CO_2 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:

$$\mathbf{I} = \begin{bmatrix} \mathbf{M_{s,s}} & \mathbf{M_{s,-s}} \\ \mathbf{M_{-s,s}} & \mathbf{M_{-s,-s}} \end{bmatrix} \tag{6}$$

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, CO_2 levels are calculated as follows:

$$\begin{bmatrix} \mathbf{C_s} \\ \mathbf{C_{-s}} \end{bmatrix} = \begin{bmatrix} \mathbf{e_s} & \mathbf{0} \\ \mathbf{0} & \mathbf{e_{-s}} \end{bmatrix} \begin{bmatrix} \mathbf{B_{s,s}} & \mathbf{B_{s,-s}} \\ \mathbf{B_{-s,s}} & \mathbf{B_{-s,-s}} \end{bmatrix} \begin{bmatrix} \mathbf{Y_s^*} \\ \mathbf{Y_{-s}^*} \end{bmatrix} \tag{7}$$

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, CO_2 levels are calculated using

$$\begin{bmatrix} \mathbf{C_s} \\ \mathbf{C_{-s}} \end{bmatrix} = \begin{bmatrix} \mathbf{e_s} & \mathbf{0} \\ \mathbf{0} & \mathbf{e_{-s}} \end{bmatrix} \begin{bmatrix} (\mathbf{I} - \mathbf{A_{s,s}^*})^{-1} & \mathbf{0} \\ \mathbf{0} & (\mathbf{I} - \mathbf{A_{-s,-s}^*})^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{Y_s^*} \\ \mathbf{Y_{-s}^*} \end{bmatrix} \tag{8}$$

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

$$\mathbf{C^{bef}} - \mathbf{C^{aft}} = \begin{bmatrix} \mathbf{e_s} & \mathbf{0} \\ \mathbf{0} & \mathbf{e_{-s}} \end{bmatrix} \begin{bmatrix} \mathbf{C_s^{bef}} - \mathbf{C_s^{aft}} \\ \mathbf{C_{-s}^{bef}} - \mathbf{C_{-s}^{aft}} \end{bmatrix} \tag{9}$$

$$\mathbf{C^{bef}} - \mathbf{C^{aft}} = \begin{bmatrix} \mathbf{B_{s,s}} - (\mathbf{I} - \mathbf{A_{s,s}^*})^{-1} & \mathbf{B_{s,-s}} \\ \mathbf{B_{-s,s}} & \mathbf{B_{-s,-s}} - (\mathbf{I} - \mathbf{A_{-s,-s}^*})^{-1} \end{bmatrix} \begin{bmatrix} \mathbf{Y_s^*} \\ \mathbf{Y_{-s}^*} \end{bmatrix}, \tag{10}$$

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), CO_2 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):

$$\mathbf{IL} = \mathbf{u_s'} \mathbf{e_s} (\mathbf{I} - \mathbf{A_{s,s}^*})^{-1} \mathbf{Y_s^*} \tag{11}$$

where $\mathbf{IL}$ refers to the CO_2 generated by the products and services created by $\mathbf{M_s}$ itself to satisfy the final demand of $\mathbf{M_s}$

$$\mathbf{ML} = \mathbf{u_s'} \mathbf{e_s} [\mathbf{B_{s,s}} - (\mathbf{I} - \mathbf{A_{s,s}^*})^{-1}] \mathbf{Y_s^*} \tag{12}$$

where $\mathbf{ML}$ is the CO_2 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 $\mathbf{M_s}$

$$\mathbf{NFL} = \mathbf{u_s'} \mathbf{e_s} \mathbf{B_{s,-s}} \mathbf{Y_{-s}^*} \tag{13}$$

where, to meet the final demand of another sector (cluster), $\mathbf{Y_{-s}^*}$, there would be CO_2 ($\mathbf{NFL}$) generated during the direct and indirect production of $\mathbf{M_s}$

$$\mathbf{NBL} = \mathbf{u_{-s}'} \mathbf{e_{-s}} \mathbf{B_{-s,s}} \mathbf{Y_s^*} \tag{14}$$

where, to satisfy the final demand of $\mathbf{M_s}$, $\mathbf{Y_s^*}$, CO_2 ($\mathbf{NBL}$) 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 CO_2 emissions

Based on the semi-closed IO model and HEM described above, impacts of household income and expenditure on CO_2 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 CO_2 emissions in Beijing

3.1.1 CO_2 emissions caused by energy consumption

Affected by energy consumption directly, total CO_2 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 CO_2 levels, partly due to urbanization causing population migration, changing lifestyles, increasing motor vehicle utilization, and so on.

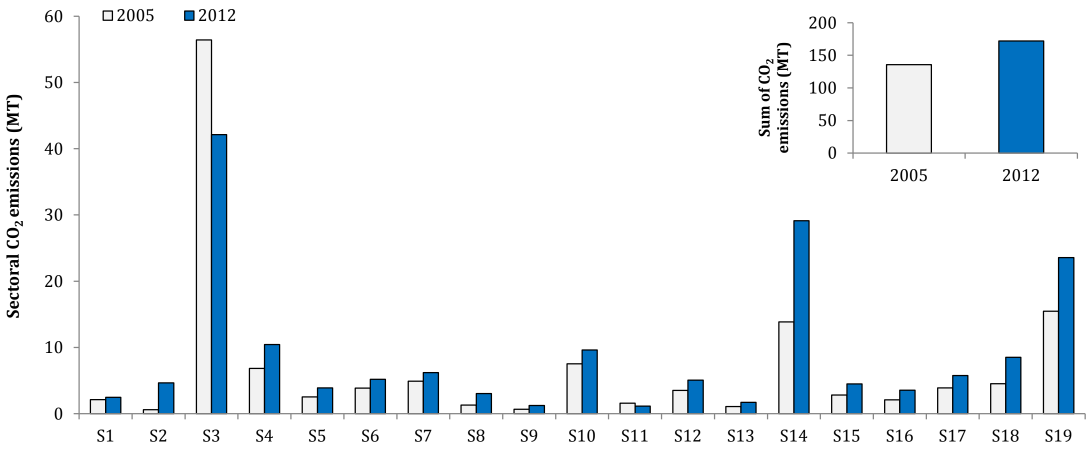


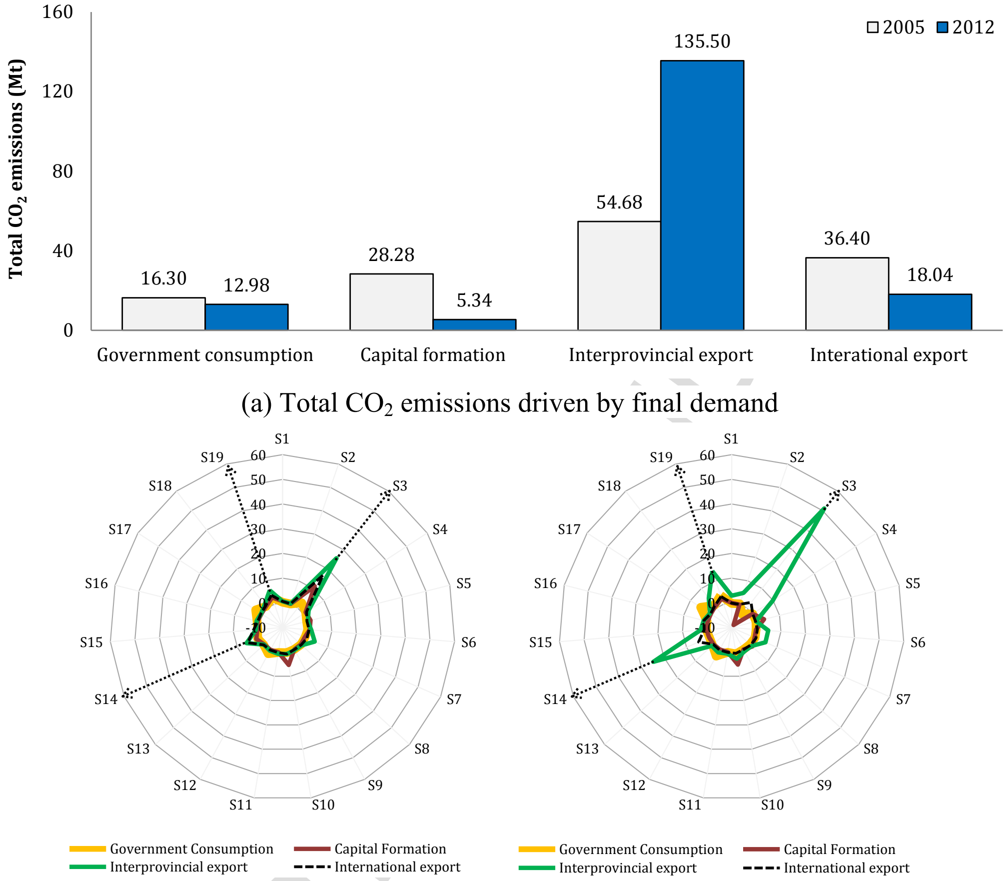
Fig.2. Total CO_2 emissions and its sectoral shares in Beijing in 2005 and 2012. Note. Sectors include 17 sectors from S1 to S17, in addition, S18 represents rural household and S19 urban household (see Table A2 in the Appendix).

3.1.2 CO_2 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 CO_2 emissions were driven mostly by Beijing's interprovincial export (Fig. 3a). By contrast, CO_2 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 CO_2 emissions with the prerequisite of maintaining healthy operation of sectoral economies.

To determine the sectoral shares of CO_2 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 CO_2 by Beijing's interprovincial export; and (2) manufacturing (S3) caused the largest amount of CO_2 leakage because its government consumption and capital formation were imported-dependent. These findings indicate the significance of import and export to CO_2 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 CO_2 emissions driven by final demand

(b) Sectoral CO_2 in 2005 (c) Sectoral CO_2 in 2012

Fig.3. Sectoral CO_2 emissions driven by final demand in Beijing in 2005 and 2012 (unit: $MtCO_2e$)

3.1.3 CO_2 emissions embodied in the intermediate input-output system

Whether "intensity targets" could be effective for CO_2 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 CO_2 intensities, "intensity targets" would be examined as well. Each sector, i, should have its CO_2 intensity considered both directly and indirectly: the direct CO_2 intensity represents direct CO_2 from unitary total output; and total CO_2 intensity refers to direct and indirect CO_2 from unitary output. Therefore, if sector i's total CO_2 intensity is more than its direct CO_2 intensity, the extra CO_2 produced by sector i is embodied in the intermediate input-output system and if not, the CO_2 generated by sector i is transferred outside the intermediate system.

Differences exist between direct CO_2 intensity and total CO_2 intensity across sectors. Specifically, in 2012, direct CO_2 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 CO_2 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 CO_2 intensity, which refers to embodied CO_2 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 CO_2 arising from the intermediate input-output system, according to their negative value of embodied CO_2 intensity (see Fig. 4c).

(a) Direct CO_2 intensity (b) Total CO_2 intensity (c) Embodied CO_2 intensity

Fig.4. Direct CO_2 intensity, total CO_2 intensity and embodied CO_2 intensity in Beijing in 2005 and 2012 (unit: tCO_2e per ten thousand yuan in constant 2005 price)

3.1.4 CO_2 emissions outsourced via import

Beijing's economy being impacted largely by import in 2012, the number of sectors outsourcing their CO_2 increased, meaning import-dependent economy in Beijing was beneficial to its CO_2 reduction. Precious studies also advocated the positive impacts of domestic and foreign import on CO_2 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 CO_2 consumption coefficients, the modified total CO_2 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 CO_2 leakage. On the contrary, in 2012, four sectors had CO_2 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 CO_2 consumption coefficient in Beijing at sector level (Unit: kg/ten yuan)

Year	2005	2012			
Producer / Consumer	S7	S1	S3	S6	S14
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 CO_2 linkages among sectors in Beijing

In terms of impacts of industry structure on CO_2 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 CO_2 in Beijing (Mi et al., 2015), to mitigate climate change. For CO_2 decomposition along supply and demand chains in this section, based on the modified hypothetical extraction method, CO_2 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 CO_2 linkages among sectoral clusters

As shown in Fig. 5, in Beijing, sectoral convergence has not progressed smoothly, leading to further CO_2 emissions accumulating in the closed circuits of sectoral supply and demand (i.e., IL). By contrast, with industrial structure upgrading and import development, CO_2 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 CO_2 in each segment of the supply and demand chains, owing to its wide-ranging contributions to Beijing's GDP. In particularly, for a certain industry, its CO_2 levels in 2012 compared to those in 2005: (1) more CO_2 emissions were induced by its increasing IL; (2) few CO_2 emissions were caused by ML; (3) for secondary industry, its imports started encouraging the largest CO_2 leakages considering negative NFL and NBL; and (4) for tertiary industry, CO_2 emissions caused by NBL remained the highest and those from NFL continued to be positive.

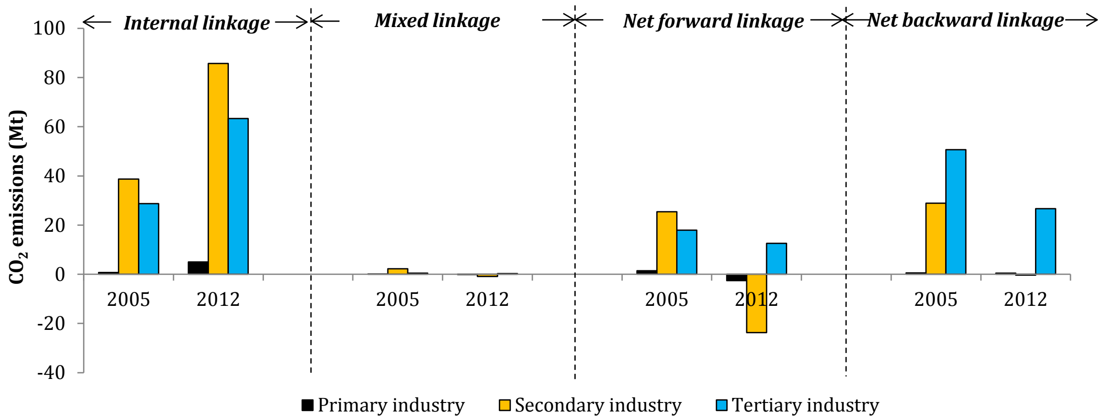


Fig.5. Overview of CO_2 linkage among sector clusters in Beijing

3.2.2 Sectoral shares of CO_2 linkages

CO_2 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 CO_2 levelled out at the range of 0 to 10 Mt CO_2 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 CO_2 intensity. In this regard, figuring out the detailed drivers of sectoral IL is also important for CO_2 reduction and needs more in-depth analysis of sectoral characteristics.

Overall, the ML of CO_2 contributed the least to the increased CO_2 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 CO_2 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 CO_2. Typically, along NBL, some sectors clearly increased their CO_2 emissions and they were wholesale and retail trade (S6), information transformation, computer services and software (S8), and finance (S9). At the same time, CO_2 reductions were encouraged by import-dependent consumption, with a declining inter-sector difference. Particularly, manufacturing (S3) and construction (S5) had obvious CO_2 leakages due to their producers' import and the large amount of Beijing's interprovincial export for their consumption (Fig. 6d).

(a) Internal linkage of CO_2 (b) Mixed linkage of CO_2

(c) Net forward linkage of CO_2 (d) Net backward linkage of CO_2

Fig.6. Sectoral shares of CO_2 linkages in Beijing. Note. In Figs. 6a, b, c and d, the bars without any colour correspond to sectoral CO_2 linkages in 2005, while the bars containing a colour correspond to sectoral CO_2 linkages in 2012.

3.3 Impacts of household income and expenditure on CO_2 emissions

In the field of impacts of household consumption on CO_2 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 considered through household income-expenditure relation. Household income-oriented impacts on their own CO_2 emissions intended to be more than household expenditure-oriented impacts in Beijing (see Fig. 7a), but they all exceeded household impacts on sectoral CO_2 as well as CO_2 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 CO_2, sectoral CO_2, and CO_2 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 CO_2 were widening while those in sectoral CO_2 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 CO_2, as well as sectoral CO_2 emissions more than rural households. Additionally, sectoral CO_2 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 CO_2 intensity of urban households decreased but that of rural households increased in 2012 (see Fig. 7c and d). Therefore, both amount and intensity of CO_2 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, CO_2 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 CO_2. 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) CO_2 (b) Urban (rural) impacts on rural (urban) CO_2

(c) Rural Impacts on sectoral CO_2 (d) Urban impacts on sectoral CO_2

(e) Categories of rural-urban disparity in 2005 (f) Categories of rural-urban disparity in 2012

Fig.7. Rural and urban impacts on CO_2 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 tCO_2e per ten thousand yuan in constant 2005 price.

4 Conclusions and policy implications

Comprehensive understanding of CO_2 emissions in Beijing could boost the effectiveness of CO_2 mitigation measures. This paper evaluated total CO_2 in Beijing in 2005 and 2012 in terms of three aspects: Aspect 1 considers the amount, drivers, efficiency, and flow of CO_2; Aspect 2 focuses on allocation of CO_2 according to sectoral linkages; and Aspect 3 points to household impacts on CO_2. 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 CO_2 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 CO_2 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 CO_2 intensity considering the total and sectoral distribution, indicating that evident changes came to CO_2 embodied in the intermediate IO system correspondingly. Both economy and CO_2 reduction could benefit from import in Beijing, regarding the sectoral distribution of total CO_2 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 CO_2 emissions accumulated in closed circuits of sectoral supply and demand. Among the sectors, manufacturing; and transportation, storage, and post contributed the most. But more CO_2 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 CO_2 emissions were caused by ML across all sectors, among which manufacturing played the leading role. In addition, tertiary industry continued to generate CO_2 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 CO_2 were greater than household expenditure-oriented impacts in Beijing, but they all exceeded household impacts on sectoral CO_2 and CO_2 emission of households excluding themselves. Besides, rural–urban disparities in both supply-side and demand-side CO_2 were widening while that in sectoral CO_2 was narrowing. Despite these divergences, urban and rural impacts on sectoral CO_2 have something in common: (1) some tertiary sectors (e.g., hotels and restaurants; real estate activities; and education) generated the increased CO_2 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 CO_2 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 CO_2 emissions from manufacturing; transportation, storage, and post; and urban household sectors. For economic drivers, adjusting the structure of final demand to reduce CO_2 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 CO_2 alleviation. For instance, these findings support the significance of CO_2 reduction in both import and export of Manufacturing, along with the interprovincial export of transportation, storage and post and urban household. Given that sectoral CO_2 intensities varied sustainably in the intermediate input-output system, final demand side, and the entire economic system, if environmental policies only consider direct CO_2 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.

Regarding aspect 2, it is necessary to decompose sectoral CO_2 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 CO_2 emissions, particularly when differing sectoral contributions to CO_2 emissions are considered in Beijing. For example, CO_2 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 CO_2 emissions. Therefore, different activities of the manufacturing sector along its supply and demand chain allow for CO_2 emissions to be decomposed.

With respect to aspect 3 indicating household CO_2 emissions have greatly contributed to the increased CO_2 in Beijing, results suggest that CO_2 reductions be increased more evidently by decreases in household income-oriented impacts than expenditure-oriented impacts. In addition, both the amount and intensity of CO_2 emissions caused by households could be considered together, along with the emphasis on thinking of the CO_2 linkages between households and typical sectors for designing environmental policies or rules. Furthermore, aiming at exploring future potentials for CO_2 reduction, urban-rural integration in Beijing deserves further promotions.

Finally, based on sectoral economy-wide effects in the field of CO_2, related incentive-based measures such as the emissions trading scheme (ETS) and the carbon tax for CO_2 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 CO_2 emissions are calculated through multiplying the amount of fossil fuel consumption of selected energy-intensive sectors by direct CO_2 emission factor which will be replaced by the indirect CO_2 emission factor of electricity consumption when the indirect CO_2 emissions are measured. Nonetheless, out of the empirical results gained from the semi-closed IO model integrated with HEM in this paper, CO_2 emissions from energy consumption are the integrated outcomes in terms of direct CO_2 emission factor, the Leontief inverse (i.e., total requirements matrix) and final demand categories. Therefore, the reassessments of CO_2 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 CO_2 emissions was considered to determine policy implications on sectoral CO_2 in terms of how each sector influences (1) the overall economic system, and (2) the intermediate input-output system. However, in the field of CO_2, identifying the key sector would pinpoint which sector has the largest potential to trigger CO_2 throughout the economy, thus helping understand the exact origins of CO_2 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 CO_2 flow and carbon balance among sectors is a recommended avenue for future researches.

Acknowledgements

We thank the financial supports from the China's National Key R&D Program (2016YFA0602801, 2016YFA0602603), National Natural Science Foundation of China (No. 71322306, 71273027, 71521002, 71673026). The views expressed in this paper are solely authors' own and do not necessarily reflect the views of the supporting agencies and authors' affiliations.

References

Batey, P.W., Madden, M., Weeks, M.J. (1987) Household Income and Expenditure in Extended Input-Output Models: A Comparative Theoretical and Empirical Analysis. Journal of Regional Science 27, 341-356.

Behrens, A. (1984) Energy and output implications of income redistribution in Brazil. Energy economics 6, 110-116.

Bell, M.L., Goldberg, R., Hogrefe, C., Kinney, P.L., Knowlton, K., Lynn, B., Rosenthal, J., Rosenzweig, C., Patz, J.A. (2007) Climate change, ambient ozone, and health in 50 US cities. Climatic Change 82, 61-76.

Cansino, J.M., Román, R., Ordóñez, M. (2016) Main drivers of changes in CO_2 emissions in the Spanish economy: A structural decomposition analysis. Energy Policy 89, 150-159.

Cardenete, M.A., Boulanger, P., Del Carmen Delgado, M., Ferrari, E., M'Barek, R. (2014) Agri-food and bio-based analysis in the Spanish economy using a key sector approach. Review of Urban & Regional Development Studies 26, 112-134.

Chen, G., Hadjikakou, M., Wiedmann, T. (2016a) Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis. Journal of Cleaner Production.

Chen, G., Wiedmann, T., Hadjikakou, M., Rowley, H. (2016b) City Carbon Footprint Networks. Energies 9, 602.

Chong, W.H.B., Guan, D., Guthrie, P. (2012) Comparative Analysis of Carbonization Drivers in China's Megacities. Journal of Industrial Ecology 16, 564–575.

Dong, Y., Ishikawa, M., Liu, X., Wang, C. (2010) An analysis of the driving forces of CO_2 emissions embodied in Japan–China trade. Energy Policy 38, 6784-6792.

Duarte, R., Sanchez-Choliz, J., Bielsa, J. (2002) Water use in the Spanish economy: an input–output approach. Ecological Economics 43, 71-85.

Fan, J.-L., Yu, H., Wei, Y.-M. (2015) Residential energy-related carbon emissions in urban and rural China during 1996–2012: From the perspective of five end-use activities. Energy and Buildings 96, 201-209.

Fan, J.L., Liao, H., Liang, Q.M., Tatano, H., Liu, C.F., Wei, Y.M. (2013) Residential carbon emission evolutions in urban–rural divided China: An end-use and behavior analysis. Applied Energy 101, 323-332.

Fan, J.L., Liao, H., Tang, B.J., Pan, S.Y., Yu, H., Wei, Y.M. (2016) The impacts of migrant workers consumption on energy use and CO 2 emissions in China. Natural Hazards 81, 725-743.

Feng, K., Hubacek, K., Sun, L., Liu, Z. (2014) Consumption-based CO_2 accounting of China's megacities: The case of Beijing, Tianjin, Shanghai and Chongqing. Ecological Indicators 47, 26-31.

Feng, Y., Chen, S., Zhang, L. (2013) System dynamics modeling for urban energy consumption and CO_2 emissions: a case study of Beijing, China. Ecological Modelling 252, 44-52.

Gudipudi, R., Fluschnik, T., Ros, A.G.C., Walther, C., Kropp, J.P. (2016) City density and CO2 efficiency. Energy Policy 91, 352-361.

Guo, S., Shao, L., Chen, H., Li, Z., Liu, J., Xu, F., Li, J., Han, M., Meng, J., Chen, Z.-M. (2012) Inventory and input–output analysis of CO_2 emissions by fossil fuel consumption in Beijing 2007. Ecological Informatics 12, 93-100.

He, Q., Jiang, X., Gouldson, A., Sudmant, A., Guan, D., Colenbrander, S., Xue, T., Zheng, B., Zhang, Q. (2016) Climate change mitigation in Chinese megacities: A measures-based analysis of opportunities in the residential sector. Applied Energy 184, 769-778.

Hoekstra, R., Van den Bergh, J.C. (2003) Comparing structural decomposition analysis and index. Energy economics 25, 39-64.

Jacobson, M.Z. (2009) Review of solutions to global warming, air pollution, and energy security. Energy & Environmental Science 2, 148-173.

Kopidou, D., Tsakanikas, A., Diakoulaki, D. (2016) Common trends and drivers of CO_2 emissions and employment: A decomposition analysis in the industrial sector of selected European Union countries. Journal of Cleaner Production 112, 4159-4172.

Krey, V., O'Neill, B.C., van Ruijven, B., Chaturvedi, V., Daioglou, V., Eom, J., Jiang, L., Nagai, Y., Pachauri, S., Ren, X. (2012) Urban and rural energy use and carbon dioxide emissions in Asia. Energy Economics 34, S272-S283.

Kucukvar, M., Egilmez, G., Tatari, O. (2014) Sustainability assessment of US final consumption and investments: triple-bottom-line input–output analysis. Journal of Cleaner Production 81, 234-243.

Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L., Britter, R. (2015) The rise of low-cost sensing for managing air pollution in cities. Environment international 75, 199-205.

Lenzen, M. (2003) Environmentally important paths, linkages and key sectors in the Australian economy. Structural Change and Economic Dynamics 14, 1-34.

Ling, S., Dabo, G., Ning, Z., Yuli, S., Chen, G.Q. (2016) Carbon emissions from fossil fuel consumption of Beijing in 2012. Environmental Research Letters 11, 114028.

Liu, L.-C., Cao, D., Wei, Y.-M. (2016) What drives intersectoral CO2 emissions in China? Journal of Cleaner Production 133, 1053-1061.

Liu, L.-C., Wu, G., Wang, J.-N., Wei, Y.-M. (2011) China's carbon emissions from urban and rural households during 1992–2007. Journal of Cleaner Production 19, 1754-1762.

Masson, V., Marchadier, C., Adolphe, L., Aguejdad, R., Avner, P., Bonhomme, M., Bretagne, G., Briottet, X., Bueno, B., de Munck, C. (2014) Adapting cities to climate change: A systemic modelling approach. Urban Climate 10, 407-429.

Mi, Z.-F., Pan, S.-Y., Yu, H., Wei, Y.-M. (2015) Potential impacts of industrial structure on energy consumption and CO_2 emission: a case study of Beijing. Journal of Cleaner Production 103, 455-462.

Miyazawa, K. (1976) Input-Output Analysis and the Structure of Income Distribution. Springer-Verlag, Berlin.

Mohareb, E.A., Kennedy, C.A. (2014) Scenarios of technology adoption towards low-carbon cities. Energy Policy 66, 685-693.

Morán, M.A.T., del Río González, P. (2007) A combined input–output and sensitivity analysis approach to analyse sector linkages and CO_2 emissions. Energy Economics 29, 578-597.

Nejat, P., Jomehzadeh, F., Taheri, M.M., Gohari, M., Majid, M.Z.A. (2015) A global review of energy consumption, CO_2 emissions and policy in the residential sector (with an overview of the top ten CO_2 emitting countries). Renewable and Sustainable Energy Reviews 43, 843-862.

Paelinck, J., De Caevel, J., Degueldre, J. (1965) Analyse quantitative de certaines phénomènes du développment régional polarisé: Essai de simulation statique d'itéraires de propogation. Bibliothèque de l'Institut de Science économique, 341-387.

Perobelli, F.S., Faria, W.R., de Almeida Vale, V. (2015) The increase in Brazilian household income and its impact on CO_2 emissions: Evidence for 2003 and 2009 from input–output tables. Energy Economics 52, 228-239.

Schultz, S. (1977) Approaches to identifying key sectors empirically by means of input‐output analysis. The Journal of development studies 14, 77-96.

Shan, Y., Guan, D., Liu, J., Liu, Z., Liu, J., Schroeder, H., Chen, Y., Shuai, Shao, Mi, Z. (2016) CO_2 emissions inventory of Chinese cities. Atmospheric Chemistry & Physics, 1-26.

Singh, S., Kennedy, C. (2015) Estimating future energy use and CO2 emissions of the world's cities. Environmental Pollution 203, 271-278.

Su, B., Ang, B. (2012) Structural decomposition analysis applied to energy and emissions: some methodological developments. Energy Economics 34, 177-188.

Talukdar, D., Meisner, C.M. (2001) Does the private sector help or hurt the environment? Evidence from carbon dioxide pollution in developing countries. World Development 29, 827-840.

Tarancon, M.A., Del Rio, P. (2007) CO_2 emissions and intersectoral linkages. The case of Spain. Energy policy 35, 1100-1116.

Tian, J., Liao, H., Wang, C. (2015) Spatial–temporal variations of embodied carbon emission in global trade flows: 41 economies and 35 sectors. Natural Hazards 78, 1125-1144.

Tian, X., Chang, M., Shi, F., Tanikawa, H. (2014) How does industrial structure change impact carbon dioxide emissions? A comparative analysis focusing on nine provincial regions in China. Environmental Science & Policy 37, 243-254.

Tian, X., Chang, M., Tanikawa, H., Shi, F., Imura, H. (2013) Structural decomposition analysis of the carbonization process in Beijing: A regional explanation of rapid increasing carbon dioxide emission in China. Energy Policy 53, 279-286.

Wang, Y., Wang, W., Mao, G., Cai, H., Zuo, J., Wang, L., Zhao, P. (2013a) Industrial CO_2 emissions in China based on the hypothetical extraction method: Linkage analysis. Energy policy 62, 1238-1244.

Wang, Y., Zhao, H., Li, L., Liu, Z., Liang, S. (2013b) Carbon dioxide emission drivers for a typical metropolis using input–output structural decomposition analysis. Energy Policy 58, 312-318.

Wang, Z., Yang, Y. (2016) Features and influencing factors of carbon emissions indicators in the perspective of residential consumption: Evidence from Beijing, China. Ecological Indicators 61, 634-645.

Wang, Z., Yin, F., Zhang, Y., Zhang, X. (2012) An empirical research on the influencing factors of regional CO_2 emissions: evidence from Beijing city, China. Applied Energy 100, 277-284.

Wang, Z., Zhang, B., Li, G. (2014) Determinants of energy-saving behavioral intention among residents in Beijing: Extending the theory of planned behavior. Journal of Renewable and Sustainable Energy 6, 053127.

Wiedenhofer, D., Guan, D., Liu, Z., Meng, J., Zhang, N., Wei, Y.-M. (2017) Unequal household carbon footprints in China. Nature Clim. Change 7, 75-80.

Wiedmann, T.O., Chen, G., Barrett, J. (2015) The concept of city carbon maps: a case study of Melbourne, Australia. Journal of Industrial Ecology.

Zhang, Q., Zhang, S., Ding, Z., Hao, Y. (2017) Does government expenditure affect environmental quality? Empirical evidence using Chinese city-level data. Journal of Cleaner Production 161, 143-152.

Zhang, X., Luo, L., Skitmore, M. (2015) Household carbon emission research: an analytical review of measurement, influencing factors and mitigation prospects. Journal of Cleaner Production 103, 873-883.

Zhang, Y. (2010) Supply-side structural effect on carbon emissions in China. Energy Economics 32, 186-193.

Zhao, Y., Zhang, Z., Wang, S., Zhang, Y., Liu, Y. (2015) Linkage analysis of sectoral CO_2 emissions based on the hypothetical extraction method in South Africa. Journal of Cleaner Production 103, 916-924.

Zhou, X., Zhang, J., Li, J. (2013) Industrial structural transformation and carbon dioxide emissions in China. Energy policy 57, 43-51.

Zhou, Y., Liu, Y., Wu, W., Li, Y. (2015) Effects of rural–urban development transformation on energy consumption and CO_2 emissions: A regional analysis in China. Renewable and Sustainable Energy Reviews 52, 863-875.

Zou, Q., Liu, X. (2016) Economic effects analysis of seawater desalination in China with input–output technology. Desalination 380, 18-28.

Appendix

Table A1 Semi-closed Input-Output table

<table>
<tr><td colspan="3" rowspan="3">Output
Input</td><td colspan="3">Intermediate demand</td><td colspan="3" rowspan="2">Final demand</td><td rowspan="3">Import</td><td rowspan="3">Total output</td></tr>
<tr><td rowspan="2">Sector(1⋯17)</td><td colspan="2">Household consumption</td></tr>
<tr><td>Urban</td><td>Rural</td><td>Government consumption</td><td>Investment</td><td>Export</td></tr>
<tr><td rowspan="3">Intermediate supply</td><td colspan="2">Sector(1⋯17)</td><td rowspan="3">I</td><td colspan="6" rowspan="3">II</td><td rowspan="3"></td></tr>
<tr><td rowspan="2">Income</td><td>Urban</td></tr>
<tr><td>Rural</td></tr>
<tr><td>Value added</td><td colspan="2">Other value added</td><td>III</td><td colspan="6"></td><td></td></tr>
<tr><td colspan="3">Total input</td><td></td><td colspan="6"></td><td></td></tr>
</table>

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 Mental 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
		Manufacture of Metal Products, Machinery and equipment repair services
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