Mapping inter-industrial CO₂ flows within China

Bai, Hongtao; Feng, Xiangyu; Hou, Huimin; He, Gang; Dong, Yan; Xu, He

Published in:
Renewable and Sustainable Energy Reviews

Link to article, DOI:
[10.1016/j.rser.2018.05.054](https://doi.org/10.1016/j.rser.2018.05.054)

Publication date:
2018

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Bai, H., Feng, X., Hou, H., He, G., Dong, Y., & Xu, H. (2018). Mapping inter-industrial CO₂ flows within China. *Renewable and Sustainable Energy Reviews*, 93, 400-408. <https://doi.org/10.1016/j.rser.2018.05.054>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Mapping Inter-Industrial CO₂ Flows within China

Hongtao Bai^{a,b,c}, Xiangyu Feng^a, Huimin Hou^a, Gang He^{c*}, Yan Dong^d, He Xu^a*

^aCollege of Environmental Science and Engineering, Nankai University, Tianjin 300350,
China

^bMOE Key Laboratory of Pollution Processes and Environmental Criteria, Nankai
University, Tianjin 300350, China

^cDepartment of Technology and Society, College of Engineering and Applied Sciences,
Stony Brook University, Stony Brook, New York 11794, United States of America

^dQuantitative Sustainability Assessment, Department of Management Engineering,
Technical University of Denmark, Kgs. Lyngby, 2800, Denmark

To whom correspondence should be addressed:

Hongtao Bai: baiht@nankai.edu.cn

Gang He: Gang.He@stonybrook.edu

1 **Abstract:** Like inter-regional CO₂ leakages, good CO₂ emission performances from
2 downstream industries in the industrial chain often result in high direct levels of CO₂
3 emissions in upstream sectors. Thus, it is necessary to rethink industrial carbon policies
4 from the perspective of consumer responsibility. As the largest emitter of CO₂ in the
5 world, China has a very comprehensive industrial system. In this study, we traced fuel-
6 related CO₂ flows between 30 Chinese industrial sectors in 2012 and explored the
7 specificities of these flows on aggregate CO₂ emission abatement for the entire
8 economy. Previous studies have focused on carbon abatement policies instituted by
9 industries generating high direct CO₂ emissions, but our results demonstrate that paying
10 more attention to CO₂ importers better limits the consumption of energy-intensive
11 materials. The construction sector, a major CO₂ flow destination because of the large-
12 scale infrastructure required to support rapid urbanization in China, exhibits the greatest
13 transfer of embodied CO₂ from energy suppliers and from the producers of energy-
14 intensive materials. Our sensitivity analysis indicates that the construction sector shows
15 considerable carbon abatement potential, which is surprisingly much greater than what
16 is feasible for most high-carbon industries. Shifting more attention to industries that
17 consume large amounts of embodied CO₂ may help achieve more cost-effective
18 decreases in CO₂ emissions in absolute terms.

19 **Highlights:**

- 20 ● The IO model and HEM are used to identify inter-industrial CO₂ flows
- 21 ● Fuel-related CO₂ flows between all 30 industrial sectors in China are mapped
- 22 ● Industrial carbon policies facilitating CO₂ emission abatement are determined
- 23 ● Construction sector shows considerable carbon abatement potential

24 **Keywords:** Carbon Emissions Embodied in Trade; Inter-Industrial Carbon Transfer;
25 Hypothetical Extraction Method; Carbon Abatement Potential

1. Introduction

CO₂ emissions are closely associated with industrial activities [1]. Local climate policy makers worldwide have always paid more attention to industries that generate high levels of direct CO₂ emissions (i.e., high-carbon industries, such as those of the energy sector; hereafter considered the same) to achieve regional low-carbon transformations. This largely reflects the production-based accounting principle, in which the producer is responsible for abating CO₂ emissions [2]. Consequently, many compulsory measures are being undertaken in regions and industries that emit large volumes of CO₂. International climate change negotiations have been based largely on this production-based principle [3]. Thus, China has instituted industrial restructuring by controlling the growth of high-carbon industries and by encouraging the development of low-carbon industries (i.e., industries generating low levels of direct CO₂ emissions; hereafter considered the same) [4].

However, such production-based policies may not always effectively decrease total CO₂ emissions throughout the entire economy. Developed countries/regions may decrease CO₂ emissions within their territorial areas, while increasing their carbon footprints in other countries/regions [5, 6]. Shifting the focus to low-carbon industries within a region may decrease regional CO₂ emission intensity levels but may not decrease total CO₂ emissions [7]. The economic system represents an interdependent and integrated collection of various industries. Production behavior is believed to be provoked or even determined by consumer demand on the industrial supply chain [8-10]. Embodied CO₂ emissions and consumption-based accounting principles have therefore been proposed as ways to increase the range of CO₂ emission mitigation options [11-14]. CO₂ emissions embodied in products and intermediate goods travel between regions and industries through upstream and downstream flows within the

1 economy.

2 The inter-regional CO₂ emission flows have been well identified over the past few
3 years, focusing on both international [9, 15-20] and domestic trade [6, 21-26]. These
4 studies show that the global economy has been closely interlinked through its complex
5 supply chain. Low CO₂ emissions in downstream industries often cause high direct CO₂
6 emissions in upstream sectors. Similar to inter-regional CO₂ leakages, the transfer of
7 inter-industrial CO₂ flows embodied in products along the supply chain are also
8 complicated. CO₂ emissions associated with complex links between industrial sectors
9 have not been well studied [27]. Although numerous studies emphasize the importance
10 of production-based CO₂ emissions and their driving forces [28-37], it is argued that
11 industrial embodied CO₂ emissions better represent CO₂ burdens. Using a multi-
12 regional input-output (IO) model, industrial embodied CO₂ emissions have been
13 analyzed in many of the inter-regional studies mentioned above. To evaluate inter-
14 industrial CO₂ emission transfers, an economic network model was used to trace CO₂
15 emissions in global supply chains [27]; these models are typically limited in resolution
16 to global to regional scales. In addition, the CO₂ emissions embodied in the supply
17 chain of several specific sectors, such as services, manufacturing, and construction
18 industries, have also been discussed [38-40]. Several studies have demonstrated links
19 between CO₂ emissions across all different industrial sectors of a country, using a
20 hypothetical extraction method (HEM) [7, 41-43]. However, they have largely focused
21 on relationships between industrial clusters rather than CO₂ flows between sectors. In
22 developing countries like China, industrialization is a necessary pathway to economic
23 prosperity. Accurate knowledge of inter-industrial CO₂ flows can be a step toward
24 global climate change mitigation. Consequently, it is necessary for local climate policy
25 makers worldwide, especially those in developing countries, to rethink the appropriate

1 industrial strategies for climate mitigation from a consumer responsibility perspective.
2 As the world's second largest economy, reflecting a vast landmass, huge population,
3 and rich natural resources, China has built a comprehensive industrial system. We focus
4 on China, as a key example, and attempt to identify industries that require large
5 embodied CO₂ emissions to satisfy consumer demands (referred to as primary
6 destinations of embodied CO₂ flows). Our aim is to determine whether policies focusing
7 on low-carbon industries more efficiently decrease CO₂ emissions than production-
8 based measures. To answer this question, we need to obtain a full understanding of CO₂
9 emission abatement effects achieved through various industrial policies. This requires
10 quantification of embodied CO₂ transferred between each pair of industrial sectors and
11 determination of the sensitivities of different industrial sectors to total CO₂ emissions
12 of the national economy.

13 In this paper, we trace embodied CO₂ flows between 30 industrial sectors and map
14 detailed inter-industrial CO₂ flows within China. To the best of our knowledge, it is the
15 first quantitative map of embodied CO₂ flow between pairs of industrial sectors in
16 China. Furthermore, based on the proposed map, we re-examine industrial CO₂
17 emission abatement potentials and determine which industrial carbon policies could
18 best facilitate CO₂ emission abatement in absolute terms for the entire Chinese economy.
19 A sensitivity analysis is performed for each industrial sector to identify the most cost-
20 effective industrial carbon policy. Our results can be used to facilitate the development
21 of Chinese industrial carbon policies and offer valuable guidelines for industrial
22 strategies for climate mitigation worldwide, especially for developing countries.

23 **2. Materials and methods**

2.1 Industrial Fuel-Related CO₂ Emissions

The fossil fuel-related CO₂ emissions generated by an industrial sector i (C_i) can be calculated as follows:

$$C_i = \sum_{k=1}^8 p_{ik} v_k \eta_k$$

$$T_i = \frac{C_i}{x_i}$$

where T_i is the direct CO₂ emission intensity of sector i (t/10⁴ ¥); x_i is the total output of sector i (10⁴ ¥); C_i is the direct CO₂ emissions generated by sector i (t/10⁴ ¥); η_k is the CO₂ emission factor for energy type k (t/TJ); p_{ik} is the amount of energy type k consumed by sector i (t); and v_k is the conversion factor for energy type k (TJ/tce). We considered the following eight fossil fuels: coal, coke, crude oil, diesel, fuel oil, gasoline, kerosene, and natural gas.

2.2 Hypothetical Extraction Method

The HEM has been used to explore the interdependent effects of changes in a sector or sectoral blocks [44-46]. This method assumes the target sector does not make inter-industrial transactions with other sectors in the hypothetical economic system. Data for the target sector are extracted to determine the influence of that sector on the entire economy, with a focus on the industrial linkages that define the target sector's relationship to the rest of the economy through direct and indirect intermediate purchases and sales made by the target sector.

In this method, an economy Z with n sectors can be described as follows:

$$x = Ax + f$$

$$x = (I - A)^{-1} f = Lf$$

where $x = \begin{bmatrix} x_1 \\ \mathbf{M} \\ x_n \end{bmatrix}$ is the total output of n sectors; $A = \begin{bmatrix} a_{11}L & a_{1n} \\ \mathbf{MO} & \mathbf{M} \\ a_{n1}L & a_{nn} \end{bmatrix}$ is the technical coefficients matrix, in which $a_{ij} = z_{ij} / x_j$ is the amount of input from sector i required directly to produce per unit output in sector j , and z_{ij} represent the intermediate output by sector i to sector j ; $L = (I - A)^{-1} = [l_{ij}]$ is known as the Leontief inverse, in which l_{ij} is the amount of output from sector i required directly and indirectly to produce per unit final demand from sector j ; and $f = \begin{bmatrix} f_1 \\ \mathbf{M} \\ f_n \end{bmatrix}$ is the total final demand.

Because this paper focuses on the inter-industrial transactions within the domestic economy, we used the import similarity assumption to remove competitive imports. [47] In this case, the economy Z is divided into domestic transactions D and imports M . We assume that: if the fraction of a given input supplied by imports is the same for each sector, then the same fraction r_i of the total output in sector i is attributed to these imports, as follows:

$$r_i = \frac{m_i}{\left(\sum_{j=1}^n z_{ij} \right) + f_i} = \frac{m_i}{x_i + m_i},$$

$$a_{ij}^d = \frac{z_{ij}^d}{x_j} = \frac{(1 - r_i)z_{ij}}{x_j} = (1 - r_i)a_{ij}$$

$$A^d = [a_{ij}^d]$$

1 where m_i is the import to sector i ; a^{d}_{ij} is the amount of domestic input from sector
2 i required directly to produce per unit output from sector j ; z^{d}_{ij} is defined as the
3 domestic transactions by sector i to sector j ; and A^d is the technical coefficients
4 matrix of the domestic intermediate input.

5 Next, if s denotes the target sector and $-s$ is all remaining sectors, then Z
6 can be described as:

$$7 \quad \begin{bmatrix} x_s \\ x_{-s} \end{bmatrix} = \begin{bmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{bmatrix} \begin{bmatrix} x_s \\ x_{-s} \end{bmatrix} + \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix}.$$

8 If we define $\begin{bmatrix} l_{s,s} & l_{s,-s} \\ l_{-s,s} & l_{-s,-s} \end{bmatrix}$ as the Leontief inverse of this input-output model, then

$$9 \quad \begin{bmatrix} x_s \\ x_{-s} \end{bmatrix} = \begin{bmatrix} l_{s,s} & l_{s,-s} \\ l_{-s,s} & l_{-s,-s} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix}.$$

10 Because the target sector s is extracted and does not make inter-industrial
11 transactions with $-s$ in the hypothetical economic system, it is obvious that
12 $A_{s,-s} = A_{-s,s} = 0$ and the hypothetical economy $\bar{Z}$ is given by:

$$13 \quad \begin{bmatrix} \bar{x}_s \\ \bar{x}_{-s} \end{bmatrix} = \begin{bmatrix} A_{s,s} & 0 \\ 0 & A_{-s,-s} \end{bmatrix} \begin{bmatrix} x_s \\ x_{-s} \end{bmatrix} + \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix}$$

$$14 \quad \begin{bmatrix} \bar{x}_s \\ \bar{x}_{-s} \end{bmatrix} = \begin{bmatrix} (I - A_{s,s})^{-1} & 0 \\ 0 & (I - A_{-s,-s})^{-1} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix}.$$

15 The change in production, which reflects the influence of the target sector s on
16 the entire economy, is estimated by:

$$17 \quad \begin{bmatrix} x_s - \bar{x}_s \\ x_{-s} - \bar{x}_{-s} \end{bmatrix} = \begin{bmatrix} l_{s,s} - (I - A_{s,s})^{-1} & l_{s,-s} \\ l_{-s,s} & l_{-s,-s} - (I - A_{-s,-s})^{-1} \end{bmatrix} \begin{bmatrix} f_s \\ f_{-s} \end{bmatrix}$$

Carbon emissions associated with the target sector s can therefore be deconstructed into four parts [46]: internal emissions (IE), which are CO₂ emissions associated with production processes in sector s ; mixed emissions (ME), which are CO₂ emissions associated with the participation of sector s and $-s$, reflecting CO₂ emissions embodied in goods that are originally sold to $-s$ by s after being processed by $-s$ and are consequently repurchased by s for production purposes; net backward linkage emissions (NBLE), which are the net emissions imported by s from $-s$ to meet the demands of s ; and net forward linkage emissions (NFLE), which are the net emission exports from s (CO₂ emitted by s and used by $-s$ to produce f_{-s}). Taking competitive imports into account, IE, ME, NBLE and NFLE can be calculated, as follows:

$$\text{IE: } T_s(I - A_{s,s}^d)^{-1} f_s$$

$$\text{ME: } T_s[l_{s,s}^d - (I - A_{s,s}^d)^{-1}] f_s$$

$$\text{NBLE: } T_{-s} l_{-s,s}^d f_s$$

$$\text{NFLE: } T_s l_{s,-s}^d f_{-s}.$$

2.3 Data Sources

China is heavily reliant on fossil fuels [48]; however, only CO₂ emissions generated through the industrial consumption of fossil fuels are considered here. Focusing on industrial CO₂ emissions, the Chinese economy is disaggregated into 30 industrial sectors, accounting for more than 96.9% of the national energy consumption in 2012. Economic and energy-related data are taken from the *Input–Output Table of China 2012* and from the *Energy Statistical Yearbook 2013* [49–50]. CO₂ emission

factors are taken from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [2]. Measures for converting physical units into coal equivalents are from the *Energy Statistical Yearbook 2013*.

3. Results and Discussion

3.1 Industrial CO₂ Emissions

Net Forward Linkage Emissions. NFLE reflect the inter-industrial embodied CO₂ exports from an industry, i.e., CO₂ emitted by an industry to meet the downstream demand; these are referred to as CO₂ exports in this paper. As shown in previous studies, *the Production and Supply of Electric Power and Heat Power sector* (abbreviated names of all sectors are given in *Table A.1*) generates the largest amount of NFLE (3.47 Bt CO₂), accounting for ~36.2% of all emissions generated in China (Fig. 1). *The Production and Supply of Electric Power and Heat Power sector* is the primary energy supplier and burns large amounts of fossil fuels to satisfy the energy demands of other industries [51], thus dominating the supply chain of China's modern economy. Industrial NFLE in China are centralized, with ~76.2% of NFLE being produced by the following three sectors: *The Production and Supply of Electric Power and Heat Power sector* (~36.2% of total NFLE); *the Petroleum Processing and Coking sector* (~21.0%), and *the Metals Mining and Dressing sector* (~19.0%). Thus, the top seven industries of China generate more than 95% of its industrial CO₂ exports.

Net Backward Linkage Emissions. NBLE reflect inter-industrial embodied CO₂ imports; therefore, the NBLE of an industry reflect direct and intermediate purchases from upstream sectors, which are later referred to as CO₂ imports in this paper. As is shown in Fig. 1, *the Construction sector* is a major generator of NBLE, 'absorbing' 2.86 Bt of CO₂ in 2012 (~29.8% of all embodied CO₂ emissions in 2012). The rapid

1 urbanization of China has enhanced activity in *the Construction sector*, as shown in *Fig.*
2 *A.4*, and the growing demand for energy-intensive materials (e.g., iron and steel) by this
3 sector strongly affects inter-industrial CO₂ flows throughout the Chinese economy. The
4 second largest embodied CO₂ emission absorber is *the Service sector*, responsible for
5 ~15.5% of all embodied CO₂ emissions. This sector is also stimulated by the
6 urbanization boom in China. However, the values for NBLE from other sectors are
7 much lower, and no other sector accounts for more than 10% of the total NBLE in China.

8 **Net Emission Transfers** The difference between the NFLE and NBLE is defined
9 as the net emission transfer value. We found that 13 industrial sectors are net CO₂
10 exporters, while the other 17 industrial sectors are net CO₂ importers. Interestingly,
11 importers with large NBLE and exporters with large NFLE are very different (*Fig. A.1*).
12 Excluding *the Transport, Storage, and Post sector* and *the Chemical Products sector*,
13 which are the only balanced sectors, few industries exhibit high levels of both CO₂
14 imports and CO₂ exports. As is shown in *Fig. A.1*, sectors having larger NBLE often
15 exhibit better CO₂ emission performances, while sectors having higher NFLE exhibit
16 much higher levels of carbon intensity.

17 **3.2 Industrial CO₂ Emissions Flows**

18 In this section, we trace CO₂ imports and exports (i.e., embodied CO₂ flows)
19 between all 30 industrial sectors of China. Our data are shown as a chord diagram (*Fig.*
20 *2*). To better visualize key linkages, industries with few CO₂ transfer flows are removed,
21 leaving 15 significant nodes in *Fig. A.2*. A complete flow dataset is given in *Table A.5*.

22 As *Fig. 2* shows, *the Production and Supply of Electric Power and Heat Power*
23 *sector*, *the Petroleum Processing and Coking sector*, and *the Metals Mining and*
24 *Dressing sector* are the most significant sources of industrial CO₂ flows in China. These

1 are all widely recognized as high-carbon industries and as key direct emitters of CO₂.
2 These sectors generate energy and manufacture energy-intensive materials, and high
3 NFLE associated with these sectors are caused by and are mainly transferred to their
4 consumers (i.e., *the Construction sector, the Service sector, and the Transportation*
5 *Equipment sector*) (Fig. A.3a). Previous studies have focused on the roles of these
6 sectors in mitigating CO₂ emissions, as they are the largest net CO₂ exporters, have
7 powerful inter-industry effects, and less mixed effects can be achieved in these
8 industries than in others [41]. It has been argued that promoting energy efficiency and
9 shifting to cleaner energy-use are the most important ways of decreasing total CO₂
10 emissions in these sectors [30-37, 52].

11 Up to 17 industries are found to represent the main destinations of industrial CO₂
12 flows, and they account for ~97.4% of total imports. *The Construction sector* is the
13 most important receiver of embodied CO₂, and so it is reasonably identified as being
14 the main CO₂ flow destination. *The Production and Supply of Electric Power and Heat*
15 *Power sector, the Metals Mining and Dressing sector, and the Petroleum Processing*
16 *and Coking sector* are the main embodied CO₂ providers to *the Construction sector*, as
17 shown in Fig. A.3b. *The Construction sector* required ~2.86 Bt of CO₂ in 2012 from
18 electricity and heat suppliers, as well as building material manufacturers, although it
19 generated low levels of direct emissions. Of the total embodied CO₂ levels required for
20 *the Construction sector*, ~34.4% is generated from *The Production and Supply of*
21 *Electric Power and Heat Power sector* and ~23.6% is generated from *the Metals Mining*
22 *and Dressing sector*. The Chinese construction sector therefore strongly stimulates the
23 expansion of energy-intensive material producers, which are emitting increasing levels
24 of CO₂. It has been suggested that the amount of embodied CO₂ consumed by *the*
25 *Construction sector* increased following a quadratic curve between 1994 and 2012, and

1 that the use of energy-intensive materials has contributed to more than 80% of this
2 increase [33].

3 Meanwhile, *the Service sector* is the second important destination for Chinese
4 industrial embodied CO₂ flows. This sector consumes a large amount of electricity and
5 gasoline. Of the total embodied CO₂ levels (1.49 Bt of CO₂) required for *the Service*
6 *sector* in 2012, ~37.3% is generated from *The Production and Supply of Electric Power*
7 *and Heat Power sector* and ~26.6% is generated from *the Petroleum Processing and*
8 *Coking sector*. *The Transportation Equipment sector*, *the Electrical Machinery and*
9 *Apparatus sector*, and *the Communication, Computers and Other Electronic Equipment*
10 *sector* are also significant embodied CO₂ destinations, consuming ~0.74, ~0.57, and
11 ~0.51 Bt of CO₂ in 2012, respectively. High levels of embodied CO₂ consumption in
12 these equipment-manufacturing industries demonstrate the dominant role of Chinese
13 products in the global economy.

14 The CO₂ flow map shows that *the Construction sector* is the main source of
15 Chinese CO₂ emissions. Unfortunately, *the Construction sector* generates such low
16 levels of direct emissions that appropriate attention has not been paid to its potential
17 role in decreasing CO₂ emissions. For example, China's National Plan on Climate
18 Change (2014–2020) has imposed priorities to restrict high carbon industries other than
19 *the Construction sector*. Under a new paradigm, focusing on sectors generating high
20 NBLE could increase the number of CO₂ abatement options available to decision
21 makers. For example, reasonable measures focused on controlling the large-scale
22 expansion of infrastructure, construction activity workloads, and improving material-
23 use efficiency in *the Construction sector* may generate better mitigation potentials than
24 current measures. It is therefore worth identifying the specific effects that CO₂
25 importers have on aggregate CO₂ emissions of the entire Chinese economy by assessing

their accumulative effects through the demand chain, as outlined below.

3.3 Analysis of Carbon Abatement Potentials

Previous studies have focused on origins (i.e., industries generating high NFLE, such as *the Production and Supply of Electric Power and Heat Power sector*, *the Metals Mining and Dressing sector*, and *the Coal Mining and Dressing sector*) as primary drivers of Chinese CO₂ emissions. However, we argue that CO₂ emission abatement may be more effectively achieved by regulating demands from downstream industries. We conducted a sensitivity analysis based on a one-industry-at-a-time approach to identify how industrial CO₂ emission abatement levels could be more effectively achieved in China than by applying regular climate policies. We took industrial scale adjustments, energy efficiency improvements, and material efficiency into account. Assuming that all inter-relationships between the 30 industrial sectors represented by the Leontief inverse matrix coefficients are fixed, we estimated the volume of national total CO₂ emissions that could be decreased (ΔTCE) through a 1% change in industrial scale (downsizing), or a 1% improvement in the efficiency of energy-use or material-use by the target industry.

(1) Industrial Scale Adjustments

A change in total CO₂ emissions in China caused by an industrial-scale adjustment (ΔTCE_{scale}) involves decreased direct emissions (Scope I) and decreased indirect emissions (Scopes II & III), as described in the pragmatic ICLEI-Local Governments for Sustainability approach [54]. Downscaling any industry will decrease the level of fossil fuel consumption of that industry. The related decrease in CO₂ emissions is defined as ΔCE_{direct} and is calculated from internal emissions, mixed emissions, and NFLE associated with industry i [7]. This variable reflects the visible change within

1 the target industry and has typically been the focus of previous policy-making processes.
 2 In addition to fuel combustion, secondary energy (e.g., electricity and heat)
 3 consumption and non-energy material-use will decline, causing all providers of
 4 embodied CO₂ (intermediate good suppliers) to decrease their direct emissions (i.e.,
 5 $\Delta NBLE_i$). In this case, $\Delta CE_{indirect}$ reflects the industrial driving effect of the target
 6 sector's scale adjustments on the rest of the economy, especially on upstream industries.

7 The equation used to calculate ΔTCE_{scale} is shown below.

$$8 \quad \Delta TCE_{scale} = \Delta CE_{direct} + \Delta CE_{indirect} = (\Delta IE_i + \Delta ME_i + \Delta NFLE_i) + \Delta NBLE_i$$

9 where $\Delta NBLE_i$ is the change in embodied CO₂ imports for industry i from other
 10 industrial sectors.

11 The abatement potential of a 1% decrease in industrial activity in each sector is
 12 shown in Fig. 3a. Direct CO₂ emissions from *the Production and Supply of Electric*
 13 *Power and Heat Power sector, the Petroleum Processing and Coking sector, and the*
 14 *Metals Mining and Dressing sector* are decreased by large amounts, while *the*
 15 *Construction sector* and *the Service sector* eliminate large volumes of indirect
 16 emissions. The total abatement potential achieved by downscaling *the Construction*
 17 *sector* by 1% is almost the same as that achieved by downscaling *the Production and*
 18 *Supply of Electric Power and Heat Power sector* (currently recognized as the sector
 19 having the greatest potential for CO₂ emission abatement) and is much greater than that
 20 achieved by downscaling other high-carbon industries, such as *the Petroleum*
 21 *Processing and Coking sector* and *the Metals Mining and Dressing sector*. The
 22 difference between these effects lies in the fact that downscaling *the Production and*
 23 *Supply of Electric Power and Heat Power sector* will decrease CO₂ emissions directly
 24 generated by *the Production and Supply of Electric Power and Heat Power sector,*

1 while downscaling *the Construction sector* will decrease emissions generated by many
2 other sectors. *The Chemical Products sector* and *the Transport, Storage, and Post sector*
3 are special cases, as downscaling them will clearly reduce both direct and indirect
4 emissions. The total abatement potentials offered by *the Chemical Products sector* and
5 *the Transport, Storage, and Post sector* are important because they generate large CO₂
6 export values.

7 Cost-benefit analyses of CO₂ emission decreases across all 30 sectors were also
8 carried out, and their corresponding results are shown in *Table A.10*. The costs of
9 downsizing are roughly estimated by changing the target industrial export values.
10 Unlike previous industrial CO₂ abatement cost-benefit analyses, we integrated
11 decreases in embodied CO₂ emissions into this calculation. The energy sectors, such as
12 *the Production and Supply of Electric Power and Heat Power sector* and *the Petroleum*
13 *Processing and Coking sector*, remain the most cost-efficient sectors to focus on, with
14 CO₂ emission abatement costs of <2000 ¥ per ton of CO₂. However, it is concerning
15 that several so-called low carbon industries, such as *the Construction sector*, have more
16 cost-efficient carbon abatement effects than high-carbon sectors, such as *the Metals*
17 *Mining and Dressing sector* and *the Gas Production and Supply sector*.

18 **(2) Energy Efficiency Improvements**

19 Energy efficiency is generally measured as an average value regardless of the
20 sectoral energy mix. This makes it difficult to identify actual carbon abatement effects
21 related to energy efficiency improvements. We classify industrial energy consumption
22 into fossil fuel combustion (which generates direct CO₂ emissions to the atmosphere)
23 and secondary energy consumption (which generates indirect CO₂ emissions imported
24 from energy product suppliers). To simplify the model, five sectors (*the Petroleum*
25 *Processing and Coking sector*, *the Production and Supply of Electric Power and Heat*

1 *Power sector, the Gas Production and Supply sector, the Petroleum and Natural Gas*
2 *Extraction sector, and the Coal Mining and Dressing sector*) are defined as energy
3 product suppliers (related uncertainties are discussed in section 3.4). In this case, the
4 scale of the target industry is kept constant while the energy efficiency level is assumed
5 to increase by 1%. The carbon abatement effect associated with greater energy
6 efficiency (ΔTCE_{energy}) can be estimated using the following equation:

$$7 \quad \Delta TCE_{energy} = \Delta CE_{direct} + \Delta CE_{indirect} = (\Delta IE_i + \Delta ME_i + \Delta NFLE_i) + \sum_{n=1}^5 \Delta NBLE_{n,i},$$

8 where $\Delta NBLE_{n,i}$ is the change in embodied CO₂ imports for industry i from energy
9 product supplier n .

10 The CO₂ emission abatement potential related to a 1% improvement in energy
11 efficiency for each industry was estimated. As is shown in Fig. 3b, improving energy
12 efficiency levels contributes considerably to CO₂ emission reductions in every sector.
13 Almost 38.5 Mt of CO₂ emissions can be prevented by improving energy efficiency
14 levels by 1% in *the Production and Supply of Electric Power and Heat Power sector*,
15 followed by *the Petroleum Processing and Coking sector* and *the Metals Mining and*
16 *Dressing sector*, with respective reductions of about 22.8 Mt and 20.3 Mt in CO₂
17 emissions. The majority of the total direct emission reduction can be attributed to these
18 sectors. Excitingly, ~17.2 Mt of CO₂ emissions can be eliminated by improving the
19 energy efficiency of *the Construction sector*. Unlike values for *the Production and*
20 *Supply of Electric Power and Heat Power sector*, 98.0% of CO₂ emissions eliminated
21 from *the Construction sector* result from indirect emission reduction (Fig. 4), related to
22 reducing the large volumes of electricity and heat consumed during construction.
23 Although improving the energy efficiency of *the Construction sector* would have a
24 limited effect on direct emissions, it could considerably help reduce national CO₂

emissions.

It is worth mentioning that energy efficiency-related CO₂ emission abatements in *the Chemical Products sector* and *the Transport, Storage, and Post sector* have hybrid effects (Fig. 4). Reduction of indirect emissions in these two sectors could contribute as much as 30% to the overall decrease in national CO₂ emissions, although actual reductions will mainly occur in *the Production and Supply of Electric Power and Heat Power sector*, *the Petroleum Processing and Coking sector*, and *the Coal Mining and Dressing sector*. Our results suggest that we should not solely focus on direct CO₂ emissions, but consider measures aimed at decreasing indirect CO₂ emissions of high energy-use sectors.

(3) Material Efficiency

Decreasing the use of energy-intensive materials by promoting efficient material usage should abate direct CO₂ emissions in upstream industries. The CO₂ emission abatement potential of the entire economy achieved by promoting efficient use of non-energy intensive materials in industry i ($\Delta TCE_{material}$) can be estimated by determining changes in volumes of embodied CO₂ imported by industry i from all industries supplying non-energy products, using the following equation:

$$\Delta TCE_{material} = \sum_{m=1}^{25} \Delta NBLE_{m,i} .$$

where $\Delta NBLE_{m,i}$ is the change in embodied CO₂ imports for industry i from non-energy product supply industry m . The non-energy product supply industries encompass all 25 sectors, excluding *the Petroleum Processing and Coking sector*, *the Production and Supply of Electric Power and Heat Power sector*, *the Gas Production and Supply sector*, *the Petroleum and Natural Gas Extraction sector*, and *the Coal Mining and Dressing sector*.

As is shown in Fig. 3c, considerable volumes of CO₂ emissions can be indirectly evaded by improving the efficiency of non-energy material-use in downstream industries. For instance, an ~11.8 Mt CO₂ emission reduction can be achieved through a 1% material efficiency increase in *the Construction sector*. This reduction stems from the manufacturers of building materials, e.g., *the Metals Mining and Dressing sector* which provides iron and steel and accounts for ~57.3% of reductions, *the Non-metallic Mineral Products sector* supplying cement and glass which contributes ~12.8% to reductions, and *the Chemical Products sector* providing architectural coatings and plastics, which contributes ~13.3% (Fig. 5).

Overall, improving material efficiency accounts for more than 20% of the total abatement effects for many industries having high NBLE, such as *the Construction sector* and *the Electrical Machinery and Apparatus sector* (Table A.9). Fig. 3d shows that the total carbon abatement effect associated with industrial scale adjustment, as well as improved energy efficiency and material-use efficiency in *the Construction sector* (~58.0 Mt) is surprisingly much greater than for *the Petroleum Processing and Coking sector* (~45.7 Mt) and *the Metals Mining and Dressing sector* (~40.8 Mt), and only slightly less beneficial than those of *the Production and Supply of Electric Power and Heat Power sector* (~77.1 Mt). We conclude that improving energy and material-use efficiency in downstream industries to reduce consumption of energy-intensive materials constitutes an efficient way of mitigating CO₂ emissions in China.

3.4 Uncertainty Analysis

The economic system comprises a complicated, interdependent, and integrated set of industries. To investigate such interdependence, we made some assumptions and simplifications to build our models. Because models are simplified representations of

real-world systems, they typically do not mimic actual conditions. The major sources of uncertainties in our method are outlined below.

Uncertainties Associated with Activity Data. (a) Default data regarding CO₂ emission factors from the IPCC are used directly in this paper. Using the default data without any correction leads to inherited uncertainties. (b) Uncertainties and errors associated with the fossil fuel energy consumption data may stem from officially published statistical yearbooks in China [55]. (c) Differences in industrial classifications between the *Input–Output Table of China 2012* and the *Energy Statistical Yearbook 2013* of China resulted in the energy consumption data for several household sectors not being discussed separately. Because this study focuses on industrial CO₂ emissions, we excluded the residential consumption sector and combined other sectors into *the Service sector* to yield 30 industrial sectors describing the Chinese economy. The residential consumption sector accounted for less than 3.2% of the total fossil fuel consumption in 2012 in China, as is shown in *Table A.11*. The 30 industrial sectors discussed in this paper provide a good overview of inter-industrial CO₂ flows in China. Furthermore, we can easily compare our results with other relevant studies. For instance, we estimated that *the Construction sector* absorbed ~2.86 Bt of CO₂ and was responsible for 29.8% of all Chinese embodied CO₂ emissions in 2012; this is roughly consistent with estimates from previous studies [56–58].

Uncertainties Related to Modeling. The methods used herein were developed based on several assumptions. (a) The HEM assumes that all inter-relationships between sectors (i.e., the Leontief inverse matrix coefficients) are fixed, while one specific industry is extracted to determine the influence of that industry on the entire economy. The nature of this method could lead to uncertainties in our results. (b) In section 3.1 dealing with carbon abatement, we assume that all the products of *the*

1 *Petroleum Processing and Coking sector, the Production and Supply of Electric Power*
2 *and Heat Power sector, the Gas Production and Supply sector, the Petroleum and Natural*
3 *Gas Extraction sector, and the Coal Mining and Dressing sector* are secondary energy
4 types. Thus, these five sectors are defined as energy product suppliers. The other 25
5 sectors are assumed to only provide non-energy products. This simplification facilitated
6 analysis of CO₂ abatement potentials; however, some uncertainty is introduced and
7 would need to be evaluated in further studies.

8 **4. Conclusions**

9 The high direct CO₂ emission levels generated through manufacturing of energy-
10 intensive materials have previously been examined to abate CO₂ levels. However, our
11 results indicated that paying more attention to technological improvements in CO₂
12 importing sectors could more effectively decrease the consumption levels of energy-
13 intensive materials. Like inter-regional CO₂ leakages, industrial disparities create
14 complex inter-industrial embodied CO₂ flows. Strong CO₂ emission performances in
15 downstream industries often occurs at the expense of unavoidably high CO₂ emissions
16 in upstream sectors to meet the demands of the downstream industries. We traced
17 embodied CO₂ flows between 30 industrial sectors in 2012 in China and re-explored
18 industrial CO₂ emission abatement potentials from a consumer responsibility
19 perspective. Uncertainties associated with the activity data and applied methods were
20 also discussed.

21 Our results showed that the most important CO₂ exporters are central to the Chinese
22 industrial system. Two energy supplying sectors (*the Production and Supply of Electric*
23 *Power and Heat Power sector* and *the Petroleum Processing and Coking sector*) and
24 one metallurgical industry sector (*the Metals Mining and Dressing sector*) were the
25 three most significant sources of industrial CO₂ flows in China, contributing

1 approximately 80% of the total CO₂ exports. However, *the Construction sector*, the
2 main destination for CO₂ emission flows, was the most significant destination for
3 embodied CO₂. These CO₂ emissions were transferred not only from energy suppliers
4 but also from energy-intensive material producers, with ~34.4% derived from *the*
5 *Production and Supply of Electric Power and Heat Power sector* and ~23.4% derived
6 from *the Metals Mining and Dressing sector*. This demonstrated that the large-scale
7 expansion of infrastructure resulting from rapid urbanization can explain the
8 tremendous increase in CO₂ emissions that has occurred in China. Sensitivity analyses
9 indicated that *the Construction sector* could make significant CO₂ emission abatement
10 contributions through scale adjustments, and improvements in energy and material
11 efficiency. The CO₂ emission abatement potential of *the Construction sector* was
12 determined to be almost the same as that of *the Production and Supply of Electric Power*
13 *and Heat Power sector*, which is currently recognized as being the main sector in which
14 CO₂ emission abatement should occur. *The Construction sector's* potential was shown
15 to be surprisingly much greater than that of other high-carbon industrial sectors. Non-
16 energy material efficiency improvements accounted for ~20.3% of *the Construction*
17 *sector* CO₂ emission abatement potential, originating mainly from building material
18 manufacturers (e.g., *the Metals Mining and Dressing sector*, and *the Non-metallic*
19 *Mineral Products sector*). The same phenomenon was found for other industries
20 presenting high CO₂ import levels. In addition to promoting energy saving in energy-
21 intensive material manufacturing processes, future emission mitigation measures
22 should focus on decreasing consumption of energy-intensive goods in downstream
23 industries. For instance, to downscale construction activities, China should reform
24 urban planning and design, avoid construction of repetitive infrastructure, and create
25 stronger incentives for more efficient, inclusive, and sustainable urbanization processes.

Lean construction methods should be adopted, while solid waste should be minimized and recycled to more efficiently use energy-intensive material.

Many official carbon policies in China are aimed at meeting the CO₂ peak target by setting requirements for decreasing CO₂ emissions on high-carbon industries [4, 59]. However, net CO₂ exporters in the industrial chain will struggle to meet their targets in absolute terms, if no measures are taken by importers of embodied CO₂ to optimize consumption through scale adjustment or technological improvements. Several industries with low carbon intensity, such as *the Construction sector* and *the Special Purpose Machinery sector*, have been found to have more cost-efficient carbon abatement effects than those achievable by high-carbon sectors, such as *the Metals Mining and Dressing sector* and *the Gas Production and Supply sector*. It has been suggested that embodied CO₂ emissions should be integrated into the industrial carbon emission trading scheme, especially into industrial carbon credit allocations. Our results showed that paying attention to the industries consuming the most embodied CO₂ and promoting efficient material-use may help us achieve more cost-effective decreases in CO₂ emissions in absolute terms.

ASSOCIATED CONTENT

Conflict of Interests

The authors declare no competing financial interests.

Acknowledgements

This research is supported by the Humanity and Social Science Youth Foundation of the Ministry of Education of China (grant number 17YJCZH002), the National Natural Science Foundation of China (41301648), the State Scholarship Fund of China

(201606205026).

References

- [1] International Energy Agency. CO₂ Emissions from Fuel Combustion (IEA, 2016),
https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf (accessed Jan 13, 2017)
- [2] Intergovernmental Panel on Climate change (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Intergovernmental Panel on Climate change, Hayama, Kanagawa, Japan).
- [3] UNFCCC, 2008. Kyoto Protocol Reference Manual: On Accounting of Emissions and Assigned Amount. United Nations Framework Convention on Climate Change. Bonn, Germany
- [4] National Development and Reform Commission. National Plan on Climate Change (2014-2020),
<http://www.sdpc.gov.cn/gzdt/201411/W020141104591413713551.pdf> (accessed Jan 13, 2017)
- [5] Kanemoto, K.; Moran, D.; Hertwich, E. Mapping the carbon footprint of nations. *Environ Sci Technol.* **2016**, 50(19): 10512-10517
- [6] Feng, K.; Davis, S.; Sun, L.; Li, X.; Guan, D.; Liu, Y.; Liu, Z.; Hubacek, K. Outsourcing CO₂ Within China. *Proc Natl Acad Sci USA.* **2013**, 9(28): 11654-11659
- [7] Wang, Y.; Wang, W.; Mao, G.; Cai, H.; Zuo, J.; Wang, L.; Zhao, P. Industrial CO₂ emissions in China based on the hypothetical extraction method: Linkage analysis. *Energ Policy.* **2013**, 62: 1238-1244

- 1 [8] Peters, G. From production-based to consumption-based national emission
2 inventories. *Ecol Econ.* **2008**, 65(1): 13-23
- 3 [9] Davis, S.; Caldeira, K. Consumption-based accounting of CO₂ emissions. *Proc*
4 *Natl Acad Sci USA.* **2010**, 107 (12): 5687-5692.
- 5 [10]Springmann, M., Integrating emissions transfers into policy-making. *Nature Clim*
6 *Change.* 2014, 4 (3): 177-181
- 7 [11]Munksgaard, J.; Pedersen, K. CO₂ accounts for open economies: producer or
8 consumer responsibility? *Energ Policy.* **2001**, 29 (4): 327-334.
- 9 [12]Peters, G.; Hertwich, E. CO₂ embodied in international trade with implications
10 for global climate policy. *Environ Sci Technol.* **2008**, 42 (5): 1401-1407
- 11 [13]Mozner, Z. A consumption-based approach to carbon emission accounting -
12 sectoral differences and environmental benefits. *J Clean Prod.* **2013**, 42: 83-95.
- 13 [14]Bai, H.; Zhang, Y.; Wang, H.; Huang, Y.; Xu, H. A Hybrid Method for
14 Provincial Scale Energy-related Carbon Emission Allocation in China. *Environ*
15 *Sci Technol.* **2014**, 48(5): 2541–2550
- 16 [15]Peters, G.; Minx, J.; Weber, C.; Edenhofer, O.; Affiliations, A. Growth in
17 Emission Transfers via International Trade from 1990 to 2008. *Proc Natl Acad*
18 *Sci USA.* **2011**, 108(21): 8903–8908.
- 19 [16]Davis, S.; Peters, G.; Caldeira, K. The supply chain of CO₂ emissions. *Proc Natl*
20 *Acad Sci USA.* **2011**, 108: 18554-18559.
- 21 [17]Jakob, M.; Marschinski, R. Interpreting trade-related CO₂ emission transfers.
22 *Nature Clim Change.* **2012**, 3: 19-23.
- 23 [18]Xu, M.; Li, R.; Crittenden, J.; Chen, Y. CO₂ emissions embodied in China's
24 exports from 2002 to 2008: A structural decomposition analysis. *Energ Policy.*
25 **2011**, 39: 7381-7388.

- 1 [19]Guo, J.; Zhang, Z.; Meng, L. China's provincial CO₂ emissions embodied in
2 international and interprovincial trade. *Energ Policy*. **2012**, 42: 486-497.
- 3 [20]Jiang, X.; Chen, Q.; Guan, D.; Zhu, K.; Yang, C. Revisiting the global net carbon
4 dioxide emission transfers by international trade: The impact of trade
5 heterogeneity of China. *J Ind Ecol*. **2016**, 20(3): 506-514.
- 6 [21]Feng, K.; Hubacek, K.; Sun, L.; Liu, Z. Consumption-based CO₂ Accounting of
7 China's Megacities: The case of Beijing, Tianjin, Shanghai and Chongqing. *Ecol*
8 *Indic*. **2014**, 47: 26–31.
- 9 [22]Meng, B.; Xue, J.; Feng, K.; Guan, D.; Fu, X. China's inter-regional spillover of
10 carbon emissions and domestic supply chains. *Energ Policy*. **2013**, 61: 1305-
11 1321.
- 12 [23]Chen, S.; Chen, B. Tracking Inter-Regional Carbon Flows: A Hybrid Network
13 Model. *Environ Sci Technol*. **2016**, 50:4731-4741.
- 14 [24]Zhang, B.; Qiao, H.; Chen, Z.; Chen, B. Growth in embodied energy transfers via
15 China's domestic trade: Evidence from multi-regional input–output analysis. *Appl*
16 *Energ*. **2016**, 184: 1093-1105.
- 17 [25]Mi, Z.; Zhang, Y.; Guan, D.; Shan, Y.; Liu, Z.; Cong, R.; Yuan, X.-C.; Wei, Y.-
18 M.; Consumption-based emission accounting for Chinese cities. *Appl Energ*.
19 **2016**, 184: 1073-108.
- 20 [26]Chen, S.; Chen, B. Urban energy consumption: Different insights from energy
21 flow analysis, input-output analysis and ecological network analysis. *Appl Energ*.
22 **2015**, 138: 99-107.
- 23 [27]Kagawa, S.; Suh, S.; Hubacek, K.; Wiedmann, T.; Nansai, K.; Minx, J. CO₂
24 emission clusters within global supply chain networks: Implications for climate
25 change mitigation. *Global Environ Chang*. **2015**, 35: 486-496.

- 1 [28]Ang, B.; Su, B. Carbon Emission Intensity in Electricity Production: A Global
2 Analysis. *Energ Policy*. **2016**, 94: 56-63.
- 3 [29]Liu, N.; Ma, Z.; Kang, J. Changes in Carbon Intensity in China's Industrial
4 Sector: Decomposition and Attribution Analysis. *Energ Policy*. **2015**, 87: 28-38
- 5 [30]Lin, B.; Wang, X. Carbon emissions from energy intensive industry in China:
6 Evidence from the iron & steel Industry. *Renew Sust Energ Rev*. **2015**, 47: 746-
7 754.
- 8 [31]Peng, L.; Zeng, X.; Wang, Y.; Hong, G. Analysis of Energy Efficiency and
9 Carbon Dioxide Reduction in the Chinese Pulp and Paper Industry. *Energ Policy*.
10 **2016**, 80: 65-75.
- 11 [32]Xu, B.; Lin, B. Reducing CO₂ Emissions in China's Manufacturing Industry:
12 Evidence from Nonparametric Additive Regression Models. *Energy*. **2016**, 101:
13 161-173.
- 14 [33]Lu, Y.; Cui, P.; Li, D. Carbon Emissions and Policies in China's Building and
15 Construction Industry: Evidence from 1994 to 2012. *Build Environ*. **2016**, 95: 94-
16 103.
- 17 [34]Wang, X.; Lin, B. How to Reduce CO₂ Emissions in China's Iron and Steel
18 Industry. *Renew Sust Energ Rev*. **2016**, 57: 1496-1505.
- 19 [35]Zhang, N.; Wei, X. Dynamic Total Factor Carbon Emissions Performance
20 Changes in the Chinese Transportation Industry. *Appl Energ*. **2015**, 146: 409-420.
- 21 [36]Lin, B.; Zhang, Z. Carbon Emissions in China's Cement Industry: A Sector and
22 Policy Analysis. *Renew Sust Energ Rev*. **2016**, 58: 1387-1394.
- 23 [37]Lin, B.; Long, H. Emissions Reduction in China's Chemical Industry – Based on
24 LMDI. *Renew Sust Energ Rev*. **2016**, 53: 1348-1355.
- 25 [38]Zhang, W.; Peng, S.; Sun, C. CO₂ emissions in the global supply chains of

1 services_ An analysis based on a multi-regional input–output model. *Energ*
2 *Policy*. **2015**, 86: 93-103.;

3 [39]Kucukvar, M.; Cansev, B.; Egilmez, G.; Onat, N.; Samadi, H. Energy-climate
4 manufacturing nexus: New insights from the regional and global supply chains of
5 manufacturing industries. *Appl Energ*. **2016**, 184, 889-904.

6 [40]Hong, J.; Shen, G.; Guo, S.; Xue, F.; Zheng, W. Energy use embodied in China’s
7 construction industry: A multi-regional input–output analysis. *Renew Sust Energ*
8 *Rev*. **2016**, 53: 1303-1312.

9 [41]Zhao, Y.; Zhang, Z. Linkage Analysis of Sectoral CO₂ Emissions Based on the
10 Hypothetical Extraction Method in South Africa. *J Clean Prod*. **2015**, 103: 916-
11 924.

12 [42]Qian, M.; Lu, Z. Based on assumptions extraction method of carbon industry
13 department correlation analysis. *China Population Resources and Environment*.
14 **2013**, 9: 34-41

15 [43]Zhao, Y.; Liu, Y. Inter-regional Linkage Analysis of Industrial CO₂ Emissions in
16 China: An application of A Hypothetical Extraction Method. *Ecol Indic*. **2016**,
17 61: 428–437.

18 [44]Cella, G. The Input-output Measurement of Inter Industry Linkages. *Oxford B*
19 *Econ Stat*. **1984**, 46(1): 73-84

20 [45]Guerra, A.; Sancho, F. Measuring Energy Linkages with the Hypothetical
21 Extraction Method: An Application to Spain. *Energy Econ*. **2010**, 32(4): 831-837.

22 [46]Duarte, R.; Sánchez-Chóliz, J.; Bielsa, J. Water Use in the Spanish Economy: An
23 Input-output Approach. *Ecol Econ*. **2002**, 43(1): 71-85.

24 [47]Miller, R.; Blair, P. Input-Output Analysis: Foundations and Extensions,
25 Cambridge, **2009**

- 1 [48]Liu, Z.; Guan, D.; Wei, W.; Davis, S.; Ciais, P.; Bai, J.; Peng, S.; Zhang, Q.
2 Reduced carbon emission estimates from fossil fuel combustion and cement
3 production in China. *Nature*, **2015**, 524: 335-338
- 4 [49]National Bureau of Statistics of China, China Statistical Yearbook 2012. China
5 Statistics Press, 2013
- 6 [50]National Bureau of Statistics of China, China Energy Statistical Yearbook 2013.
7 China Statistics Press, 2015
- 8 [51]He, G.; Avrin, A.; Nelson, J.; Johnston, J.; Mileva, A.; Tian, J.; Lammen, D.
9 SWITCH-China: A Systems Approach to Decarbonizing China's Power System.
10 *Environ Sci Technol.* **2016**, 50: 5467–5473
- 11 [52]Guo, Y.; Tian, J.; Chertow, M.; Chen, L. Greenhouse gas mitigation in Chinese
12 eco-industrial parks by targeting energy infrastructure: a vintage stock model.
13 *Environ Sci Technol.* **2016**, 50: 11403-11413
- 14 [53]Krzywinski, M.; Schein, J.; Birol, I.; Connors, J.; Gascoyne, R.; Horsman,, D.;
15 Jones, S.; Marra, M. Circos: an Information Aesthetic for Comparative
16 Genomics. *Genome Res.* **2009**, 19: 1639-1645
- 17 [54]Kennedy, C.; Steinberger, J.; Gasson, B.; Hansen, Y.; Hillman, T.; Havranek, M.;
18 Pataki, D.; Phdungsilp, A.; Ramaswami, A.; Mendez, G. Methodology for
19 inventorying greenhouse gas emissions from global cities. *Energ Policy.* **2010**, 38
20 (9): 4828-4837
- 21 [55]Geng, Y.; Tian, M.; Zhu, Q.; Zhang, J.; Peng, C. Quantification of provincial-
22 level carbon emissions from energy consumption in China. *Renew Sust Energ*
23 *Rev.* **2011**, 15 (8): 3658-3668.
- 24 [56]Guan, J.; Zhang, Z.; Chu, C. Quantification of building embodied energy in China
25 using an input-out-based hybrid LCA model. *Energy and Building.* **2016**, 110:

1 443-452

2 [57]Zhang, X.; Wang, F. Hybrid input-output analysis for life-cycle energy

3 consumption and carbon emissions of China's building sector, *Building and*

4 *Environment*. **2016**, 104, 188-197

5 [58]Zhang, Z.; Wang, B. Research on the life-cycle CO₂ emission of China's

6 construction sector. *Energy and Buildings*. **2016**, 112, 244-255

7 [59]National Development and Reform Commission. China's Policies and Actions

8 for Addressing Climate Change (2013),

9 <http://qhs.ndrc.gov.cn/zcfg/201311/W020131107533601343247.pdf> (accessed

10 Jan 13, 2017)