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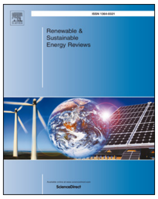

Mapping inter-industrial CO_2 flows within China

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ABSTRACT

Like inter-regional CO_2 leakages, good CO_2 emission performances from downstream industries in the industrial chain often result in high direct levels of CO_2 emissions in upstream sectors. Thus, it is necessary to rethink industrial carbon policies from the perspective of consumer responsibility. As the largest emitter of CO_2 in the world, China has a very comprehensive industrial system. In this study, we traced fuel-related CO_2 flows between 30 Chinese industrial sectors in 2012 and explored the specificities of these flows on aggregate CO_2 emission abatement for the entire economy. Previous studies have focused on carbon abatement policies instituted by industries generating high direct CO_2 emissions, but our results demonstrate that paying more attention to CO_2 importers better limits the consumption of energy-intensive materials. The construction sector, a major CO_2 flow destination because of the large-scale infrastructure required to support rapid urbanization in China, exhibits the greatest transfer of embodied CO_2 from energy suppliers and from the producers of energy-intensive materials. Our sensitivity analysis indicates that the construction sector shows considerable carbon abatement potential, which is surprisingly much greater than what is feasible for most high-carbon industries. Shifting more attention to industries that consume large amounts of embodied CO_2 may help achieve more cost-effective decreases in CO_2 emissions in absolute terms.

1. Introduction

CO_2 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 CO_2 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 CO_2 emissions [2]. Consequently, many compulsory measures are being undertaken in regions and industries that emit large volumes of CO_2. 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 CO_2 emissions; hereafter considered the same) [4].

However, such production-based policies may not always effectively decrease total CO_2 emissions throughout the entire economy. Developed countries/regions may decrease CO_2 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 CO_2 emission intensity levels but may not decrease total CO_2 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 CO_2 emissions and consumption-based accounting principles have therefore been proposed as ways to increase the range of CO_2 emission mitigation options [11–14]. CO_2 emissions embodied in products and intermediate goods travel between regions and industries through upstream and downstream flows within the economy.

The inter-regional CO_2 emission flows have been well identified over the past few years, focusing on both international [9,15–20] and domestic trade [6,21–26]. These studies show that the global economy has been closely interlinked through its complex supply chain. Low CO_2 emissions in downstream industries often cause high direct CO_2 emissions in upstream sectors. Similar to inter-regional CO_2 leakages, the transfer of inter-industrial CO_2 flows embodied in products along the supply chain are also complicated. CO_2 emissions associated with complex links between industrial sectors have not been well studied

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[27]. Although numerous studies emphasize the importance of production-based CO_2 emissions and their driving forces [28–37], it is argued that industrial embodied CO_2 emissions better represent CO_2 burdens. Using a multi-regional input-output (IO) model, industrial embodied CO_2 emissions have been analyzed in many of the inter-regional studies mentioned above. To evaluate inter-industrial CO_2 emission transfers, an economic network model was used to trace CO_2 emissions in global supply chains [27]; these models are typically limited in resolution to global to regional scales. In addition, the CO_2 emissions embodied in the supply chain of several specific sectors, such as services, manufacturing, and construction industries, have also been discussed [38–40]. Several studies have demonstrated links between CO_2 emissions across all different industrial sectors of a country, using a hypothetical extraction method (HEM) [7,41–43]. However, they have largely focused on relationships between industrial clusters rather than CO_2 flows between sectors. In developing countries like China, industrialization is a necessary pathway to economic prosperity. Accurate knowledge of inter-industrial CO_2 flows can be a step toward global climate change mitigation. Consequently, it is necessary for local climate policy makers worldwide, especially those in developing countries, to rethink the appropriate industrial strategies for climate mitigation from a consumer responsibility perspective. As the world's second largest economy, reflecting a vast landmass, huge population, and rich natural resources, China has built a comprehensive industrial system. We focus on China, as a key example, and attempt to identify industries that require large embodied CO_2 emissions to satisfy consumer demands (referred to as primary destinations of embodied CO_2 flows). Our aim is to determine whether policies focusing on low-carbon industries more efficiently decrease CO_2 emissions than production-based measures. To answer this question, we need to obtain a full understanding of CO_2 emission abatement effects achieved through various industrial policies. This requires quantification of embodied CO_2 transferred between each pair of industrial sectors and determination of the sensitivities of different industrial sectors to total CO_2 emissions of the national economy.

In this paper, we trace embodied CO_2 flows between 30 industrial sectors and map detailed inter-industrial CO_2 flows within China. To the best of our knowledge, it is the first quantitative map of embodied CO_2 flow between pairs of industrial sectors in China. Furthermore, based on the proposed map, we re-examine industrial CO_2 emission abatement potentials and determine which industrial carbon policies could best facilitate CO_2 emission abatement in absolute terms for the entire Chinese economy. A sensitivity analysis is performed for each industrial sector to identify the most cost-effective industrial carbon policy. Our results can be used to facilitate the development of Chinese industrial carbon policies and offer valuable guidelines for industrial strategies for climate mitigation worldwide, especially for developing countries.

2. Materials and methods

2.1. Industrial Fuel-Related CO_2 Emissions

The fossil fuel-related CO_2 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 CO_2 emission intensity of sector i ($t/10^4$ ¥); x_i is the total output of sector i (10^4 ¥); C_i is the direct CO_2 emissions generated by sector i ($t/10^4$ ¥); η_k is the CO_2 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 $x = [x_1 \vdots x_n]$ is the total output of n sectors; $A = [a_{11} \cdots a_{1n} \vdots \quad \ddots \quad \vdots a_{n1} \cdots a_{nn}]$ 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 $f = [f_1 \vdots f_n]$ 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:

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

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

$$A^d = [a^d{}_{ij}]$$

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

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

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

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

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

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

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

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

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

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

Carbon emissions associated with the target sector s can therefore be deconstructed into four parts [46]: internal emissions (IE), which are CO_2 emissions associated with production processes in sector s; mixed emissions (ME), which are CO_2 emissions associated with the participation of sector s and $-s$, reflecting CO_2 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 (CO_2 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:

IE: $T_s(I - A^d{}_{s,s})^{-1}f_s$

ME: $T_s[l^d{}_{s,s} - (I - A^d{}_{s,s})^{-1}]f_s$

$NBLE$: $T_{-s}l^d{}_{-s,s}f_s$

$NFLE$: $T_s l^d{}_{s,-s}f_{-s}$.

2.3. Data sources

China is heavily reliant on fossil fuels [48]; however, only CO_2 emissions generated through the industrial consumption of fossil fuels are considered here. Focusing on industrial CO_2 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]. CO_2 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 CO_2 emissions

3.1.1. Net forward linkage emissions

NFLE reflect the inter-industrial embodied CO_2 exports from an industry, i.e., CO_2 emitted by an industry to meet the downstream demand; these are referred to as CO_2 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 CO_2), 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 CO_2 exports.

3.1.2. Net backward linkage emissions

NBLE reflect inter-industrial embodied CO_2 imports; therefore, the NBLE of an industry reflect direct and intermediate purchases from upstream sectors, which are later referred to as CO_2 imports in this paper. As is shown in Fig. 1, *the Construction sector* is a major generator of NBLE, 'absorbing' 2.86 Bt of CO_2 in 2012 (~29.8% of all embodied CO_2 emissions in 2012). The rapid urbanization of China has enhanced activity in *the Construction sector*, as shown in Fig. A.4, and the growing demand for energy-intensive materials (e.g., iron and steel) by this sector strongly affects inter-industrial CO_2 flows throughout the Chinese economy. The second largest embodied CO_2 emission absorber is *the Service sector*, responsible for ~15.5% of all embodied CO_2 emissions. This sector is also stimulated by the urbanization boom in China. However, the values for NBLE from other sectors are much lower, and no other sector accounts for more than 10% of the total NBLE in China.

3.1.3. Net emission transfers

The difference between the NFLE and NBLE is defined as the net emission transfer value. We found that 13 industrial sectors are net CO_2 exporters, while the other 17 industrial sectors are net CO_2 importers. Interestingly, importers with large NBLE and exporters with large NFLE are very different (Fig. A.1). Excluding *the Transport, Storage, and Post sector* and *the Chemical Products sector*, which are the only balanced sectors, few industries exhibit high levels of both CO_2 imports and CO_2 exports. As is shown in Fig. A.1, sectors having larger NBLE often exhibit better CO_2 emission performances, while sectors having higher NFLE exhibit much higher levels of carbon intensity.

3.2. Industrial CO_2 emissions flows

In this section, we trace CO_2 imports and exports (i.e., embodied CO_2 flows) between all 30 industrial sectors of China. Our data are shown as a chord diagram (Fig. 2). To better visualize key linkages, industries with few CO_2 transfer flows are removed, leaving 15 significant nodes in Fig. A.2. A complete flow dataset is given in Table A.5.

As Fig. 2 shows, *the Production and Supply of Electric Power and Heat Power sector*, *the Petroleum Processing and Coking sector*, and *the Metals Mining and Dressing sector* are the most significant sources of industrial CO_2 flows in China. These are all widely recognized as high-carbon industries and as key direct emitters of CO_2. These sectors generate energy and manufacture energy-intensive materials, and high NFLE associated with these sectors are caused by and are mainly transferred to their consumers (i.e., *the Construction sector*, *the Service sector*, and *the Transportation Equipment sector*) (Fig. A.3a). Previous studies have focused on the roles of these sectors in mitigating CO_2 emissions, as they are the largest net CO_2 exporters, have powerful inter-industry effects, and less mixed effects can be achieved in these industries than in others [41]. It has been argued that promoting energy efficiency and shifting to cleaner energy-use are the most important ways of decreasing total CO_2 emissions in these sectors [30–37,52].

Up to 17 industries are found to represent the main destinations of industrial CO_2 flows, and they account for ~97.4% of total imports. *The Construction sector* is the most important receiver of embodied CO_2, and so it is reasonably identified as being the main CO_2 flow destination. *The Production and Supply of Electric Power and Heat Power sector*, *the Metals Mining and Dressing sector*, and *the Petroleum Processing and Coking sector* are the main embodied CO_2 providers to *the Construction sector*, as shown in Fig. A.3b. *The Construction sector* required ~2.86 Bt of CO_2 in 2012 from electricity and heat suppliers, as well as building material manufacturers, although it generated low levels of direct emissions. Of the total embodied CO_2 levels required for *the Construction sector*, ~34.4% is generated from *The Production and Supply of Electric Power and Heat Power sector* and ~23.6% is generated from *the Metals Mining and Dressing sector*. The Chinese construction sector therefore strongly stimulates the expansion of energy-intensive material producers, which are emitting increasing levels of CO_2. It has been suggested that the amount of embodied CO_2 consumed by *the Construction sector* increased following a quadratic curve between 1994 and 2012, and that the use of energy-intensive materials has contributed to

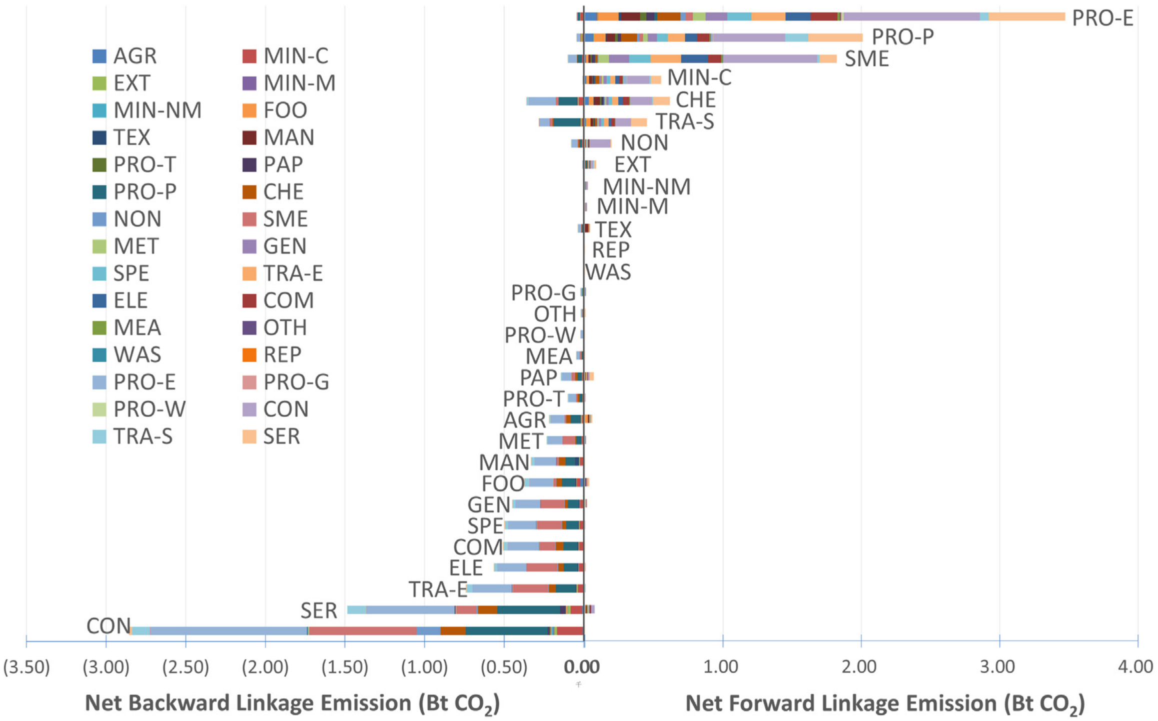

Fig. 1. Balance of industrial CO_2 emission imports and exports in China. Colors within each bar denote components of net backward linkage emissions (NBLE) and net forward linkage emissions (NFLE) of the industry concerned, i.e., industries from which the NBLE and NFLE of the industry of concern originate. Sectors on the vertical axis are sorted based on net emission transfers. Labels on the left denote industries with net embodied CO_2 emission inputs (i.e., negative net emission transfers), and labels on the right denote industries with net CO_2 outputs. Mixed and internal emissions contribute very small proportions of CO_2 emissions for most industries, and so they are not shown. The full names of the sectors are given in Table A.1, and detailed data are shown in Table A.2-A.4.

more than 80% of this increase [33].

Meanwhile, *the Service sector* is the second important destination for Chinese industrial embodied CO_2 flows. This sector consumes a large amount of electricity and gasoline. Of the total embodied CO_2 levels (1.49 Bt of CO_2) required for *the Service sector* in 2012, ~37.3% is generated from *The Production and Supply of Electric Power and Heat Power sector* and ~26.6% is generated from *the Petroleum Processing and Coking sector. The Transportation Equipment sector*, *the Electrical Machinery and Apparatus sector*, and *the Communication, Computers and Other Electronic Equipment sector* are also significant embodied CO_2 destinations, consuming ~0.74, ~0.57, and ~0.51 Bt of CO_2 in 2012, respectively. High levels of embodied CO_2 consumption in these equipment-manufacturing industries demonstrate the dominant role of Chinese products in the global economy.

The CO_2 flow map shows that *the Construction sector* is the main source of Chinese CO_2 emissions. Unfortunately, *the Construction sector* generates such low levels of direct emissions that appropriate attention has not been paid to its potential role in decreasing CO_2 emissions. For example, China's National Plan on Climate Change (2014–2020) has imposed priorities to restrict high carbon industries other than *the Construction sector*. Under a new paradigm, focusing on sectors generating high NBLE could increase the number of CO_2 abatement options available to decision makers. For example, reasonable measures focused on controlling the large-scale expansion of infrastructure, construction activity workloads, and improving material-use efficiency in *the Construction sector* may generate better mitigation potentials than current measures. It is therefore worth identifying the specific effects that CO_2 importers have on aggregate CO_2 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 CO_2 emissions. However, we argue that CO_2 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 CO_2 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 CO_2 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.

3.3.1. Industrial scale adjustments

A change in total CO_2 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 CO_2 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 the target industry and has typically been the focus of previous policy-making processes. In addition to fuel combustion, secondary energy (e.g., electricity and heat) consumption and non-energy material-use will decline, causing all providers of embodied CO_2 (intermediate good suppliers) to decrease their direct emissions

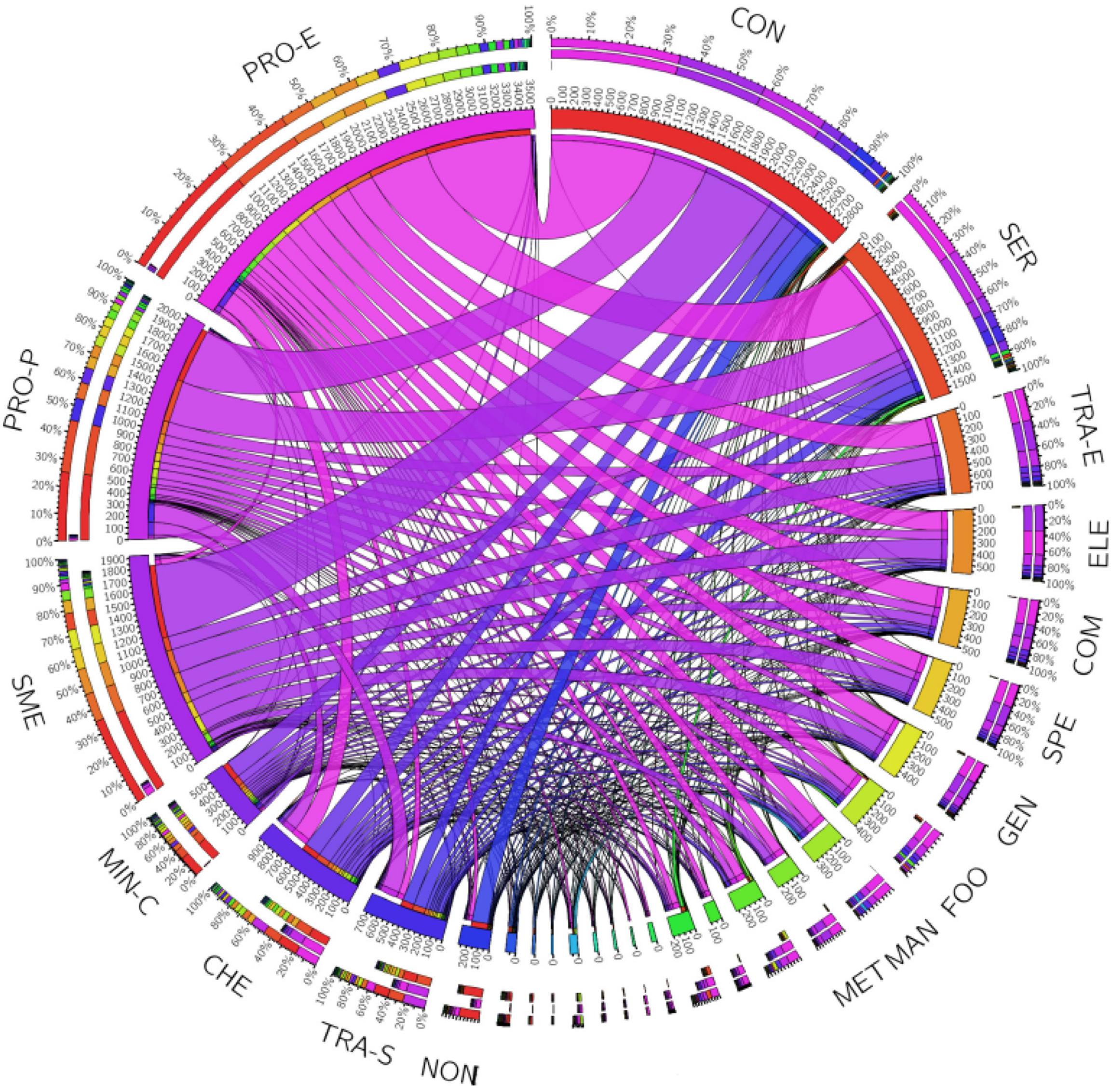

Fig. 2. Chord diagram of CO_2 emission flows (with units of Mt CO_2) between the 30 Chinese industrial sectors in 2012. Ribbons touch the flow origins but terminate a short distance before reaching the destinations [53]. The full names of the sectors are given in Table A.1.

(i.e., $\Delta NBLE_i$). In this case, $\Delta CE_{indirect}$ reflects the industrial driving effect of the target sector's scale adjustments on the rest of the economy, especially on upstream industries. The equation used to calculate ΔTCE_{scale} is shown below.

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

where $\Delta NBLE_i$ is the change in embodied CO_2 imports for industry i from other industrial sectors.

The abatement potential of a 1% decrease in industrial activity in each sector is shown in Fig. 3a. Direct CO_2 emissions from *the Production and Supply of Electric Power and Heat Power sector*, *the Petroleum Processing and Coking sector*, and *the Metals Mining and Dressing sector* are decreased by large amounts, while *the Construction sector* and *the Service sector* eliminate large volumes of indirect emissions. The total abatement potential achieved by downscaling *the Construction sector* by 1% is almost the same as that achieved by downscaling *the Production and Supply of Electric Power and Heat Power sector* (currently recognized as the sector having the greatest potential for CO_2 emission abatement) and is much greater than that achieved by downscaling other high-carbon industries, such as *the Petroleum Processing and Coking sector* and *the Metals Mining and Dressing sector*. The difference between these effects lies in the fact that downscaling *the Production and Supply of Electric Power and Heat Power sector* will decrease CO_2 emissions directly generated by *the Production and Supply of Electric Power and Heat Power sector*, while downscaling *the Construction sector* will decrease emissions generated by many other sectors. *The Chemical Products sector* and *the Transport, Storage, and Post sector* are special cases, as downscaling them will clearly reduce both direct and indirect emissions. The total abatement potentials offered by *the Chemical Products sector* and *the Transport, Storage, and Post sector* are important because they generate large CO_2 export values.

Cost-benefit analyses of CO_2 emission decreases across all 30 sectors were also carried out, and their corresponding results are shown in Table A.10. The costs of downsizing are roughly estimated by changing the target industrial export values. Unlike previous industrial CO_2 abatement cost-benefit analyses, we integrated decreases in embodied CO_2 emissions into this calculation. The energy sectors, such as *the Production and Supply of Electric Power and Heat Power sector* and *the Petroleum Processing and Coking sector*, remain the most cost-efficient sectors to focus on, with CO_2 emission abatement costs of $<$ 2000 ¥ per ton of CO_2. However, it is concerning that several so-called low carbon industries, such as *the Construction sector*, have more cost-efficient carbon abatement effects than high-carbon sectors, such as *the Metals*

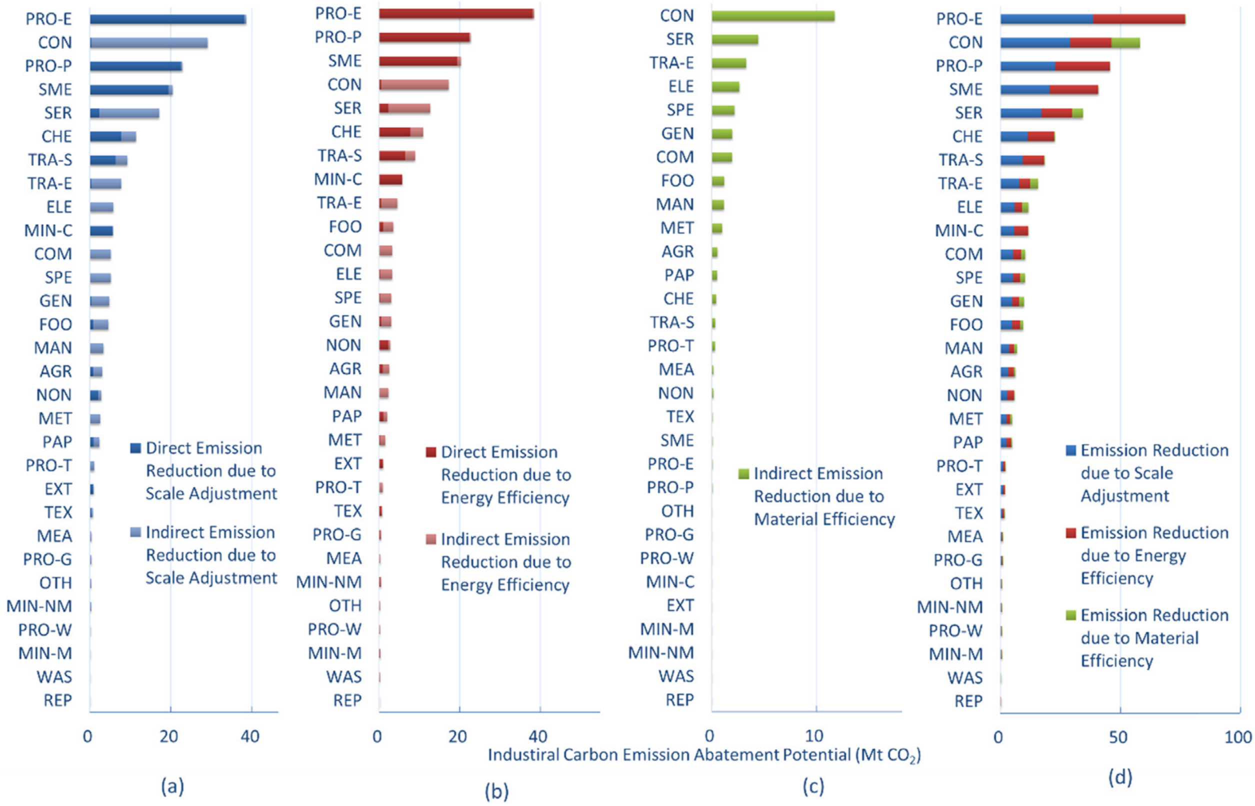

Fig. 3. Industrial CO_2 emission abatement potentials induced through 1% industrial scale adjustments, 1% energy efficiency improvements, and 1% material efficiency promotion in China. More detailed data are shown in Table A.6-A.9. The full names of the sectors are given in Table A.1.

Mining and Dressing sector and *the Gas Production and Supply sector*.

3.3.2. Energy efficiency improvements

Energy efficiency is generally measured as an average value regardless of the sectoral energy mix. This makes it difficult to identify actual carbon abatement effects related to energy efficiency improvements. We classify industrial energy consumption into fossil fuel combustion (which generates direct CO_2 emissions to the atmosphere) and secondary energy consumption (which generates indirect CO_2 emissions imported from energy product suppliers). To simplify the model, five sectors (*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*) are defined as energy product suppliers (related uncertainties are discussed in Section 3.4). In this case, the scale of the target industry is kept constant while the energy efficiency level is assumed to increase by 1%. The carbon abatement effect associated with greater energy efficiency (ΔTCE_{energy}) can be estimated using the following equation:

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

where $\Delta NBLE_{n,i}$ is the change in embodied CO_2 imports for industry i from energy product supplier n.

The CO_2 emission abatement potential related to a 1% improvement in energy efficiency for each industry was estimated. As is shown in Fig. 3b, improving energy efficiency levels contributes considerably to CO_2 emission reductions in every sector. Almost 38.5 Mt of CO_2 emissions can be prevented by improving energy efficiency levels by 1% in *the Production and Supply of Electric Power and Heat Power sector*, followed by *the Petroleum Processing and Coking sector* and *the Metals Mining and Dressing sector,* with respective reductions of about 22.8 Mt and 20.3 Mt in CO_2 emissions. The majority of the total direct emission reduction can be attributed to these sectors. Excitingly, ~17.2 Mt of CO_2 emissions can be eliminated by improving the energy efficiency of *the Construction sector*. Unlike values for *the Production and Supply of Electric Power and Heat Power sector*, 98.0% of CO_2 emissions eliminated from *the Construction sector* result from indirect emission reduction (Fig. 4), related to reducing the. large volumes of electricity and heat consumed during construction. Although improving the energy efficiency of *the Construction sector* would have a limited effect on direct emissions, it could considerably help reduce national CO_2 emissions.

It is worth mentioning that energy efficiency-related CO_2 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 CO_2 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 CO_2 emissions, but consider measures aimed at decreasing indirect CO_2 emissions of high energy-use sectors.

3.3.3. Material efficiency

Decreasing the use of energy-intensive materials by promoting efficient material usage should abate direct CO_2 emissions in upstream industries. The CO_2 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 CO_2 imported by industry i from all industries supplying non-energy products, using the following equation:

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

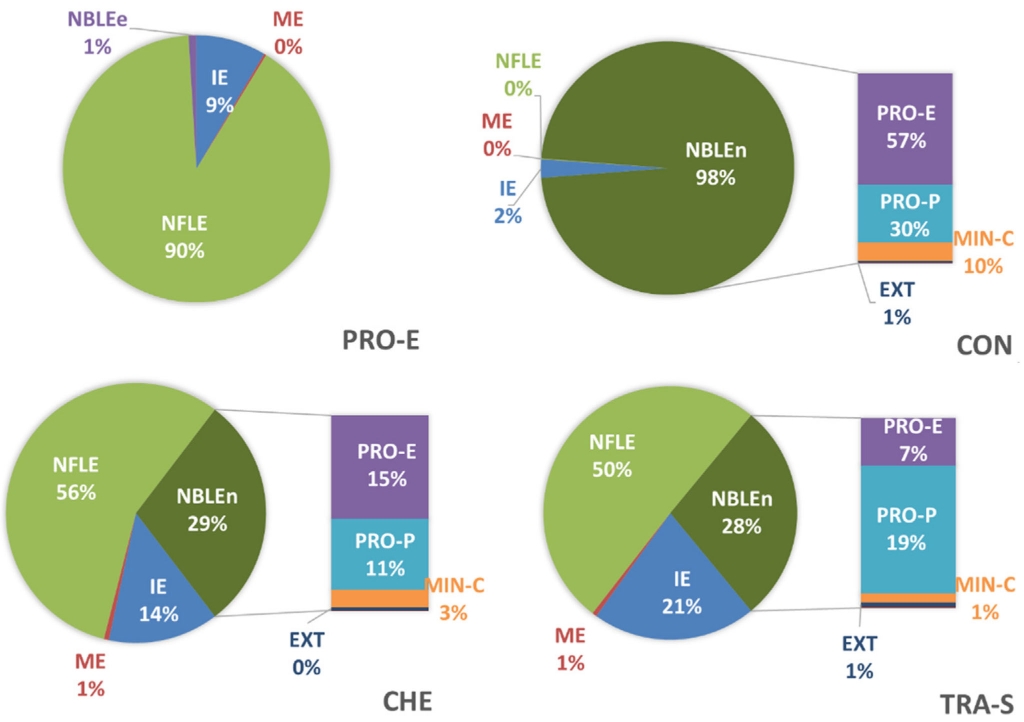

Fig. 4. The CO_2 emission abatement potential related to energy efficiency improvements in the Production and Supply of Electric Power and Heat Power sector (PRO-E), the Construction sector (CON), the Chemical Products sector (CHE), and the Transport, Storage and Post sector (TRA-S).

where $\Delta NBLE_{m,i}$ is the change in embodied CO_2 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 CO_2 emissions can be indirectly evaded by improving the efficiency of non-energy material-use in downstream industries. For instance, an ~11.8 Mt CO_2 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 CO_2 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.

3.4.1. Uncertainties associated with activity data

(a) Default data regarding CO_2 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 CO_2 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 CO_2 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 CO_2 and was responsible for 29.8% of all Chinese embodied CO_2 emissions in 2012; this is roughly consistent with estimates from previous studies [56–58].

3.4.2. 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 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*

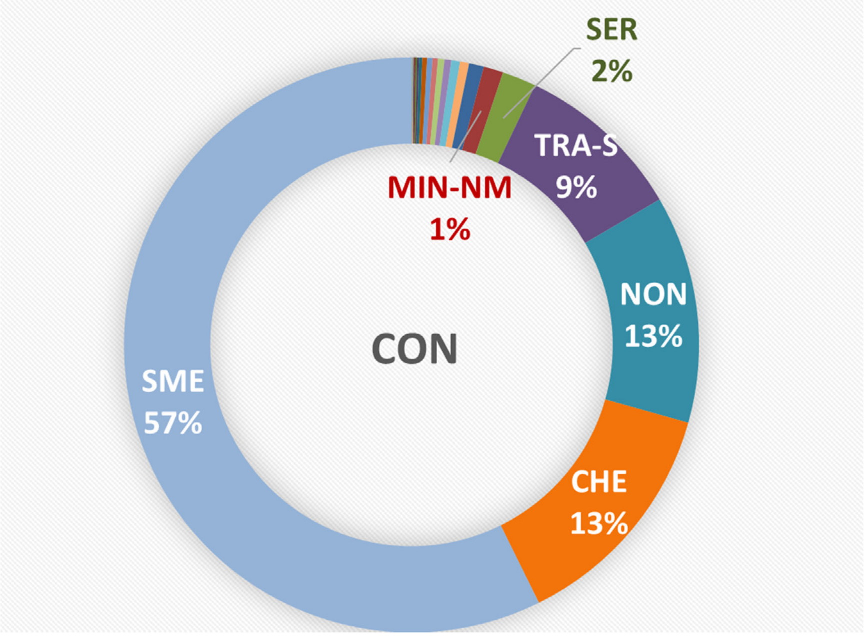

Fig. 5. CO_2 emission abatement potential related to material efficiency promotion in *the Construction sector* (CON).

Natural Gas Extraction sector, and *the Coal Mining and Dressing sector* are secondary energy types. Thus, these five sectors are defined as energy product suppliers. The other 25 sectors are assumed to only provide non-energy products. This simplification facilitated analysis of CO_2 abatement potentials; however, some uncertainty is introduced and would need to be evaluated in further studies.

4. Conclusions

The high direct CO_2 emission levels generated through manufacturing of energy-intensive materials have previously been examined to abate CO_2 levels. However, our results indicated that paying more attention to technological improvements in CO_2 importing sectors could more effectively decrease the consumption levels of energy-intensive materials. Like inter-regional CO_2 leakages, industrial disparities create complex inter-industrial embodied CO_2 flows. Strong CO_2 emission performances in downstream industries often occurs at the expense of unavoidably high CO_2 emissions in upstream sectors to meet the demands of the downstream industries. We traced embodied CO_2 flows between 30 industrial sectors in 2012 in China and re-explored industrial CO_2 emission abatement potentials from a consumer responsibility perspective. Uncertainties associated with the activity data and applied methods were also discussed.

Our results showed that the most important CO_2 exporters are central to the Chinese industrial system. Two energy supplying sectors (*the Production and Supply of Electric Power and Heat Power sector* and *the Petroleum Processing and Coking sector*) and one metallurgical industry sector (*the Metals Mining and Dressing sector*) were the three most significant sources of industrial CO_2 flows in China, contributing approximately 80% of the total CO_2 exports. However, *the Construction sector*, the main destination for CO_2 emission flows, was the most significant destination for embodied CO_2. These CO_2 emissions were transferred not only from energy suppliers but also from energy-intensive material producers, with ~34.4% derived from *the Production and Supply of Electric Power and Heat Power sector* and ~23.4% derived from *the Metals Mining and Dressing sector*. This demonstrated that the large-scale expansion of infrastructure resulting from rapid urbanization can explain the tremendous increase in CO_2 emissions that has occurred in China. Sensitivity analyses indicated that *the Construction sector* could make significant CO_2 emission abatement contributions through scale adjustments, and improvements in energy and material efficiency. The CO_2 emission abatement potential of *the Construction sector* was determined to be almost the same as that of *the Production and Supply of Electric Power and Heat Power sector*, which is currently recognized as being the main sector in which CO_2 emission abatement should occur. *The Construction sector*'s potential was shown to be surprisingly much greater than that of other high-carbon industrial sectors. Non-energy material efficiency improvements accounted for ~20.3% of *the Construction sector* CO_2 emission abatement potential, originating mainly from building material manufacturers (e.g., *the Metals Mining and Dressing sector*, and *the Non-metallic Mineral Products sector*). The same phenomenon was found for other industries presenting high CO_2 import levels. In addition to promoting energy saving in energy-intensive material manufacturing processes, future emission mitigation measures should focus on decreasing consumption of energy-intensive goods in downstream industries. For instance, to downscale construction activities, China should reform urban planning and design, avoid construction of repetitive infrastructure, and create 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 CO_2 peak target by setting requirements for decreasing CO_2 emissions on high-carbon industries [4,59]. However, net CO_2 exporters in the industrial chain will struggle to meet their targets in absolute terms, if no measures are taken by importers of embodied CO_2 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 CO_2 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 CO_2 and promoting efficient material-use may help us achieve more cost-effective decreases in CO_2 emissions in absolute terms.

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Conflict of Interests

The authors declare no competing financial interests.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2018.05.054.

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