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The effect of technology spillover on CO_2 emissions embodied in China-Australia trade

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Highlights

1. We investigated the effect of technology spillover on global emission reductions.
2. We considered the emission reductions potential under trade structure optimization.
3. We adopted SDA to examine the key drivers of embodied CO_2 emissions in China-Australia trade.
4. We examined embodied CO_2 in China-Australia trade with disaggregated sectors.

The effect of technology spillover on CO_2 emissions embodied in China-Australia trade

Keywords: embodied CO_2 emissions; technology spillover; input-output; China-Australia trade

1 Introduction

The impact of trade on CO_2 emissions, links two contemporary global issues: (1) the China-U.S. trade war and (2) climate change. Amid the increasing likelihood of a decoupling between China and the US, the environmental impact of trade is an additional reason to safeguard the current global free trade regime. China and Australia's bilateral trade is a useful case to study in terms of assessing the impact of CO_2 emissions for a number of reasons. First, China-Australia trade is very important to the two countries, which have each committed to reduced emissions. Under the Paris Agreement, China committed to peak carbon emissions around 2030 (Gallagher et al., 2019). While Australia will seek to reduce its emissions to between 26-28% based on 2005 levels by 2030 (Malik et al., 2018). In order to meet their climate targets, both China and Australia need to implement effective measures to control their total emissions.

Second, the increasing trade volume and its embedded emissions have complicated the efforts of each country to reduce these emissions. China is Australia's largest trading partner; one third of Australia's foreign trade is conducted with China. Previous studies show that the CO_2 emissions embodied in China-Australia trade have increased rapidly over the last two decades. For instance, CO_2 emissions embodied in the exports of Australia to China increased by 12.98 Mt between 2002 and 2010 (Tan et al., 2013). Australia outsourced 30.94 Mt of CO_2 emissions to China through bilateral trade between 2010-2011 (Jayanthakumaran and Liu, 2016). The scale of these emissions further escalated when the China-Australia Free Trade Agreement (ChAFTA) came into effect on 20 December 2015 (Qi and Zhang, 2018). Under the ChAFTA, nearly all goods traded between the two countries were made tariff free, which substantially enhanced bilateral trade as well as increasing CO_2 emissions. According to ChAFTA, up to 97% of Australian exported products to China and 100% of Chinese exported products to Australia are tariff free (Xiang et al., 2017).

Third, the China-Australia trade model suggests that international trade can be a win-win for the countries involved. It not only leads to the obvious economic benefits, it can also lead to emissions reductions through developing green trade strategies and smarter trade policies, such as export structure optimization. Unlike China’s trade with other partners, the China-Australia trade relationship is highly complimentarily and so it has distinct emissions impacts. Chinese exports focus on manufactured goods while in return Australia’s exports focus on energy and resources, services and agricultural products. Previous studies, such as Jayanthakumaran and Liu (2016) and Tan et al. (2013), indicate that China-Australia trade contributes significantly to global CO_2 emissions reduction. By comparing the embodied CO_2 emissions in a hypothetical “no trade” scenario with CO_2 embodiment in the actual trade, the authors found that global emissions decreased because China imported Australian primary products instead of producing them itself. In contrast, many of China’s bilateral trade, such as the China-US trade relationship (Guo et al., 2010; Shui and Harriss, 2006) and the China-UK trade relationship (Li and Hewitt, 2008), increased global CO_2 emissions substantially. The China-UK trade relationship resulted in an additional 117 Mt of CO_2 emissions above global CO_2 emissions for 2004 (Li and Hewitt, 2008). In 2005, China-US trade increased global CO_2 emissions by 385 Mt (Guo et al., 2010).

For the aforementioned reasons, it is instructive to study the embodied CO_2 emissions in the China-Australia trade relationship to understand how green trade strategies contribute to emissions reductions as well as how it promotes bilateral trade growth. Analysing the embodied CO_2 emissions in China-Australia trade is informative for policy-makers in other countries because it provides a set of *actual* policies that have led to decreases in CO_2 emissions embodied in trade.

At present, several studies have been conducted to assess embodied CO_2 emissions in China-Australia trade, however, gaps remain in the body of knowledge in this area. Existing studies conclude that China has been a net CO_2 exporter in its trade with Australia, and that overall China-Australian trade contributes to global CO_2 emissions reductions (Jayanthakumaran and Liu, 2016; Tan et al., 2013; Wang et al., 2019). However, these studies do not evaluate the reduction potential under trade structure optimization in the future. In addition, they do not assess the reduction potential of technology spillover between China and Australia. Technology spillover refers to the process of technology transfer as trading partners, in this case a developed and emerging economy, learn and improve from one another (Keller, 2004). International trade is one of the most important channels for transnational technology spillover (Timmer et al., 2014; Veréb and Ferreira, 2018). Importing high-technology intermediate goods has the potential to generate substantial technology spillover effects (Acharya and Keller, 2008). The importing nation can imitate the advanced technologies from the exporting nation in order to improve their own technology prowess. With the deepening of bilateral communication and cooperation, the industrial productivity of both China and Australia will continue to grow due to the technology spillover effect, which could affect embodied CO_2 emissions in China-Australia trade. Therefore, it is necessary to simulate China-Australia embodied CO_2 emissions reductions under export structure optimization (i.e. smarter trade scenario, hereafter) and technology spillover to inform decision-makers to implement smarter trade policies and achieve mutual benefit and win-win results.

The formulation of green trade policies requires quantitative assessment of the influence factors of embodied CO_2 emissions, which can be further combined with scenario simulations to project the future to take into account structural change and technical dynamics. Structural decomposition analysis (SDA) and index decomposition analysis (IDA) are two decomposition techniques widely adopted to assess the driving factors for energy-related CO_2 emissions. For example, Wood (2009) analysed the driving forces of Australia's total greenhouse gas emissions over a 30-year time period based on SDA. Tan et al. (2013) examined the influence factors of the embodied CO_2 emissions in China-Australia trade adopting IDA. Compared to the IDA method, SDA is based on input-output models, which can distinguish the technological and final demand effects on changes to CO_2 emissions. Also, SDA can identify the indirect effects of driving factors, while IDA can only accounts for direct effects (Su and Ang, 2012; Zhao et al., 2016). A number of previous studies have applied SDA to investigate the influencing factors for CO_2 emissions increase at different regional levels (Lenzen, 2016). For instance, several studies have found that the rapid growth of export volume has been the main driving force for Chinese exported CO_2 emissions to increase (Meng et al., 2018; Mi et al., 2018; Xu et al., 2011), while Feng et al. (2012) and Wu and Wang (2017) examined the influence factors for interregional CO_2 transfers in China. Other related studies have identified the drivers of energy-related CO_2 emissions in metropolitan areas such as Beijing (Wang et al., 2013; Wei et al., 2017). These are also compared and included in Tab.S1, Supplementary Information (SI). Scenario simulations are useful tools for assessing emerging trends, organizing scientific insights, and considering policy alternatives (Brown et al., 2001), which can address the third gap in the knowledge base that this study has identified. For instance, Guan et al. (2008) constructed several scenarios to illustrate future potential Chinese emissions up to the year 2030. The results under the "westernizing lifestyle" scenario and the "carbon capture and storage" scenario, reflect the potential upper and lower bounds of Chinese emissions. Xia et al. (2019) predict the evolution of indirect household carbon emissions by combing regression and scenario analysis, the results from which recommend that policy-makers should focus on optimizing residents' consumption behaviours.

In order to investigate the gaps in the knowledge base, this study seeks to contribute to the literature in at least two aspects. Firstly, we examine the contribution of China-Australia trade on global CO_2 emissions under different scenarios. Under the "smarter trade" scenario, we simulate China-Australian embodied CO_2 emissions changes where high-emissions products are produced by the nation with lower emission intensity. Under a “technology spillover” scenario, we simulate China-Australia embodied CO_2 emissions changes where the industrial emission intensity is improved due to the technology effects between the two countries.

Secondly, by constructing future technological progress and exports increase scenarios, we seek to predict the China-Australia embodied CO_2 emissions in 2020, 2025, and 2030. These predictions are based on the influencing factors of the embodied CO_2 emissions in China-Australia bilateral trade identified by SDA using long term series disaggregated sectoral input-output tables from the Eora input output database (Lenzen et al., 2012; Lenzen et al., 2013). Modelling these predictions will help to inform decision-makers to implement green trade strategies and emission reduction policies. A recent study conducted by Wang et al. (2019) investigated carbon emissions embodied in China-Australia trade from 2015-2022 by constructing a multi-step forecasting procedure. The results indicate the importance of increasing R&D investment in achieving CO_2 reductions. However, the study neglects the characteristics of the recent China-Australian trade structure, the technology spillover and their impacts on embodied CO_2 emissions. The neglect of these characteristics means the study does not provide a comprehensive picture of embodied CO_2 emissions trends up to 2030, which is regarded as the key time frame for achieving reduction commitments for both China and Australia.

The article is divided into three sections. Section Two describes the methodology including the research approach, the data and its analysis. Section Three outlines the findings and discussion, which focus on embedded emissions, their drivers and future scenarios. Lastly, Section Four concludes the article with a set of policy implications.

2 Methodology and data

The framework of this study is illustrated in Fig. 1. Employing the Eora multi-regional input output (MRIO) database, we estimate the impact of China-Australian trade on emissions reduction. In order to do this, we calculate the embodied CO_2 emissions in China-Australian trade adopting the Emissions Embodied in Bilateral Trade (EEBT) method, and take the results as “Factual scenario”. We then compare the embodied CO_2 emissions in China-Australian trade with the results under no trade scenario, smarter trade scenario, and technology spillover scenario to assess the effect of China-Australia trade on global carbon reductions.

Second, we estimate the driving forces of the embedded emissions. We evaluate the effect of emission intensity, production technology, export structure, and export volume on embodied CO_2 emissions in China-Australian trade based on the results of structural decomposition analysis (SDA).

Third, we project the future trend of the embedded emissions in the China-Australian trade. In order to provide a future projection of embodied CO_2 emissions in China-Australia trade, we develop the latest five years of growth (LFYG) scenario based on the results of SDA (shown in SI). We set the rates of technological progress and export increase in 2020, 2025, and 2030 under the BAU scenario according to the results in LFYG scenario. Then we simulate the future reduction potential of China-Australia trade on global CO_2 emissions under the technology spillover scenario.

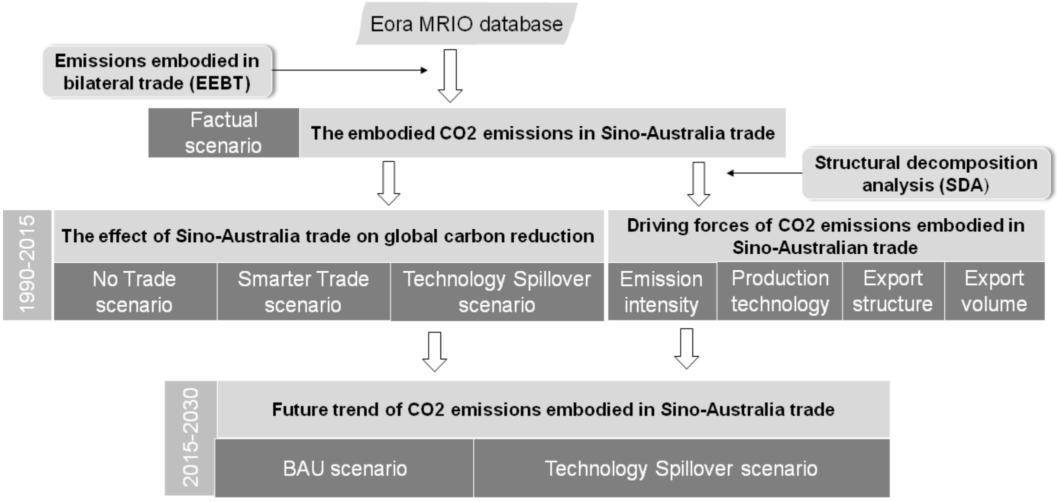

Figure 1. The framework of this study

2.1 Emissions embodied in bilateral trade approach

Input output analysis has been widely used to examine the environmental and social factors embodied in international/regional/sectoral trade (Lenzen et al., 2018), such as CO_2 emissions (Davis and Caldeira, 2010; Feng et al., 2013; Wu, 2019), energy use (Wu and Chen, 2017), air pollution (He et al., 2019), water (Zhang and Anadon, 2014), corruption (Xiao et al., 2018), and inequality (Alsamawi et al., 2014). Emissions embodied in bilateral trade (EEBT) and multi-regional input-output (MRIO) methods have been popular approaches when calculating the carbon footprint embodied in interregional trade. Since "*the EEBT model is better for analysis of trade and climate policy where transparency is important*" (Peters, 2008, p5), we employed it to examine the CO_2 emissions embodied in China-Australia trade in this study.

The CO_2 emissions caused in region *r* to meet the demands in region *s* can be obtained from Equation (1).

$$\mathbf{C}^{rs} = \mathbf{f}^{r}(\mathbf{I} - \mathbf{A}^{rr})^{-1}\mathbf{e}^{rs} \quad (1)$$

where *r* and *s* denote different regions.

$\mathbf{C}^{rs}$ denotes the embodied CO_2 emissions in the exports from region r to region s.

$\mathbf{f}^{r}$ denotes the sectoral CO_2 emissions intensity of region *r*, which can be obtained by sectoral CO_2 emissions divided by the corresponding output.

I is the identity matrix.

A is a matrix of intermediate consumption coefficients.

$\mathbf{e}^{rs}$ is the exports from region r to region s.

2.2 Scenario simulations for trade's emission impact

Three scenarios -"no trade" scenario, "smarter trade" scenario, and "technology spillover" scenario, are designed to simulate the embodied CO_2 emissions changes.

Under the "no trade" scenario, the goods are assumed to be produced domestically instead of been imported. This method has been widely used to investigate the impact of bilateral trade on global CO_2 emissions, such as China-UK

(Li and Hewitt, 2008), China-US (Guo et al., 2010; Shui and Harriss, 2006), and China-Australia (Jayanthakumaran and Liu, 2016; Tan et al., 2013). In line with Jayanthakumaran and Liu (2016), and Tan et al. (2013), we assume that China's goods are produced domestically as opposed to been imported from Australia, and that Australia's goods are produced domestically instead of been imported from China. We then compared the CO_2 emissions under a "no trade" scenario with the embodied CO_2 emissions in the bilateral trade. The basic idea is shown in Equations (2)-(6). Equations (2) and (3) represent the embodied CO_2 emissions, Equations (4) and (5) represent the CO_2 emissions in the "no trade" scenario. If $\triangle \mathbf{C} > 0$, it means that China-Australia trade causes global CO_2 increases; If $\triangle \mathbf{C} < 0$, it means China-Australia trade contributes to global CO_2 reductions.

$$\mathbf{C}^{\mathrm{C}\to\mathrm{A}} = \mathbf{F}^{\mathrm{C}}(\mathbf{I}-\mathbf{A}^{\mathrm{C}})\mathbf{E}^{\mathrm{C}\to\mathrm{A}} \quad (2)$$

$$\mathbf{C}^{\mathrm{A}\to\mathrm{C}} = \mathbf{F}^{\mathrm{A}}(\mathbf{I}-\mathbf{A}^{\mathrm{A}})\mathbf{E}^{\mathrm{A}\to\mathrm{C}} \quad (3)$$

$$\mathbf{C}^{\mathrm{C}}_{\mathrm{notrade}} = \mathbf{F}^{\mathrm{C}}(\mathbf{I}-\mathbf{A}^{\mathrm{C}})\mathbf{E}^{\mathrm{A}\to\mathrm{C}} \quad (4)$$

$$\mathbf{C}^{\mathrm{A}}_{\mathrm{notrade}} = \mathbf{F}^{\mathrm{A}}(\mathbf{I}-\mathbf{A}^{\mathrm{A}})\mathbf{E}^{\mathrm{C}\to\mathrm{A}} \quad (5)$$

$$\Delta\mathbf{C} = (\mathbf{C}^{\mathrm{C}\to\mathrm{A}} + \mathbf{C}^{\mathrm{A}\to\mathrm{C}}) - (\mathbf{C}^{\mathrm{C}}_{\mathrm{notrade}} + \mathbf{C}^{\mathrm{A}}_{\mathrm{notrade}}) \quad (6)$$

Where, $\mathbf{C}^{\mathrm{C}\to\mathrm{A}}$ and $\mathbf{C}^{\mathrm{A}\to\mathrm{C}}$ are the embodied CO_2 emissions in China's exports to Australia, and Australia's exports to China, respectively. $\mathbf{F}^{\mathrm{C}}$ and $\mathbf{F}^{\mathrm{A}}$ denote the emission intensity in China and Australia respectively. $\mathbf{A}^{\mathrm{C}}$ and $\mathbf{A}^{\mathrm{A}}$ denote the direct consumption coefficient matrix in China and Australia, respectively. $\mathbf{E}^{\mathrm{C}\to\mathrm{A}}$ and $\mathbf{E}^{\mathrm{A}\to\mathrm{C}}$ denote the exports from China to Australia, and the exports from Australia to China, respectively.

In the "smarter trade" scenario, we compared the sectoral emission intensity between China and Australia to begin with. If emission intensity of sector i in China is higher compared with Australia, i.e. $f_i^{\mathrm{C}} > f_i^{\mathrm{A}}$, then the export from China to Australia $e_i^{\mathrm{C}\to\mathrm{A}}$ is produced by Australia itself. Therefore, the embodied CO_2

emissions in the exports of China and Australia would change, as illustrated in Equation (7a).

$$\begin{aligned}
&\mathbf{C}_{\text{smarter}}^{\mathrm{C}\rightarrow\mathrm{A}}=\begin{bmatrix} c_1^{\mathrm{C}\rightarrow\mathrm{A}} \\ \vdots \\ c_i^{\mathrm{C}\rightarrow\mathrm{A}} \\ \vdots \end{bmatrix}=\begin{bmatrix} f_1^{\mathrm{C}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{C}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{C}} \end{bmatrix}\times\begin{bmatrix} l_{11}^{\mathrm{C}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{C}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{C}} & \cdots & \cdots & l_{nn}^{\mathrm{C}} \end{bmatrix}\times\begin{bmatrix} e_1^{\mathrm{C}\rightarrow\mathrm{A}} \\ \cdots \\ 0 \\ e_n^{\mathrm{C}\rightarrow\mathrm{A}} \end{bmatrix} \\
&\mathbf{C}_{\text{smarter}}^{\mathrm{A}\rightarrow\mathrm{C}}=\begin{bmatrix} c_1^{\mathrm{A}\rightarrow\mathrm{C}} \\ \vdots \\ c_i^{\mathrm{A}\rightarrow\mathrm{C}} \\ \vdots \end{bmatrix}=\begin{bmatrix} f_1^{\mathrm{A}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{A}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{A}} \end{bmatrix}\times\begin{bmatrix} l_{11}^{\mathrm{A}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{A}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{A}} & \cdots & \cdots & l_{nn}^{\mathrm{A}} \end{bmatrix}\times\begin{bmatrix} e_1^{\mathrm{A}\rightarrow\mathrm{C}} \\ \cdots \\ e_i^{\mathrm{A}\rightarrow\mathrm{C}}+e_i^{\mathrm{C}\rightarrow\mathrm{A}} \\ e_n^{\mathrm{A}\rightarrow\mathrm{C}} \end{bmatrix}
\end{aligned} \tag{7a}$$

Where, c_i denotes the embodied $\mathrm{CO_2}$ emissions of sector i. $\mathrm{C}\rightarrow\mathrm{A}$ denotes from China to Australia, $\mathrm{A}\rightarrow\mathrm{C}$ denotes from Australia to China. f_i denotes the emissions intensity of the sector i. l_{ij} denotes the element of Leontief inverse matrix. $e_i^{\mathrm{A}\rightarrow\mathrm{C}}$ denotes the exports of sector i from Australia to China. $e_i^{\mathrm{C}\rightarrow\mathrm{A}}$ denotes the exports of sector i from China to Australia.

Similarly, the embodied $\mathrm{CO_2}$ emissions in trade between China and Australia are shown in Equation (7b), when emission intensity of sector i in Australia is higher compared with China, i.e. $f_i^{\mathrm{A}} > f_i^{\mathrm{C}}$.

$$\begin{aligned}
&\mathbf{C}_{\text{smarter}}^{\mathrm{C}\rightarrow\mathrm{A}}=\begin{bmatrix} c_1^{\mathrm{C}\rightarrow\mathrm{A}} \\ \vdots \\ c_i^{\mathrm{C}\rightarrow\mathrm{A}} \\ \vdots \end{bmatrix}=\begin{bmatrix} f_1^{\mathrm{C}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{C}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{C}} \end{bmatrix}\times\begin{bmatrix} l_{11}^{\mathrm{C}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{C}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{C}} & \cdots & \cdots & l_{nn}^{\mathrm{C}} \end{bmatrix}\times\begin{bmatrix} e_1^{\mathrm{C}\rightarrow\mathrm{A}} \\ \cdots \\ e_i^{\mathrm{C}\rightarrow\mathrm{A}}+e_i^{\mathrm{A}\rightarrow\mathrm{C}} \\ e_n^{\mathrm{C}\rightarrow\mathrm{A}} \end{bmatrix} \\
&\mathbf{C}_{\text{smarter}}^{\mathrm{A}\rightarrow\mathrm{C}}=\begin{bmatrix} c_1^{\mathrm{A}\rightarrow\mathrm{C}} \\ \vdots \\ c_i^{\mathrm{A}\rightarrow\mathrm{C}} \\ \vdots \end{bmatrix}=\begin{bmatrix} f_1^{\mathrm{A}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{A}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{A}} \end{bmatrix}\times\begin{bmatrix} l_{11}^{\mathrm{A}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{A}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{A}} & \cdots & \cdots & l_{nn}^{\mathrm{A}} \end{bmatrix}\times\begin{bmatrix} e_1^{\mathrm{A}\rightarrow\mathrm{C}} \\ \cdots \\ 0 \\ e_n^{\mathrm{A}\rightarrow\mathrm{C}} \end{bmatrix}
\end{aligned} \tag{7b}$$

The “technology spillover” scenario is designed to simulate the emission reduction effect due to technology convergence between the two countries. Under this scenario, the lower sectoral emission intensity between China and Australia would be adopted for calculation. For example, if emission intensity of sector i in China is higher compared with Australia, i.e. $f_i^{\mathrm{C}} > f_i^{\mathrm{A}}$, we assume that the emission intensity of sector i in China would reduce to f_i^{A} through technology spillover. Therefore, the embodied CO_2 emissions in trade between China and Australia are expected to be lower under the "technology spillover" scenario. The idea is illustrated in Equation (8).

$$\mathbf{C}_{\mathrm{techspillover}}^{\mathrm{C}\to\mathrm{A}} = \begin{bmatrix} c_1^{\mathrm{C}\to\mathrm{A}} \\ \vdots \\ c_i^{\mathrm{C}\to\mathrm{A}} \\ \vdots \end{bmatrix} = \begin{bmatrix} f_1^{\mathrm{C}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{A}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{C}} \end{bmatrix} \times \begin{bmatrix} l_{11}^{\mathrm{C}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{C}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{C}} & \cdots & \cdots & l_{nn}^{\mathrm{C}} \end{bmatrix} \times \begin{bmatrix} e_1^{\mathrm{C}\to\mathrm{A}} \\ \cdots \\ e_i^{\mathrm{C}\to\mathrm{A}} \\ e_n^{\mathrm{C}\to\mathrm{A}} \end{bmatrix}$$

$$\mathbf{C}_{\mathrm{techspillover}}^{\mathrm{A}\to\mathrm{C}} = \begin{bmatrix} c_1^{\mathrm{A}\to\mathrm{C}} \\ \vdots \\ c_i^{\mathrm{A}\to\mathrm{C}} \\ \vdots \end{bmatrix} = \begin{bmatrix} f_1^{\mathrm{A}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{A}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{A}} \end{bmatrix} \times \begin{bmatrix} l_{11}^{\mathrm{A}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{A}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{A}} & \cdots & \cdots & l_{nn}^{\mathrm{A}} \end{bmatrix} \times \begin{bmatrix} e_1^{\mathrm{A}\to\mathrm{C}} \\ \cdots \\ e_i^{\mathrm{A}\to\mathrm{C}} \\ e_n^{\mathrm{A}\to\mathrm{C}} \end{bmatrix}$$

when $f_i^{\mathrm{C}} > f_i^{\mathrm{A}}$; (8a)

$$\mathbf{C}_{\mathrm{techspillover}}^{\mathrm{C}\to\mathrm{A}} = \begin{bmatrix} c_1^{\mathrm{C}\to\mathrm{A}} \\ \vdots \\ c_i^{\mathrm{C}\to\mathrm{A}} \\ \vdots \end{bmatrix} = \begin{bmatrix} f_1^{\mathrm{C}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{C}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{C}} \end{bmatrix} \times \begin{bmatrix} l_{11}^{\mathrm{C}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{C}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{C}} & \cdots & \cdots & l_{nn}^{\mathrm{C}} \end{bmatrix} \times \begin{bmatrix} e_1^{\mathrm{C}\to\mathrm{A}} \\ \cdots \\ e_i^{\mathrm{C}\to\mathrm{A}} \\ e_n^{\mathrm{C}\to\mathrm{A}} \end{bmatrix}$$

$$\mathbf{C}_{\mathrm{techspillover}}^{\mathrm{A}\to\mathrm{C}} = \begin{bmatrix} c_1^{\mathrm{A}\to\mathrm{C}} \\ \vdots \\ c_i^{\mathrm{A}\to\mathrm{C}} \\ \vdots \end{bmatrix} = \begin{bmatrix} f_1^{\mathrm{A}} & 0 & 0 & 0 \\ 0 & \cdots & 0 & 0 \\ 0 & 0 & f_i^{\mathrm{C}} & 0 \\ 0 & 0 & 0 & f_n^{\mathrm{A}} \end{bmatrix} \times \begin{bmatrix} l_{11}^{\mathrm{A}} & \cdots & \cdots & l_{1\mathrm{n}}^{\mathrm{A}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ l_{n1}^{\mathrm{A}} & \cdots & \cdots & l_{nn}^{\mathrm{A}} \end{bmatrix} \times \begin{bmatrix} e_1^{\mathrm{A}\to\mathrm{C}} \\ \cdots \\ e_i^{\mathrm{A}\to\mathrm{C}} \\ e_n^{\mathrm{A}\to\mathrm{C}} \end{bmatrix}$$

when $f_i^{\mathrm{A}} > f_i^{\mathrm{C}}$; (8b)

Other factors in trade, such as production costs, tariffs, exchange rates, reciprocal demand/supply, and factor endowments, are not considered in the "smarter trade" scenario, although these factors are important. For example, the production cost may be higher in Australia since the wages of workers are much higher than they are in China. Besides, the resources endowment and industrial structure in China and Australia are very different. Therefore, the “smarter trade” scenario may be impractical. In addition, we only considered the embodied CO_2 emissions in China-Australia trade and compared the sectoral emission intensity between these two countries in the study. Import demand may be satisfied from other countries with even lower emissions intensity, and more significant technology spillover effect could be anticipated from other countries as well.

2.3 Structural decomposition analysis

Structural decomposition analysis (SDA) has been extensively used to examine the driving power of environmental factors, such as material flows (Liang et al., 2017), energy use (Guevara et al., 2016), water (Feng et al., 2017; Zhang et al., 2018), and CO_2 emissions (Mohlin et al., 2018). SDA results may vary according to different study periods, regional, and sectoral aggregation (Su et al., 2010; Su and Ang, 2012). A more detailed description can be found in Dietzenbacher and Los (2010).

In order to identify the driving factors of embodied CO_2 emissions in China-Australia trade, we followed the methods used by Meng et al. (2018) and Mi et al. (2018), and adopted polar decompositions as the approximation of the average of overall forms of decomposition. We considered four factors: emission intensity, production structure, export structure, and export volume.

$$\Delta \mathbf{C}^{e} = \underbrace{\Delta \mathbf{F}\mathbf{L}\mathbf{E}_{S}\mathbf{E}_{V}}_{\text{emission intensity effect}} + \underbrace{\mathbf{F}\Delta \mathbf{L}\mathbf{E}_{S}\mathbf{E}_{V}}_{\text{production structure effect}} + \underbrace{\mathbf{F}\mathbf{L}\Delta \mathbf{E}_{S}\mathbf{E}_{V}}_{\text{export structure effect}} + \underbrace{\mathbf{F}\mathbf{L}\mathbf{E}_{S}\Delta \mathbf{E}_{V}}_{\text{export volume effect}} \quad (9)$$

where Δ is the difference operator;

$\mathbf{C}^{\mathbf{te}}$ is the embodied CO_2 emissions in trade;

$\mathbf{L}$ is the Leontief inverse matrix $\mathbf{(L\text{-}A)^{-1}}$;

$\mathbf{E_S}$ is export structure; and

$\mathbf{E_V}$ is the export volume.

Based on the SDA results, we predict future embodied CO_2 emissions in China-Australia trade by constructing “The latest five years growth” (LFYG) scenario. Under the LFYG scenario, the effects of emission intensity, production structure, export structure, and export volume on exported CO_2 emission during 2015-2020, 2020-2025, and 2025-2030 are assumed to be unchanged as they were during the period of 2010-2015. Therefore, we can project the embodied CO_2 emissions in China-Australia trade till 2030 and provide the baseline for scenario comparison.

2.4 Data

In this study, we used Chinese IO tables (123-sector) and Australian IO tables (345-sector) to calculate the embodied CO_2 emissions in exports. Then we aggregated 345 sectors in Australia’s IO tables into 123 in order to be consistent with the sectors in China’s IO tables to facilitate scenarios simulation.

The input-output table and CO_2 emissions data used in our study were taken from the Eora MRIO database, which provides a time series of high-resolution IO tables with matching environmental and social satellite accounts for 190 economies. The main data sources include input-output tables and aggregated data from national statistical offices, I-O compendia from Eurostat, IDE-JETRO, the OECD, the United Nations (UN) National Accounts Main Aggregates Database, the UN National Accounts Official Data, the UN Comtrade international trade database, and the UN Service trade international trade database. In order to manipulate and integrate a large number of different data sets, the UN created a custom data processing language (AISHA) (Geschkea et al., 2011). This language contains commands for locating specific sections of the MRIO table time series and is linked to a library of concordance matrices that assist with the aggregation, disaggregation, and reclassification steps necessary to align disparate data. More detailed information is outlined in Lenzen et al. (2012) and Lenzen et al. (2013).

3 Results and discussions

3.1 CO_2 *Emissions embodied in China-Australian bilateral trade*

The embodied CO_2 emissions in China-Australia trade are compared in Fig. 2. The growth trends of embodied CO_2 emissions in the exports of Australia to China are similar under different sector resolutions. T-tests indicate there is no significant difference between the detailed disaggregated sectors (blue line with circular mark in Fig. 2) and the aggregated sectors (blue line with triangle mark in Fig. 2) (at the 5% significance level). While there is no particular level of sector disaggregation that can be considered to be the ‘correct’ level, the levels around 40 sectors appear to be sufficient to capture the overall share of emissions embodied in a country's exports. When data availability is not an issue, it is preferable to use data with a higher level of sector disaggregation (Su et al., 2010). Therefore, we use the detailed disaggregated sectoral data when examining the sectoral CO_2 emissions embodied in exports, as well as conducting structural decomposition analysis.

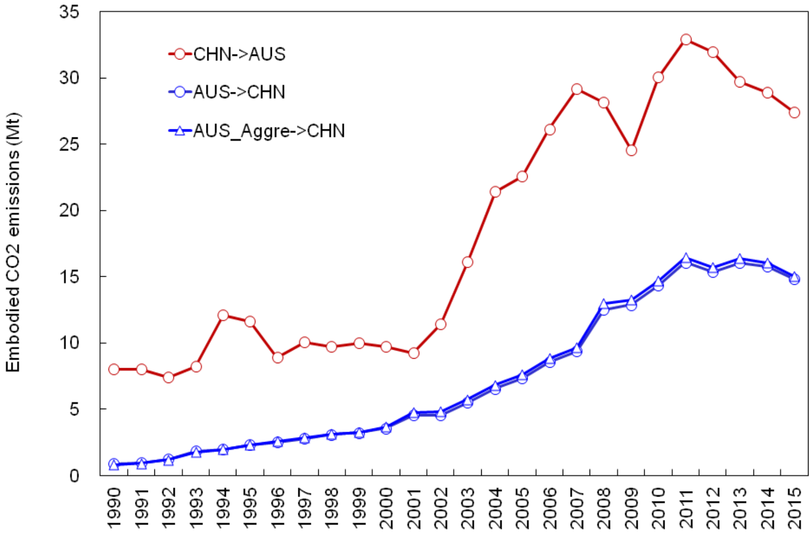

Figure 2. The embodied CO_2 emissions in China-Australia bilateral trade

(CHN->AUS denotes the embodied CO_2 emissions from China to Australia; AUS->CHN denotes the embodied CO_2 emissions from Australia to China)

As illustrated in Fig.2, CO_2 emissions embodied in Australia’s exports to China has been increasing, and peaked in 2011 at a value of 16.1 Mt. This is related to its sustained economic growth, growing population and the increasing import demand for its products to China. By contrast, the trend of CO_2 emissions embodied in China's exports to Australia has gone through some fluctuations during the study period, which experienced a rapid increase during 2002-2007 with an average increase rate of 21.7%. The rapid increase is related to an exports surge after China joined the WTO. From 2001 to 2007, China's exports to Australia quadrupled from 53.9 billion US dollars in 2001 to 220.3 billion in 2007 (Lenzen et al., 2013), which caused a significant increase in its exported CO_2 emissions. There is a significant drop during 2007-2009 due to the global financial crisis. Afterwards, CO_2 emissions embodied in the exports of China to Australia increased in parallel with the economic recovery from 2009-2011. From 2011-2015, China's exported CO_2 emissions to Australia reduced gradually with the continuous decline of its carbon dioxide emissions intensity and the constant improvement in production technology (Guan et al., 2018).

China has been a net CO_2 exporter during 1990-2015 in its trade with Australia. The accumulated net exported CO_2 emissions from China to Australia were 284.8 Mt. This amount is approximately 70% of Australia's emission for 2017 (Muntean et al., 2018). This is consistent with findings from the previous literature (Jayanthakumaran and Liu, 2016; Tan et al., 2013; Wang et al., 2019). The average value of net export-CO_2 emissions from China to Australia is 13.1 Mt since 2000, which is close to the total CO_2 emissions of many developed economies such as Finland, Sweden, and Switzerland (Boden et al., 2017). Therefore, it is important for China to take effective measures to reduce its exported CO_2 emissions since approximately 20-30% of its total emissions are caused by exports (Huang et al., 2019; Mi et al., 2018).

CO_2 emissions embodied in China-Australia bilateral trade in this study are compared with the results in previous studies, as illustrated in Tab.1. The results of embodied CO_2 emissions from China to Australia in this study are lower than the findings in Wang et al. (2019) and Jayanthakumaran and Liu (2016), however, they are higher than the findings reported by Tan et al. (2013). The embodied CO_2

emissions from Australia to China in this study are lower compared with the results reported by Tan et al. (2013), Wang et al. (2019), and Jayanthakumaran and Liu (2016). There are several reasons for this. The first is the different data sources. Steen-Olsen et al. (2016) found that significant differences exist at the national and sectoral level when comparing results based on three main MRIO databases. Secondly, different data processing, such as sector aggregation and disaggregation, could cause differences among these results. Thirdly, we adopted the IO data at the basic price for the calculation, while other studies used the purchasing power parity exchange rate or currency exchange rate for conversion (Jayanthakumaran and Liu, 2016; Tan et al., 2013; Wang et al., 2019).

Table 1 Comparison with results of existing studies (Mt CO_2 emissions)

	Embodied CO_2 from CHN to AUS					Embodied CO_2 from AUS to CHN				
	2002	2008	2009	2010	2011	2002	2008	2009	2010	2011
Tan et al. (2013)	10.4			27.8		9.6			23.3	
Jayanthakumaran and Liu (2016)		49.5		52.5			11.7		21.6	
Wang et al. (2019)	10.8	33.4	33.6	40.9	48.3	8.6	14.7	16.5	17.6	20.0
This study	11.4	28.2	24.5	30.0	32.9	4.6	12.5	12.9	14.3	16.1

Notes: CHN stands for China, AUS stands for Australia. The first three rows of this table are drawn by Wang et al. (2019).

3.2 Embodied CO_2 emissions in China-Australian trade at sectoral level

The 123 sectoral embodied CO_2 emissions from China to Australia are illustrated in Fig.3. The embodied CO_2 emissions are drawn mainly from electricity and stream production and supply, due to the coal-dominated energy mix in China. Electricity consumption is a necessary input for other sectoral production (Liu et al., 2016). Other sectors with high embodied exported CO_2 emissions include air passenger transport, highway freight and passengers, and cement and cement asbestos products.

This is because transportation and the production of cement industries are highly energy-intensive industries in China.

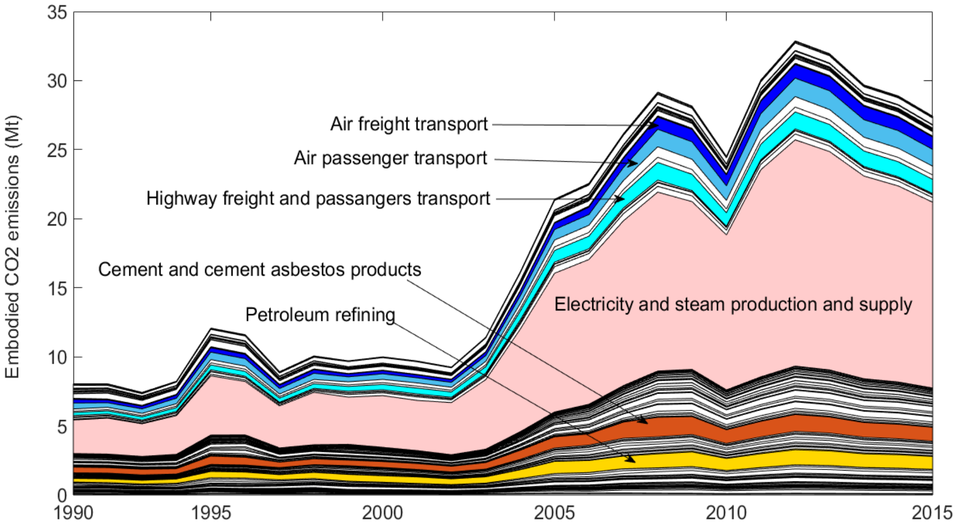

Figure 3. Sectoral embodied CO_2 emissions in China's exports to Australia

Sectoral embodied CO_2 emissions from Australia to China are illustrated in Fig.4. There are large amounts of CO_2 emissions embodied in the sectors of energy, transportation, irons ore, and iron and steel semi-manufacturing. Since iron and steel are necessary materials in the construction of buildings and other forms of infrastructure, China has had a large demand for these products due to its rapid industrialization and urbanization over the last four decades.

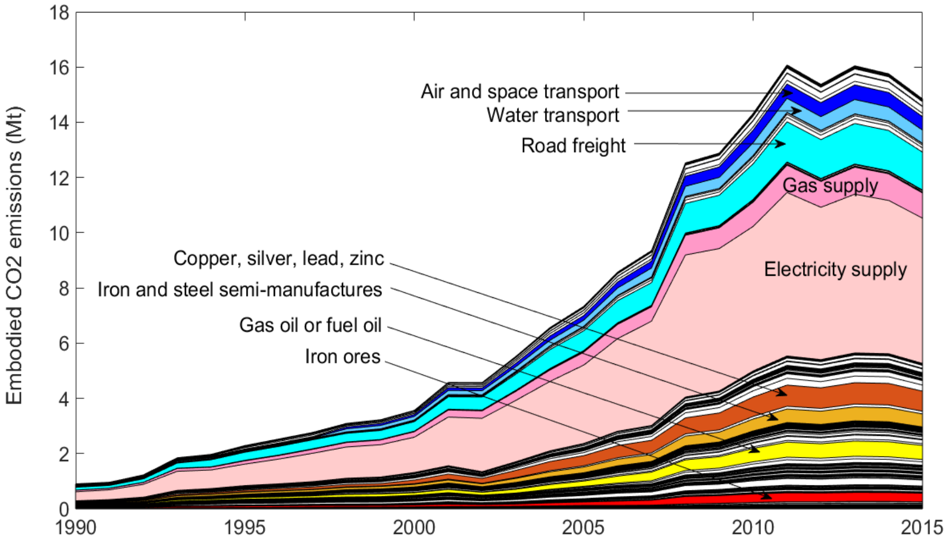

Figure 4. Sectoral embodied CO_2 emissions in Australia's exports to China

Since the embodied CO_2 emissions in exports are dominated by several sectors for both China and Australia, we further calculate the change in the proportion of sectoral embodied CO_2 emissions in exports for both countries. The reason for this is to examine the sectoral embodied CO_2 emissions variations to acquire more detailed information. The top 10 and bottom 10 variations in sectoral embodied CO_2 emissions are illustrated in Fig.5 and Fig.6, respectively.

The proportion of sectoral embodied CO_2 emissions changed by degrees during different periods of time for both China and Australia (Fig.5-6). Nevertheless, the fluctuation of the proportion of sectoral embodied CO_2 emissions are continuing to trend downwards over time. For example, the proportion of embodied CO_2 emissions for sector 260 from Australia to China increased by 1.4% for the period 1990-1995, while for the period 2010-2015 it rose by 0.3% only. The proportion of embodied CO_2 emissions for sector 240 from Australia to China decreased by 2.1% during 1990-1995, while it declined by 1.1% from 2010-2015. The situation is similar for the sectoral embodied CO_2 emissions from China to Australia (Fig.6).

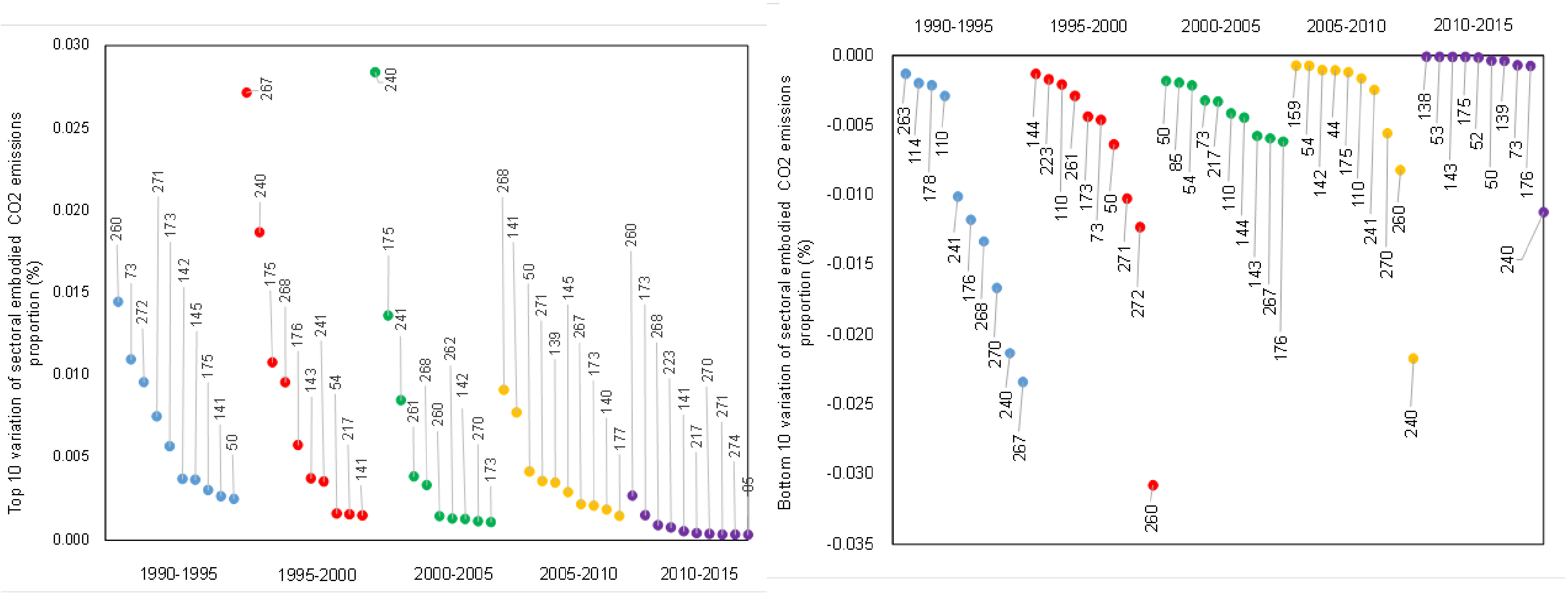

Figure 5. The top 10 and bottom 10 variation of sectoral embodied CO_2 emissions proportion for Australia

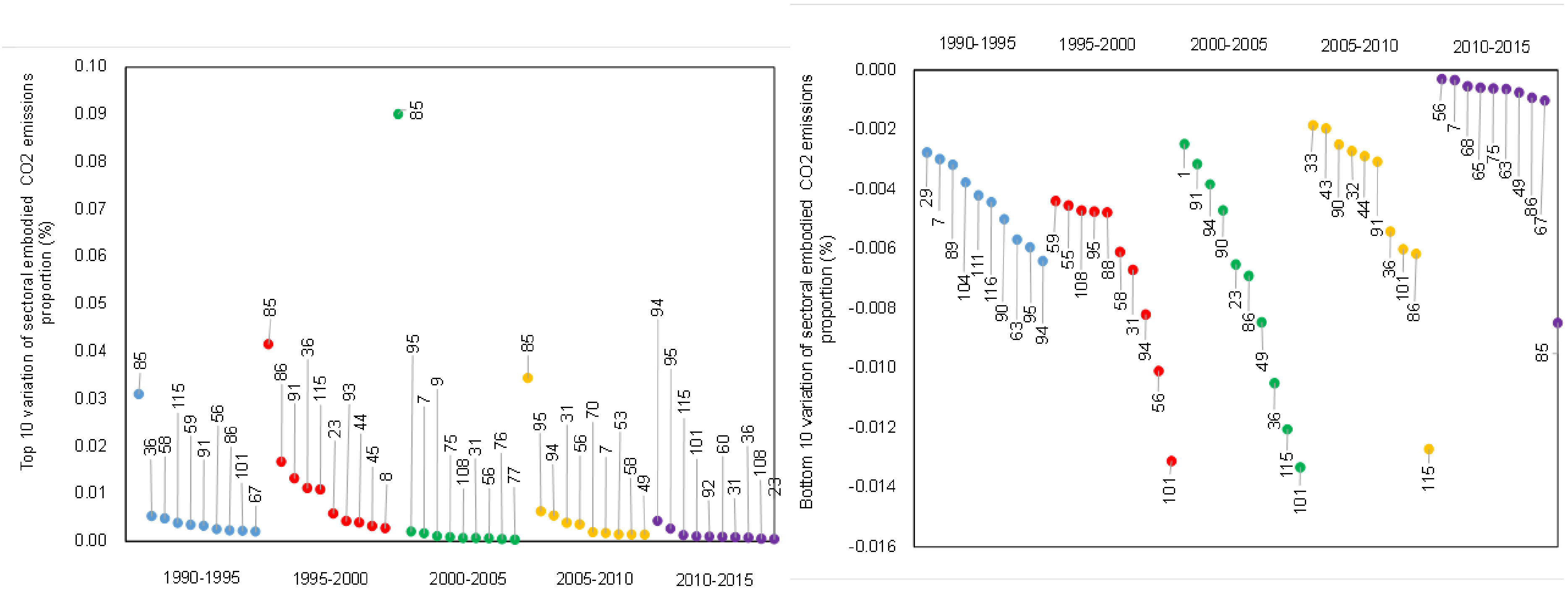

Figure 6. The top 10 and bottom 10 variation of sectoral embodied CO$_2$ emissions proportion for China

3.3 The effects of China-Australia trade on global CO_2 emissions

The total embodied CO_2 emissions under a no trade scenario, smarter trade scenario, technology spillover scenario are compared with the factual emissions, as illustrated in Fig. 7. The results of a no trade scenario indicate that China-Australia trade contributes to global CO_2 emissions reduction to a significant degree. The accumulation of 281.96 Mt of CO_2 emissions were reduced during 1990-2015 due to China-Australia trade. These results are supported by findings from Jayanthakumaran and Liu (2016), and Tan et al. (2013).

The emissions reduction effects are significant under the smarter trade scenario and technology spillover scenario. Compared to the factual scenario, the accumulated reduced CO_2 emissions could reach 315.49 Mt and 323.72 Mt respectively, which is equivalent to the total fossil fuel CO_2 emissions of Poland in 2017 (Muntean et al., 2018). This reflects the significance of improving emissions intensity and technology spillover on global carbon dioxide emissions reduction.

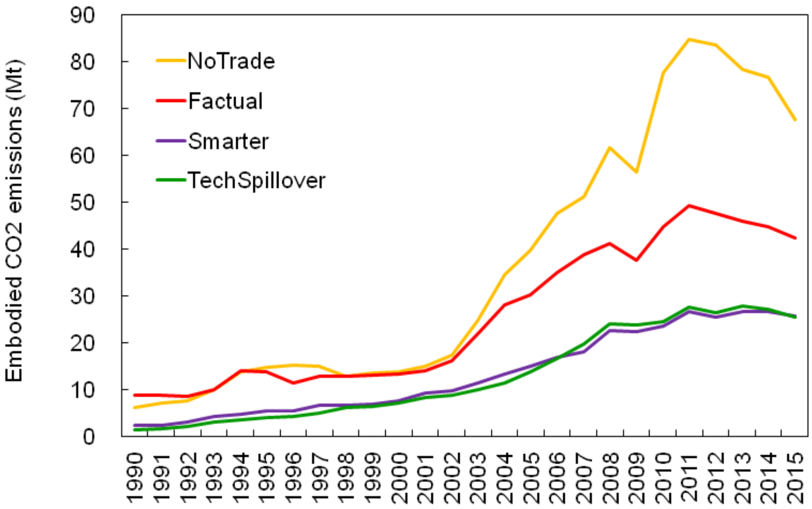

Figure 7. The results under different scenarios

Embodied CO_2 emissions under factual scenario, smarter scenario, and technology spillover scenarios are compared in order to identify the most effective mitigation solution (in Fig. 8). Under the factual scenario, China has been a net CO_2 exporter so that embodied CO_2 emissions from China to Australia account for

64.3-67.1% of the total for the period 2010-2015. By contrast, under the smarter trade scenario, almost all of the embodied CO_2 emissions are outsourced to Australia, since the sectoral emission intensity in Australia is lower than it is in China. Although global carbon reductions can be achieved under the smarter trade scenario (Fig.7), it is unrealistic and difficult to implement since the resource endowment and production structure in China and Australia are very different. However, under the technology spillover scenario, embodied CO_2 emission in China's exports to Australia reduced to a great extent. For example, embodied CO_2 emissions from China to Australia under technology spillover scenario are only 33.6-39.3% compared to those under the factual scenario. Besides, embodied CO_2 emissions from Australia to China also reduced slightly due to the technology spillover effect. Therefore, promoting technology spillover between China and Australia is an effective means for dealing with the trade-climate dilemma. Both China and Australia should improve their energy efficiency, reduce sectoral emission intensity, and promote technology spillover to reduce the embodied CO_2 emissions in trade, as well as mitigating global climate change.

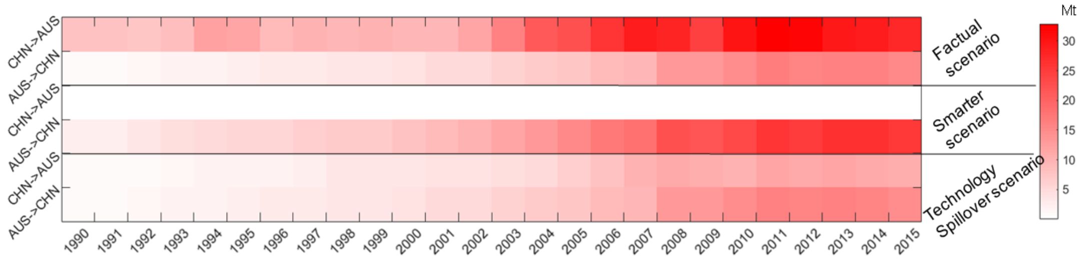

Figure 8. Embodied CO_2 emissions between China-Australia trade under different scenarios

(CHN->AUS denotes the embodied CO_2 emissions from China to Australia; AUS->CHN denotes the embodied CO_2 emissions from Australia to China)

Furthermore, we examine the reduction potential of each sector due to technology spillover in China to identify the key sectors based on data from 2015. The reduction potential of each sector varies at different degrees, as illustrated in Fig.9.

The numbers and the corresponding sectors are given in Tab. S2. The sector with the largest reduction potential is electricity and steam production and supply, which could reduce CO_2 emissions by 7.3 Mt, followed by air passenger transport (-1.1 Mt), cement and cement asbestos products (-0.9 Mt), air freight transport (-0.7 Mt), resident and other services (-0.5 Mt), steel-processing (-0.3), petroleum refining (-0.3 Mt), and metal products (-0.3 Mt). Therefore, it is more efficient for China to reduce its exported emissions to Australia through strengthening technology spillover of these sectors as there is greater potential to reduce emissions.

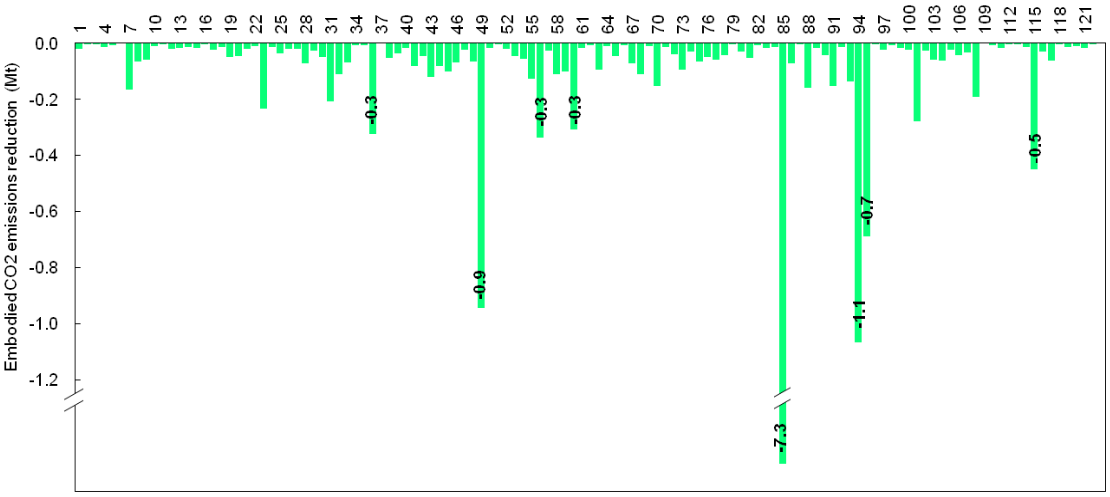

Figure 9. The reduction of embodied CO_2 emissions in China's exports to Australia

3.4 Driving forces for the China-Australian embodied CO_2 emissions

Structural decomposition analysis has been conducted to examine the driving forces for China's exported CO_2 emissions to Australia and Australia's exported CO_2 emissions to China every five years in order to make the results comparable. The results for the period 1990-1995, 1995-2000, 2000-2005, 2005-2010, and 2010-2015 are illustrated in Fig. 10.

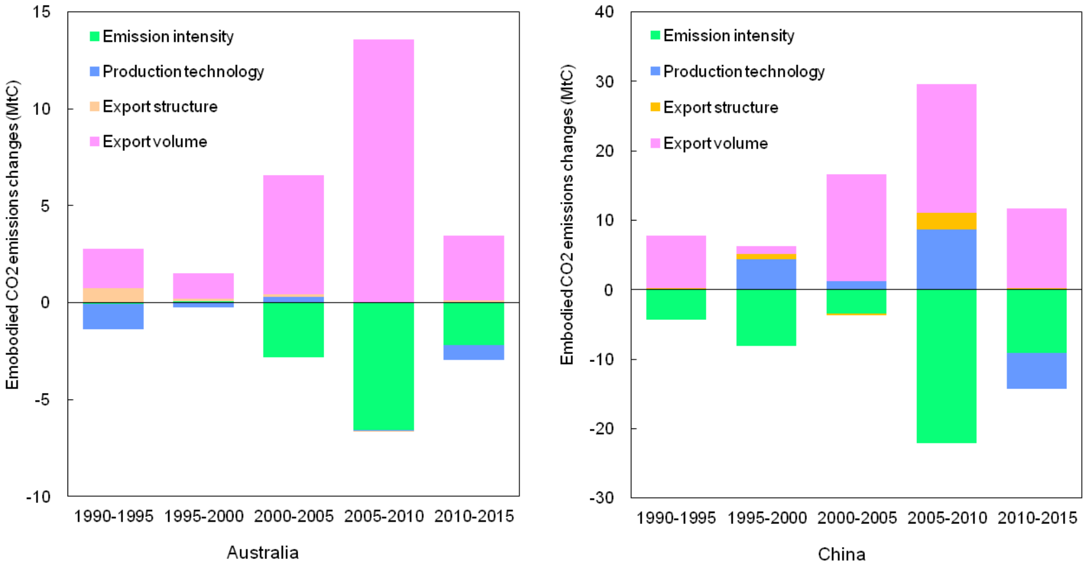

Figure 10. SDA results

For the CO_2 emissions from Australia to China, as shown in the left panel in Fig.10, export volume is the most significant driving force for embodied CO_2 emissions increase from 1990 to 2015. Whereas, emission intensity is the main factor to reduce embodied CO_2 emissions from Australia to China since 2000. There is no significant effect of production structure on Australia's exported CO_2 emissions to China from 2005-2010. This is due to a lack of improvement of industrial structure during the global financial crisis period. This is supported by Muhammad et al. (2015), who found a strong positive correlation between financial performance and environmental performance before the global financial crisis for Australian companies, however, there was no relationship during global financial crisis (Muhammad et al., 2015).

For the embodied CO_2 emissions from China to Australia, as shown in the right panel in Fig.10, export volume has been the largest driving force of embodied CO_2 emissions increase, while emission intensity has been the strongest factor to offset embodied CO_2 emissions increases. The effect of production structure on exported CO_2 emissions varies during different periods. From 2010-2015, production structure helped to reduce China's exported CO_2 emissions to Australia due to the production efficiency improvement and industrial structure optimization. These results are consistent with findings from Xu et al. (2011) and Tan et al. (2013). Since the Chinese economy entered into a "new normal", the economic growth rate and economic development model have changed significantly with the Chinese government paying more attention to the 'quality of economic growth' as opposed to the pursuit of 'economic growth by any means' (Mi et al., 2018).

However, for both China and Australia, the effect of export structure on exported CO_2 emissions is not significant. This reflects that the China-Australia bilateral export structure has been relatively stable over the study period. As mentioned above, the variations of the proportion of sectoral exported CO_2 emissions for both China and Australia are within a narrow range. This is supported by Jayanthakumaran and Liu (2016), who found that the majority of Australia's exports to China are primary goods, such as coal, iron ore, crude petroleum, and gold, while the majority of China's exports to Australia are manufactured goods, such as metal, petroleum, paper, furniture, and clothing.

3.5 The effect of technology spillover on future China-Australian embodied CO_2 emissions

Based on the results of the LYFG scenario, we can set the growth rates of technological progress and export volume of China and Australia in 2020, 2025, and 2030 (as shown in Tab.S3), then simulate the embodied CO_2 emissions in China-Australia trade and use these results as the BAU scenario. Following on from this, we can simulate the reduction potential of China-Australian embodied CO_2 emissions under the technology spillover scenario.

The results indicate that global CO_2 emissions will be further reduced due to the spillover effect (as illustrated in Fig.11). The reduction in global CO_2 emissions will reach 34.7%, 26.1%, and 32.7% in 2020, 2025, and 2030 respectively, since embodied CO_2 emissions in the exports of China to Australia will be reduced substantially. Therefore, global carbon reduction can be achieved by providing technological assistance to China and reducing its sectoral emission intensity (Liu et al., 2016).

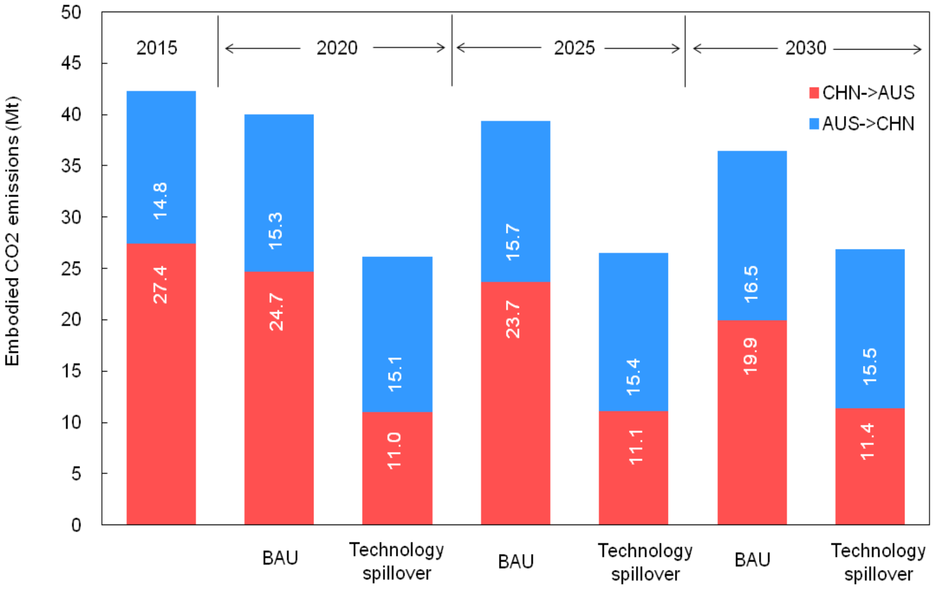

Figure 11. Future global reduction potential under technology spillover scenario

4 Conclusions and policy implications

China and Australia's bilateral trade is a useful case in which to study the emissions impact of trade more generally for a number of reasons. These include the volume and its growth potential, the embedded emissions, and its unique contribution to global emissions reductions. While there are some studies on the embedded emissions of China-Australian trade, these did not analyze the emission reductions potential under trade structure optimization and the benefits of technology spillover.

In the current study, we estimated the embodied CO_2 emissions in China-Australia trade in the period 1990 to 2015 based on the EEBT method using detailed disaggregated sectors information from the Eora MRIO database. The embodied emissions results show that China has been a net CO_2 exporter in its trade with Australia. The exported CO_2 emissions come from a number of industrial sectors including electricity, transportation, and cement. Each of these industries represents an energy-intensive sector of the Chinese economy, which have a strong backward and forward linkage (Huang et al., 2018).

SDA results indicate that export volume has been the dominant contributor to the embodied CO_2 emissions increase in China-Australia trade, while emissions intensity helps to offset these to a significant degree. Export structure has a limited effect on embodied CO_2 emissions since the structure of China-Australia trade has not changed much. The reduction of emissions intensity and production structure optimization has significantly reduced China's exported CO_2 emissions to Australia for the period 2010-2015.

The results under the no trade scenario indicate that China-Australia trade helps to reduce global CO_2 emissions and the reductions could be more significant under the smarter trade scenario and technology spillover scenario, which emphasize the importance of reducing sectoral emission intensity for global carbon reduction. Developed economies can play an important role here by assisting developing economies to become more energy efficient, making a significant contribution to reducing global emissions (Keho, 2016).

There are a number of policy implications that arise from this research. First, China-Australia trade not only promotes economic growth, but also contributes to global carbon reductions and so provides a number of insights for policy makers. It is of great importance for bilateral economic growth and global climate mitigation to ensure that China-Australia trade avoids the growing sentiment for trade protectionism. Second, it is effective for global climate mitigation as it creates a basis for strong ties and cooperation between developed and emerging economies, particularly when it comes to technological assistance and transfer, which has shown to lead to substantial carbon reductions. Technology transfer between developed and emerging economies, such as the accessibility to renewable energy innovations, should be promoted and widely used to achieve global CO_2 emissions reduction targets. Third, considerable emissions reduction can be accomplished by improving the carbon intensity of several sectors in China. Policy priority should be given to the electricity, transportation and cement industries as reductions in these industry sectors has significant potential to reduce carbon emissions. For example, installing more energy-efficient technologies in electricity and steam production and supply. Managers of manufacturing enterprises should take the opportunity to work from the “new normal” growth model as well as optimize the allocation of all kinds of resources through innovation to improve their production efficiency. Lastly, Australia can reduce its embodied CO_2 emissions by developing more low-carbon goods and services to trade. For example, it could cultivate new economic growth points and promote the development of renewable energy, tourism, services and hi-tech agriculture, rather than continuing to depend on exporting carbon generating raw materials such as coal.

A number of issues should be further addressed in future research. Firstly, the effects of technology spillover on embodied non-CO_2 emissions can be examined to overcome the underestimation of the impacts of climate policies (Nong, 2020). Secondly, computable general equilibrium (CGE) model needs to be adopted to simulate future trends of embodied CO_2 emissions and non-CO_2 emissions in China-Australia trade considering prices changes and demand-supply responses after the implementation of ChAFTA under the market mechanisms (Meng et al., 2018; Tran et al., 2019). Thirdly, since both China and Australia are large nations with distinct spatial disparity, further studies at sub-national levels can help decision-makers in both countries to formulate policies based on regional energy conservation and emission reduction patterns.

Acknowledgments

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***Declaration of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

***Credit Author Statement**

Rui Huang: Conceptualization, Methodology, Writing- Original draft preparation

Guangwu Chen: Conceptualization, Methodology, Writing- Original draft preparation.

Guonian Lv: Software, Validation.

Arunima Malik: Writing- Reviewing and Editing

Xunpeng Shi: Writing- Reviewing and Editing, Supervision

Xiaotian Xie: Visualization, Investigation.

Figure(s)

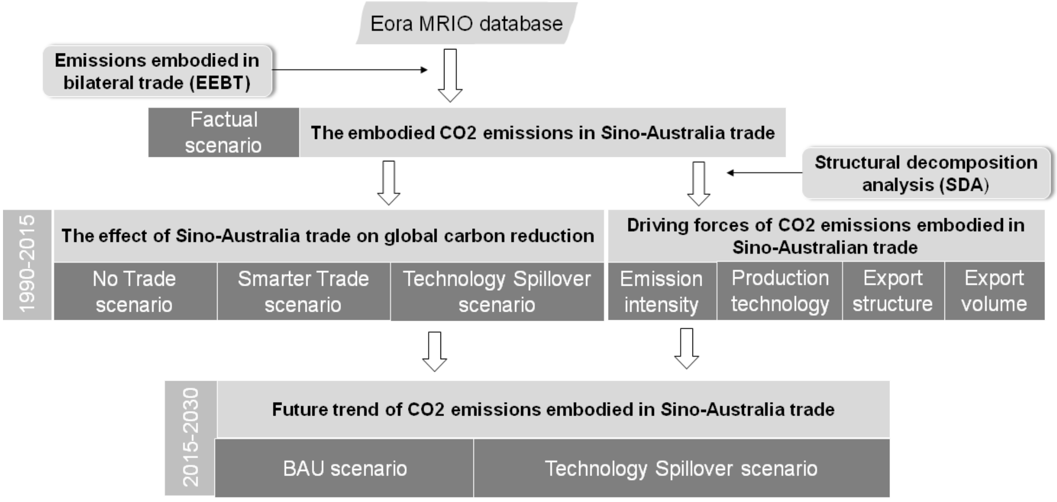

Figure 1. The framework of this study

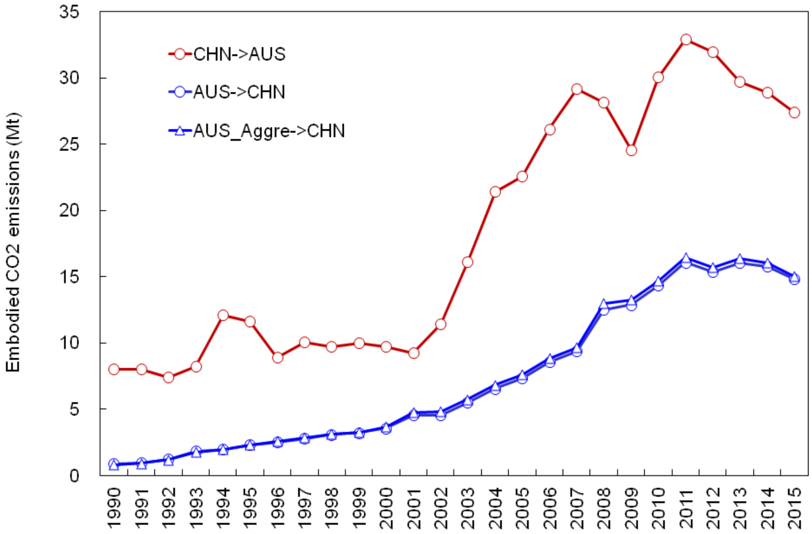

Figure 2. The embodied CO_2 emissions in China-Australia bilateral trade

(CHN->AUS denotes the embodied CO_2 emissions from China to Australia; AUS->CHN denotes the embodied CO_2 emissions from Australia to China)

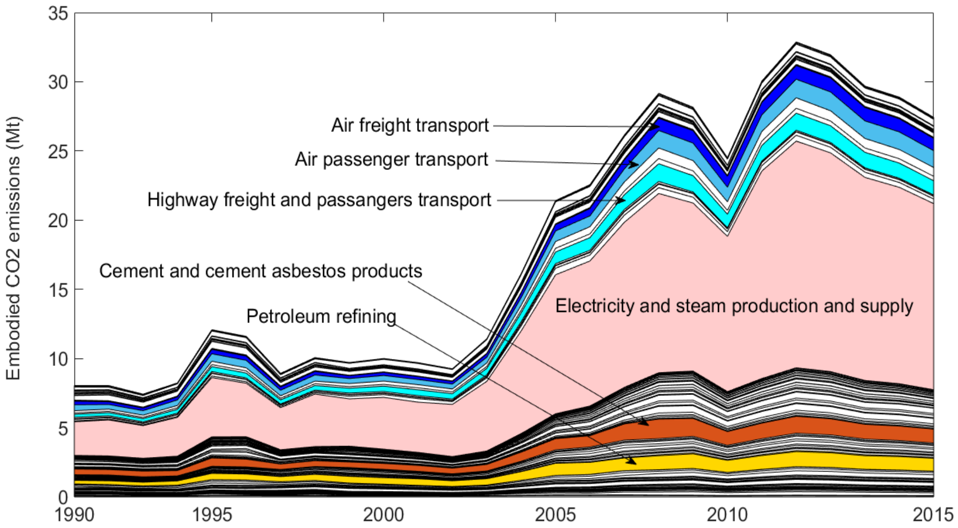

Figure 3. Sectoral embodied CO_2 emissions in China's exports to Australia

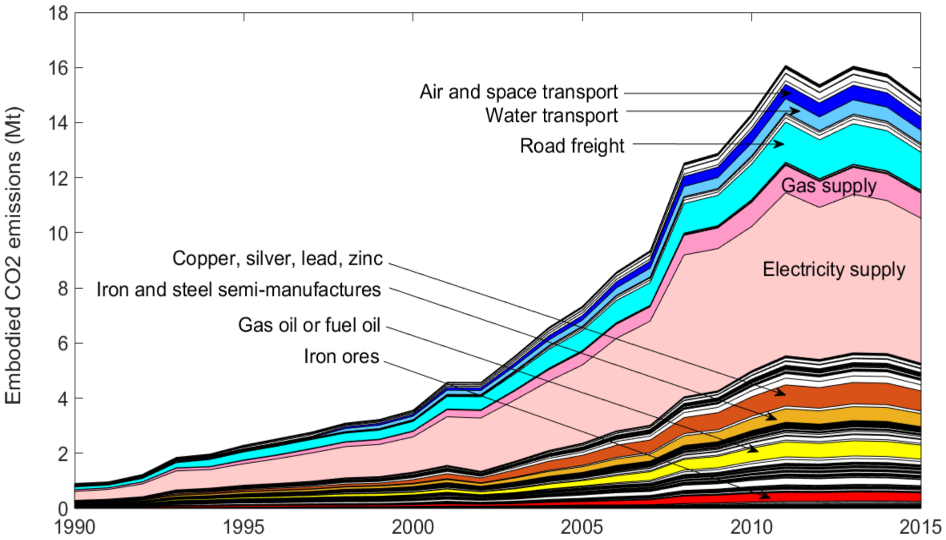

Figure 4. Sectoral embodied CO_2 emissions in Australia's exports to China

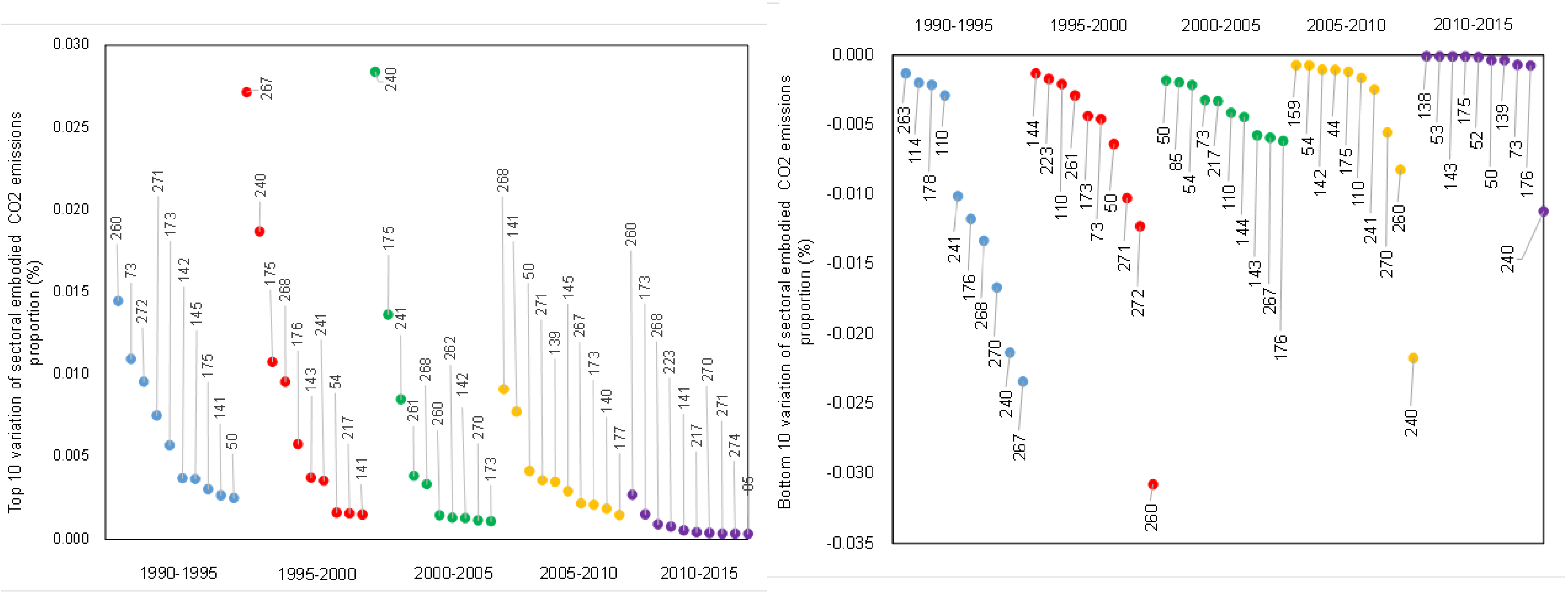

Figure 5. The top 10 and bottom 10 variation of sectoral embodied CO_2 emissions proportion for Australia

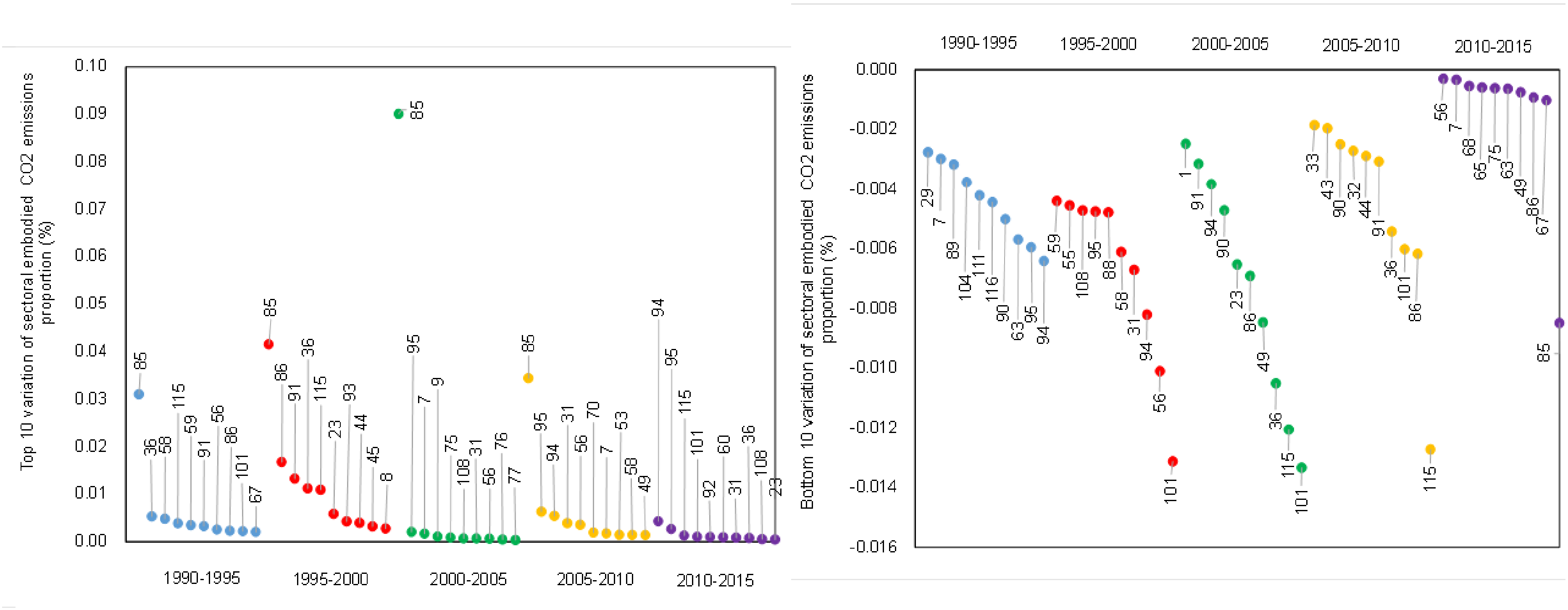

Figure 6. The top 10 and bottom 10 variation of sectoral embodied CO$_2$ emissions proportion for China

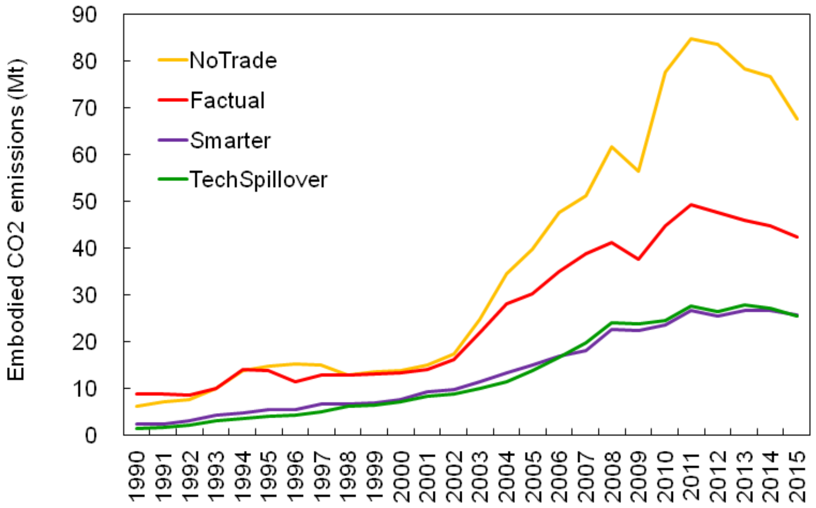

Figure 7. The results under different scenarios

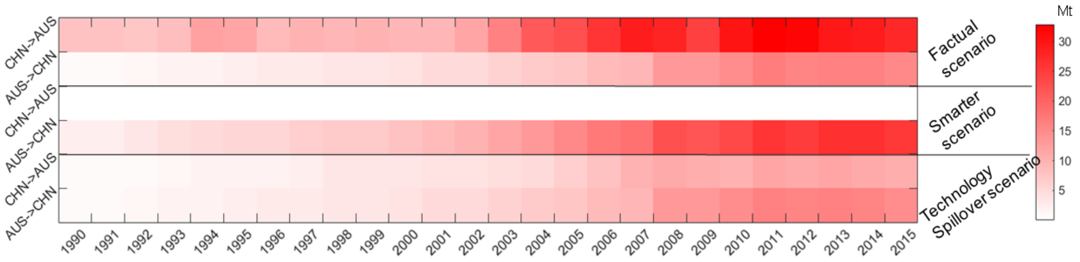

Figure 8. Embodied CO_2 emissions between China-Australia trade under different scenarios

(CHN->AUS denotes the embodied CO_2 emissions from China to Australia; AUS->CHN denotes the embodied CO_2 emissions from Australia to China)

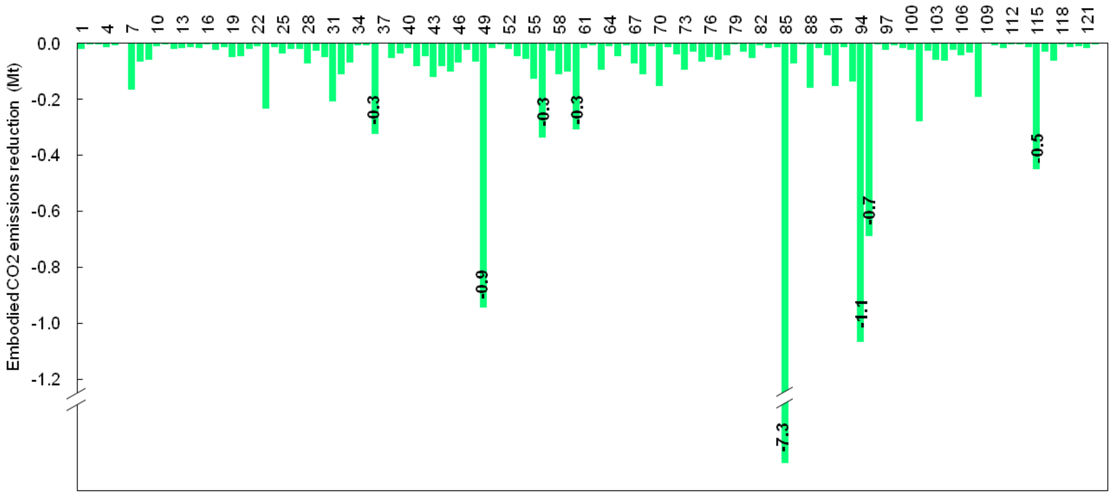

Figure 9. The reduction of embodied CO_2 emissions in China's exports to Australia

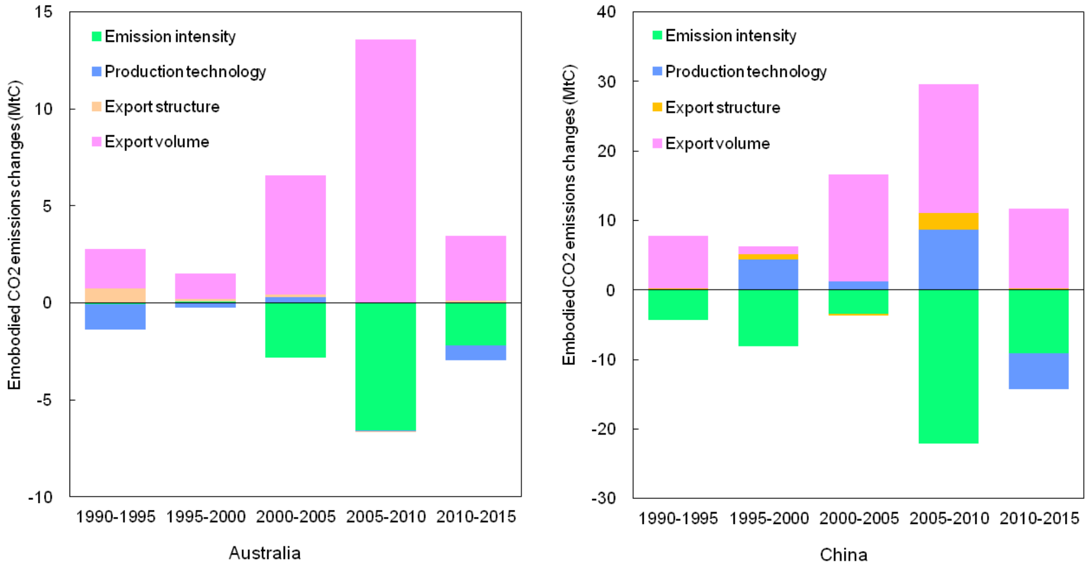

Figure 10. SDA results

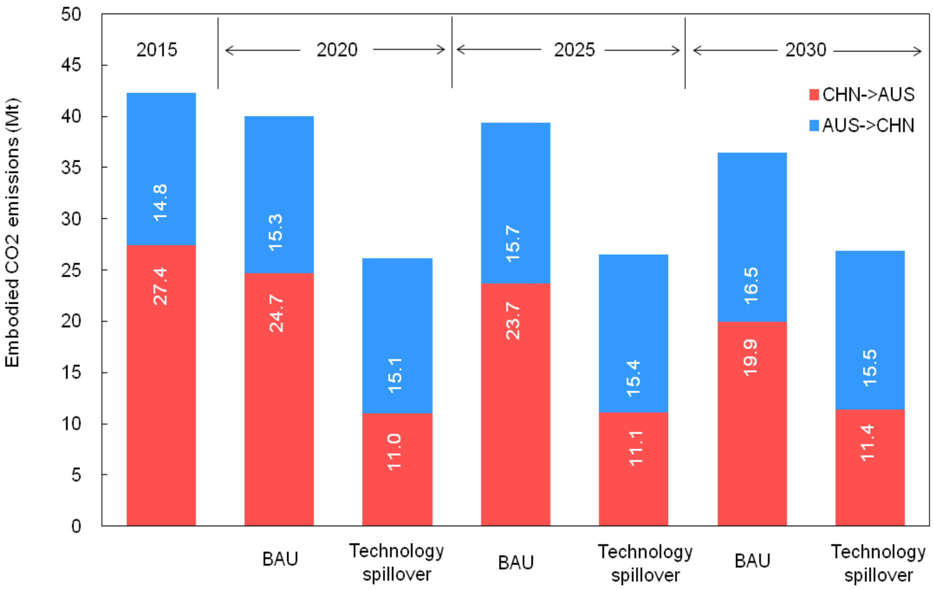

Figure 11. Future global reduction potential under technology spillover scenario