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ENVIRON-ECONOMIC BALANCE ANALYSIS IN BILATERAL INDUSTRIAL TRADE: A COMPARISON BETWEEN AUSTRALIA AND CHINA

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Abstract. Exchanges of products and services in bilateral industries may be accompanied by environmental and economic inequalities which lead to imbalanced situations in relation to environmental protection and economic development. In a close trade relationship between two countries such as Australia and China, their industries inevitably affect each other. This study maps the embodied CO_2 emissions and value added in bilateral trade under the input–output model and measures the unequal exchanges in such trade using an originally established industrial environ-economic balance index. The bilateral trade between Australia and China is taken as an example to validate the outcomes of the research method. The results indicate that in 2014, Australia transferred 580.90 billion tons of CO_2 and 105.85 billion USD of value added to China, while approximately 375.65 billion tons of CO_2 and 25.15 billion USD of value added flowed from China to Australia. China's manufacturing, construction, and services and other industries, and China's and Australia's real estate activities industries had net inflows of embodied CO_2 emissions and value added, indicating these industries paid economic costs in return for reducing environmental pressure. In inter-industrial trade between Australia and China, 49 pairs of bilateral industrial trades were relatively fairly balanced, while the remaining 15 pairs of inter-industrial trades were imbalanced. The established environ-economic balance analysis method and quantitative findings are valuable for better understanding the environment impacts of the economic development of national economies and developing national policies in corresponding to the rising environmental issues.

Keywords: bilateral industrial trade, economic development, industrial environ-economic balance index, input–output model.

JEJ Classification: D57, F63, Q27, Q56.

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Introduction

With increasing global production fragmentation, industries participate in long production chains which involve a wide range of upstream and downstream industries, and thus build close industrial networks with other industries. These industries inevitably cause CO_2 emissions in addition to the economic benefits to other industries by stimulating production activity (Arce et al., 2016). Furthermore, the accelerated development of international trade has intensified these industrial relationships, leading to increased CO_2 emissions and economic transfer in international production chains (van der Zwaan et al., 2018). Previous studies of industrial trade in terms of CO_2 emissions mainly focused on the magnitude of CO_2 emissions of specific industries induced by per unit of output or final demand, neglecting that the formulation of mitigation policy needs to consider a balance of economic development and environmental pressure (Gao et al., 2022). Additionally, the imbalance of environmental costs and economic benefits in trade has drawn great attention from academics and governments. However, a few studies have focused on the environmental pressure and economic benefits of industries in a country to formulate corresponding mitigation policies.

China is one of the most important economic partners for Australia, and Australia has ranked in 8th position among trade partners for China since 2008. Products and services produced in Australia and exported to China experienced an annual growth rate of 25% and the volume of China's exports to Australia grew at an average 8% per annum over the period 2008–2015 (Jayanthakumaran & Liu, 2016). The implementation of the China–Australia Free Trade Agreement since 2015 is expected to strength the trade relationship between these two countries. However, this wave of closer bilateral trade has come with the attendant effect of increasing the CO_2 emissions embodied in trade, which consequently causes environmental pollution and global warming, and sustainable development in China and Australia has attracted attention (Yuan et al., 2020). The net embodied CO_2 emissions of trade between Australia and China increased by 604.54% over the period 2000–2014 (S. Wang et al., 2019). Although Australia suffers from environmental pollution through Australia–China trade due to the strengthening bilateral relationship, this bilateral trade has increased the value added of Australia. Therefore, analysis of the environ-economic balance in such bilateral trade should be paid more attention.

To improve our understanding, this paper establishes an industrial environ–economic balance index (EI) to explore the unequal industrial relationships in bilateral trade from consumption-based and production-based perspectives. This paper defines the EI as the ratio of net embodied CO_2 emissions to net value added in order to explore unequal trade situations from an industrial perspective. This paper is the first study to measure the environmental pollution and economic benefits in inter-industrial trade between bilateral trade partners and to conduct analysis of the environ-economic balance of production activities in such trade patterns at an industrial level. The establishment of emission-mitigation policies based on the EI is likely to balance the relationship between economic development and environmental protection. The remainder of this paper is organized as follows. Section 1 reviews the underpinning literature. The research methods, data sources, and data processing are presented in Section 2. The numerical results and related discussion are reported in Section 3. The last Section summarizes the conclusions of this research and proposes potential policy recommendations.

1. Literature review

1.1. Embodied CO_2 emissions in industrial trade

Industrial trade measurement can be used to investigate the industrial demand pulling effect and the supply driving effect, and it has also been widely used in previous studies to analyze the CO_2 emissions embodied in inter-industrial trade in order to map CO_2 paths among industries (Sun et al., 2020). Two major methods are favored for analyzing industrial trade by measuring CO_2 emissions, CO_2 multipliers and the hypothetical extraction method (HEM). Leontief CO_2 multipliers based on the research of Alcántara et al. (2010) provide us with a way to determine where mitigation policies should be targeted at what demand, and what strategies should be oriented toward adjusting production structures. Of particular interest in embodied CO_2 in inter-industrial trade, HEM with its focus on a specific industry is employed to analyze industrial relationships by hypothetically extracting a single industry from the economy (Du et al., 2019). The major advantage of HEM is that it considers not only the relative magnitude of the final demand of each industry within the economy, but also the relative effect of this final demand on the overall output of this economy (Temurshoev & Oosterhaven, 2014). HEM has been widely used not only to reveal the position or role of a certain industry within the CO_2 transfer system, such as the trade and transport industry, but also to evaluate the effect of the industry on the CO_2 emissions of other industries (Sajid et al., 2019). For example, Y. Wang et al. (2013) and Ali (2015) employed HEM to investigate the characteristics of CO_2 emissions among industries in China, Italy, and South Africa, respectively. Piaggioab et al. (2014) used HEM to identify the industries that contributed most to energy-related CO_2 emissions in Uruguay.

Despite the growing concern about industrial trade with regard to CO_2 emissions, the existing literature has merely considered the economic benefits. From the perspective of consumers, inter-industrial trade can bring about the transfer of economic benefits, especially due to industrial discrepancies in economic structures and production technologies (Nansai et al., 2020). In fact, industrial mitigation policies, such as reducing the effect of CO_2 multipliers or weakening industrial CO_2 emissions, are biased because these policies neglect the balance of the relationship between economic development and environmental protection (Zafirakis et al., 2015). Inter-industrial trade can increase the welfare of undeveloped industries under the condition that the environmental pollution is properly compensated for by the economic benefits (Zhang et al., 2018b). Therefore, analysis of the environ-economic balance in inter-industrial trade requires more attention.

1.2. Environ-economic balance analysis in trade using input-output model

Environmental economists have long discussed the possible harm from economic growth to the environment (Lapinskienė et al., 2014). Additionally, previous studies have confirmed that economic development increases CO_2 emissions to some extent and a balance between economic development and environmental protect has become a challenge for each economy in the world (Shahbaz et al., 2016). An increasing number of studies have analyzed the question of how trade affects environmental protection and economic development using input-output models. A wide range of indicators, such as embodied CO_2 emissions as the undesirable output and embodied value added as the desirable output, have been employed to account for the environmental pollution and economic benefits caused by trade. For example, van der Zwaan et al. (2018) applied a African multi-regional input–output model to assess the sustainability of textile and clothing consumption using the indicators of labor and embodied CO_2 emissions, finding that imbalance between environmental pressure and labour employment occurred in trade in Asian and European regions. Perobelli et al. (2015) analyzed the impact of international trade on Brazil's income and embodied CO_2 emissions to measure the benefits and costs of participating in global value chains. Xu et al. (2021) took both embodied value added and trade-caused CO_2 emissions into account, attempting to construct a framework to share CO_2 responsibility from the perspective of value-added trade. Zhang et al. (2018a) proposed a regional environmental inequality index to quantify the unbalanced situation between the environmental pollution and economic benefits embodied in the interregional trade within an economy; this index assumes the net embodied CO_2 is positive as the prior condition.

The aggregate embodied CO_2 intensity (AEI) is defined as the ratio of embodied CO_2 emissions in embodied value added and was first proposed by Su and Ang (2017) at the national level. The national AEI framework includes the AEI from aggregate, final demand (including exports), and sector levels. Since then, the AEI has been adopted in studies from national, regional, and sectoral perspectives. For example, Z. Wang et al. (2020) calculated the AEI in the inter-regional trade of China to identify important Chinese provinces in which carbon emission performance needs to be more effective. Zhu et al. (2018) attempted to address the intensity issue and strengthen the mitigation policies of India by evaluating the aggregated CO_2 intensity and drivers of the increase in emission intensity. The AEI was also employed in several national and regional energy or emissions studies, such as in Singapore (Su & Ang, 2020), with international trade (Yang & Su, 2019), and with normal and processing exports in China (Zhu et al., 2020). Su et al. (2019) further used an aggregated CO_2 intensity indicator to determine production efficiency and conducted structural path analysis and structural decomposition analysis of the national AEI. In recent years, the national AEI framework has been extended to regional and global levels in consideration of spatial aggregation (Su et al., 2021).

Previous literature has mainly focused on the analysis of environ-economic balance in bilateral trade, and inter-industrial and interregional trade within an economy, using embodied CO_2 emissions and embodied value-added indicators. However, the unequal exchange of embodied CO_2 emissions and value added in inter-industrial trade between two countries is still poorly understood, which hinders our understanding of industrial environmental responsibility and processes in environmental justice. Additionally, the quantized degree of environ-economic balance or imbalance between trade partners is still being ignored. For implementation of climate change management policy, it is also important to highlight the balance between economic development and environmental protection (Liobikienė et al., 2017). Assessing the inequality indicators in a pair of trade partners, rather than only the physical quantized embodied CO_2 emissions or value added, can help to clarify the positions of trade participants and to formulate compensation policies to handle unequal exchanges between consumers and producers, improving the imbalanced situations of environmental protection and economic benefits in such trade to some extent.

2. Research methods and data

2.1. Embodied CO_2 emissions and value added in bilateral trade

The emissions embodied in bilateral trade (EEBT) and the multi-regional input–output (MRIO) model have been commonly employed in previous studies to estimate the embodied CO_2 emissions in international trade (Peters & Hertwich, 2008). Both EEBT and MRIO models can calculate embodied CO_2 emissions, but they differ in allocating the intermediate consumption (Su & Ang, 2011). This study employs a simplified version of the EEBT model because it is more transparent and appropriate for quantitative analysis of bilateral relationships without consideration of a third country. Additionally, the research model proposed in this study can be employed with a pair of countries which are bilateral trade partners.

The conditions that there are two countries (1 and 2) and N industries in each country are presented as the prior assumptions for the input–output model. There is a basic block in the biregional input–output system describing how the gross output of each country is used by the intermediate or final inputs to another country. For the biregional input–output table, the standard horizonal balance is expressed as:

$$\begin{bmatrix} \boldsymbol{X}_1 \\ \boldsymbol{X}_2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{Z}_{11} + \boldsymbol{Z}_{12} \\ \boldsymbol{Z}_{21} + \boldsymbol{Z}_{22} \end{bmatrix} + \begin{bmatrix} \boldsymbol{Y}_{11} + \boldsymbol{Y}_{12} \\ \boldsymbol{Y}_{21} + \boldsymbol{Y}_{22} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{11} & \boldsymbol{A}_{12} \\ \boldsymbol{A}_{21} & \boldsymbol{A}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{X}_1 \\ \boldsymbol{X}_2 \end{bmatrix} + \begin{bmatrix} \boldsymbol{Y}_{11} + \boldsymbol{Y}_{12} \\ \boldsymbol{Y}_{21} + \boldsymbol{Y}_{22} \end{bmatrix}, \tag{1}$$

where X_1 is the output of country 1, Z_{12} represents the intermediate output used by country 2 from country 1, and Y_{12} is the final demand of country 2 satisfied by products and services produced in country 1. The biregional input–output coefficient matrix A can be computed by $A = Z\hat{X}^{-1}$, where the symbol ^ represents the diagonal version of the matrix X. After rearranging Eq. (1), the standard input–output model can be expressed in Leontief form as:

$$\begin{bmatrix} \boldsymbol{X}_1 \\ \boldsymbol{X}_2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{I} - \boldsymbol{A}_{11} & -\boldsymbol{A}_{12} \\ -\boldsymbol{A}_{21} & \boldsymbol{I} - \boldsymbol{A}_{22} \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{Y}_{11} + \boldsymbol{Y}_{12} \\ \boldsymbol{Y}_{21} + \boldsymbol{Y}_{22} \end{bmatrix} = \begin{bmatrix} \boldsymbol{L}_{11} & \boldsymbol{L}_{12} \\ \boldsymbol{L}_{21} & \boldsymbol{L}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{Y}_{11} + \boldsymbol{Y}_{12} \\ \boldsymbol{Y}_{21} + \boldsymbol{Y}_{22} \end{bmatrix}, \tag{2}$$

where L_{12} represents the sub-matrix of the Leontief inverse matrix from country 1 to country 2 (Dietzenbacher & Los, 1998). The total outputs of country 1 and country 2 can be decomposed into Eqs (3a) and (3b), respectively:

$$\boldsymbol{X}_1 = \boldsymbol{L}_{11}\left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \boldsymbol{L}_{12}\left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right); \tag{3a}$$

$$\boldsymbol{X}_2 = \boldsymbol{L}_{21}\left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \boldsymbol{L}_{22}\left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right). \tag{3b}$$

The exports from country 1 to country 2, E_{12}, include two components, final products and intermediate products, and E_{12} is computed by the following equation:

$$\boldsymbol{E}_{12} = \boldsymbol{Y}_{12} + \boldsymbol{Z}_{12} = \boldsymbol{Y}_{12} + \boldsymbol{A}_{12}\boldsymbol{X}_2 = \boldsymbol{Y}_{12} + \boldsymbol{A}_{12}\boldsymbol{L}_{21}\left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \boldsymbol{A}_{12}\boldsymbol{L}_{22}\left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right). \tag{4a}$$

Similarly, exports from country 2 to country 1, E_{21}, are divided into two components as shown in Eq. (4b):

$$\boldsymbol{E}_{21} = \boldsymbol{Y}_{21} + \boldsymbol{Z}_{21} = \boldsymbol{Y}_{21} + \boldsymbol{A}_{21}\boldsymbol{X}_1 = \boldsymbol{Y}_{21} + \boldsymbol{A}_{21}\boldsymbol{L}_{11}\left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \boldsymbol{A}_{21}\boldsymbol{L}_{12}\left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right). \tag{4b}$$

For a biregional input–output model, the exports of country 1 to country 2 are equal to the imports to country 2 from country 1. A direct CO_2 emissions column vector DE consists of the element DE_1 denoting the direct CO_2 emissions generated by country 1. The CO_2 emissions intensity column vector F represents the direct CO_2 emissions per unit of output and the element F_1 can be formulated by $F_1 = DE_1 / X_1$. This paper focuses on bilateral trade without consideration of a third country and the embodied CO_2 emissions and value added thus are calculated by the first-order trade. The embodied CO_2 emissions in the trade from country 1 to country 2, C_{12}, and from country 2 to country 1, C_{21}, are formulated by Eqs (5a) and (5b), respectively:

$$\boldsymbol{C}_{12} = \hat{\boldsymbol{F}}_1 \boldsymbol{E}_{12} = \hat{\boldsymbol{F}}_1 \boldsymbol{Y}_{12} + \hat{\boldsymbol{F}}_1 \boldsymbol{A}_{12} \boldsymbol{L}_{21} \left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \hat{\boldsymbol{F}}_1 \boldsymbol{A}_{12} \boldsymbol{L}_{22} \left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right); \tag{5a}$$

$$\boldsymbol{C}_{21} = \hat{\boldsymbol{F}}_2 \boldsymbol{E}_{21} = \hat{\boldsymbol{F}}_2 \boldsymbol{Y}_{21} + \hat{\boldsymbol{F}}_2 \boldsymbol{A}_{21} \boldsymbol{L}_{11} \left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \hat{\boldsymbol{F}}_2 \boldsymbol{A}_{21} \boldsymbol{L}_{12} \left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right). \tag{5b}$$

The typical element C_{12}^{mq} in the matrix of C_{12} represents the CO_2 emissions generated by the production activity in industry m of country 1 induced by the demand of industry q in country 2.

The value added V_1 denotes the value added for country 1, with a typical element V_1^m representing the value added of industry m in country 1. The value-added coefficient v is defined by the value added per unit of total output and a typical element v_1^m is formulated by $v_1^m = V_1^m / X_1^m$. The domestic value added of country 1 in its exports to country 2 and the domestic value added of country 2 in its exports to country 1 are calculated using Eqs (6a) and (6b), respectively:

$$\boldsymbol{V}_{12} = \hat{\boldsymbol{v}}_1 \boldsymbol{E}_{12} = \hat{\boldsymbol{v}}_1 \boldsymbol{Y}_{12} + \hat{\boldsymbol{v}}_1 \boldsymbol{A}_{12} \boldsymbol{L}_{21} \left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \hat{\boldsymbol{v}}_1 \boldsymbol{A}_{12} \boldsymbol{L}_{22} \left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right); \tag{6a}$$

$$\boldsymbol{V}_{21} = \hat{\boldsymbol{v}}_2 \boldsymbol{E}_{21} = \hat{\boldsymbol{v}}_2 \boldsymbol{Y}_{21} + \hat{\boldsymbol{v}}_2 \boldsymbol{A}_{21} \boldsymbol{L}_{11} \left(\boldsymbol{Y}_{11} + \boldsymbol{Y}_{12}\right) + \hat{\boldsymbol{v}}_2 \boldsymbol{A}_{21} \boldsymbol{L}_{12} \left(\boldsymbol{Y}_{21} + \boldsymbol{Y}_{22}\right). \tag{6b}$$

The typical element V_{12}^{mq} in the matrix V_{12} represents that the value added of industry m in country 1 is embodied in its exports to industry q in country 2.

2.2. Industrial environ-economic balance index in bilateral trade

The net flow of embodied CO_2 emissions from industry m in country 1 to industry q in country 2 (NC_{12}^{mq}) is formulated via Eq. (7):

$$NC_{12}^{mq} = C_{12}^{mq} - C_{21}^{qm}, \tag{7}$$

where $NC_{12}^{mq} > 0$ indicates that the final demand of industry q in country 2 causes an increase in CO_2 emissions in industry m in country 1, indicating that industry m in country 1 provides carbon-intensive products for the final demand purpose of industry q in country 2. A negative value of NC_{12}^{mq} means that industry m in country 1 uses carbon-intensive products from industry q in country 2 to satisfy its final demand.

The net embodied value added from industry m in country 1 to industry q in country *2* (NV_{12}^{qm}) through bilateral trade is calculated by:

$$NV_{12}^{mq} = V_{12}^{mq} - V_{21}^{qm}. \tag{8}$$

$NV_{12}^{mq} > 0$ denotes that industry *m* in country 1 gains value added by exporting products to industry *q* in country 2. $NV_{12}^{mq} < 0$ represents that industry *m* in country 1 pays economic benefits to industry *q* in country 2. These situations, $NC_{12}^{mq} = 0$ and $NV_{12}^{mq} = 0$, cannot reflect practical meanings and thus are not taken into consideration in this study.

The industrial environ-economic balance index matrix is denoted by EI, with the typical element EI_{12}^{mq} representing the EI for industry *m* in country 1 in the bilateral inter-industrial trade with industry *q* in country 2, with a unit of ton/USD. EI_{12}^{mq} and EI_{21}^{qm} in the matrix are calculated by:

$$EI_{12}^{mq} = NC_{12}^{mq} \,/\, NV_{12}^{mq}; \tag{9a}$$

$$EI_{21}^{qm} = NC_{21}^{qm} \,/\, NV_{21}^{qm}. \tag{9b}$$

According to the directions of NC_{12}^{mq} and NV_{12}^{mq}, the classification of cases of EI_{12}^{mq} and its reflection is presented as Figure 1.

Case 1: $NC_{12}^{mq} > 0\, and\, NV_{12}^{mq} > 0$. Industry *m* in country 1 emits CO_2 emissions in producing products to be consumed by industry *q* in country *2* and accordingly gains economic benefits. A larger value of EI_{12}^{mq} in Case 1 represents that industry *m* in country 1 earns relatively fewer economic benefits but suffers more environmental pollution caused by trade with industry *q* in country 2 and thus reflects that industry *m* in country 1 faces more serious inequality than industry *q* in country 2.

Case 2: $NC_{12}^{mq} < 0\, and\, NV_{12}^{mq} < 0$. Industry *m* in country 1 tends to reduce CO_2 emissions by purchasing products from industry *q* in country *2* and pays economic costs in return to industry *q* in country *2*. A larger value of EI_{12}^{mq} in Case 2 indicates that industry *q* in country 2 gains relatively less value added by providing carbon-intensive products to industry *m* in country 1 and thus reflects a relatively unequal situation for industry *q* in country 2.

Case 3: $NC_{12}^{mq} > 0\, and\, NV_{12}^{mq} < 0$. Industry *m* in country *1* not only bears the increase in CO_2 emissions induced by the final demand of industry *q* in country 2, but also loses value added in the inter-industrial trade with industry *q* in country 2. A smaller value of EI_{12}^{mq} indicate that industry *m* in country 1 faces a serious environ-economic imbalance.

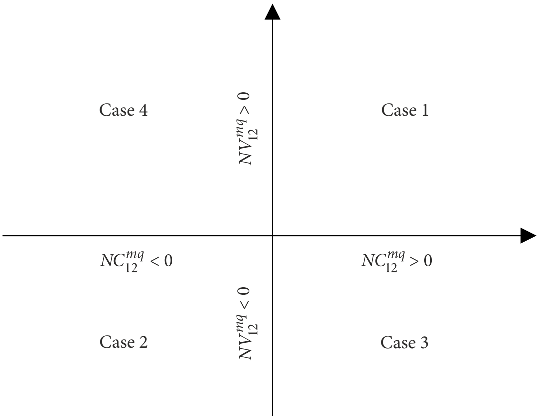

Figure 1. The classification of cases

Case 4: $NC_{12}^{mq} \langle 0\, and\, NV_{12}^{mq} \rangle 0$. Industry *m* in country 1 consumes carbon-intensive products produced in industry *q* in country 2 and gains value added in this bilateral relationship. A smaller value of EI_{12}^{mq} reflects that industry *q* in country 2 suffers a more serious unequal situation in such bilateral trade.

Cases 1 and 2 represent relatively fair industrial trade between industry *m* in country 1 and industry *q* in country 2. Cases 3 and 4 represent unequal industrial trade between industry *m* in country 1 and industry *q* in country 2.

2.3. Data source and data treatment

This study uses the industrial trade between Australia and China as an example to validate the outcomes of the research method proposed above. A bilateral national input–output table is established from the World Input–Output Database (WIOD), which provides inter-industrial trade data on 56 sectors in each country (Timmer et al., 2015). To be consistent with the sector classification, the data on CO_2 emissions and value added in sectors of Australia and China has also been obtained from the environmental account of the WIOD. The latest version of the input–output table in WIOD was released for 2014 and thus this study investigates the bilateral industrial trade between Australia and China in 2014. For simplicity of numerical calculation and analysis, the 56 sectors of each country in the input–output table and environmental account in the WIOD are aggregated into 8 major industries according to the International Standard Industrial Classification of All Economic Activities (ISIC) (United Nations, 2008). The potential effects of sector aggregation on the calculation results are not taken into consideration in the numerical example (Su et al., 2010).

3. Research results

3.1. Embodied CO_2 emissions in inter-industrial trade between Australia and China

The distribution of embodied CO_2 emissions in upstream industries plays an important role in clarifying the CO_2 emission structure. In this paper, the upstream industrial distribution of embodied CO_2 emissions is revealed, that is, the CO_2 emissions generated by the production activities in upstream industries. Figure 2 presents the embodied CO_2 flows between Australia and China in 2014.

In 2014, the embodied CO_2 emissions in products transferred from Australia to China comprised 580.90 billion tons, while China exported products accompanied by 375.65 billion tons of CO_2 to Australia. As major CO_2 contributors, Australia's mining and utilities industries transferred 47.26% and 25.43% total CO_2 to China, respectively, and large proportions of the CO_2 generated by these two industries were received by China's manufacturing and construction industries. Australia's construction and services and other industries received large amounts of CO_2 from China, especially from China's utilities and manufacturing industries. Approximately 182.39 and 154.14 billion tons of CO_2 generated by the production activities of China's manufacturing and utilities industries, respectively, were caused by Australia's industries, particularly Australia's construction and services and

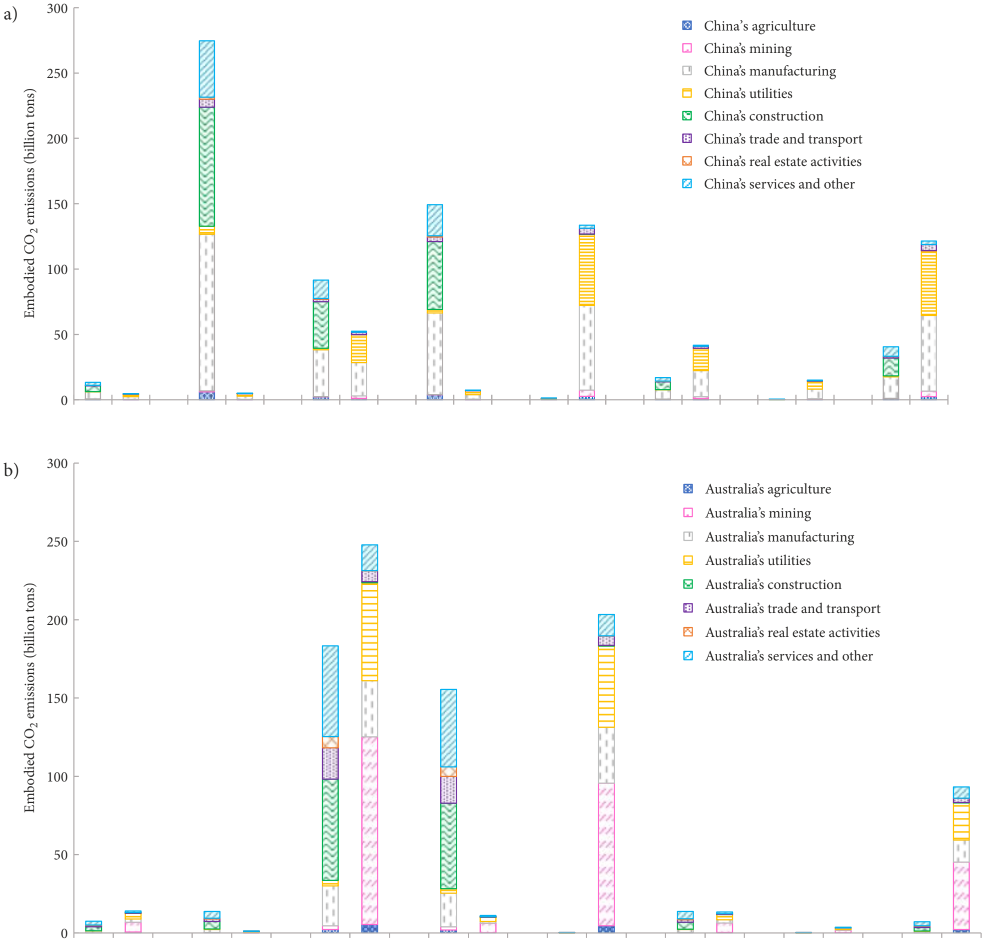

Figure 2. Embodied CO_2 flows in 2014 in: a – exports from and imports to Australia; b – exports from and imports to China

other industries. China's manufacturing and construction industries were major receivers of CO_2 emissions from Australia, inducing 41.90% and 34.25% of CO_2 emissions, respectively, from Australia to China. Additionally, Australia's and China's real estate activities industries were less involved in bilateral trade, as their embodied CO_2 emissions in their exports and imports were relatively small compared to those of other industries.

The net flow of CO_2 emissions embodied in trade between Australia and China at the industrial level is helpful for measuring the imbalance in CO_2 exchange in inter-industrial trade. The industrial distribution of net CO_2 emissions is calculated using Eq. (7) and Figure 3 displays the net flows of CO_2 emissions embodied in bilateral industrial trade between Australia and China in 2014.

The major direction of net CO_2 emission flows was from Australia to China. Australia's mining and utilities industries had large outflows of embodied CO_2 emissions to China, particularly to China's manufacturing and utilities industries. These Australian industries

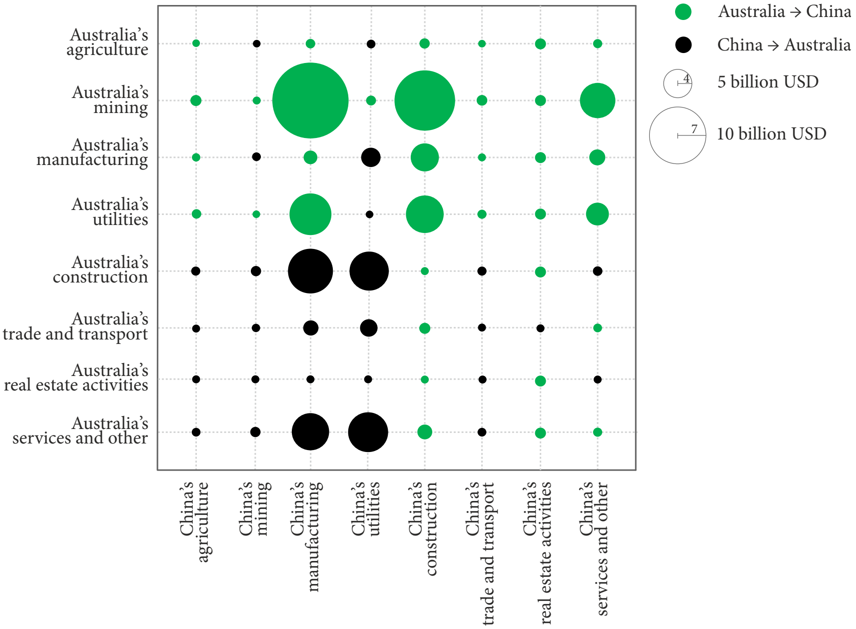

Figure 3. Net CO_2 emissions in inter-industrial trade between Australia and China in 2014

produced products based on large-scale carbon-intensive energy resources and thus they exported products with high carbon intensities to China. Australia's construction, trade and transport, and services and other industries had large inflows of embodied CO_2 emissions from China, mainly from China's manufacturing and utilities industries, reflecting that these Australian industries transferred environmental pressure by importing products from China. The CO_2 intensity of China's utilities industry was 47.83 ton/USD, which was the largest among all China's and Australia's industries, so this industry tended to have net outflows of embodied CO_2 emissions in bilateral trade with Australia. China's and Australia's real estate activities industries were net importers of CO_2 emissions in 2014, mainly absorbing imported products generated by Australia's mining industry and China's manufacturing industry, respectively.

Previous research evaluated the CO_2 emissions embodied in the Australia–China trade of final products (S. Wang et al., 2019), while the research presented in this paper considers the CO_2 emissions embodied in both intermediate and final products. As expected, the results of this research are comparatively large because of the contributions of intermediate products. Additionally, Wang et al. (2019) studied the embodied CO_2 emissions in Australia–China trade at the national level, while this study highlights the CO_2 emissions embodied in industrial imports and exports in their bilateral trade.

3.2. Embodied value added in inter-industrial trade between Australia and China

The embodied value added is treated as an indicator to measure the economic benefits of supplying products to other industries or countries. The value added embodied in the exchange of traded products between Australia and China has been computed and Figure 4 presents the embodied value added in bilateral industrial trade between Australia and China in 2014.

China received 105.85 billion USD value added embodied in bilateral trade from Australia, while the value added in products transferred from China to Australia was 25.15 billion USD. The Australian mining industry performed production tasks to satisfy the final demand of China, accompanied by 53.86 billion USD value added. Such high value added generated by Australia's mining industry was mainly induced by China's industries, such as manufacturing

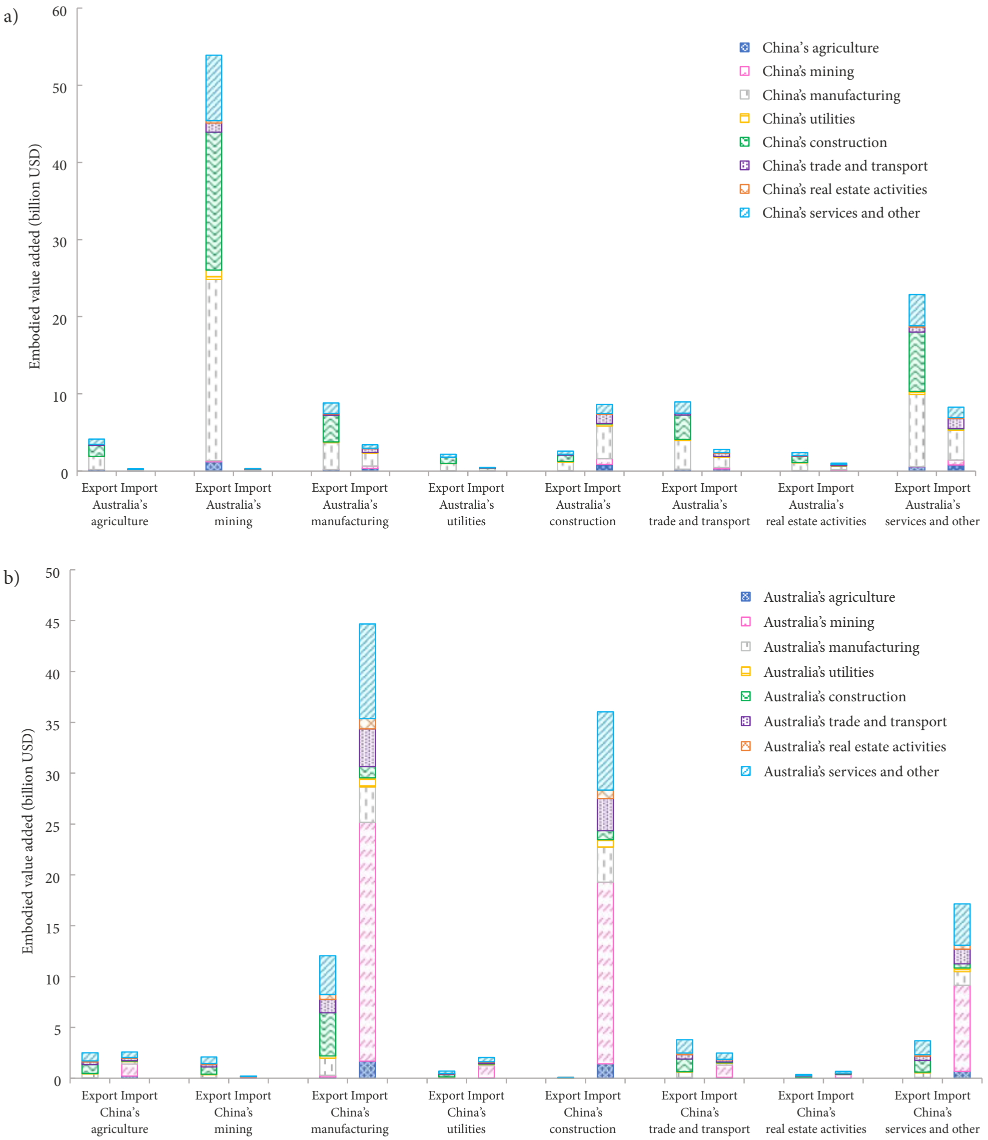

Figure 4. Embodied value-added flows in 2014 in: a – exports from and imports to Australia; b – exports from and imports to China

(23.34 billion USD), construction (17.66 billion USD), and services and other industries (9.33 billion USD). Australia's construction industry received 8.54 billion USD of value added embodied in bilateral traded products from China, approximately 49.07% of which was from China's manufacturing industry. In China, the manufacturing and services and other industries contributed 47.63% and 19.35%, respectively, of the total value added embodied in China's bilateral trade with Australia. Australia's services and other industry obtained approximately 8.46 billion USD of value added embodied in traded products produced in China and its construction industry received 30.57% of total economic benefits from China.

The net value added between Australia and China was calculated according to Eq. (8) to clarify the exchange of economic benefits between industries in such bilateral trade. Figure 5 presents the net value added of inter-industrial trade between Australia and China in 2014.

The main direction of embodied value added in bilateral trade was from Australia to China. Australia's mining industry had large amounts of net embodied value added in bilateral trade with China's manufacturing, construction, and services and other industries, indicating that Australia's mining industry obtained economic benefits when trading with these Chinese industries. Australia's services and other industry had net inflows of embodied value added in bilateral trade from China's manufacturing industry, which was different to the direction of net CO_2 emissions in such bilateral industrial trade, indicating that Australia's services and other industry gained economic benefits but induced an increase in CO_2 emissions in China's manufacturing industry.

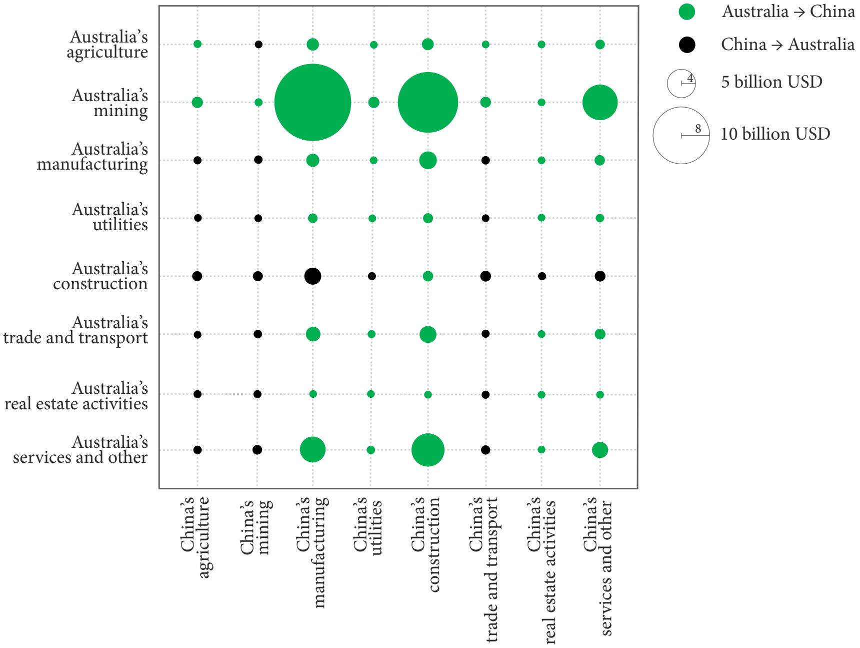

Figure 5. Net value added in inter-industrial trade between Australia and China in 2014

3.3. Environ-economic balance analysis of inter-industrial trade between Australia and China

In 2014, the total net embodied CO_2 emissions in bilateral trade between Australia and China was 201.84 billion tons and the total net value added in such trade was 80.60 billion USD, with an EI of 2.54. The main directions of the net embodied CO_2 flow and value-added flow in traded products both originated from Australia to China, indicating that Australia was gaining economic benefits by exporting carbon-intensive products to China.

According to the directions of the net embodied CO_2 emissions and value added in bilateral industrial trade, Australia's and China's industries can be categorized into 4 groups. The first group of industries had net inflows of embodied CO_2 emissions and value added, including China's manufacturing, construction, and services and other industries, and China's and Australia's real estate activities industries, and these industries paid economic costs in return for reducing environmental pressure in 2014. The second group of industries, such as Australia's agriculture, mining, utilities, and manufacturing industries and China's mining industry, had net outflows of CO_2 emissions and value added, showing that these industries obtained economic benefits from bilateral trade by providing carbon-intensive products to other industries. Industries in the third group had a net outflow of embodied CO_2 emissions and an inflow of embodied value added, indicating that they not only generated CO_2 emissions induced by other industries but also lost economic benefits. In this case study, China's utilities industry had net outflows of embodied CO_2 emissions of 143.20 billion tons and net inflows of 1.34 billion USD of embodied value added in bilateral trade with Australia, so it is classified in the third group. Three industries, Australia's trade and transport, and services and other industries and China's trade and transport industry, are in the fourth group, with net inflows of CO_2 emissions and net outflows of value added in bilateral trade, indicating that these industries obtained economic benefits and transferred environmental pressure to other industries.

To better understand the unbalanced situation between the economic benefits and environmental costs in inter-industrial trade between Australia and China, the EI was calculated using Eqs (9a) and (9b) and Table 1 displays the EI values of inter-industrial trade between Australia and China in 2014. It should be noted that the EI in Table 1(b) is the transposition of the matrix of EI in Table 1(a). The bilateral industrial relationship in Case 1 of Table 1a is equal to that of Case 2 of Table 1(b) and the inter-industrial trade in Case 3 of Table 1(a) is equal to that of Case 4 of Table 1(b).

As described in Section 3, the bilateral industrial trade in Cases 1 and 2 is relatively fair. There are 31 pairs of bilateral industrial trades in Case 1 of Table 1(a) and 18 pairs of bilateral industrial trades in Case 2 of Table 1(a). This section takes the example of bilateral industrial trade between Australia's agriculture industry and China's construction industry in Case 1 of Table 1(a) to illustrate the relatively fair environ-economic situation. Australia's agriculture industry had net outflows of embodied CO_2 emissions of 4.47 billion tons and value added of 1.40 billion USD toward China's construction industry, with an EI of 3.20 ton/USD, indicating that Australia's agriculture industry earned value added through trading with China's construction industry. Similar balanced situations for bilateral industrial trades are colored orange in Table 1. The EI in bilateral trade from China's real estate activities industry

Table 1. Industrial environ-economic balance index in 2014 in inter-industrial trade: a – from Australia to China; b – from China to Australia (unit: ton/USD)

a)

Destination / Origin	China's agriculture	China's mining	China's manufacturing	China's utilities	China's construction	China's trade and transport	China's real estate activities	China's services and other
Australia's agriculture	3.24	7.37	2.07	–58.19	3.20	2.78	3.81	3.28
Australia's mining	5.16	4.70	5.03	3.42	5.10	5.16	5.17	5.12
Australia's manufacturing	–8.04	6.36	5.87	–2095.55	10.41	–0.52	87.93	14.49
Australia's utilities	637.69	–1.11	87.01	–10.63	68.85	–146.14	138.32	84.00
Australia's construction	3.15	6.59	20.40	283.15	0.49	3.81	0.30	2.78
Australia's trade and transport	9.68	6.92	–5.44	–230.18	1.89	5.20	6.71	1.87
Australia's real estate activities	7.80	6.93	–13.76	–428.61	0.09	5.86	–4.98	–1.26
Australia's services and others	5.55	6.90	–7.50	–256.38	1.77	5.39	5.37	1.68

b)

Destination / Origin	Australia's agriculture	Australia's mining	Australia's manufacturing	Australia's utilities	Australia's construction	Australia's trade and transport	Australia's real estate activities	Australia's services and others
China's agriculture	3.24	5.16	–8.04	637.69	3.15	9.68	7.80	5.55
China's mining	7.37	4.70	6.36	–1.11	6.59	6.92	6.93	6.90
China's manufacturing	2.07	5.03	5.87	87.01	**20.40**	–5.44	–13.76	–7.50
China's utilities	–58.19	3.42	–2095.55	–10.63	283.15	–230.18	–428.61	–256.38
China's construction	3.20	5.10	10.41	68.85	0.49	1.89	0.09	1.77
China's trade and transport	2.78	5.16	–0.52	–146.14	3.81	5.20	5.86	5.39
China's real estate activities	3.81	5.17	87.93	138.32	0.30	6.71	–4.98	5.37
China's services and other	3.28	5.12	14.49	84.00	2.78	1.87	–1.26	1.68

Case 1 Case 2 Case 3 Case 4

to Australia's construction industry was 0.30 ton/USD with negative net embodied CO_2 emissions and value added, indicating that Australia's construction industry contained value added by providing products to China's real estate activities industry. For industrial trade in Case 1 and Case 2, a larger value of EI indicates more outsourced CO_2 emissions generated and less value added retained by the producer, such as for Australia's utilities industry when trading with China's agriculture industry and for China's utilities industry in bilateral trade with Australia's construction industry.

The inter-industrial trade in Table 1 colored green indicates the imbalanced environ-economic situations of Case 3 and Case 4. In Table 1(a), 5 pairs of inter-industrial trades are categorized into Case 3 and 10 pairs of inter-industrial trades are classified into Case 4. For example, the bilateral trade between Australia's utilities industry and China's trade and transport industry was categorized into Case 3 because the former industry had a net outflow of embodied CO_2 emissions to and a net inflow of embodied value added in traded products from the latter industry and so the former industry faced imbalance when trading with the latter one. In Case 4 of Table 1(a), the inter-industrial trade between Australia's manufacturing industry and China's utilities industry had an outstanding EI of −2095.55 ton/USD, illustrating that China's utilities industry not only suffered CO_2 emissions but also lost economic benefits in such trade.

Conclusions and policy recommendations

This study has analyzed the imbalanced industrial relationships between bilateral trade partners and proposes policy recommendations to mitigate CO_2 emissions and resolve environ-economic imbalance. Input–output analysis has been employed to map the CO_2 emissions and value added embodied in bilateral inter-industrial trade. An original industrial environ-economic balance index has been established to evaluate the unequal situation for producers caused by such trade patterns based on CO_2 emissions and value-added indicators. This study provides insight into the issues of economic development and environment pressure in national economies and thus is helpful for decision-making in international trade policies. The research model established in this study is targeted at pairs of bilateral trade partners and could be extended to 3 or more countries with further research. The case study between Australia and China indicates that in 2014, CO_2 emissions generated by Australia's mining industry accounted for 47.26% of total CO_2 emissions caused by Australia–China trade and this industry contributed 50.88% of value added to China. In China, the manufacturing industry transferred 48.55% of CO_2 emissions in bilateral trade to Australia and the mining industry transferred 44.63% of total value added when trading with Australia. Due to the great impact of inter-industrial trade on CO_2 emissions, it is imperative to pay more attention to establishing bilaterally shared emission policies among producers and consumers along the global supply chains, instead of only beyond the intermediate boundaries. Production efficiency should be considered when launching mitigation policies for the construction industry because such policies could alleviate the environmental burden of the construction industry and reduce the costs of upstream production industries.

The net embodied CO_2 emissions and value added in bilateral inter-industrial trade between Australia and China have been employed to measure the inequalities of environmental costs and economic benefits in such trade. China's manufacturing, construction, and services and other industries, and China's and Australia's real estate activities industries reduced their environmental pressure by transferring production processes to other countries. Australia's agriculture, mining, utilities, and manufacturing industries and China's mining industry obtained value added by providing products to other countries. According to the EI results, 49 pairs of bilateral industrial trades between Australia and China among 64 pairs were equal, while the remaining 15 pairs were unequal. For example, China's utilities industry had a net outflow of CO_2 emissions and an inflow of value added in bilateral trade, indicating that this industry faced a serious unequal situation in such trade. The most imbalanced situation in bilateral inter-industrial trade occurred in the trade relationship between Australia's manufacturing industry and China's utilities industry. China's utilities industry in this unequal relationship not only suffered CO_2 emissions, but also lost economic benefits caused by bilateral trade with Australia's manufacturing industry. It is necessary to establish integrated policies or strategies to reduce such inequalities in inter-industrial trade and thus promote environ-economic fairness and justice.

Future research should seek to incorporate the effects of sector aggregation into the analysis of the enviro-economic balance in bilateral inter-industrial trade. Furthermore, the MRIO approach could be adopted to develop the method of analysis of the enviro-economic balance in trade among multiple national economies. In addition, the driving forces of the environ-economic imbalance need be investigated via decomposition approaches that analyze changes in embodied CO_2 emissions with economic variables, over years, and across countries.

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