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Title: Structural Emission Attribution in the Global Supply Chain and Climate Policy Making

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Abstract: To develop effective policies to mitigate climate change, it is important to understand the emission accounting of the sectors comprising the global supply chain network and implement the appropriate policies. Focusing on the relationship between sectors' position in the global supply chain and its policy implications, this study develops a structural position analysis framework based on input-output analysis. Our framework reveals high-priority sectors and transactions, and the best strategies for CO_2 emission reduction in the global supply chain. We also expand the discussion on emission reduction policies to inter-sectoral and international collaboration based on a multi-regional input-output table, focusing on cross-border transactions. The results indicate that the United States (U.S.) and China have different priorities and characteristics (even vis-à-vis the same industry), and that joint emission reduction policies should be coordinated to take advantage of each country's emission reduction potential. Our findings suggest that, in the U.S. and Europe, policies to promote the reduction of direct emissions from production of goods for exports through carbon taxes are important. Contrarily, in Asian countries, carbon emissions originate mainly from intermediate goods trades, suggesting the need for mandatory life cycle assessment reporting and emissions disclosure. Our analytical framework thus proposes specific policies that could effectively reduce specific sectors and transactions' carbon footprints.

1. INTRODUCTION

Understanding the complex structure of the global supply chain network and the characteristics of its constituent sectors and transactions is important for both economic policy and environmental management. In terms of global climate change actions, unprecedented efforts are needed in emission reduction policies (Intergovernmental Panel on Climate Change, 2021). Additionally, the issue of emission transfer (instead of the reduction of domestic emissions) has been discussed, with emphasis on international cooperation (e.g., Japan–China hydrogen cooperation and Japan–United States [U.S.] technology cooperation) and the control of carbon leakages.

With growing research on carbon leakage and sectoral emissions at the global level, the European Union has submitted the carbon border adjustment mechanisms proposal to provide benefits to low-emission companies in target sectors. However, conflicts have surfaced between developing countries seeking to engage in free trade in accordance with the World Trade Organization's principles and developed countries seeking to implement environmental regulations for international trade. This is because, for emerging countries, the economic growth expected from free trade far outweighs the benefits of implementing environmental regulations. Thus, there is an urgent need to create a mechanism to provide incentives for implementing environmental regulations (Japan External Trade Organization, 2021; Wood et al., 2019). Various studies have demonstrated the emission reduction effects of global supply chain participation (Antweiler et al., 2001; Shi et al., 2021), and it is important to establish complementary supply chains from both an economic and environmental perspective, as well as implement environmental policies that focus on international coordination and global supply chain management (Kagawa et al., 2015; Tokito, 2018).

To develop fair and effective policies for mitigating climate change, various greenhouse gas (GHG) emission accounting methods have been developed in input-output (IO) analysis. The production-based emission (PBE) accounting method helps us to identify the main emitters of GHGs (e.g., the energy sector), whereas the consumption-based emission (CBE) accounting method enables us to identify the final consumers of products (e.g., the construction sector), who directly and indirectly contribute to GHG emissions (Dietzenbacher et al., 2020; Peters et al., 2011; Wiedmann, 2009). Additionally, Liang et al. (2016) introduced the betweenness-based emission (BBE) accounting method to identify critical transmitters (i.e., sectors emerging in supply-chain paths with large emissions, such as the metal sector) that can contribute to a significant reduction in the carbon footprint along global supply chain networks. In other words, BBE covers the emissions that an industry induces upstream through intermediate goods manufacturing. Specifically, PBE, BBE, and CBE identify upstream sectors, midstream sectors, and downstream sectors, respectively, in the supply chain. In this paper, we collectively refer to PBEs, BBEs, and CBEs as "*position-based emissions*." Position-based emission accounting allows us to assign responsibility and a role in emission reduction to all industries in the supply chain that may benefit through production and provides us with an understanding of the various supply chain structures.

The structural position of sectors in the supply chain affects policies' effectiveness. Sectors located upstream of a production process with higher emission intensity often require technological improvements for cleaner production. Conversely, consumption policies (such as eco-labeling) are effective for downstream sectors to reduce embodied emissions through the supply chain. Additionally, an effective policy for middle-stream sectors is green supply chain management for intermediate sectors and restrictions on the use of intermediate goods with high BBE. However, the three aforementioned accounting methods—PBE, BBE, and CBE—are independent and have distinct criteria. Therefore, it is difficult to compare these three emission accounting methods, and it is difficult for policymakers to judge which climate policy should be prioritized using position-based emission accounting (Tokito et al., 2022).

For example, the construction sector tends to have high PBE and CBE, which makes it difficult for policymakers to understand which climate policy should be prioritized—emission intensity reduction or green procurement.

When comprehensively discussing each industry's responsibility for emissions (i.e., emitting industries, emission-inducing industries as intermediate goods sectors, and emission-inducing industries as final goods sectors), it is necessary to evaluate the emissions through supply chains involved in a specific industry sector. Specifically, these emissions can be calculated by the sum of emissions from the supply chain paths passing through the industry at least once from the graph theoretical perspective, and these emissions are equivalent to hypothetical extraction impacts (HEM, Cella, 1984; Hertwich, 2021) widely used in IO analysis (Hanaka et al., 2022; Tokito et al., 2022).

For further analyses, Hanaka et al. (2022) developed the *structural attribution analysis* framework to quantitatively identify specific sectors' structural positions within a supply-chain network. They calculated the gross emissions from all supply chain paths passing through a specific sector using the HEM and decomposed them into three types: production-oriented emissions (POEs), consumption-oriented emissions (COEs), and betweenness-oriented emissions (BOEs). We refer to POEs, COEs, and BOEs as "*position-oriented emissions*," in contrast to position-based emissions.

The left-hand side of Figure 1 shows the seven patterns of supply-chain paths passing through the car production sector (i–vii). The emissions accounting for all PBE, CBE, and BBE are interpreted as the reduction potential of emissions associated with a sector. Position-based emissions account for the emissions of all supply-chain paths in which a particular sector is in a specific position (production, betweenness, and consumption). For example, PBEs of car production comprise total emissions from supply chain paths whose emission sector is car production and are calculated as (i) + (ii) + (iii) + (v) (Figure 1). Therefore, if a sector is a producer (emitter) and a final goods sector in a supply chain path, emissions from this supply chain path are counted in the sector's PBE and CBE (pattern (iii) in Figure 1). PBE, CBE, and BBE are different criteria, and therefore, it is difficult to compare the structural position of each sector. The position-oriented emissions accounting proposed by Hanaka et al. (2022) aimed to elucidate sectors' structural position. The right-hand side of Figure 1 shows the criteria for position-based emissions and position-oriented emissions for the seven supply chain patterns of car production (Hanaka et al., 2022). A sector's position-oriented emissions are calculated by allocating emissions associated with all supply chain paths passing through the sector. The advantage of structural attribution analysis is that it can compare sectors' individual characteristics (production, betweenness, and consumption-oriented), which cannot be accomplished by existing emission accounting methods (position-based emissions). Therefore, this approach can provide an understanding of a specific sector based on the three structural positions, thus helping us disentangle supply chain complexity and allocate limited environmental budgets efficiently.

Hanaka et al. (2022) used structural attribution analysis to identify potential policymakers, but they did not prioritize policy enforcement target sectors based on their HEM impacts. Therefore, the present study offers valuable insights for life cycle assessment (LCA) and the reporting of Scope 3 emissions, a task that has already been undertaken by companies worldwide (Greenhouse Gas Protocol, 2008). Specifically, it provides a global and comprehensive supply chain analysis that cannot be carried out using the stacked method. In the implementation of the clean development mechanism (CDM) and international collaboration, it is crucial to consider country-specific industrial characteristics due to international fragmentation. It is also possible to discuss the simplicity of technology transfer through CDM and establish clear standards for reducing carbon dioxide (CO_2) emissions that may be relevant not only for policymaking but for policy implementation as well; this may be accomplished by comparing the structural position of each country in each industry. Effective budget allocation through these analyses, combined with emission reporting by companies that act, can make a significant contribution to emission reduction. It is meaningful to examine budget allocation and government guidelines from a macro perspective through an IO analysis. This could enable companies to implement specific emission reduction strategies by referring to their individual reports.

[Insert Figure 1]

Although structural attribution analysis successfully identifies the characteristics of a specific sector, it should be noted that the sector may have different structural positions for each trading partner. For example, the iron or steel sectors behave as *production-oriented* sectors when they trade with sectors that mainly produce intermediate goods (such as components of engines for a motor vehicle) and have *betweenness-oriented* characteristics when they trade with sectors that mainly produce final goods (such as motor vehicles; Hanaka et al., 2022). Furthermore, even within the same iron sector, the quality and emission intensity of iron for construction and motor vehicles vary significantly and from company to company. This indicates that the features of the transactions linking sectors are different for each trading partner. Therefore, extending the structural attribution analysis to transactions can enhance the specificity and feasibility of policy. Reportedly, no study has addressed these points. This study develops a new structural position analysis framework that extends to inter-sector transactions based on global supply chain network structures and visualizes the characteristics of sectors and transactions within the complex network structure. Furthermore, this framework allows us to advocate for specific CO_2 emission reduction measures through inter-sector collaboration. Therefore, this study develops the structural attribution analysis of Hanaka et al. (2022) from two perspectives (in the discussion of its results and methodology) and applies the analysis to a multi-region IO framework. This paper's discussion section focuses on the development of budget allocation and implementation guidelines for policymakers through country- and industry-specific sector structural position analysis as well as technology transfer through emission-oriented similarity.

Furthermore, this study focuses on cross-border transactions, identifies the characteristics of the international transactions, and discusses which emission reduction policy should be adopted by expanding the methodology used by Hanaka et al. (2022). From the perspective of global emissions reduction through international cooperation, the benefits of focusing on international transactions are twofold. First, it facilitates coordination among sectors and companies in domestic transactions. Second, since the orientation of the important transactions is clear, it allows us to understand whether focusing on the consumption side or the supply side is more important, which is useful for policymaking. These results suggest that incorporating environmental rules, including guidelines on specific policies (e.g., carbon tax, CO_2 emissions disclosure, eco-labeling, and supply chain engagement) into the economic partnership could effectively reduce specific sectors and transactions' carbon footprint.

The rest of this paper is organized as follows: Section 2 explains the methodology and data used; Sections 3, 4, and 5 present this study's findings, discuss their implications for relevant literature, and present the conclusions, respectively.

2. METHODS

Figure 1 provides an overview of our methods, while a detailed breakdown is presented as follows. Let $\mathbf{Z} = \left(z_{ij}^{rs}\right)$ be a transaction matrix of a multi-regional IO table, where z_{ij}^{rs} is an intermediate input from industry *i* in country *r* to industry *j* in country *s*. Let $\mathbf{x} = (x_i^r)$ be the total output vector and $\mathbf{f} = (\sum_s F_i^{rs})$ be the final demand vector, where F_i^{rs} is the final demand from industry *i* in country *r* to final consumers in country *s*. In the multi-regional IO analysis framework, the following holds:

$$\mathbf{x} = \mathbf{Z} + \mathbf{f}. \tag{1}$$

After defining the intermediate input coefficient matrix $\mathbf{A} = (a_{ij}^{rs}) = (z_{ij}^{rs}/x_j^s)$, Eq. (1) can be reformulated as

$$\begin{gathered}\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f}\\ (\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{f}\\ \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}.\end{gathered} \tag{2}$$

In Eq. (2), $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} = \left(l_{ij}^{rs}\right)$ is called the Leontief inverse matrix, whose elements represent the output of industry *i* in country *r* that is directly and indirectly needed to satisfy one unit of final demand from industry *j* in country *s*.

2.1 Hypothetical Extraction Method

We used the HEM to calculate the sum of the emissions of the supply chain paths passing through a specific sector and transaction. This method was originally developed to evaluate a sector's importance in the economy (Paelinck et al., 1965; Schultz, 1977; Strassert, 1968; Meller & Marfan, 1981; Dietzenbacher). The total output through the supply chain associated with a specific sector can be obtained by the decrease according to the difference between the total output of the original IO system and the total output of the hypothetical IO system excluding the sector. We call this difference a sector's HEM impact, which can be formulated as follows: First, $\overline{\mathbf{A}^{(p)}}$ indicates the partial technical coefficient matrix for sector p, where $\overline{a_{ij}^{(p)}} = a_{ij}$ if neither i nor j is p and otherwise 0. Thus,

$$\overline{\mathbf{A}^{(p)}} = \begin{bmatrix} a_{11} & \cdots & 0 & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ 0 & \cdots & 0 & \cdots & 0 \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & 0 & \cdots & a_{nn} \end{bmatrix}.$$

Subsequently, the total output of the hypothetical IO system can be represented as

$$\mathbf{i}'\left(\mathbf{I} - \overline{\mathbf{A}^{(p)}}\right)^{-1}\mathbf{f} = \mathbf{i}'\overline{\mathbf{L}^{(p)}}\mathbf{f},$$

where $\overline{\mathbf{L}^{(p)}} = \left(\mathbf{I} - \overline{\mathbf{A}^{(p)}}\right)^{-1}$ and $\mathbf{i}$ is a column vector in which all elements are 1. Thus, the HEM impact of sector p is defined as

$$HEM_p = \mathbf{i}'\mathbf{L}\mathbf{f} - \mathbf{i}'\overline{\mathbf{L}^{(p)}}\mathbf{f} = \mathbf{i}'\left(\mathbf{L} - \overline{\mathbf{L}^{(p)}}\right)\mathbf{f}. \quad (3)$$

Let $\mathbf{J}^{(pq)}$ be a matrix whose (p, q)th element is 1 and the others are 0. For simplicity, $\mathbf{J}^{(p)}$ denotes $\mathbf{J}^{(pp)}$ and $\mathbf{J}^{(-p)} = \mathbf{I} - \mathbf{J}^{(p)}$. Then, the output of sector p for the final demand of sector p, $\mathbf{i}'\mathbf{J}^{(p)}\mathbf{f}(= f_p)$, which does not have an intermediate input structure, is not included in HEM impact in this study. By replacing $\mathbf{i}'$ with an emission coefficient vector $\mathbf{e}$, Eq. (3) can be generalized to the HEM impact of a sector concerning emissions, which is the difference between the total emission of the original IO system and the total emission of the hypothetical IO system:

$$HEM_p = \mathbf{e}'\mathbf{L}\mathbf{f} - \mathbf{e}'\overline{\mathbf{L}^{(p)}}\mathbf{f} = \mathbf{e}'\left(\mathbf{L} - \overline{\mathbf{L}^{(p)}}\right)\mathbf{f}.$$

According to Tokito et al. (2022) and Hanaka et al. (2022), HEM_p can be interpreted as the gross emissions from all supply chain paths passing through sector p from the perspective of network theory and as the emission reduction potential for sector p.

2.2 Structural Position Analysis for Sectors

From the network perspective, $\mathbf{e}'\overline{\mathbf{L}^{(p)}}\mathbf{f}$ can be interpreted as the total emissions associated with the whole supply chain, excluding sector p; in other words, this represents the total emissions along all the supply chain paths not passing through sector p. Thus, $\mathbf{e}'\left(\mathbf{L} - \overline{\mathbf{L}^{(p)}}\right)\mathbf{f}$ represents the total emissions along all the supply chain paths passing through sector p at least once. In structural position analysis, $\mathbf{e}'\left(\mathbf{L} - \overline{\mathbf{L}^{(p)}}\right)\mathbf{f}$ is decomposed into three types of emissions: POEs (POE_p), BOEs (BOE_p), and COEs (COE_p). Thus,

$$HEM_p = \mathbf{e}'\left(\mathbf{L} - \overline{\mathbf{L}^{(p)}}\right)\mathbf{f} = POE_p + BOE_p + COE_p.$$

Here, POE_p, BOE_p, and COE_p are defined as follows:

$$POE_p = v_p^P + \frac{1}{2}v_p^{PC} + \frac{1}{2}v_p^{PB} + \frac{1}{3}v_p^{PBC},$$

$$BOE_p = v_p^B + \frac{1}{2}v_p^{PB} + \frac{1}{2}v_p^{BC} + \frac{1}{3}v_p^{PBC}, \text{ and}$$

$$COE_p = v_p^C + \frac{1}{2}v_p^{PC} + \frac{1}{2}v_p^{BC} + \frac{1}{3}v_p^{PBC}.$$

The values v_p^{PBC}, v_p^{PB}, v_p^{PC}, v_p^{BC}, v_p^{P}, v_p^{B}, and v_p^{C}, which represent seven types of emissions along all the supply chain paths passing through sector p in Figure 1 (see the Supporting Information for the formal definitions). Additionally, the production-oriented score (POS), betweenness-oriented score (BOS), and consumption-oriented score (COS) of *sector* p are defined as follows:

$$POS_p = \frac{POE_p}{HEM_p},$$

$$BOS_p = \frac{BOE_p}{HEM_p},$$

$$COS_p = \frac{COE_p}{HEM_p}.$$

In this paper, we further develop and use the structural position analysis for sector aggregation. The details of the decomposition are provided in the Supporting Information.

2.3 Structural Position Analysis for Transactions

In this subsection, we propose position-oriented emissions and a position-oriented score for transactions. The total emissions along all the supply chain paths passing through a transaction from sector p to sector q at least once that are equivalent to the HEM impact of the transaction are formulated as $HEM_{pq} = \mathbf{e}'\left(\mathbf{L} - \overline{\mathbf{L}^{(pq)}}\right)\mathbf{f}$, where $\overline{\mathbf{L}^{(pq)}} = \left(\mathbf{I} - \overline{\mathbf{A}^{(pq)}}\right)^{-1}$ and $\overline{\mathbf{A}^{(pq)}}$ is the partial technical coefficient matrix for a transaction from sector p to sector q, where $\overline{a_{ij}^{(pq)}} = 0$ if $i = p$ and $j = q$, and otherwise $\overline{a_{ij}^{(pq)}} = a_{ij}$. Thus,

$$\overline{\mathbf{A}^{(pq)}} = \begin{bmatrix} a_{11} & \cdots & a_{1q} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{p1} & \cdots & 0 & \cdots & a_{pn} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nq} & \cdots & a_{nn} \end{bmatrix}.$$

We also define $\overline{\mathbf{T}^{(pq)}} = \overline{\mathbf{L}^{(pq)}} - \mathbf{I} = \overline{\mathbf{A}^{(pq)}}\,\overline{\mathbf{L}^{(pq)}}$.

Figure 2 shows the position-oriented emissions of transactions from the metal production sector to the car production sector in the supply chain. The total emissions along all the supply chain paths passing through the transaction from the metal production sector to the car production sector at least once can be divided into seven patterns, as shown in Figure 2. The position-oriented emissions of a transaction are calculated by allocating emissions associated with all the supply chain paths passing through the transaction.

[Insert Figure 2]

In structural position analysis, $\mathbf{e}'\left(\mathbf{L} - \overline{\mathbf{L}^{(pq)}}\right)\mathbf{f}$ is decomposed into three types of emissions: POE POE_{pq}, BOE BOE_{pq}, and COE COE_{pq}. Thus,

$$HEM_{pq} = \mathbf{e}'\left(\mathbf{L} - \overline{\mathbf{L}^{(pq)}}\right)\mathbf{f} = POE_{pq} + BOE_{pq} + COE_{pq}.$$

Here, POE_{pq}, BOE_{pq}, and COE_{pq} are defined as follows:

$POE_{pq} = g_{pq}^{P} + \frac{1}{2} g_{pq}^{PC} + \frac{1}{2} g_{pq}^{PB} + \frac{1}{3} g_{pq}^{PBC}$,

$BOE_{pq} = g_{pq}^{B} + \frac{1}{2} g_{pq}^{PB} + \frac{1}{2} g_{pq}^{BC} + \frac{1}{3} g_{pq}^{PBC}$, and

$COE_{pq} = g_{pq}^{C} + \frac{1}{2} g_{pq}^{PC} + \frac{1}{2} g_{pq}^{BC} + \frac{1}{3} g_{pq}^{PBC}$.

The values g_{pq}^{PBC}, g_{pq}^{PB}, g_{pq}^{PC}, g_{pq}^{BC}, g_{pq}^{P}, g_{pq}^{B}, and g_{pq}^{C}, which represent seven types of emissions along all the supply chain paths passing through the transaction (p, q) in Figure 2 (see the Supporting Information for the formal definitions).. As with the case of sectors, the POS, BOS, and COS of *transactions* from sector p to sector q are defined as follows:

$$POS_{pq} = \frac{POE_{pq}}{HEM_{pq}},$$

$$BOS_{pq} = \frac{BOE_{pq}}{HEM_{pq}}, \text{ and}$$

$$COS_{pq} = \frac{COE_{pq}}{HEM_{pq}}.$$

In this study, we apply the proposed method to Exiobase 3.8 for 2015 (Stadler et al., 2018, 2021), a database that includes data on 163 industries and 49 regions, to visualize the structural positions of sectors and transactions in the global supply chain. It should be noted that the results, especially HEM, are affected by a sector aggregation or rough sector classification problem (See Supporting Information). In addition, see Dietzenbacher et al. (1993, 2013) for an explanation of HEM for the sector or regional aggregation.

3. RESULTS

3.1 Structural Position Analysis for Sectors

Figure 3 visualizes the structural position of each sector listed in Exiobase, with the three axes representing POS, BOS, and COS. The numbers in the figure represent sector codes, and details are shown in the Supplementally Information. The size of each circle in Figure 3 indicates the HEM impact (HEM_p) of each sector, and the color represents each region. We can see the industries in China (green) and the rest of Asia (blue) have a large HEM impact. Each region has a different distribution of the sector's structural positions. The Middle East region has a concentration of industries with a large HEM impact on the production-oriented side (lower left), while Europe has more industries with small-scale production orientation and a large HEM impact in the betweenness- and consumption-oriented side (from the top to the lower right of the triangle graph). The Middle East exhibits high direct CO_2 emissions from raw materials production, while Europe has industries that induce high indirect carbon emissions through the production of final goods and intermediate goods. The sectors with a large HEM impact in the Asian region are located between production- and betweenness-oriented industries (i.e., industries that have a relatively high emission intensity and induce high CO_2 emission through the supply chain) and between betweenness- and consumption-oriented industries (i.e., industries that are used both as intermediate and final goods sectors), which are located from the left-center to the right-center of the triangle graph.

Figure 4 shows the structural position of the U.S. sectors. Compared to Chinese sectors in Figure 3, the top HEM-impact sectors include strongly betweenness-oriented manufacturing industries, such as basic iron (#72), electrical machinery (#88), and machinery and equipment (#86), as well as production-oriented manufacturing industries, such as the cement industry (#69) in China. Other business activities (#135) and consumption-oriented services such as public administration and defense (#136), real estate activities (#131), and health and social work (#138) are among the top HEM-impact sectors in the U.S. Further, China has industries with large HEM impacts in the production- and betweenness-oriented side (from lower left to top), while the U.S. has industries with large HEM impacts in the betweenness- and consumption-oriented side (from the top to the lower right of the triangle graph), similar to Europe. In terms of budget allocation for climate mitigation, the main focus in China is on reducing emission intensity and the use of intermediate goods with high emissions for the manufacturing sectors. Incentives need to be provided to each office of the manufacturing sector to manage their supply chain in a greener way through subsidies. In the U.S., it is necessary to establish consumption policies (such as eco-labels) for the service industry and guidelines that interweave multiple measures. When promoting cooperation between the U.S. and China in emission reduction, it is necessary to consider the structural position of sectors in each country, as there is a difference in the amount of emissions that can be reduced through similar policies.

[Insert Figures 3 and 4]

Among the relatively large HEM-impact sectors, chemicals (#63), petroleum refinery (#57), and manufacture of basic iron (#72) are industries whose structural position in the supply chain varies from region to region. Figure 5 visualizes the structural positions of these sectors in each region. The chemicals industry is identified as a betweenness-oriented sector; however, the chemicals sectors in China and the rest of the world are different from the viewpoint of COEs. The reason for this is that chemical products are scarcely consumed as final products in China. Additionally, the chemicals industry accounts for a large share of POEs in China and Russia and has significant upstream-induced emissions, as well as its own emissions. The chemicals industry has higher COEs in Canada and Latin America, whereas, in the U.S., it exhibits all structural positions to the same degree. In all regions, the HEM impact of the chemicals sector is high, indicating that budgets should be allocated to emission reduction, although different reduction policies are needed in different regions.

The petroleum refinery industry can be divided into three major patterns: production-oriented (Africa, the Middle East, and Russia); betweenness-oriented (China); and the rest of the world, where all structural positions appear symmetrical. The petroleum refinery sectors in Africa, the Middle East, and Russia, which are production-oriented, exhibit emission intensities twice as large as those of the U.S., Japan, and other Asian regions. It is necessary to transfer technologies with low direct emissions through the CDM and joint implementation (JI).

Basic iron appears between production- and betweenness-oriented in all regions (i.e., basic iron has significant direct and indirect emissions as an intermediate goods sector); however, the ratios to HEM impact vary widely. The basic iron sector in Russia is more production-oriented; China, Europe, and Latin America show similar characteristics; and the rest of the regions, especially the Middle East and the U.S., are more betweenness-oriented. As the inducement to electricity is significant in regions that are highly betweenness-oriented, upstream emissions cannot be ignored in emission reduction strategies.

[Insert Figure 5]

3.2 Structural Position Analysis for Transactions

Figure 6 shows the top 30 international transactions for HEM impact (HEM_{pq}). The width of the edges represents the HEM impact of the transaction, and their colors reflect the largest structural position ($POS_{pq}, BOS_{pq}, COS_{pq}$). By focusing on international trade, production-oriented sectors with high emission intensity (e.g., the electricity [#96–107] sector) and betweenness-oriented sectors (e.g., the transmission and distribution [#108–109] sector), are not ranked high, while consumption-oriented construction industry (#113) is also underrepresented. These sectors are not directly connected to foreign industries and require domestic supply chain management and coordination, while the extraction of crude petroleum (#21), petroleum refinery (#57), and chemicals (#63) industries have an important role in reducing emissions through trade deals. Additionally, the presence of the Asian (WWA) and Middle East (WWM) regions is more prominent compared with the U.S. and China, indicating that these countries are important regions in the global supply chain.

The international transaction with the largest HEM impact is that between the Canadian extraction of crude petroleum industry (#21) to the U.S. petroleum refinery industry (#57), with 52.7 Mt-CO_2. The second largest HEM impact is from the WWM extraction of crude petroleum industry (#21) to the Chinese petroleum refinery industry (#57), with 27.6Mt- CO_2, 46.7% of which was betweenness-oriented. Overall, most transactions are from the extraction of crude petroleum industry to the petroleum refinery industry. Export transactions from the Middle East extraction of crude petroleum industry (#21) are betweenness- and consumption-oriented, while the export transaction from the extraction of crude petroleum industry in the rest of the world is production-oriented. This means that transactions from the Middle East extraction of crude petroleum industry (#21) occur between mid- and downstream in the global supply chain. This is because the extraction of crude petroleum in the Middle East requires much higher electricity inputs (especially from gas and oil), compared with other regions. The structural position of these transactions differs across countries.

Many transactions between China and the rest of Asia (WWA) have large HEM impacts, with those between the WWA nonmetallic mineral products (#71) industry to the Chinese construction industry (#113) having the largest HEM impact. Nonmetallic minerals from WWA play an important role in Chinese building materials, which induce significantly high emissions within WWA for electricity and other purposes.

The WWA chemicals (#63) and China’s basic iron (#72) industries exhibit several top edges with a large HEM impact, indicating that they are hubs. The WWA chemicals (#63) industry has consumption-oriented export transactions with the Chinese health and social work industry (#138), while exports to the Chinese and Indian chemicals industries are betweenness-oriented. Contrarily, imports from China’s office machinery (#87) and leather industry (#49) industries are more betweenness-oriented. Chemical products are more likely to appear in the global supply chain because of their diversity of suppliers and sources, as well as their ease of crossing borders (Tokito et al., 2022).

[Insert Figure 6]

4. DISCUSSION

Applying structural position analysis, industries with a high priority for policymaking were identified. Multi-oriented sectors (including betweenness-oriented ones) that are from the center to the top of the triangle graph (e.g., copper production in WWA and paper manufacturing in the U.S.) did not rank high in the position-*based* emission analysis. Budgetary allocations and reduction policies need to be clearly devised for these industries. This study proposes the following domestic policy framework:

1. Prioritize industries for emission reductions based on the HEM and allocate the budget considering industries' emission reduction potential.
2. Specify how the budget will be used based on their structural position, considering multi-orientation.

The general framework for the use of the budget will be a reduction policy that fits each structural position, but some flexibility is required according to each company's LCA report. In this study, we promote initiatives at the individual business site level for firms. Firms with a broad supply chain from upstream to downstream need to implement policies from several perspectives, and to do so, they need to assign each reduction policy to the most appropriate business site. Firms should prepare CSR reports based on their initiatives and promote the structural position of each business site and the emission reductions it is implementing. For example, as the chemicals industry in the U.S. exhibits all orientations (production, betweenness, and consumption) to the same degree, it is necessary for each company to allocate a budget for each necessary business location and implement its own effective policy for energy use, materials, supply chain management, and so on. If the framework is to be carried out within the global network, it could be coordinated with other countries with a similar industrial orientation (e.g., basic iron in China, Latin America, and Europe, petroleum refineries in Asia and Latin America) to promote a common "transition" strategy. Furthermore, by providing new incentives to reduce HEM impact in addition to the assigned amount and credits of carbon emissions under the Paris Agreement, further emission reduction can be achieved through CDM and JI if countries involved in emissions (intermediate inducers) that have been previously overlooked can be identified.

As seen from the structural position analysis of industry sectors, there are sectors with structural positions to the same degree (such as those located in the center of the triangle graph), which have diverse characteristics for each trading partner. Moreover, even within the same industry, a given structural position may differ across regions. Even in the same industry, the process may differ across countries, depending on vertical intra-sector trade in the global supply chain, while technology may also differ. Therefore, policy guidelines should be established for each transaction's structural position rather than implementing the same policy to industries and commodities (Figure 7).

1. Determine the critical transactions that require focused policymaking based on their HEM impact.
2. Determine the policy for each transaction based on their most significant structural position.
   i. In the case of production-oriented sectors, the intensity of emissions should be reduced since exporting industries have large direct emissions and are located at the upstream of

the global supply chain with large emissions. Specifically, it is important to eco-enhance the import side's acquisition strategy through a carbon tax, as well as to compensate and invest in the export side through carbon tax revenues.

ii. In the case of betweenness-oriented sectors, the export side is an intermediate industry that induces large emissions upstream from its own industry; therefore, it is important to manage its materials and energy. On the contrary, the import side is an intermediate industry that is in great demand from downstream industries; therefore, the restrictions on the use of goods from that industry in the importing country are important. Hence, it is necessary to have the entire supply chain disclose emissions based on these reports in accordance with the Task Force on climate-related financial disclosure through the preparation of LCA reports for the export side and the listing and management of suppliers on the import side.

iii. In the case of consumption-oriented sectors, the trade is between the primary supplier and the final goods manufacturer. LCA reporting to the export side (primary supplier) and disclosure of LCA emissions to the import side (final goods industry) are required. Moreover, demand policies (such as eco-labeling) are needed in final consumption countries.

[Insert Figure 7]

In particular, the chemicals industry in WWA, which is a hub sector, has betweenness-oriented export transactions to Indian and Chinese chemicals. This suggests that in the Asian region, the chemicals sector would basically be an industry where LCA reporting and supplier disclosure are important. Moreover, the Asian region has many large betweenness-oriented trades in terms of its overall industry and is a hub connecting upstream industries with high emission intensity and extensive final consumption in each region. Taking advantage of the vast trading blocs (e.g., the Trans-Pacific Partnership and the Regional Comprehensive Economic Partnership), thorough supply chain emission control and the establishment of a green supply chain in Asia will greatly contribute to global emission reduction.

As the U.S. and European countries have many production-oriented import transactions, especially from oil and gas extraction sectors, it is crucial to reduce direct emissions among trade partners. Establishing a carbon tax on direct emissions will encourage low-carbon competition at the corporate level, while carbon tax revenues will be used to invest in technology in emitting countries, thereby contributing to emission reduction from both the supply and demand sides.

5. CONCLUSIONS

In this study, we developed a framework that enables the comprehensive discussion of emission reduction policies from the perspectives of traditional production- and consumption-based accounting, as well as emission reduction policies through supply chain management based on BBE accounting. The findings of this study can be used to identify the emissions generated throughout the supply chain of each industry in each country (not limited to emitting sectors or consuming countries/final products), as well as the emission characteristics and necessary policies for each sector. Through this study, we were able to plan budget allocation by country and analyze stakeholders with whom technology sharing and transfer is desirable. Furthermore, by extending the existing methodology, we were able to identify the characteristics of international intermediate goods trade transactions and propose policy guidelines according to the different nature and characteristics of these transactions.

Note that this study only refers to the emissions involved in each of its structural positions; further research is needed on the actual emission reduction potential and reduction costs, which should be analyzed in combination with firm-level reporting and the analysis of marginal reduction costs. However, for policymakers, a macro perspective using IO could prove useful for formulating policies, as the longer the supply chain, the more effective it is. To reduce GHG emissions, including those in developing countries, it is necessary to create new rules to keep the benefits of CDM for emitting countries. In this context, it is imperative to add value to the reduction potential of the entire supply chain by providing new incentives for consumption policies and the establishment of green supply chains. Accordingly, this study's findings will significantly contribute toward this goal.

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SUPPORTING INFORMATION

[Insert Supporting Information summary text here. *See example.*]

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information provides the formulation of structural position analysis for sectors

Supporting Information S2: This supporting information provides the extension of structural attribution analysis to sector aggregation

Supporting Information S3: This supporting information provides the formulation of structural position analysis for transactions

Supporting Information S4: This supporting information provides sector/regional aggregations and the robustness of structural position approach

Figure Legends

Figure 1. Calculation of position-based and position-oriented emissions in the car production supply chain.

Figure 2. Calculations of position-oriented emissions of transactions from the metal production sector to the car production sector along the supply chain.

Figure 3. Triangle graphs of all regions

Figure 4. Triangle graphs of the U.S. The size of circles is scaled by setting the maximum HEM impact value in each sample to 1.

Figure 5. Triangle graphs of the chemicals (#63), manufacture of basic iron (#72), and petroleum refinery (#57) industries. The size of the circles is scaled by setting the maximum HEM impacts value in each sample to 1.

Figure 6. Mapping of the top 30 transactions according to their HEM impact.

Figure 7. Policy application from the result of structural position analysis of transaction