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Multi-regional decomposition of direct and indirect carbon emissions in ASEAN

John Raphael C. Teng[1], Raymond R. Tan[2], Meng Li[3], Ivan Henderson V. Gue[1,2]

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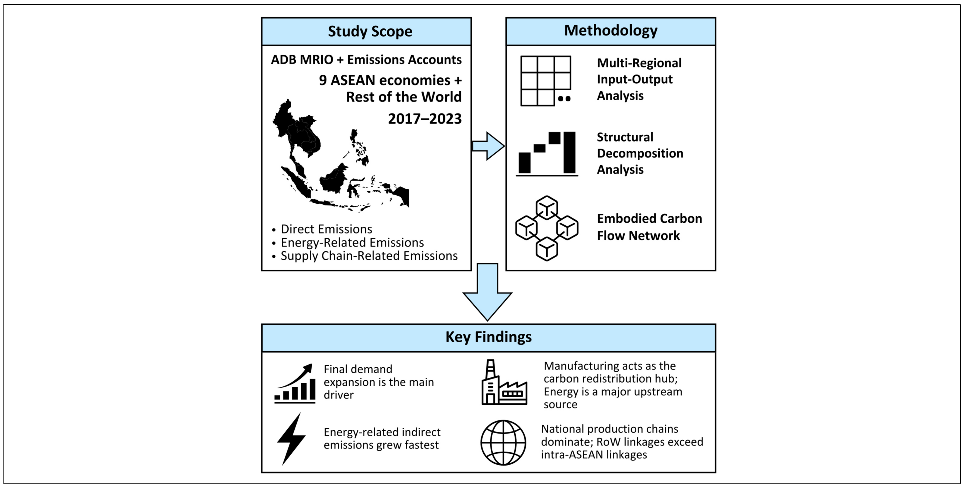

Abstract

As Association of Southeast Asian Nations (ASEAN) economies deepen their role in regional and global production networks, carbon responsibility is increasingly shared across production, consumption, and trade systems. This study assesses direct and indirect carbon emissions across nine ASEAN economies from 2017 to 2023 using an environmentally extended multi-regional input-output framework with Logarithmic Mean Divisia Index (LMDI)-based structural decomposition analysis (SDA). Direct, energy-related indirect, and supply chain-related emissions were quantified using Asian Development Bank multi-regional input-output tables and environmental satellite accounts. Emission changes were decomposed into emission intensity, economic system structure, final demand structure, and total final demand effects. Embodied carbon flow matrices traced carbon transfers through intermediate transactions, final demand, ASEAN economies, and the Rest of the World (RoW). Results show that direct emissions increased by 19.76% (2,363.10 to 2,829.95 MtCO_2e), while indirect emissions increased by 7.83% (4,003.85 to 4,317.47 MtCO_2e), with energy-related indirect emissions showing the highest growth rate among the indirect categories at 16.72% (1,176.48 to 1,373.17 MtCO_2e). LMDI-based SDA results indicate that emissions growth was mainly driven by global final demand expansion, while negative emission intensity effects partly offset

[1]Department of Mechanical Engineering, De La Salle University, Manila 0922, Philippines.
[2]Center for Engineering and Sustainable Development Research, De La Salle University, Manila 0922, Philippines.
[3]School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.

Correspondence to: Dr. Ivan Henderson V. Gue, Department of Mechanical Engineering, De La Salle University, Manila 0922, Philippines. E-mail: ivan.gue@dlsu.edu.ph

emission increases in all three categories. Country-sector hotspots included Indonesia's energy and mining sectors, and Vietnam's manufacturing sector. Embodied carbon flow results identify manufacturing as the central carbon redistribution hub and energy as a major upstream source. National production chains dominated ASEAN embodied flows, while RoW-linked exchanges were larger than intra-ASEAN exchanges. These findings highlight the need for coordinated regional and country-specific strategies targeting cleaner energy systems, industrial networks, and material supply chains.

INTRODUCTION

Continued growth in carbon emissions places increasing pressure on the remaining carbon budget for limiting global warming. Since global emissions reached 41.6 Gt CO_2 in 2024 against an estimated remaining budget of 1,110 Gt CO_2, accelerated decarbonization remains central to sustainable development[1]. However, achieving decarbonization is a challenge due to the structure of global production systems. As contemporary industrial manufacturing is deeply integrated into international trade and global value chains, carbon emissions are functionally fragmented across multiple cross-border economic systems. Consequently, downstream processes and consumption drive upstream environmental burdens, embodying significant volumes of carbon emissions. Effective management of global carbon emissions should address the component embodied in international trade[2]. Production-based and consumption-based environmental accounting are, therefore, critical considerations in environmental governance. This is of concern for economic regions such as the Association of Southeast Asian Nations (ASEAN), where supply chain linkage risks and territorial carbon emissions may undermine regional green transition initiatives.

The ASEAN economic bloc comprises 11 member states, namely Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, and Vietnam. In 2024, the region accounted for 8.4% of the global population and recorded a nominal gross domestic product (GDP) of US$3.9 trillion, positioning ASEAN as the fifth-largest economy globally[3]. In recent decades, the bloc has become a pivotal player in the global value chain as a manufacturing hub[4]. However, the region's economic expansion has been associated with rising energy consumption and carbon emissions[5], with ASEAN accounting for 4.75% of global carbon emissions in 2020[6]. These rising emissions run parallel with the region's vulnerability to climate change. Member states such as the Philippines, Myanmar, Vietnam, and Thailand are consistently ranked among the world's most vulnerable nations to climate risks[7].

Decarbonizing ASEAN requires an analysis of each member state's carbon footprint. In particular, the accounting of direct and indirect carbon emissions is of significance as it reveals environmental responsibilities across fragmented value chains. In corporate reporting, greenhouse gas (GHG) emissions are categorized according to "scopes": Scope 1 covers direct emissions from on-site activities, Scope 2 covers indirect emissions from the generation of purchased energy, and Scope 3 covers all other value-chain indirect emissions[8]. From a macroeconomic perspective, these categories can be represented as direct territorial emissions, energy-related indirect emissions, and supply-chain embodied carbon in multi-regional-based accounting frameworks[9].

Categorization of emissions requires a region-wide, multi-sectoral framework capable of tracking embodied carbon throughout the region's complex economic network. The Multi-Regional Input-Output (MRIO) structure provides a mathematical depiction of trade flows between regions and industries[10]. It extends the input-output model of Leontief[11] to analyze intersectoral and interregional production linkages. When coupled with environmental satellite accounts, the trade flows and industry emissions are mapped via the Environmentally Extended Multi-Regional Input-Output (EEMRIO) model. The EEMRIO model provides an empirically grounded framework for calculating direct and indirect carbon emissions across multiple nodes of a global or regional economic system[12].

In existing literature, input-output (IO) models have been widely adopted to analyze the carbon footprints of individual ASEAN member states, such as the Philippines[13], Singapore[14], Vietnam[15], Indonesia[16], and Thailand[17]. However, these single-country studies omit the complex structural interdependencies between member states and their respective industries. To capture regional shifts, alternative studies have examined the dynamic trajectory of ASEAN's carbon emissions. For instance, Sandu *et al.*[18] utilized the Logarithmic Mean Divisia Index (LMDI) to analyze regional energy-related emissions, while Zhang *et al.*[19] applied the LMDI approach to evaluate the decoupling patterns between economic growth, energy use, and emissions across China and ASEAN. Additionally, Chen *et al.*[20] employed Structural Decomposition Analysis (SDA) to investigate emission drivers between China and the bloc. Despite these findings, previous macro-decomposition works did not consider emission classifications and their underlying economic drivers, which may lead to incomplete attribution of emissions responsibility and poorly targeted mitigation strategies.

Although previous works have examined the carbon footprints of individual member states or evaluated aggregate regional emissions trends, limited research has investigated the ASEAN region through a unified, multi-regional framework. In particular, existing literature lacks a comprehensive examination of direct and indirect carbon emissions across multiple ASEAN member states, their underlying drivers, and their cross-border embodied carbon flows. To address this gap, this study examines nine ASEAN economies with complete and comparable data for 2017-2023 using an EEMRIO framework. It quantifies greenhouse gas emissions according to three classifications: direct emissions, energy-related indirect emissions, and supply chain-related emissions. An LMDI-based SDA is then applied to identify the drivers of changes in each emissions category. The study further maps embodied carbon flows within ASEAN and between ASEAN and the rest of the world. The resulting output maps the region's trade-embodied carbon in detail, providing critical insights into the carbon emissions across ASEAN's economic systems, thereby offering a vital analysis of the region's sustainable transition given its expanding role in the global economy.

The rest of this paper is organized as follows: Section 2 presents the methodological framework, Section 3 describes the data and sectoral aggregation, Section 4 reports the results, Section 5 discusses the main findings and policy implications, and Section 6 concludes the study and presents recommendations for future work.

METHODOLOGICAL FRAMEWORK

This study adopts an EEMRIO framework with LMDI-based SDA to examine the drivers of GHG emissions changes in ASEAN. The overall analytical workflow is summarized in Figure 1. The framework integrates economic input-output transactions, environmental satellite accounts, and decomposition analysis to trace how emissions are generated and transferred across sectors, countries, and supply-chain linkages.

Following the EEMRIO approach of Hertwich and Wood[12], the Leontief model was used to construct category-specific emissions accounts for direct, energy-related indirect, and supply chain-related emissions. LMDI-based SDA was then applied to quantify the contributions of emission intensity, economic system structure, final demand structure, and total final demand to changes in emissions. Finally, embodied emissions intensities were used to map embodied carbon flows in intermediate transactions and final demand.

EEMRIO framework

MRIO analysis extends the classic Leontief[11] input-output framework to represent production interdependencies and trade linkages across multiple countries or regions[10]. In an MRIO system, each region contains a set of economic sectors that purchase intermediate inputs from, and supply outputs to,

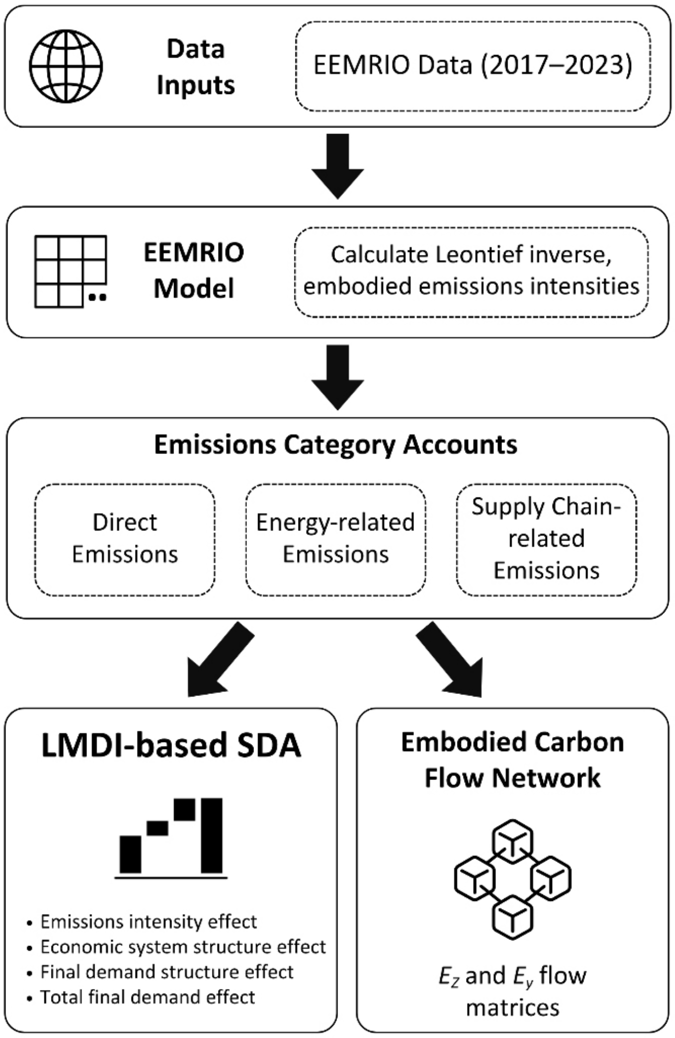

Figure 1. Methodological framework using EEMRIO and LMDI-based SDA. EEMRIO: Environmentally extended multi-regional input-output; SDA: structural decomposition analysis; LMDI: logarithmic mean Divisia index.

other sectors both domestically and internationally. This structure enables the tracing of supply chains beyond national borders by tracking how final demand in one country induces production in upstream sectors located in other countries.

The Leontief model computes the total sectoral output required to satisfy a given level of final demand while accounting for inter-sectoral input requirements embedded in the production system:

$$x = (I - A)^{-1} y = Ly \tag{1}$$

where x is the total output vector, I is the identity matrix, A is the technical coefficient matrix, where each element a_{ij} represents the monetary input from sector i required to produce one unit of output in sector j, y is the final demand vector, and L is the Leontief inverse, which captures both direct and indirect production requirements across the supply chain.

EEMRIO extends the model to environmental impacts with the inclusion of the environmental satellite accounts[21]. It calculates the total environmental impact (e.g., emissions) based on the output levels from Eq. (1)

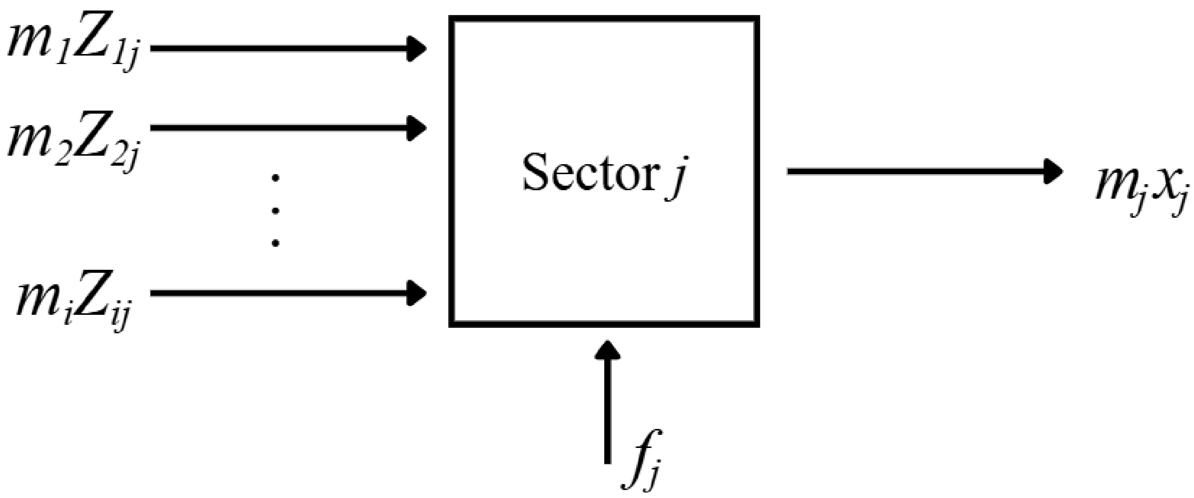

Figure 2. Schematic of the embodied emissions balance for a single production process.

$$c = \hat{s}x \tag{2}$$

where **c** is the total emissions vector and $\hat{s}$ is the diagonalized emissions intensity matrix, with the hat notation indicating that the vector has been converted into a diagonal matrix.

Mapping embodied carbon flow

In the EEMRIO framework, the embodied emissions associated with a sector's output are defined as the combined contribution of emissions released directly during production and the upstream emissions embodied in the intermediate goods and services used as inputs to that production process[12]. Figure 2 illustrates this accounting logic.

In matrix form, the relationship is written as:

$$f^{dir} + mZ = m\hat{x} \tag{3}$$

where f^{dir} is the vector of direct emissions specifically, as reported in the environmental satellite accounts, Z is the intermediate transactions matrix, $\hat{x}$ is the diagonal matrix of total output, and m is the vector of embodied emissions intensity per unit output. The formulation assumes that each sector produces a homogeneous output with a single embodied emissions intensity, such that the embodied emissions intensity of product i used as an intermediate input is the same regardless of its destination[12]. This implies that the same intensity m_i applies whether the product is purchased as an intermediate input by sector j or delivered to final demand, ensuring consistency when tracing embodied emissions through the MRIO system.

The embodied emissions intensity vector is calculated by rearranging Eq. (3) and right-multiplying by $\hat{x}^{-1}$, capturing economy-wide production requirements using the Leontief inverse:

$$m = s^{dir}(I - A)^{-1} \tag{4}$$

where the vector m captures the total direct and indirect emissions required throughout the production system to produce one unit of sectoral output.

The embodied carbon flows associated with intermediate transactions are calculated as:

$$E_Z = \widehat{m}Z \tag{5}$$

while embodied carbon in final demand is calculated as:

$$E_y = \widehat{m}y \tag{6}$$

where $\hat{m}$ is the diagonal matrix of embodied intensities. The matrix E_Z has the same dimensions as Z and can be interpreted as embodied carbon transferred from producing sectors to purchasing sectors through intermediate inputs, whereas E_y represents embodied carbon attributable to final demand categories. Together, these quantities form the basis for constructing the embodied carbon flow table used in the subsequent results analysis.

Direct emissions and emissions embodied in final demand represent different stages of the producer-side carbon-flow account. Direct emissions identify emissions generated within each economy, whereas E_y represents emissions embodied in its products delivered to final demand across all destinations. Differences between these measures reflect production specialization, the carbon intensity and composition of final products, and the allocation of output between intermediate and final uses. The present analysis focuses on the indirect emissions and supply-chain influence of producers and does not reallocate emissions according to the location of final consumption. Indirect emissions are represented by the carbon embodied in intermediate inputs purchased from the economy[22]. The indirect emissions of sector j are defined as the total carbon embodied in its intermediate inputs, computed by summing the embodied emissions inflows from all supplying sectors:

$$C_j^{ind} = \sum_i (E_Z)_{ij} \tag{7}$$

where C_j^{ind} is the indirect emissions of sector j and $(E_Z)_{ij}$ denotes the embodied emissions transferred from supplying sector i to purchasing sector j through intermediate transactions.

This indirect emissions quantity is disaggregated into its energy-related and supply chain-related components, consistent with the category-based framework introduced earlier, where emissions are grouped into "scopes"[8]. This study instead uses "categories" to reflect the macroeconomic, sector-level unit of analysis rather than a firm-level accounting boundary. Because the embodied emissions intensity m in Eq. (4) includes cumulative emissions from all upstream production tiers, Eq. (7) intentionally attributes the same underlying emissions to multiple stages of the supply chain. For example, emissions from material production are included in the material sector's direct emissions and are also embodied in the outputs of downstream sectors that use those materials. This repeated attribution follows the indirect emissions framework of Hertwich and Wood[12] and is intended to identify the sectors that have influence over upstream emissions and the corresponding mitigation leverage points. Accordingly, the sectoral indirect emissions values should not be added to direct emissions to represent a unique regional emissions total.

To distinguish energy-related from other supply chain-related indirect emissions, the direct-emissions vector from the environmental satellite account was separated according to the source of the underlying direct emissions before propagation through the MRIO system.

$$f^{dir} = f^{en} + f^{sc} \tag{8}$$

where f^{en} retains direct emissions classified under the Intergovernmental Panel on Climate Change (IPCC) source category "Main Activity Electricity and Heat Production", while f^{sc} contains the remaining direct emissions sources. These source-based emissions vectors were converted into direct intensity vectors:

$$s^{en,0} = f^{en}\widehat{x}^{-1} \tag{9}$$

$$s^{sc,0} = f^{sc}\widehat{x}^{-1} \tag{10}$$

The superscript 0 distinguishes these source-specific direct intensity vectors from the category-specific intensity vectors subsequently used in the LMDI-based SDA. The corresponding embodied emissions intensity vectors were then calculated as:

$$m^{en} = s^{en,0}(I - A)^{-1} \tag{11}$$

$$m^{sc} = s^{sc,0}(I - A)^{-1} \tag{12}$$

These were then used to construct separate embodied flow matrices:

$$E_Z^{en} = \widehat{m}^{en} Z \tag{13}$$

$$E_Z^{sc} = \widehat{m}^{sc} Z \tag{14}$$

Energy-related and supply chain-related indirect emissions for sector j were then obtained by summing the column inflows of these matrices:

$$C_j^{en} = \sum_i \left(E_Z^{en}\right)_{ij} \tag{15}$$

$$C_j^{sc} = \sum_i \left(E_Z^{sc}\right)_{ij} \tag{16}$$

where C_j^{en} represents energy-related embodied emissions and C_j^{sc} represents supply chain-related embodied emissions.

The two indirect emissions categories reconcile with the total indirect emissions defined in Eq. (7). Since the direct emissions vector is partitioned exhaustively as defined in Eq. (8), the corresponding direct emissions intensities satisfy $s^{dir} = s^{en,0} + s^{sc,0}$. Because the EEMRIO model is linear, the total embodied emissions intensity can therefore be expressed as

$$m = m^{en} + m^{sc} \tag{17}$$

Consequently, the total embodied intermediate-flow matrix is the sum of its energy-related and supply chain-related components:

$$E_Z = E_Z^{en} + E_Z^{sc} \tag{18}$$

Summing the column inflows for sector j therefore gives

$$C_j^{ind} = C_j^{en} + C_j^{sc} \tag{19}$$

Thus, the energy-related and supply chain-related emissions constitute a complete partition of the total indirect emissions calculated from the embodied intermediate flows. Because the source-specific emissions intensities were propagated through the full multiregional input-output system, the resulting energy-related and supply chain-related emissions include upstream emissions embodied in both domestic and imported intermediate inputs.

The category-specific emissions intensity vectors were then defined as:

$$s^{en} = C^{en}\widehat{x}^{-1} \tag{20}$$

$$s^{sc} = C^{sc}\widehat{x}^{-1} \tag{21}$$

where s^{en} represents energy-related emissions intensity, and s^{sc} represents supply chain-related emissions intensity. All EEMRIO calculations, including the technical coefficient matrix, Leontief inverse, embodied emissions intensities, and embodied carbon flow matrices, were performed using the original 35-sector MRIO system. Sectoral results were aggregated to the eight composite sectors only after the emissions and embodied-flow calculations were completed.

LMDI-based structural decomposition analysis

After constructing the three emissions categories, LMDI-based SDA was applied separately to direct, energy-related, and supply chain-related emissions to identify the drivers of their changes between 2017 and 2023. SDA is a comparative analytical method that decomposes the changes in a variable, such as emissions, into the contributions of several underlying structural drivers. For emissions category k, the category-specific emissions intensity is defined as:

$$s_i^k = \frac{C_i^k}{x_i}, \quad k \in \{dir, en, sc\} \tag{22}$$

$$s \begin{cases} s^{dir}, \text{ for direct emissions} \\ s^{en}, \text{ for energy - related emissions} \\ s^{sc}, \text{ for supply chain - related emissions} \end{cases} \tag{23}$$

where C_i^k is the emissions assigned to region-sector pair i under category k, and x_i is its total economic output. Accordingly, s^{dir} represents direct emissions per unit of output, s^{en} represents energy-related indirect emissions per unit of output, and s^{sc} represents other supply chain-related indirect emissions per unit of output. These category-specific intensity vectors used in the LMDI-based SDA are distinct from the source-specific direct intensity vectors $s^{en,0}$ and $s^{sc,0}$ used earlier to construct the indirect emissions categories.

Substituting Eq. (1) into Eq. (2), the basic emissions identity for each emissions category is expressed as:

$$C^k = 1^T \boldsymbol{c}^k = s^k L y \tag{24}$$

where 1 is an $m \times 1$ vector of ones and C^k is the scalar aggregate emissions for category k.

To separate the effect of changes in the composition of final demand from the effect of changes in the overall scale of final demand, the final demand vector is decomposed into:

$$y = y_s y_{tot} \tag{25}$$

where y represents final demand for each region-sector output summed across all final-demand destinations in the full MRIO system. Accordingly, y_{tot} is the total final demand across all economies in the MRIO system, while y_s is the normalized distribution of this global final demand across region-sector outputs. Because final-demand destinations are aggregated in y, the decomposition does not separately identify demand originating from ASEAN and Rest of the World (RoW) economies. The reported decomposition effects refer to their contributions to emissions generated by ASEAN sectors; thus, the total final demand effect represents the effect of changes in the global final-demand scale on ASEAN emissions.

Substituting Eq. (25) into Eq. (24), the total change in emissions between t_1 and t_2 is then written as:

$$\Delta C^k = C^{k,t2} - C^{k,t1} = s^{k,t2} L^{t2} y_s^{t2} y_{tot}^{t2} - s^{k,t1} L^{t1} y_s^{t1} y_{tot}^{t1} \tag{26}$$

The total emissions change is decomposed into a simple four-factor decomposition identity[14]:

$$\Delta C^k = \Delta C_{eint}^k + \Delta C_{lstr}^k + \Delta C_{ystr}^k + \Delta C_{ytot}^k \tag{27}$$

where ΔC_{eint}^k is the emission intensity effect, ΔC_{lstr}^k is the Leontief economic system structure effect, ΔC_{ystr}^k is the final demand structure effect, and ΔC_{ytot}^k is the total final demand effect.

Several decomposition approaches are available, including LMDI method[23], Dietzenbacher and Los (D&L) method[24], and Shapley-Sun-Albrecht (SSA) method[25]. Comparative assessments indicate no clear overall preference among these methods in terms of theoretical foundations, adaptability, and ease of interpretation[26]. In this study, the additive LMDI method was selected because it provides complete, residual-free decomposition and produces theoretically consistent results[23,27]. It is also consistent in aggregation, meaning that the estimated effects at the subgroup level can be summed to obtain the corresponding effects at the aggregate level[28]. These properties make LMDI an appropriate and practical method for the four-factor decomposition applied in this study.

For the element-wise LMDI decomposition, the contribution associated with each pair of indices i and j is defined as:

$$q_{ij}^{k,t} = s_i^{k,t} L_{ij}^t y_{s,j}^t y_{tot}^t \tag{28}$$

such that:

$$c_i^{k,t} = \sum_j q_{ij}^{k,t}, C^{k,t} = \sum_i c_i^{k,t} = \sum_i \sum_j q_{ij}^{k,t} \tag{29}$$

This notation distinguishes the region-sector emissions vector c, the aggregate scalar emissions C, and the individual cell-level contributions q_{ij}.

The corresponding logarithmic-mean weight is:

$$w_{ij}^k = \frac{q_{ij}^{k,t2} - q_{ij}^{k,t1}}{\ln\left(q_{ij}^{k,t2}\right) - \ln\left(q_{ij}^{k,t1}\right)} \tag{30}$$

The individual effects are then calculated as:

$$\Delta C_{eint}^k = \sum_i \sum_j w_{ij}^k \ln\left(\frac{s_i^{k,t2}}{s_i^{k,t1}}\right) \tag{31}$$

$$\Delta C_{lstr}^k = \sum_i \sum_j w_{ij}^k \ln\left(\frac{L_{ij}^{t2}}{L_{ij}^{t1}}\right) \tag{32}$$

$$\Delta C^{k}_{ystr} = \sum_{i}\sum_{j} w^{k}_{ij} \ln\left(\frac{y^{t2}_{s_j}}{y_{s^{t1}_j}}\right) \tag{33}$$

$$\Delta C^{k}_{ytot} = \sum_{i}\sum_{j} w^{k}_{ij} \ln\left(\frac{y^{t2}_{tot}}{y^{t1}_{tot}}\right) \tag{34}$$

The emissions intensity vector s^k has dimension $1 \times m$, the Leontief inverse L has dimension $m \times m$, the normalized final-demand structure vector y_s has dimension $m \times 1$, and y_{tot} is a scalar representing total final demand. Specifically, s^k_i represents category-k emissions per unit of output in region-sector pair i, L_{ij} is the total output required from i to satisfy one unit of final demand for j, and $y_{s,j}$ is the share of total final demand associated with j. The calculation is performed element by element: s_i scales row i of the Leontief inverse, $y_{s,j}$ scales column j, and y_{tot} scales the complete matrix. s_i is measured in $MtCO_2e$ per million constant-2010 USD, L_{ij} and $y_{s,j}$ are dimensionless, and y_{tot} is measured in million constant-2010 USD; therefore, the resulting emission changes ΔC are expressed in $MtCO_2e$.

Because the LMDI method requires positive values for logarithmic calculations, zero observations in the individual decomposition factors were replaced with a small positive constant before the decomposition was performed. A value of 10^{-20} was adopted following the small-value strategy of Ang and Liu[29], who showed that sufficiently small replacement constants generally provide stable LMDI results. In both 2017 and 2023, one zero value occurred in the category-specific emissions intensity vector s, 158 zero values occurred in the Leontief inverse L, one zero value occurred in the normalized final demand structure vector y_s, and no zero values occurred in total final demand y_{tot}. The zero observations occurred at the same positions in 2017 and 2023 and therefore represented zero-to-zero (Type I) changes. The replacement was applied directly to these individual zero-valued factors before the logarithmic mean and decomposition terms were calculated.

Negative values were also checked in the category-specific emissions intensity vectors s, the Leontief inverse L, the normalized final demand structure vector y_s, and total final demand y_{tot}, and no negative values were present in the variables entering the decomposition. Although individual components of the original final-demand accounts may contain negative values, such as changes in inventories, final demand was summed across both final-demand categories and destination economies before constructing the final-demand vector y. The resulting y and normalized y_s therefore contained no negative values in the years analyzed.

The sensitivity of the results to the small-value replacement was assessed by repeating the complete decomposition using constants of 10^{-10}, 10^{-15}, 10^{-20}, and 10^{-25}. No differences were observed in any of the four decomposition effects across these replacement values, indicating that the choice of the small-value constant had no observable effect on the reported results. This stability is consistent with Ang and Liu[29], who demonstrated that the small-value strategy can provide robust results when the selected constant is sufficiently small, particularly for Type I zero-changes. Given the demonstrated stability of the LMDI results, a complementary polar decomposition was not undertaken.

These numerical checks establish the stability of the decomposition results; however, the interpretation of the resulting effects differs across emissions categories. For direct emissions, the emission intensity effect reflects changes in emissions released directly by each sector per unit of output. For energy-related and supply chain-related emissions, the intensity effects represent changes in the corresponding embodied emissions per unit of sectoral output. Because these indirect-emissions intensities are constructed from the EEMRIO system, they may reflect not only changes in upstream direct emissions intensity but also changes in input composition, supplier sourcing, and upstream production linkages. The indirect-emissions intensity effects should therefore be interpreted as composite embodied-intensity effects rather than as pure measures of production efficiency. The economic system structure effect captures changes in inter-sectoral production system linkages, while the final demand structure and total final demand effects capture changes in the composition and overall scale of global final demand, respectively.

DATA

This study used Asian Development Bank (ADB) MRIO tables and corresponding Environmentally-Extended Multi-Regional Input-Output Tables (EE-MRIOT) satellite accounts covering 2017 to 2023[30,31]. The current-price MRIO tables correspond to the latest annual releases available at the time of the analysis, with release vintages ranging from August 2024 to August 2025. The environmental satellite accounts were taken from the August 2025 release. ADB specifies that the EE-MRIOTs are intended for use in conjunction with its MRIO tables[31]. ADB does not designate any year as estimated, preliminary, or provisional. For the LMDI-based SDA, the September 2025 release of the ADB MRIO tables at constant 2010 prices[32] was used to minimize the influence of price changes across years.

The full MRIO system covers 35 sectors across 72 economies and an aggregated RoW region. The system included nine ASEAN member economies with complete data, namely Brunei (BRU), Cambodia (CAM), Indonesia (INO), Laos (LAO), Malaysia (MAL), the Philippines (PHI), Singapore (SIN), Thailand (THA), and Vietnam (VIE). Myanmar was excluded because complete and comparable data required for the analysis were unavailable. Timor-Leste was also excluded due to unavailable data and because it was not yet a full ASEAN member during the study period, attaining full membership only in October 2025[33]. Accordingly, references to "ASEAN" for the remainder of the study denote ASEAN-9 unless otherwise specified. All non-ASEAN economies were aggregated into RoW.

Sectoral aggregation was performed to improve interpretability and align results with sector-level policy discussions[34]. Following standard IO aggregation practice described by Miller and Blair[10], the original 35 ADB sectors were consolidated into eight composite sectors: Agriculture, Forestry, and Other Land Use+ (AFOLU+), Mining and Quarrying (MINING), Manufacturing (MANUF), Energy (ENERGY), Construction (CONST), Trade (TRADE), Services (SERV), and Transport (TRANS). The detailed mapping of the original sectors into the eight aggregated sectors is provided in Supplementary Table 1. Food manufacturing was grouped under AFOLU+ to capture food-system-related production linkages, since dietary change and food supply chains are typically discussed within AFOLU-related mitigation pathways[12].

To assess the robustness of the estimated emissions trends, the results were compared with the Greenhouse Gas Footprints (GHGFP) 2025 edition: Emissions embodied in production by scope[35], based on the Organisation for Economic Co-operation and Development (OECD) Inter-Country Input-Output (ICIO) framework. The same nine ASEAN economies were aggregated over the common period 2017-2022. OECD Scope 1 represents direct production-based emissions from fuel combustion and industrial processes; Scope 2 represents upstream emissions embodied in domestic energy inputs; and Scope 3 upstream represents other indirect emissions embodied in intermediate inputs[36]. These indicators were compared with the direct, energy-related, and supply chain-related categories of this study, respectively, while OECD Scope 3 downstream was excluded. Direct household emissions were also excluded from both sides of the comparison. In the ADB EE-MRIOT, household emissions are reported separately from the emissions assigned to the 35 production sectors and were not included in the sectoral direct-emissions vector used in this study. Similarly, OECD Scope 1 in the production-by-scope dataset represents direct emissions from industries and excludes the separately accounted direct emissions of households. The correspondence is approximate rather than exact because OECD Scope 2 is limited to domestic energy inputs, whereas the energy-related category in this study captures the energy-related embodied emissions identified within the ADB MRIO system. Differences may also arise from the emissions sources, sectoral classifications, geographical structure, and construction of the two MRIO databases.

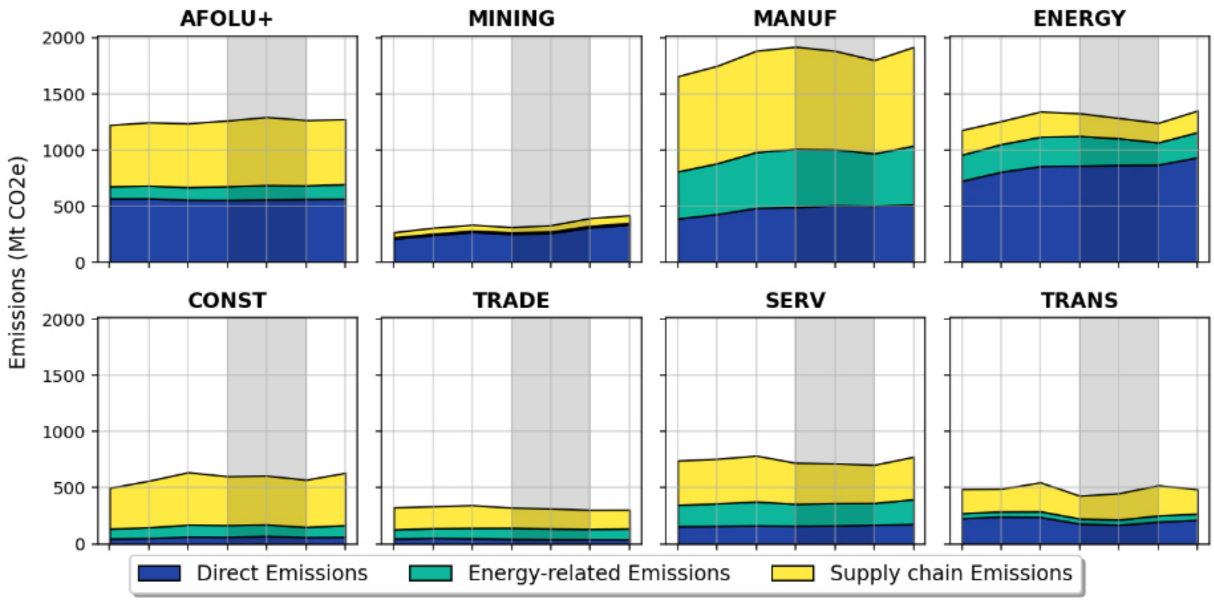

Figure 3. ASEAN sectoral emissions by category from 2017 to 2023. The shaded region denotes the pandemic period from 2020 to 2022. ASEAN: Association of Southeast Asian Nations; AFOLU+: agriculture, forestry, and other land use+; MINING: mining and quarrying; MANUF: manufacturing; ENERGY: energy; CONST: construction; TRADE: trade; SERV: services; TRANS: transport.

RESULTS

ASEAN emission trends

Recent ASEAN emissions dynamics are assessed using a category-based breakdown of sectoral GHG emissions from 2017 to 2023, separating direct emissions from energy-related and supply chain indirect emissions. Figure 3 presents ASEAN sectoral GHG emissions from 2017 to 2023 decomposed into direct emissions, energy-related indirect emissions, and other supply chain indirect emissions, with the shaded band indicating the pandemic period from 2020 to 2022. The corresponding annual sector-level numerical values for each emissions category are provided in Supplementary Table 2. From 2017 to 2023, ASEAN's GHG growth was strongly shaped by direct emissions and rapidly rising energy-related indirect emissions. Direct emissions increased by 19.76%, rising from 2,363.10 to 2,829.95 $MtCO_2e$, which outpaced the 7.83% increase in indirect emissions from 4,003.85 to 4,317.47 $MtCO_2e$. Within indirect emissions, energy-related indirect emissions grew more quickly, increasing by 16.72% from 1,176.48 to 1,373.17 $MtCO_2e$, while the remaining supply chain emissions showed more modest growth of 4.14%, rising from 2,827.37 to 2,944.30 $MtCO_2e$.

During the 2020-2022 pandemic period, the three emissions categories followed different trajectories. From 2019 to 2020, direct emissions declined by 76.59 $MtCO_2e$, or 2.87%, mainly because transport emissions fell by 58.43 $MtCO_2e$, followed by reductions in mining, trade, services, and construction. Supply chain-related emissions showed a larger decline of 159.83 $MtCO_2e$, or 5.18%, with the largest reductions occurring in transport, services, construction, trade, and energy. In contrast, energy-related emissions increased slightly by 19.37 $MtCO_2e$, or 1.44%, as increases in manufacturing, AFOLU+, and trade outweighed declines in services and transport.

The recovery after the pandemic was also uneven. By 2023, direct emissions were 5.92% above their 2019 level, mainly due to increases in mining and energy. Energy-related emissions also recovered and were 1.88% above 2019, with services contributing to the increase. Supply chain-related emissions, however, remained 4.49% below their 2019 level, mainly because manufacturing and mining had not fully returned to their

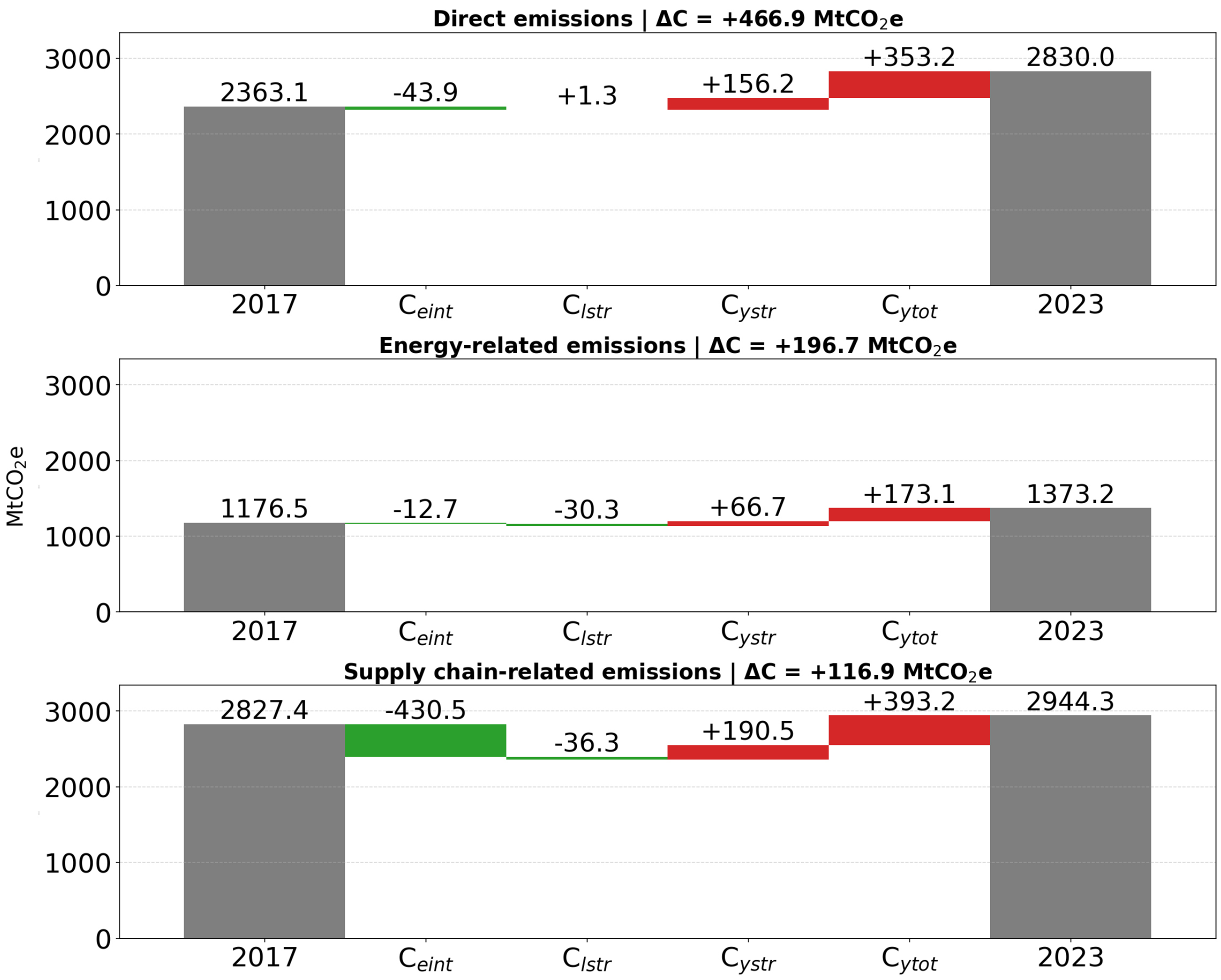

Figure 4. LMDI-Based SDA of ASEAN emissions by category. ASEAN: Association of Southeast Asian Nations; SDA: structural decomposition analysis; LMDI: logarithmic mean Divisia index.

earlier levels.

Figure 4 illustrates the LMDI-based structural decomposition results, identifying the drivers of emissions change across direct, energy-related, and supply chain-related emissions. The corresponding sector-level decomposition results are provided in Supplementary Table 3. The results show that ASEAN's emissions growth was largely driven by the expansion of global final demand, while the economic system structure had a comparatively smaller influence across all categories. For direct emissions, the increase of 466.85 $MtCO_2e$ was mainly driven by the total final demand effect, which contributed 353.20 $MtCO_2e$, followed by the final demand structure effect at 156.19 $MtCO_2e$. These increases were partly offset by the emission intensity effect, which reduced emissions by 43.86 $MtCO_2e$, indicating some improvement in direct emissions intensity.

Energy-related indirect emissions increased by 196.69 $MtCO_2e$. This growth was mainly driven by the total final demand effect at 173.06 $MtCO_2e$ and final demand structure effect at 66.72 $MtCO_2e$. In contrast, the emission intensity and economic system structure effects reduced emissions by 12.74 and 30.35 $MtCO_2e$, respectively. This indicates that growth in energy-related emissions was primarily demand-driven, while changes in energy-related emissions intensity and production linkages partly moderated the increase.

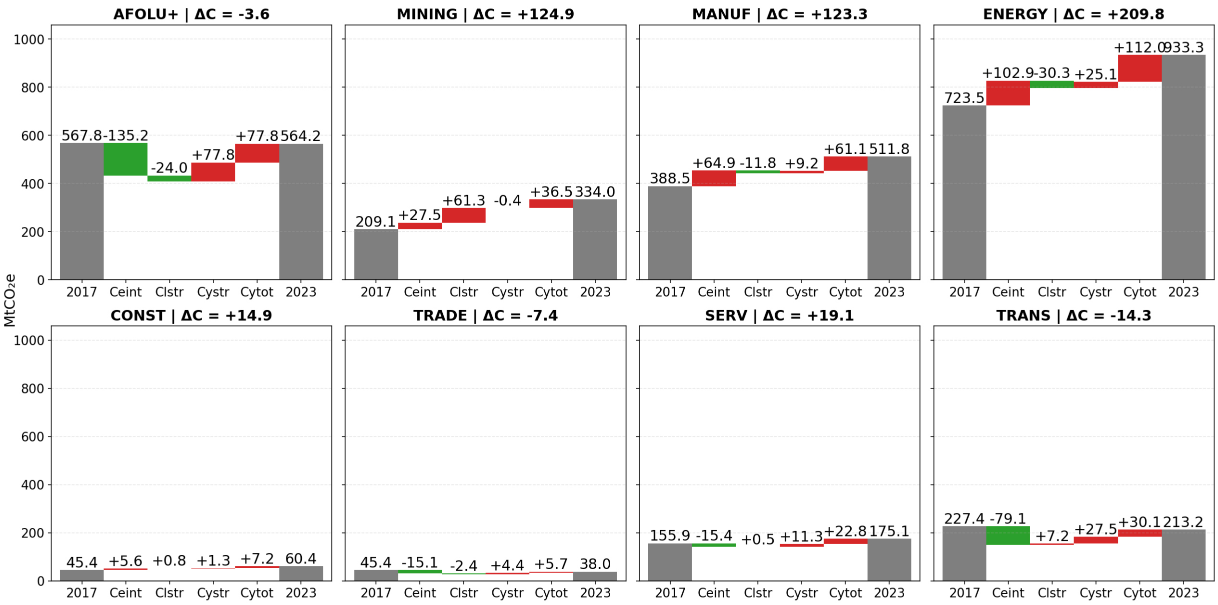

Figure 5. LMDI-Based SDA of ASEAN direct emissions by sector. ASEAN: Association of Southeast Asian Nations; SDA: structural decomposition analysis; AFOLU+: agriculture, forestry, and other land use+; MINING: mining and quarrying; MANUF: manufacturing; ENERGY: energy; CONST: construction; TRADE: trade; SERV: services; TRANS: transport; LMDI: logarithmic mean Divisia index.

Supply chain-related emissions increased by 116.93 $MtCO_2e$. The total final demand and final demand structure effects contributed 393.20 and 190.48 $MtCO_2e$, respectively, but these increases were largely offset by a strong negative emission intensity effect of 430.48 $MtCO_2e$ and a negative economic system structure effect of 36.27 $MtCO_2e$. This suggests that the negative composite supply chain-related embodied-intensity effect, together with changes in economic system structure, substantially limited the increase despite strong demand-driven pressures.

Sectoral emission trends and decomposition

ASEAN emissions exhibit distinct growth patterns across categories from 2017 to 2023. Figure 5 illustrates the sector-level results for direct emissions, showing how emission intensity, economic system structure, final demand structure, and total final demand contributed to each sector's change. The results show that the largest direct emissions increases were concentrated in the energy, mining, and manufacturing sectors. The energy sector recorded the largest absolute increase, with emissions rising by 209.76 $MtCO_2e$, mainly driven by the total final demand effect at 112.01 $MtCO_2e$ and the emission intensity effect at 102.92 $MtCO_2e$. This indicates that the sector's emissions growth was driven by both rising demand and higher direct emissions intensity. Mining and manufacturing also showed strong increases of 124.91 and 123.34 $MtCO_2e$, respectively. In mining, the economic system structure effect was the largest contributor at 61.26 $MtCO_2e$, suggesting that changes in production linkages increased demand for mining-related emissions. In manufacturing, the increase was mainly driven by emission intensity and total final demand effects, which contributed 64.89 and 61.10 $MtCO_2e$, respectively. In contrast, AFOLU+, trade, and transport recorded declines in direct emissions, largely because negative emission intensity effects offset positive demand-driven pressures. AFOLU+ emissions remained nearly stable because the large negative emission intensity effect of 135.18 $MtCO_2e$ counterbalanced the positive final demand structure and total final demand effects. Similarly, transport emissions decreased by 14.28 $MtCO_2e$, as the negative emission intensity effect of 79.13 $MtCO_2e$ outweighed increases from final demand structure and total final demand.

Figure 6 displays the sector-level results for energy-related indirect emissions, showing the drivers of changes in energy-related embodied emissions across ASEAN sectors. The largest increase occurred in

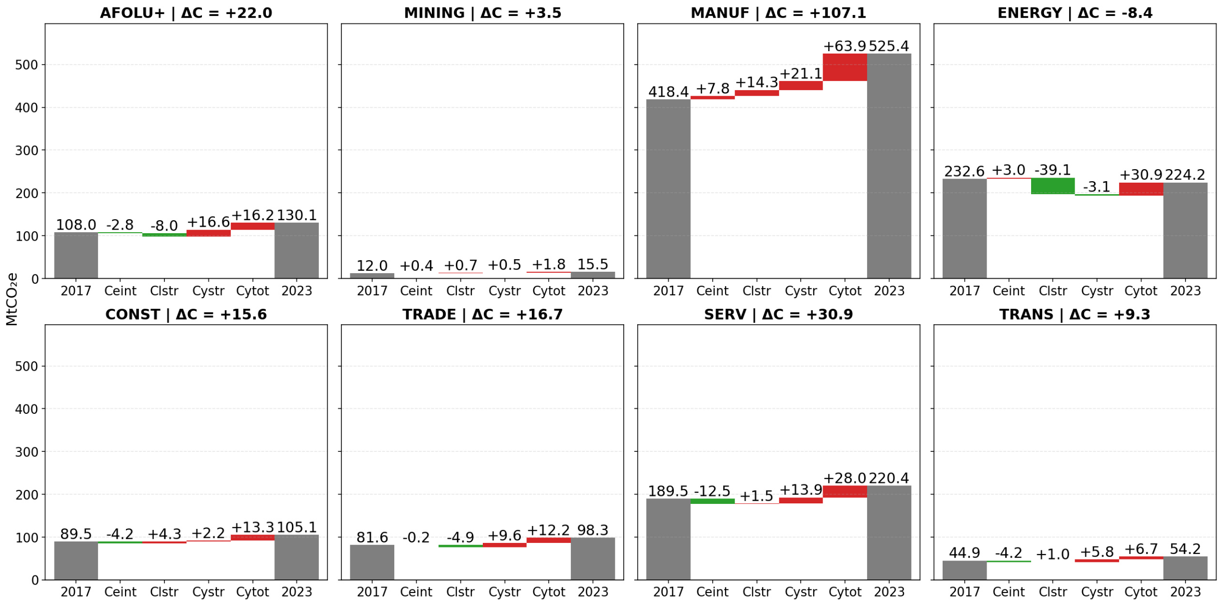

Figure 6. LMDI-Based SDA of ASEAN energy-related emissions by sector. ASEAN: Association of Southeast Asian Nations; SDA: structural decomposition analysis; AFOLU+: agriculture, forestry, and other land use+; MINING: mining and quarrying; MANUF: manufacturing; ENERGY: energy; CONST: construction; TRADE: trade; SERV: services; TRANS: transport; LMDI: logarithmic mean Divisia index.

manufacturing, which rose by 107.07 $MtCO_2e$. This increase was mainly driven by the total final demand effect at 63.91 $MtCO_2e$, followed by the final demand structure effect at 21.08 $MtCO_2e$ and the economic system structure effect at 14.32 $MtCO_2e$. This indicates that manufacturing's energy-related emissions growth was driven mainly by increasing demand and changes in production linkages. Services recorded the second-largest increase at 30.94 $MtCO_2e$, mainly due to the total final demand effect of 28.03 $MtCO_2e$ and the final demand structure effect of 13.94 $MtCO_2e$. These increases were partly offset by a negative emission intensity effect of 12.49 $MtCO_2e$. AFOLU+ also increased by 22.03 $MtCO_2e$, with positive final demand effects outweighing negative emission intensity and economic system structure effects. Trade, construction, transport, and mining recorded smaller increases that were also largely supported by total final demand growth. In contrast, the energy sector was the only sector to record a decline, decreasing by 8.41 $MtCO_2e$. This was mainly due to a negative economic system structure effect of 39.15 $MtCO_2e$, which more than offset the positive total final demand effect of 30.86 $MtCO_2e$.

Figure 7 presents the sector-level results for supply chain-related emissions, identifying how upstream embodied emissions changed across ASEAN sectors. The largest increase occurred in construction, which rose by 103.37 $MtCO_2e$, mainly driven by the total final demand effect at 56.60 $MtCO_2e$, supported by a positive emission intensity effect of 23.72 $MtCO_2e$ and economic system structure effect of 14.47 $MtCO_2e$. This suggests that construction-related supply chain emissions expanded because of both rising demand and higher composite embodied emissions intensity. AFOLU+ and manufacturing also recorded increases of 32.22 and 30.04 $MtCO_2e$, respectively, although both showed large negative emission intensity effects. In AFOLU+, the total final demand and final demand structure effects of 76.96 and 78.07 $MtCO_2e$ outweighed the negative emission intensity and economic system structure effects. Manufacturing showed a similar pattern, where the strong total final demand effect of 117.47 $MtCO_2e$ and positive final demand structure effect of 25.87 $MtCO_2e$ offset reductions from emission intensity and economic system structure. Mining also increased by 22.99 $MtCO_2e$, supported by positive effects across all four drivers. In contrast, trade, energy, and services recorded declines in supply chain-related emissions. Trade decreased by 30.39 $MtCO_2e$, mainly

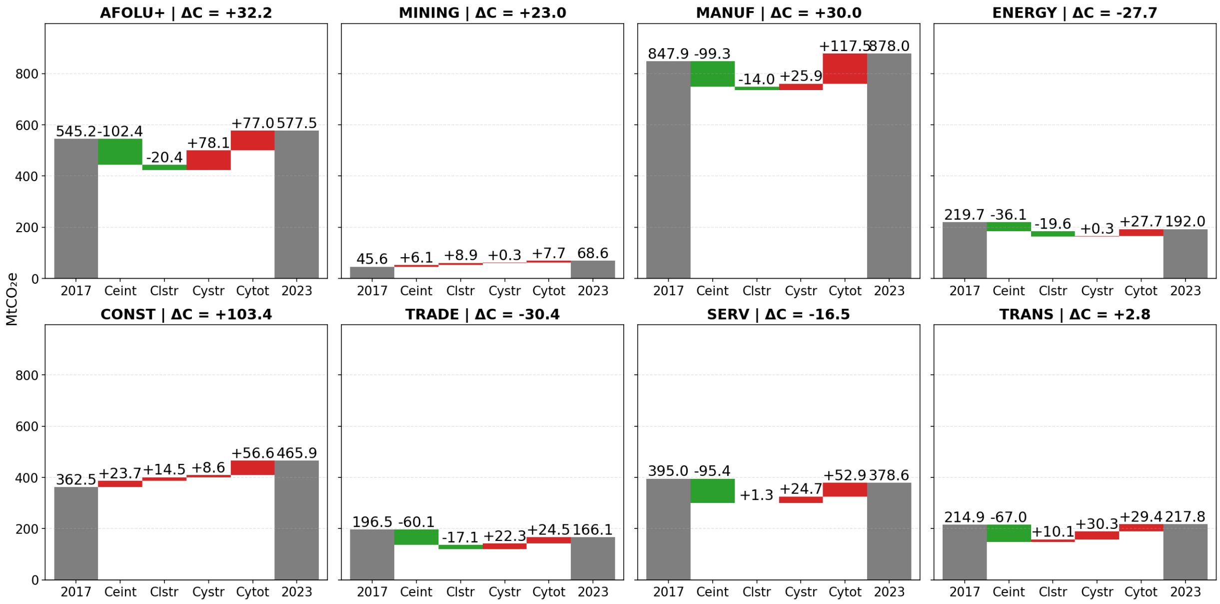

Figure 7. LMDI-Based SDA of ASEAN supply chain-related emissions by sector. ASEAN: Association of Southeast Asian Nations; SDA: structural decomposition analysis; AFOLU+: agriculture, forestry, and other land use+; MINING: mining and quarrying; MANUF: manufacturing; ENERGY: energy; CONST: construction; TRADE: trade; SERV: services; TRANS: transport; LMDI: logarithmic mean Divisia index.

because of a negative composite embodied-emission intensity effect of 60.11 $MtCO_2e$ and a negative economic system structure effect of 17.13 $MtCO_2e$. Energy declined by 27.67 $MtCO_2e$, while services decreased by 16.46 $MtCO_2e$, with both reductions also driven by negative composite embodied intensity effects.

Country-sector drivers of emissions change

Figure 8 presents the top three country-sector drivers and offsets, ranked by their net change in emissions between 2017 and 2023. The complete country-sector LMDI-based SDA matrices are provided in Supplementary Tables 4-6. The results below additionally highlight country-sector pairs with the largest individual decomposition effects. These effect-level rankings may differ from the net-change ranking shown in Figure 8. Rather than showing uniform changes across all countries, the results indicate that emissions growth was concentrated in specific country-sector pairs. Among the individual decomposition effects, the largest positive emission intensity effect was observed in Indonesia's energy sector, contributing 108.10 $MtCO_2e$, indicating that changes in the energy sector's emissions intensity were a major driver of ASEAN's direct emissions increase. Indonesia also showed a large positive economic system structure effect in mining at 64.15 $MtCO_2e$, suggesting that changing production linkages strengthened the role of mining-related emissions in the regional production system. Vietnam's manufacturing and Indonesia's energy sectors also contributed strongly to emissions growth, particularly through positive economic system structure and final demand effects. In contrast, AFOLU+ in Indonesia and Vietnam recorded large negative emission intensity effects of -50.58 and -42.11 $MtCO_2e$, respectively, while Singapore's transport sector showed a substantial negative emission intensity effect of -40.33 $MtCO_2e$. These negative effects indicate that improvements in emissions intensity in selected sectors helped moderate ASEAN's overall direct emissions growth.

For energy-related emissions, the largest net increase came from Vietnam's manufacturing sector, which rose by 112.75 $MtCO_2e$. This increase was supported by all four decomposition effects, with the economic system structure effect contributing the most at 39.52 $MtCO_2e$, followed by total final demand at 26.00 $MtCO_2e$, final

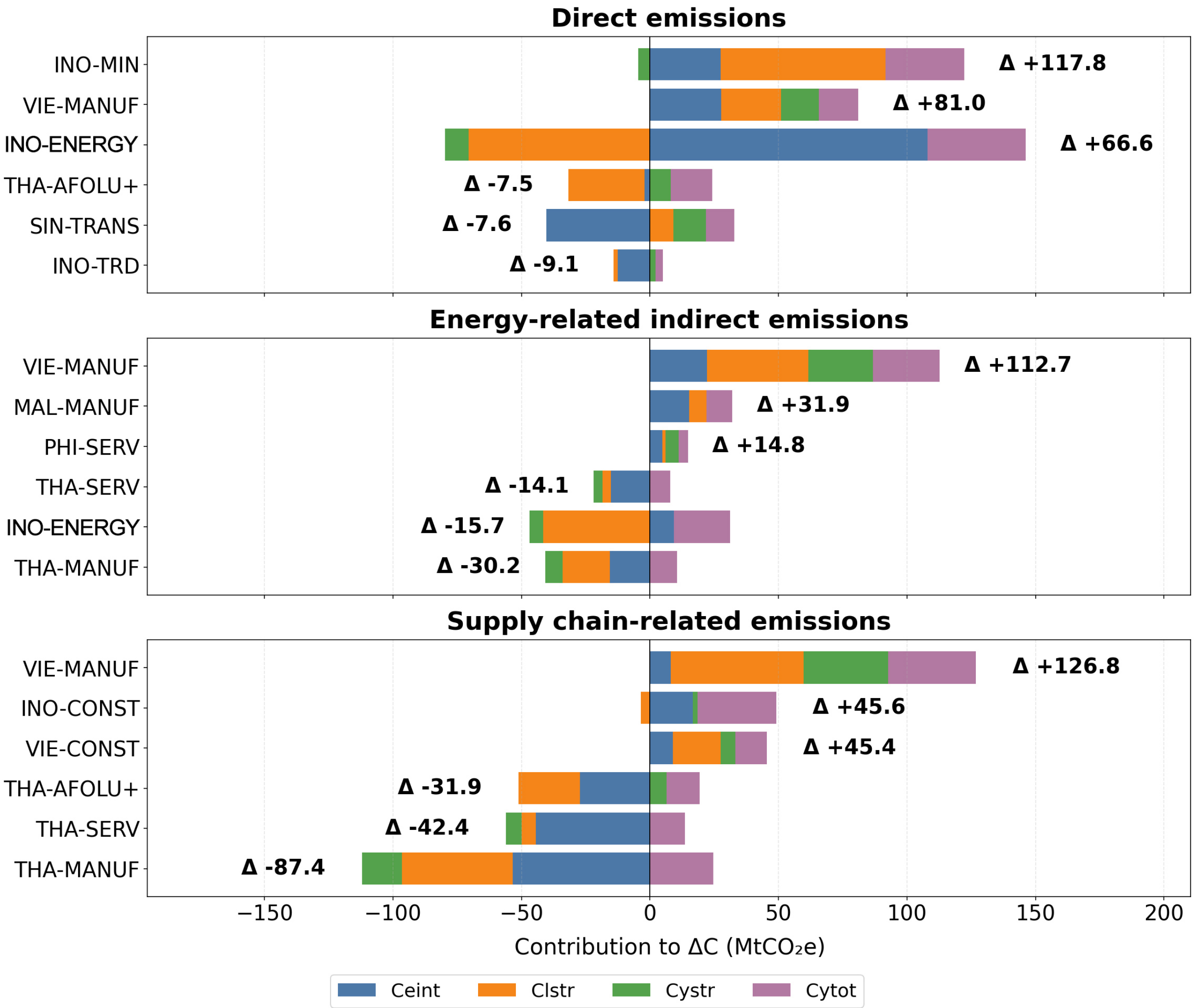

Figure 8. Top three country-sector drivers and offsets based on net emissions change from 2017 to 2023. INO: Indonesia; VIE: Vietnam; MANUF: manufacturing; THA: Thailand; AFOLU+: agriculture, forestry, and other land use+; SIN: Singapore; TRANS: transport; MAL: Malaysia; PHI: Philippines; SERV: services; CONST: construction; MIN: mining and quarrying; TRD: trade; ENERGY: energy.

demand structure at 25.12 $MtCO_2e$, and emission intensity at 22.11 $MtCO_2e$. Malaysia's manufacturing sector recorded the second-largest increase at 31.87 $MtCO_2e$, mainly driven by the emission intensity effect of 15.27 $MtCO_2e$ and total final demand effect of 10.12 $MtCO_2e$. The Philippines' services sector also increased by 14.81 $MtCO_2e$, supported by positive contributions from all four effects, particularly final demand structure and emission intensity. The largest net reductions occurred in Thailand's manufacturing sector, Indonesia's energy sector, and Thailand's services sector. Thailand's manufacturing sector declined by 30.21 $MtCO_2e$, mainly due to negative economic system structure and emission intensity effects of 18.43 and 15.65 $MtCO_2e$, respectively. Indonesia's energy sector decreased by 15.73 $MtCO_2e$, largely because of a strong negative economic system structure effect of 41.64 $MtCO_2e$ despite positive emission intensity and total final demand effects. Thailand services declined by 14.07 $MtCO_2e$, mainly due to a negative emission intensity effect of 15.21 $MtCO_2e$, together with negative economic system structure and final demand structure effects.

For supply chain-related emissions, the largest net increase occurred in Vietnam's manufacturing sector, which rose by 126.82 $MtCO_2e$. This increase was driven mainly by the economic system structure effect at 51.69 $MtCO_2e$, followed by total final demand at 34.06 $MtCO_2e$ and final demand structure at 32.92 $MtCO_2e$. Construction also emerged as a major source of growth in Indonesia and Vietnam, increasing by 45.57 and

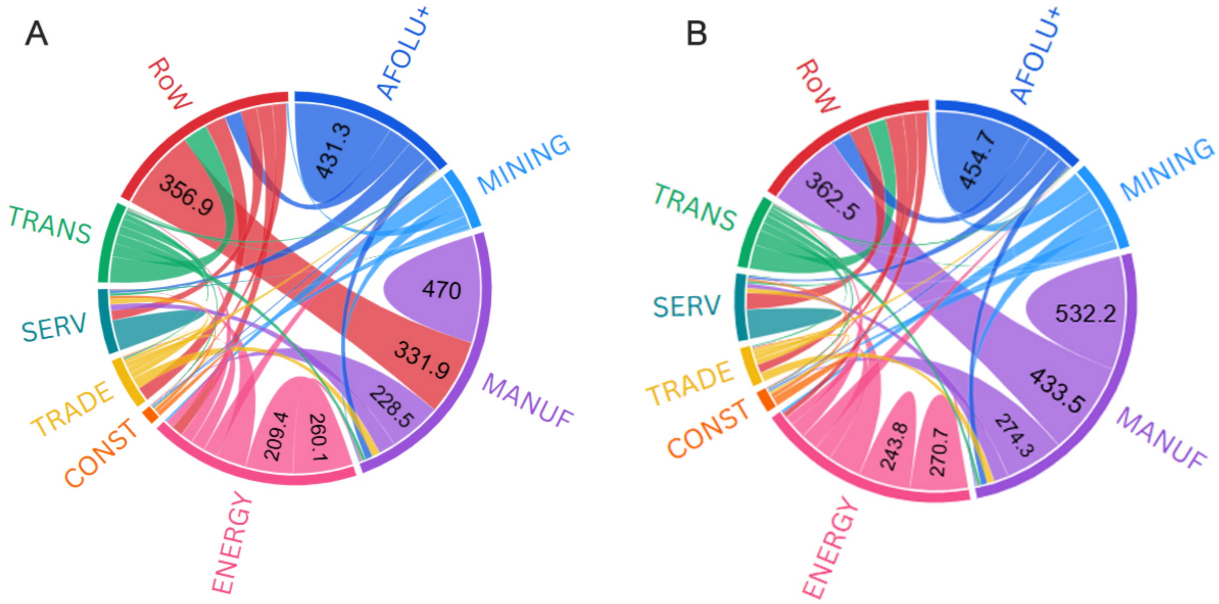

Figure 9. Embodied carbon flow through ASEAN sectors with RoW in (A) 2017 and (B) 2023 ($MtCO_2e$). ASEAN: Association of Southeast Asian Nations; RoW: rest of the world; AFOLU+: agriculture, forestry, and other land use+; MINING: mining and quarrying; MANUF: manufacturing; ENERGY: energy; CONST: construction; TRADE: trade; SERV: services; TRANS: transport.

45.42 $MtCO_2e$, respectively. In Indonesia, the construction increase was mainly driven by the total final demand effect of 30.58 $MtCO_2e$, while in Vietnam it was supported by positive economic system structure effect of 18.47 $MtCO_2e$. The largest net reductions occurred in Thailand's manufacturing, services, and AFOLU+ sectors. Thailand's manufacturing sector declined by 87.40 $MtCO_2e$, mainly because of negative emission intensity and economic system structure effects of 53.33 and 43.11 $MtCO_2e$, respectively. Thailand services decreased by 42.42 $MtCO_2e$, largely due to a negative emission intensity effect of 44.36 $MtCO_2e$, while Thailand AFOLU+ declined by 31.85 $MtCO_2e$ because negative emission intensity and economic system structure effects outweighed positive demand effects.

Embodied carbon flow for ASEAN

Tables 1 and 2 and Figure 9 present the embodied carbon flows across ASEAN sectors and RoW in 2017 and 2023. The corresponding sectoral embodied carbon flow matrices for 2017 and 2023 are provided in Supplementary Table 7. The embodied carbon flow table is organized like an input-output table: rows indicate the supplying sectors and columns indicate the purchasing sectors. Each entry (i,j) represents embodied emissions transferred from sector i to sector j through intermediate transactions. The main interior block therefore represents embodied emissions transferred through inter-industry transactions within ASEAN and between ASEAN and RoW. The bottom row reports sectoral direct emissions, F, and the right-most column reports embodied emissions associated with final demand, E_y, allowing the table to be read as a complete carbon flow account linking production, intermediate use, and final use. RoW-to-RoW transactions are excluded so that the tables capture domestic ASEAN flows, intra-ASEAN linkages, and ASEAN-RoW exchanges. For compact presentation in Tables 1 and 2, abbreviated sector labels are used: AFO, MIN, MNF, ERG, CON, TRD, SER, and TRN, corresponding respectively to AFOLU+, MINING, MANUF, ENERGY, CONST, TRADE, SERV, and TRANS.

Total embodied carbon transferred through intermediate transactions within ASEAN increased from approximately 3,166.44 $MtCO_2e$ in 2017 to 3,482.50 $MtCO_2e$ in 2023, an increase of 316.06 $MtCO_2e$ or 9.98%. Manufacturing-to-manufacturing remained the largest internal pathway, increasing from 470.03 to 532.22

Table 1. Embodied carbon flow of ASEAN sectors with RoW in 2017 ($MtCO_2e$)

	AFO	MIN	MNF	ERG	CON	TRD	SER	TRN	RoW	Ey
AFO	431.3	0.3	53.6	0.7	10.7	5.8	98.2	2.2	103.3	515.1
MIN	0.8	19.7	56.5	91.8	39.3	0.2	0.8	0.1	49.9	7.7
MNF	31.4	4.8	470.0	11.7	228.5	34.7	72.9	15.6	331.9	453.1
ERG	62.8	10.0	209.4	260.1	34.1	62.5	130.4	53.7	50.7	302.1
CON	4.4	3.8	2.0	2.2	20.8	8.5	15.3	3.0	1.2	436.2
TRD	25.3	1.5	48.4	6.6	22.4	14.3	27.4	7.7	61.3	108.5
SER	9.9	4.1	26.7	4.0	12.8	23.8	134.5	11.9	41.9	470.9
TRN	15.4	4.7	42.8	5.7	23.2	37.9	33.6	57.3	113.3	153.5
RoW	72.0	8.6	356.9	69.5	60.1	90.4	71.4	108.4	-	
Direct (F)	567.8	209.1	388.5	723.5	45.4	45.4	155.9	227.4		

ASEAN: Association of Southeast Asian Nations; RoW: rest of the world; AFO: agriculture, forestry, and other land use+; MIN: mining and quarrying; MNF: manufacturing; ERG: energy; CON: construction; TRD: trade; SER: services; TRN: transport.

Table 2. Embodied carbon flow of ASEAN sectors with RoW in 2023 ($MtCO_2e$)

	AFO	MIN	MNF	ERG	CON	TRD	SER	TRN	RoW	Ey
AFO	454.7	0.3	46.2	1.0	8.3	5.3	78.0	2.4	98.4	577.1
MIN	1.2	41.5	86.0	89.6	80.4	0.4	1.3	0.1	104.9	12.8
MNF	31.8	5.8	532.2	9.4	274.3	32.4	68.7	14.1	433.5	512.9
ERG	80.0	13.1	270.7	243.8	42.2	80.3	155.1	73.4	25.3	365.6
CON	4.5	4.9	4.4	2.8	40.9	10.3	20.3	4.3	4.3	534.7
TRD	21.9	1.6	42.0	7.8	17.4	12.2	25.2	7.2	40.3	126.7
SER	9.4	3.2	22.2	4.0	10.7	22.5	137.0	10.8	76.8	477.3
TRN	13.9	3.4	37.2	5.2	17.0	38.7	24.4	71.0	113.1	161.2
RoW	90.1	10.3	362.5	52.6	79.8	62.1	89.1	88.5	-	
Direct (F)	564.2	334.0	511.8	933.3	60.4	38.0	175.1	213.2		

ASEAN: Association of Southeast Asian Nations; RoW: rest of the world; AFO: agriculture, forestry, and other land use+; MIN: mining and quarrying; MNF: manufacturing; ERG: energy; CON: construction; TRD: trade; SER: services; TRN: transport.

$MtCO_2e$. Manufacturing-to-construction also increased from 228.54 to 274.34 $MtCO_2e$, while energy-to-manufacturing rose from 209.36 to 270.73 $MtCO_2e$. AFOLU+-to-AFOLU+ remained another major pathway, increasing from 431.31 to 454.69 $MtCO_2e$.

The largest absolute increases occurred in manufacturing-to-manufacturing and energy-to-manufacturing, which rose by 62.19 and 61.37 $MtCO_2e$, respectively. These were followed by manufacturing-to-construction, which increased by 45.80 $MtCO_2e$, and mining-to-construction, which increased by 41.03 $MtCO_2e$. In contrast, AFOLU+-to-services declined from 98.23 to 78.01 $MtCO_2e$, while energy-to-energy decreased from 260.13 to 243.76 $MtCO_2e$.

Manufacturing continued to occupy a central position in the embodied carbon network. Its total embodied carbon inflow from intermediate suppliers increased from approximately 1,266.28 to 1,403.38 $MtCO_2e$, while its intermediate outflow increased from approximately 1,201.68 to 1,402.31 $MtCO_2e$. Energy also remained an important upstream supplier, with its embodied intermediate outflow increasing from approximately 873.76 to 983.93 $MtCO_2e$.

Manufacturing also recorded the largest increase in embodied emissions associated with intermediate exports to RoW, rising from 331.87 $MtCO_2e$ in 2017 to 433.52 $MtCO_2e$ in 2023. These values represent emissions embodied in intermediate goods and services supplied by ASEAN sectors to production activities in RoW and do not include products delivered directly to foreign final demand. In contrast, energy recorded the largest decline in embodied exports, decreasing by 25.40 $MtCO_2e$ over the same period. On the import side, embodied emissions associated with intermediate imports from RoW represent emissions embodied in foreign intermediate inputs used by ASEAN production sectors. Construction, AFOLU+, and services showed the largest increases in these imported embodied emissions from RoW, rising by 19.67, 18.07, and 17.68 $MtCO_2e$, respectively. Trade recorded the largest decline in embodied imports, decreasing by 28.28 $MtCO_2e$.

Emissions embodied in final demand increased from approximately 2,447.02 $MtCO_2e$ in 2017 to 2,768.30 $MtCO_2e$ in 2023. In 2023, AFOLU+ recorded the largest value at 577.15 $MtCO_2e$, followed by construction at 534.72 $MtCO_2e$, manufacturing at 512.88 $MtCO_2e$, and services at 477.29 $MtCO_2e$. The largest increase occurred in construction, rising by 98.49 $MtCO_2e$, followed by energy, AFOLU+, and manufacturing, which increased by 63.53, 62.08, and 59.81 $MtCO_2e$, respectively.

Tables 3 and 4 and Figure 10 present the corresponding embodied carbon flows across the nine ASEAN economies and RoW. The corresponding country-level embodied carbon flow matrices for 2017 and 2023 are provided in Supplementary Table 8. Domestic transactions remained substantially larger than intra-ASEAN transactions in both years, indicating that ASEAN's embodied carbon structure continued to be organized mainly around national production systems. Indonesia recorded the largest domestic flow in both periods, increasing moderately from approximately 1,083.28 $MtCO_2e$ in 2017 to 1,099.16 $MtCO_2e$ in 2023. The largest increase occurred in Vietnam, where domestic embodied flows rose from 500.15 to 828.47 $MtCO_2e$. Malaysia also recorded a substantial increase, from 313.81 to 434.81 $MtCO_2e$. Thailand showed the largest decrease in domestic embodied flow, from 600.60 to 381.04 $MtCO_2e$.

Despite the growth of several domestic production flows, the largest intra-ASEAN pathways remained relatively small. In 2023, the leading cross-border exchanges included Malaysia-to-Singapore at 16.26 $MtCO_2e$ and Laos-to-Thailand at 12.34 $MtCO_2e$. Their limited size relative to the domestic flows of Indonesia, Vietnam, Malaysia, and Thailand indicates that intra-ASEAN embodied carbon exchanges remained secondary to within-country supply-chain activity.

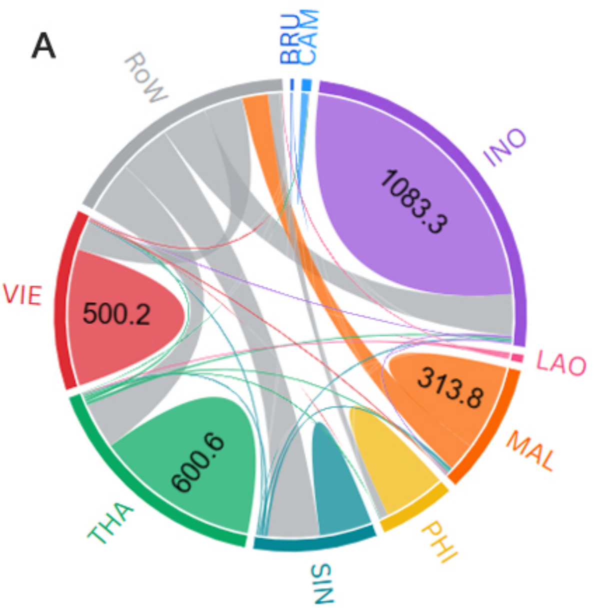

Figure 10. Embodied carbon flow through ASEAN countries with RoW in (A) 2017 and (B) 2023 ($MtCO_2e$). ASEAN: Association of Southeast Asian Nations; RoW: rest of the world; INO: Indonesia; LAO: Laos; MAL: Malaysia; PHI: Philippines; SIN: Singapore; THA: Thailand; VIE: Vietnam; BRU: Brunei; CAM: Cambodia.

ASEAN's embodied emissions in intermediate exports to RoW increased from approximately 753.49 $MtCO_2e$ in 2017 to 896.62 $MtCO_2e$ in 2023. In contrast, embodied emissions in intermediate imports from RoW remained broadly stable, decreasing slightly from approximately 837.41 to 834.97 $MtCO_2e$. The increase in exports was driven mainly by Vietnam, whose embodied exports to RoW rose from 103.38 to 182.63 $MtCO_2e$, and Indonesia, whose exports increased from 150.34 to 224.98 $MtCO_2e$. Considering intermediate trade only, Indonesia shifted from a net embodied import position of approximately 14.36 $MtCO_2e$ in 2017 to a net export position of 89.29 $MtCO_2e$ in 2023. Thailand similarly shifted from a net embodied import position of 23.45 $MtCO_2e$ to a net embodied export position of 10.65 $MtCO_2e$. Malaysia's net export position also increased from 11.49 to 25.57 $MtCO_2e$, while the Philippines' net import position widened from approximately 14.25 to 42.86 $MtCO_2e$.

Indonesia recorded the largest direct emissions and the largest emissions embodied in final demand in both 2017 and 2023. Its direct emissions increased from 886.18 to 1,116.29 $MtCO_2e$, while its embodied final demand increased from approximately 896.50 to 1,015.36 $MtCO_2e$. Vietnam also recorded a large increase in embodied final demand, rising from approximately 405.77 to 528.52 $MtCO_2e$, together with a substantial increase in direct emissions from 358.28 to 512.91 $MtCO_2e$.

Cross-database comparison of emissions estimates

Table 5 compares the ASEAN emissions estimates from the ADB EEMRIO framework with the Greenhouse Gas Footprint Indicators over the common period 2017-2022. The closest agreement is observed for direct emissions. Although the ADB estimates are 5.01%-10.51% higher than the OECD values, both datasets show increasing emissions from 2017 to 2019, a decline in 2020, and a subsequent recovery. Both datasets also capture similar pandemic-period movements: direct emissions declined by 2.87% in the ADB results and 3.71% in the OECD estimates from 2019 to 2020, while energy-related emissions remained relatively stable.

Larger differences are observed for the indirect categories. The ADB energy-related estimates are 42.33%-63.49% higher than the corresponding OECD Scope 2 values, while the ADB supply chain-related estimates are 6.61%-22.40% lower than OECD Scope 3 upstream emissions. However, when the two indirect categories are combined, the differences between the databases are considerably smaller during 2017-2020. In 2017, total indirect emissions differed by 6.85%. This difference narrowed to 2.97% in 2018, 2.43% in 2019, and 0.91% in 2020. The databases then diverged, with ADB total indirect emissions 1.58% lower than OECD in 2021 and 10.09% lower in 2022.

The contrasting differences partly arise from how the two frameworks partition upstream energy emissions. OECD Scope 2 is restricted to emissions embodied in domestic energy inputs, while other upstream emissions remain within Scope 3 upstream[36], whereas the energy-related category in this study traces emissions originating from the IPCC Main Activity Electricity and Heat Production source category through the full multiregional production network. This broader boundary may shift a larger share of upstream emissions into the energy-related category, contributing to the higher ADB energy-related estimates and lower supply chain-related estimates relative to OECD. The smaller differences observed when the two indirect categories are combined, particularly during 2017-2020, indicate that category allocation accounts for part of the observed discrepancy. However, the combined indirect estimates begin to diverge after 2020, with ADB estimates 1.58% lower in 2021 and 10.09% lower in 2022. This residual difference cannot be attributed solely to the allocation of emissions between indirect categories. The ADB direct-emissions estimates are also consistently 5.01%-10.51% higher than the OECD estimates, indicating differences in the underlying emissions satellite accounts. These differences, together with variation in sectoral allocation and the production structures represented by the ADB MRIO and OECD ICIO systems, can propagate through the Leontief framework and affect the resulting indirect emissions estimates.

DISCUSSION

The results reveal how ASEAN's emissions are shaped by the interaction of economic growth, sectoral production structures, and embodied carbon flows. Rather than showing a single emissions pattern across the region, the findings indicate that emissions are distributed unevenly across categories, sectors, and countries. The decomposition results identify the main drivers of emissions change over time, while the embodied carbon flow analysis shows how emissions are transmitted through production networks and trade linkages.

Demand-driven emissions growth and partial intensity improvements

Global final demand expansion was the dominant source of emissions growth across the three categories, indicating that increases in the overall scale of demand increased production requirements and associated emissions within ASEAN. This pattern is consistent with the broader challenge of reducing emissions intensity while economic demand continues to expand, but the present decomposition does not directly evaluate decoupling between GDP growth and emissions. This finding is consistent with Zhang *et al.*[19], who found no aggregate decoupling between economic growth and carbon emissions in ASEAN over the past two decades.

The negative intensity effects across all three emissions categories indicate lower emissions per unit of sectoral output, although their interpretation differs by category. For direct emissions, the negative intensity effect reflects a reduction in emissions released directly per unit of output. For energy-related and supply chain-related emissions, the negative effects represent reductions in embodied emissions intensity rather than pure production-efficiency improvements. Because these indirect intensities are constructed through the EEMRIO system, they may reflect cleaner upstream production as well as changes in input composition, supplier sourcing, and upstream production linkages. The particularly large negative supply chain-related

Table 3. Embodied carbon flow of ASEAN countries with RoW in 2017 ($MtCO_2e$)

	BRU	CAM	INO	LAO	MAL	PHI	SIN	THA	VIE	RoW	Ey
BRU	6.8	0.0	0.0	0.0	2.4	0.0	0.1	0.2	0.0	1.1	8.9
CAM	0.0	26.5	0.0	0.0	0.4	0.0	0.1	1.4	1.1	4.0	45.4
INO	0.0	0.1	1,083.3	0.0	9.4	5.3	6.6	8.3	3.2	150.3	896.5
LAO	0.0	0.1	0.0	11.3	0.0	0.0	0.0	11.7	1.1	2.9	22.8
MAL	0.9	0.2	4.9	0.0	313.8	2.8	11.6	7.2	3.9	106.0	257.5
PHI	0.0	0.0	0.4	0.0	1.5	226.9	1.9	2.2	0.7	29.3	240.0
SIN	0.3	1.0	9.3	0.2	11.8	3.3	193.6	10.6	8.1	188.1	135.3
THA	0.1	2.0	11.9	3.1	10.2	5.5	4.2	600.6	11.2	168.3	434.9
VIE	0.0	3.5	2.5	0.5	4.1	2.7	4.2	3.3	500.2	103.4	405.8
RoW	1.2	7.1	164.7	2.2	94.5	43.5	190.2	191.8	142.2	-	
Direct (F)	10.2	38.4	886.2	32.5	260.6	213.0	149.2	414.8	358.3		

ASEAN: Association of Southeast Asian Nations; RoW: rest of the world; BRU: Brunei; CAM: Cambodia; INO: Indonesia; LAO: Laos; MAL: Malaysia; PHI: Philippines; SIN: Singapore; THA: Thailand; VIE: Vietnam.

Table 4. Embodied carbon flow of ASEAN countries with RoW in 2023 ($MtCO_2e$)

	BRU	CAM	INO	LAO	MAL	PHI	SIN	THA	VIE	RoW	Ey
BRU	4.5	0.0	0.2	0.0	0.3	0.4	0.9	0.2	0.3	3.6	10.7
CAM	0.0	28.9	0.1	0.0	0.1	0.0	0.3	0.4	4.3	10.7	58.0
INO	0.2	0.4	1,099.2	0.0	8.3	8.2	8.4	7.9	5.2	225.0	1,015.4
LAO	0.0	3.3	0.0	17.0	0.0	0.0	0.2	12.3	3.6	5.8	22.9
MAL	0.7	0.2	4.4	0.0	433.8	2.5	16.3	4.9	2.9	104.6	271.7
PHI	0.0	0.0	0.6	0.0	0.8	246.4	1.5	1.4	0.7	36.7	302.5
SIN	0.3	0.4	9.1	0.0	8.4	3.9	232.0	6.4	3.9	165.8	160.7
THA	0.1	4.9	8.2	4.5	7.0	4.6	7.6	381.0	9.2	161.9	397.9
VIE	0.2	4.4	4.6	0.5	3.5	6.8	4.6	5.6	828.5	182.6	528.5
RoW	3.4	14.0	135.7	1.6	79.0	79.5	172.3	151.3	198.3	-	
Direct (F)	11.6	46.3	1,116.3	41.4	300.8	238.3	146.8	415.5	512.9		

ASEAN: Association of Southeast Asian Nations; RoW: rest of the world; BRU: Brunei; CAM: Cambodia; INO: Indonesia; LAO: Laos; MAL: Malaysia; PHI: Philippines; SIN: Singapore; THA: Thailand; VIE: Vietnam.

Table 5. Comparison of ASEAN emissions estimates from the ADB EEMRIO and OECD greenhouse gas footprint databases, 2017-2022 ($MtCO_2e$)

	Direct		Energy-related		Supply chain-related		Total indirect	
	ADB	OECD	ADB	OECD	ADB	OECD	ADB	OECD
2017	2,363.10	2,182.40	1,176.48	719.61	2,827.37	3,027.42	4,003.85	3,747.03
2018	2,546.54	2,324.29	1,249.23	782.33	2,897.39	3,244.70	4,146.62	4,027.03
2019	2,671.75	2,438.84	1,347.81	876.16	3,082.82	3,449.19	4,430.63	4,325.35
2020	2,595.16	2,348.42	1,367.18	876.44	2,922.99	3,375.24	4,290.17	4,251.68
2021	2,626.68	2,413.14	1,323.41	846.49	2,920.17	3,465.22	4,243.58	4,311.71
2022	2,705.05	2,576.05	1,229.58	863.90	2,856.24	3,680.67	4,085.82	4,544.57

ASEAN: Association of Southeast Asian Nations; ADB: Asian Development Bank; EEMRIO: environmentally extended multi-regional input-output; OECD: Organisation for Economic Co-operation and Development.

intensity effect therefore indicates a substantial reduction in embodied upstream emissions per unit of sectoral output. However, these intensity-side reductions were not sufficient to offset the emissions pressure from expanding final demand. This reflects a scale mechanism in which the additional ASEAN production required to satisfy growing global final demand outweighed reductions in emissions intensity. Similar ASEAN-focused studies report that energy efficiency and fuel-mix improvements can slow emissions growth but are generally insufficient to offset rising economic activity and energy demand[18].

The pandemic-period changes also appear to reflect temporary disruption rather than structural decarbonization. Reductions in mobility and economic activity during COVID-19 resulted in substantial but largely temporary declines in emissions[37]. The subsequent recovery of direct and energy-related emissions in the ADB-based estimates suggests that much of this reduction was reversed as economic activity resumed, consistent with the rapid rebound of global emissions toward pre-pandemic levels[38]. Supply chain-related emissions followed a slower recovery in the ADB results, remaining below their 2019 level through 2023. This pattern may reflect changes in intermediate input use, sourcing patterns, and the restoration of international production networks following the pandemic[39]. However, this interpretation is database-dependent, as the OECD Scope 3 upstream estimates show a stronger post-2020 increase in upstream emissions. The post-pandemic trajectory should therefore be interpreted cautiously and does not provide sufficient evidence of a fundamental structural change in ASEAN's upstream emissions system.

Sectoral responsibility across emissions categories

The simultaneous growth of direct and energy-related indirect emissions indicates that ASEAN's emissions remain closely connected to both carbon-intensive production and dependence on fossil-based energy inputs. The negative energy-related intensity effect indicates that embodied energy-related emissions intensity declined over the study period. The reduction may reflect lower emissions from upstream electricity and heat production, shifts toward suppliers with lower energy-related footprints, or changes in the composition of intermediate inputs. The continued increase in total energy-related emissions therefore appears to have been driven more by expanding economic activity and final demand than by worsening energy intensity. This pattern is consistent with earlier ASEAN studies showing that economic growth, population change, and fossil energy use remain major drivers of emissions, even when efficiency gains help moderate emissions growth[40]. Regional decarbonization therefore requires both cleaner production and energy systems and measures that address the growing scale of energy and material demand.

The distribution of emissions categories also varies strongly by sector. Energy and mining are dominated by direct emissions because these activities involve direct fuel combustion or process-related emissions. More importantly, these upstream sectors also form a large part of the carbon footprints of downstream sectors through electricity and raw materials. Manufacturing, construction, and services therefore tend to exhibit larger indirect emissions, reflecting their downstream position in the production network and their dependence on carbon-intensive upstream activities. Prior work similarly shows that complex industries can have carbon footprints dominated by supply-chain emissions, demonstrating the importance of accounting for indirect emissions across the full production network[41]. This supports the use of a category-based accounting framework, since direct emissions alone would understate the carbon responsibility of downstream sectors that drive upstream emissions.

Country-sector concentration of emissions drivers

The concentration of emissions growth in a small number of country-sector combinations indicates that ASEAN's regional trend is strongly influenced by national production structures and development pathways. In Indonesia, the importance of the energy and mining sectors is consistent with an economy that remains dependent on fossil fuels and resource extraction. Coal, oil, and natural gas continue to account for a substantial share of the country's energy mix[42], while critical minerals such as nickel and other mineral commodities occupy important positions in domestic and international production chains[43]. This creates a trade-off in which expanding mineral processing can support economic growth and low-carbon technologies while also increasing emissions from extraction, processing, and energy use.

Vietnam's pattern reflects a different development pathway, where rapid industrialization and export-oriented manufacturing have increased dependence on electricity, industrial inputs, and upstream supply chains. The country's historical reliance on coal-based generation further increases the carbon implications of manufacturing growth[44]. As Vietnam becomes more integrated into global manufacturing networks[45], growth in sectors such as electronics, machinery, textiles, and other export-oriented industries can increase demand for energy, materials, transport, and intermediate inputs throughout the domestic and international supply chain. This dependence on carbon-intensive energy and upstream inputs may increasingly affect Vietnam's export competitiveness as major markets and multinational buyers place greater emphasis on the carbon intensity of traded products[46,47].

The construction-related supply-chain effects in Indonesia and Vietnam highlight the upstream carbon implications of infrastructure development and urbanization. Construction itself may have relatively limited direct emissions, but it induces substantial production of cement, steel, electricity, transport, and other carbon-intensive inputs[48]. Indonesia's infrastructure expansion and project pipeline[49] and Vietnam's urban growth and rising demand for construction materials[50] help explain the prominence of construction in supply-chain-related emissions.

Thailand provides a contrasting case, where changes in production efficiency, input use, or supply-chain organization may have helped limit emissions growth despite continued demand pressures. This suggests that emissions mitigation can result from improving efficiency within individual sectors and from changes in how sectors source and combine intermediate inputs. This is consistent with previous evidence that efficiency improvements have partly offset emissions associated with rising consumption in Thailand[51]. Thailand therefore illustrates how efficiency gains and changes in production structure can partially separate industrial growth from corresponding increases in embodied emissions.

Evolution of embodied carbon flows

The comparison between 2017 and 2023 indicates both persistence and intensification in ASEAN's embodied carbon structure. Manufacturing remained the central redistribution hub because it simultaneously absorbed carbon-intensive electricity, materials, and industrial inputs and supplied intermediate products to construction, services, and external markets. Its centrality lies in its intermediate position within the production network, where embodied carbon is accumulated from upstream sectors and redistributed through processed outputs to multiple downstream users. Strong manufacturing-to-manufacturing linkages further show that emissions were transmitted through multiple stages of processing before products reached final users. Rather than reflecting a complete restructuring of the regional production network, the results indicate that several existing carbon-intensive linkages became larger and more influential over time. This pattern is consistent with ASEAN's role as a major production base in global value chains[4] and with broader evidence that industry is an important source and transmitter of supply-chain emissions[12].

Energy occupied a more upstream position because the carbon intensity of electricity and fuel inputs affected emissions throughout the production network. Construction represented a different type of leverage point, as much of its emissions exposure originated from demand for cement, steel, transport, electricity, and other carbon-intensive inputs rather than from direct sectoral emissions. Previous footprint studies likewise show that indirect emissions account for a substantial share of construction and industrial carbon footprints[48,52]. These network positions suggest that mitigation should combine cleaner energy supply, lower-carbon industrial production, material efficiency, and procurement strategies targeting embodied emissions.

At the country level, domestic embodied intermediate flows remained substantially larger than intra-ASEAN intermediate flows, indicating that upstream production requirements are still organized predominantly within national supplier networks. This implies that ASEAN's embodied production emissions remain strongly conditioned by domestic energy systems, material suppliers, and industrial structures rather than by intra-regional sourcing alone. The continued dominance of Indonesia and the substantial growth of domestic flows in Vietnam therefore reflect not only their larger production bases but also the concentration of resource- and manufacturing-intensive linkages within their national supply chains. However, these patterns should not be interpreted as simple rankings of environmental performance, since embodied carbon flows are also influenced by economic scale, sectoral specialization, and trade orientation. The results therefore reinforce the need to treat ASEAN as a heterogeneous production system rather than a uniform economic bloc.

RoW-linked intermediate flows further reveal ASEAN's position within global production networks. Intermediate imports represent foreign embodied emissions entering ASEAN production through imported inputs, while intermediate exports represent ASEAN embodied emissions passed onward into production activities outside the region. The increase in embodied intermediate exports therefore indicates a growing upstream role for ASEAN industries within global value chains rather than necessarily an increase in emissions embodied in goods delivered directly to foreign consumers. Indonesia's shift from a net embodied intermediate-import position to a net intermediate-export position suggests a stronger role as an upstream supplier of carbon-intensive intermediate products, while Vietnam's growing intermediate exports are consistent with its expanding manufacturing integration into global production networks. In contrast, the widening intermediate-import position of the Philippines indicates greater dependence of domestic production on foreign upstream inputs. Although ASEAN's total embodied intermediate imports from RoW remained broadly stable, differences across countries and sectors suggest that foreign upstream-carbon dependence was redistributed rather than uniformly reduced. Regional emissions therefore cannot be understood solely through domestic or intra-ASEAN relationships, as both imported intermediate inputs and external demand shape the carbon intensity of production[17,20]. ASEAN decarbonization must therefore address persistent domestic production structures while also responding to the influence of global demand and international supply chains.

Differences in emissions estimates

The post-2020 divergence in total indirect emissions reported in the cross-database comparison indicates that differences in category allocation alone cannot fully explain the variation between the two databases. Differences in the construction of the underlying emissions accounts may also contribute. Although the two systems draw partly on common emissions sources such as the Emissions Database for Global Atmospheric Research (EDGAR), their emissions data are constructed differently. The ADB EE-MRIOT integrates EDGAR-based GHG inventories with energy-balance, transport, and tourism accounts[31], whereas the OECD GHG Footprint framework primarily draws on Air Emissions Accounts and supplements data gaps with sources including EDGAR, International Energy Agency (IEA), and United Nations Framework Convention on Climate Change (UNFCCC)[36]. These differences are then propagated through different interindustry structures represented by the ADB MRIO and OECD ICIO systems, causing the resulting indirect emissions estimates to diverge further. Indirect emissions are particularly sensitive to these differences because they depend not only on the direct emissions assigned to each sector but also on the intermediate production requirements linking sectors and economies.

Previous studies have shown that MRIO-based estimates can vary because of differences in economic structure, underlying emissions data, emissions-allocation procedures, and overall database construction[53]. Carbon multipliers may also be affected by sector aggregation and background-system detail, as activities grouped within the same broad sector can have substantially different emissions characteristics[54]. Thus, the similar temporal pattern in direct emissions across the two databases provides some confidence in the broad production-based trend, while differences in absolute direct-emissions levels and the post-2020 divergence in combined indirect emissions demonstrate that the magnitudes of upstream emissions remain database-sensitive. Indirect emissions estimates should therefore be interpreted primarily as model-based measures of upstream dependencies, sectoral patterns, and mitigation leverage points rather than as directly interchangeable inventories across MRIO databases.

Implications for ASEAN decarbonization strategy

The results suggest that ASEAN decarbonization strategies should address both direct production emissions and supply-chain pathways. Growth in global final demand can offset improvements in ASEAN production efficiency, meaning that supply-side measures should be complemented by interventions influencing procurement, material use, consumption, and investment. Even where carbon capture and utilization technologies are considered, both direct and indirect emissions remain relevant to identifying mitigation opportunities across production systems[55,56]. Indirect emissions accounting is therefore useful for locating intervention points beyond the sectors in which emissions physically occur[12].

Among these interventions, grid decarbonization is especially important because the carbon intensity of electricity also affects the embodied emissions of manufacturing, services, construction, agriculture, and traded products. Cleaner power systems can reduce emissions simultaneously across several downstream activities. This may also influence the competitiveness of ASEAN producers as international markets increasingly consider product carbon intensity and supply-chain transparency[47]. However, relocating production to economies with cleaner grids should not substitute for decarbonizing electricity systems throughout the region.

The findings demonstrate that ASEAN's embodied carbon flows through intermediate production chains are dominated by domestic production chains. This static snapshot, however, serves as a baseline for an evolving regional trade dynamic. If regional and global production linkages continue to deepen, cross-border embodied carbon flows may become increasingly important for ASEAN decarbonization strategies. Establishing proactive regional coordination mechanisms is therefore critical to prevent intra-regional carbon leakage before cross-border supply chain flows solidify. Moreover, regional cooperation is necessary to harmonize carbon accounting systems, facilitate technology transfer, and establish unified decarbonization standards - enabling ASEAN to collectively navigate external trade policies while maintaining competitive, low-carbon regional supply chains.

A uniform regional policy would be insufficient because the principal emissions drivers differ across countries and sectors. These regional efforts should be complemented by nationally tailored strategies that target each economy's dominant emissions categories and sectoral drivers[14,15,18,40]. In particular, the results revealed concerns regarding the surge in carbon emissions across specific sectors among member states - most prominently within Indonesia's mining sector and Vietnam's manufacturing sector. For Indonesia's mining sector, the surge in direct emissions was driven by the economic system structure effect and total final demand growth, indicating a demand-driven trend. This trajectory is consistent with Indonesia's downstream mineral processing ("hilirisasi") policy, which prohibits raw ore exports, resulting in a substantial surge in domestic processing demand. This development may provide context for the observed demand-related growth of the aggregated mining sector. This creates a policy trade-off. While mining is a critical enabler of the global green transition - supplying over half of the world's nickel[57] - it remains tied to a carbon-heavy extraction and smelting process. Consequently, supply-side interventions alone (e.g., installing on-site renewable energy technologies) will be insufficient to fully offset the demand-driven momentum. To effectively curb the industry's expanding emissions footprint, supply-side efforts must be strongly coupled with demand-side governance frameworks, such as green public procurement standards and secondary mineral circularity mechanisms.

Vietnam's manufacturing results suggest that its emissions growth is linked to both how goods are produced and how rapidly the industrial system is expanding. Rising direct emissions point to increased carbon intensity within manufacturing activities, while the growth of energy-related and supply chain-related emissions indicates that industrial expansion is also increasing demand for electricity, materials, transport, and other upstream inputs. Vietnam's continued reliance on fossil-based energy, particularly coal and oil, increases the carbon implications of this industrial growth[58]. At the same time, rapid economic expansion and deeper integration into global production networks have increased the scale and complexity of manufacturing activity[45]. The carbon intensity of export-oriented production may become increasingly relevant as major markets implement carbon-related trade measures, including the European Union's Carbon Border Adjustment Mechanism (CBAM)[59]. Consequently, mitigating these emissions requires a dual policy approach - decarbonizing supply-side energy (e.g., accelerating renewable energy integration into the power mix) and strengthening supply chain governance (e.g., expanding eco-industrial parks and incentivizing green freight logistics) to balance economic growth with environmental sustainability.

The findings reinforce the relevance of ASEAN's current policy direction. The ASEAN Strategy for Carbon Neutrality[60] emphasizes green value-chain integration, circular economy supply chains, and green industry development. The Action Plan for Sustainable Agriculture in ASEAN[61] and ASEAN AgriTrade initiatives[62,63] support low-carbon agriculture, renewable energy use in agricultural systems, food loss reduction, and sustainable agri-food value chains. The ASEAN Renewable Energy Long-term Roadmap[64] and the ASEAN Power Grid[65] are especially important because grid decarbonization can reduce emissions across multiple sectors and countries. The results support a coordinated approach that combines grid decarbonization, sector-specific mitigation, supply-chain management, circular material use and nationally differentiated implementation.

CONCLUSIONS

This study provides an assessment of ASEAN's direct and indirect emissions and identifies the structural drivers and embodied carbon pathways underlying regional emissions change. Direct, energy-related, and supply chain-related emissions were quantified using an EEMRIO model, while emission changes were decomposed using an LMDI-based SDA framework into emission intensity, economic system structure, final demand structure, and total final demand effects. Embodied carbon flows were mapped across ASEAN sectors, member economies, and RoW. The results show that ASEAN emissions growth was mainly driven by global final-demand expansion, indicating that growth in the overall scale of demand increased production requirements and associated carbon emissions within ASEAN. Negative emission intensity effects across all three categories partly offset emissions growth. For the indirect categories, these effects represent reductions in composite embodied emissions intensity and may reflect changes in upstream emissions intensity, input composition, supplier sourcing, and production linkages. However, these gains were not sufficient to offset the emissions pressure associated with expanding global final demand.

The sectoral and country-sector results show that emissions growth was concentrated in specific production systems rather than evenly distributed across ASEAN. Direct emissions growth was driven mainly by energy, mining, and manufacturing, particularly within Indonesia's energy and mining sectors. Vietnam's manufacturing sector emerged as an important source of growth across all three categories, reflecting the interaction between industrial expansion, energy use, and upstream production requirements. Construction in Indonesia and Vietnam also generated substantial supply-chain pressures, while several sectors in Thailand acted as major offsets. These differences demonstrate that regional coordination should be complemented by country-specific strategies that reflect each economy's production structure, energy system, and industrial specialization.

The embodied carbon flow analysis further shows that manufacturing functions as the main hub of embodied carbon redistribution, while energy acts as a major upstream source of embodied emissions to downstream sectors. At the regional level, embodied carbon flows through intermediate production are concentrated within national supply chains, while ASEAN-RoW intermediate exchanges are larger than intra-ASEAN cross-border exchanges. ASEAN's embodied emissions in intermediate exports to RoW increased, while those associated with intermediate imports remained broadly stable.

These findings indicate that ASEAN decarbonization requires both sector-specific mitigation and supply-chain-aware strategies that address where emissions are produced, transmitted, and ultimately driven by demand. Grid decarbonization should be treated as a central priority because cleaner electricity can reduce both direct energy-sector emissions and embodied emissions transmitted to downstream sectors. This information can guide policy decisions by identifying priority sectors, upstream supply-chain linkages, and cross-border coordination needs for reducing embodied emissions.

The use of aggregated sectors improves interpretability but may mask differences within broad sector groups, particularly in manufacturing, energy, and AFOLU+. The EEMRIO framework also captures average sectoral relationships and does not fully reflect firm-level supply chains or technology variation within sectors. Future research can address these limitations by using more detailed sectoral classifications and extending the decomposition analysis to examine additional drivers such as population, energy mix, trade structure, and import dependence. Total final demand may also be disaggregated into household and government consumption, investment, and export components to identify demand-specific emission drivers and support more targeted policy recommendations. Disaggregating final demand destinations by consuming economy would allow the calculation of consumption-based emissions. Further studies may examine bilateral embodied carbon flows with major trade partners, incorporate other environmental indicators, and include

Myanmar and Timor-Leste once consistent MRIO and environmental satellite-account data become available.

DECLARATIONS

Authors' contributions

Conceptualization: Gue, I. H. V.; Tan, R. R.
Methodology: Teng, J. R. C.; Gue, I. H. V.; Li, M.
Data curation, formal analysis: Teng, J. R. C.
Writing - original draft: Teng, J. R. C.; Gue, I. H. V.
Writing - review & editing: Teng, J. R. C.; Gue, I. H. V.; Tan, R.; Li, M.

Availability of data and materials

The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding author.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tools ChatGPT (version GPT-5.5, OpenAI, released 2026-04-23) and Gemini (version Gemini 3.1 Pro, released 2026-02-19; version Gemini 3.7 Flash, released 2026-08-13) were used to support language editing, manuscript organization, and refinement of selected text for clarity and conciseness. AI assistance was also used to help draft and revise Python code for data visualization. All analytical methods, results, interpretations, references, and final manuscript content were reviewed, verified, and approved by the authors. No AI-generated text, code, or references were used without author checking and correction. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Supplementary Materials

Supplementary Materials

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