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Methodological Challenges in Carbon Footprint Accounting Across Global Supply Chains

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Abstract

Carbon footprint accounting has become increasingly more complex as supply chains expand globally. This study examines the methodological limitations of carbon footprint accounting as well as the effects of transparency constraints and inconsistencies in reporting standards across global supply chains, with particular emphasis on Scope 2 and Scope 3 emissions. By utilizing emissions data from countries with the highest levels of emissions, this research compares the industrial combustion and transportation sectors as key components of supply chain systems. This study uses the relationship between sectoral emissions and gross domestic product (GDP) to understand structural differences in supply chains, reporting standards, and methodologies. The findings indicate that the observed variations in cross-country emissions are influenced by supply chain structure, differences in tracking and reporting, and regulatory framework and methodologies. Scope 3 emissions, which frequently account for the largest share of total emissions, are among the least accurately and transparently tracked and reported. Overall, inconsistent tracking and limited transparency create significant disparities not only between countries but also between reported and actual emissions, underscoring that these reports reflect the methodologies used. These findings underscore the need for global reporting standards, transparency in reporting, and the implementation of technology to enhance tracking. Globalized standards lead to more accuracy, comparability, and overall credibility of supply chain accounting.

Keywords
Greenhouse Gas Emission, Carbon Reporting, Carbon Tracking, Caron Footprint, Supply Chain.

1. Introduction
As global supply chains grow increasingly complex, accurately accounting for their carbon footprints has emerged as one of the most urgent challenges for modern businesses. Carbon footprint accounting measures the total amount of carbon dioxide and other greenhouse gas (GHG) emissions that a company is responsible for. This includes both direct emissions from its own operations and indirect emissions produced across its entire supply chain. While many companies have made strides in reducing emissions within their immediate operations, for example, manufacturing and energy use, these efforts have often focused narrowly on the company's physical processes, which are classified under Scope 1 and 2 emissions, frequently overlooking the indirect impacts of operational activities, procurement practices, and supplier networks (Benjaafar et al 2013). This oversight is particularly significant because a company's

supply chain, which falls under Scope 3 emissions, represents the largest portion of its overall carbon footprint, often accounting for approximately 80% of total emissions (GHG Protocol 2011). Despite the vast majority of a company's emissions stemming from its supply chain, many companies struggle to account for and reduce these emissions effectively. The challenge arises from the sheer complexity of modern supply chains, which can involve hundreds or thousands of suppliers across multiple countries, each with varying levels of environmental reporting, regulatory compliance, and operational transparency. In the absence of effective systems to track and verify emissions across the entire supply network, vast amounts of carbon dioxide continue to be released unchecked, undermining broader corporate sustainability efforts and limiting the ability to make meaningful reductions.

1.1 Objective and Research Questions

The objective of this study is to examine the methodological challenges in carbon footprint accounting across global supply chains, with particular focus on Scope 2 and 3 emissions. The paper evaluates how deficiencies in transparency and absence of standardized reporting frameworks compromise the reliability and comparability of emissions data. By utilizing data from countries with highest levels of emissions, the proposed study illustrates the urgent need for standardized accounting and improved tracking systems to truly understand the impact of global supply chain carbon emissions. The study addresses two research questions: RQ1: How do transparency limitations and inconsistent reporting standards affect the comparability of supply-chain-related emissions across major emitting countries?
RQ2: What do differences in different sector emissions reveal about the structural position of Scope 2 and Scope 3 emissions within national supply chains?

By utilizing data from countries with the highest levels of emissions, the study illustrates the urgent need for standardized accounting and improved tracking systems to more accurately interpret global supply chain carbon emissions.

2. Literature Review

Understanding and reporting GHG emissions is essential for companies seeking to reduce their carbon footprint and meet climate goals. This section provides an overview of key concepts, reporting methods, and tracking technologies and their environmental impacts.

Scope 3 emissions constitute the largest share of corporate greenhouse gas emissions due to the upstream and downstream activities in the supply chain, but are the most challenging to quantify. Schmidt et al. (2022) outlines this fact, and emphasizes that the estimation of the amount of emissions requires combining corporations activity data and emission factors. Difficulties arise when attempting to calculate emissions with multi-tier supply chains. Two current approaches: life cycle assessment (LCA) and environmentally extended input-output (EEIO) analysis enable corporations to estimate their emissions, but both methods have significant tradeoffs. LCA provides detailed product specific emissions data, but is demanding and difficult to scale on a large level. EEIO provides comprehensive sector and economic analysis but lacks detailed product level information. Schmidt et al. (2022) highlights that hybrid approaches combining the detail of LCA and comprehensiveness of EEIO are recommended to improve scope 3 emissions data in complex supply chains. In the Environmentally Extended Input-Output and Production Layer Decomposition study conducted by Retegi et al. (2026). Their results showed that indirect emissions dominate most value chains and that conducting value-chain-based sustainability assessments can yield more comprehensive decarbonization strategies. Their study directly examines the adoption of different sustainability-oriented approaches to account for greenhouse gas emissions and how evaluations shape climate policy options. When carbon accounting focuses only on scope 1 emissions, the electricity, gas, and raw material sections are shown as the leading emitters and are primary candidates for policy intervention. Once scopes 2 and 3 are included, the leading emitters shift to those with high downstream activities in their value chains, showing the substantial, indirect impact supply chains have relative to individual sectors. By including scope 2 and 3 emissions, the way intervention policies are shaped changes dramatically, and shows the need for regulation of value chain activities.

In another study on the impact of scope 3 emissions of greenhouse gases (Herwich and Wood, 2018), they conducted an input-output investigation of indirect carbon dioxide emissions from five global economy sectors: energy supply, transport industry, buildings, agriculture, and forestry, challenging the previous works that were focused on allocating emissions between production and consumption. Methodologically, their studies combine life-cycle assessment (LCA) with multi-regional input–output (MRIO) models to trace embodied emissions across the connected sectors, revealing that industries often exert greater influence through their supply chains than through direct operations. Double counting of emissions is not redundancy, but an opportunity to identify multiple points of mitigation opportunities throughout the production process. Herwich and Woods call for a systematic approach to carbon accounting, in which decarbonization strategies address reductions in carbon emissions across the supply chain, not only through clean energy consumption. Stenzel and Waichman's (2023) discussion of data sharing as solution for scope 3 emissions accounting looks at the current roadblocks to implementation, and possible solutions to navigate. Data sharing amongst suppliers and firms along the supply chain can provide a more accurate and comprehensive analysis of scope 3 emissions, since firms already collect most of this data with little effort due to digitalization of their supply chain activities. The largest obstacle to data sharing is the concern of a firm's confidential information being shared, therefore putting them at a competitive disadvantage, or revealing their trade secrets. Data trusts, or 'homomorphic encryption technologies', have emerged in recent years, making it possible to minimize the risk of sharing firm confidential information, while still providing data on scope 3 emissions. Legal concerns regarding data sharing regard data ownership, access, and the re-use of data, as scope 3 emissions data is not currently covered by any laws or legislature. The concern of consistency in tracking and use of data also creates a difficulty when it comes to carbon emissions accounting. Going forward, it is essential to implement a standardized method for the collection and analysis of carbon emissions data, to where it can be used seamlessly between firms in the value chain. By creating a unified standard of data collection, and implementing encrypted sharing, scope 3 emissions can be more accurately account for, and reduced, in global supply chains. Khan and Teh's (2025) research on the use of artificial intelligence for GHG scope 3 emissions measurement dissects the emergence of AI in addressing the complexities of scope 3 accounting. They introduce Critical Systems Thinking (CTS) as a foundational framework for the practicality of AI utilization for the emphasis it has on critical awareness of assumptions and contexts, implementation with attention to power dynamics and the need for continuous improvement and methodological pluralism. Application of AI is limited, Khan and Ten suggest using CST as a foundational framework to guide the development of AI accounting in Scope 3 value chain. They confirm the usage of AI accounting is a potential solution for scope 3 emissions measurement and reporting both in and across firms, resulting in the improvement of policies and governing of the emissions. The gaps in the usage of AI arise from the lack of accurate and encompassing data from supply chain activities. AI in its current form cannot address the complexity of current systems but can be applied limitedly to provide carbon reductions approaches. While more research is needed in the area of AI implementation, Khan and Teh provide a strong starting point for the possible frameworks and usage of it in scope 3 emissions accounting, to provide a more accurate system for data collection, reporting, and assurance of scope 3 emissions.

2.1 Climate Change Crisis

The theory of the greenhouse effect is almost two centuries old, first described by the mathematician Joseph Fourier in 1827. Fourier's theory reasoned that if the outgoing infrared energy is blocked by gases in the atmosphere, analogous to a pane of glass in a greenhouse, the temperature of the surface of the planet would rise (Archer and Rahmstorf 2010). In 1896, Svante Arrhenius discovered that climate change is sensitive to changes in the concentration of the greenhouse gas carbon dioxide in the atmosphere. The theory of greenhouse gas effects is undisputed in the scientific community. In the 1970s the impact of secondary greenhouse gasses methane, chlorofluorocarbons, and nitrous oxide from human activities were discovered, and were shown to rival the imbalances from carbon dioxide, although being emitted at a slower rate (Archer and Rahmstorf 2010). The Intergovernmental Panel on Climate Change (IPCC) is tasked with assessing scientific, technical, and socio-economic information relevant to understanding the risks of human-induced climate change. The IPCC publishes reports called Scientific Assessments every five years or so that summarize the current state of human involvement in climate change. The first IPCC report, published in 1990, found no evidence of human-induced warming sufficient to alter the climate. However, in 1995, the IPCC's second report concluded, "the balance of evidence suggests a discernible human influence on global climate". The third assessment strengthened the previous findings further in 2001: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (Archer and Rahmstorf 2010). The accelerating rate of global warming underscores the shared responsibility of all nations to pursue significant GHG emission reductions.

2.2 Scope of Emissions

Greenhouse gas (GHG) emissions fall into three categories: Scope 1, Scope 2, and Scope 3. Scope 1 covers all emissions produced directly by the resources a company owns, for example, those from a company-owned car. Scope 2 encompasses indirect emissions resulting from a company's purchased energy, including electricity and steam. Scope 1 and 2 emissions can be easily tracked by a company, as they are directly generated by its operations. Scope 3 emissions encompass all indirect emissions from a company's activities and value chain, with the supply chain being the most significant contributor. Scope 3 emissions regularly represent the largest source of emissions for companies.

Scope 3 emissions offer the greatest opportunities to drive GHG reductions and achieve various GHG-related business objectives (GHG Protocol 2011). The GHG Protocol identifies Scope 3 as a frequent majority share of total corporate emissions, but also as the most estimation-intensive component because organizations often rely on supplier data, secondary emission factors, spend-based approximations, and boundary assumptions that vary by category and data availability. Carbon footprint accounting in supply chains aims to provide a more accurate and comprehensive accounting of Scope 3 emissions, thereby encouraging companies to become more efficient and sustainable.

2.3 Carbon Reporting

Carbon reporting is the process of calculating and disclosing all greenhouse gas (GHG) emissions of a company. The tracking process entails totaling, assessing, and then reporting their risks and impact on global warming (Carbon Chain 2025). Reporting to the Carbon Disclosure Project (CDP) makes data public. The CDP is a non-profit global organization that serves as the only independent environmental disclosure system, partnering with leaders in enterprise, capital, policy, and science to enable Earth-positive business decisions and protect future generations (Carbon Disclosure Project 2025). In 2023, the CDP reported that less than half of the 18,500 companies that provided data did not disclose supply chain-related emissions (Pedersen 2023). Given that approximately 80% of most organizations' carbon footprints stem from Scope 3 emissions within their supply chains, insufficient tracking infrastructure and inconsistent reporting practices lead to major distortions, incomplete datasets, and systemic underreporting of overall emissions. Carbon reporting helps increase transparency and accountability in global climate action and, in turn, builds trust with consumers and shareholders. A method of accountability that has been underutilized is carbon pricing. Carbon pricing is a policy mechanism that adds a direct monetary cost to a product based on the GHG emissions associated with its production (Asian Development Bank 2021). This can occur through a carbon tax, where the company pays a fixed price per ton of carbon emitted, or through an overall limit on the company's emissions. The challenges associated with carbon pricing stem largely from its reliance on accurate and transparent emissions reporting. While carbon pricing can provide strong financial incentives for companies to reduce GHG emissions, its effectiveness is reliant on the integrity of a company's current carbon accounting methods. Despite its potential, the adoption of carbon pricing remains limited in many regions and sectors, meaning its capacity to systematically enforce accountability and incentivize large-scale emissions reductions is far from fully realized. Carbon reporting is crucial for companies to identify supply chain problem areas that need to be addressed. It raises awareness of carbon-related risks and enables reductions to be made and proven through reporting.

2.4 Tracking Methods

Accurate tracking is needed for effective reporting. Tracking methods, such as AI and sensors, enable companies to calculate their Supply Chain's Scope 3 emissions more accurately. Direct measurement of GHG emissions can be achieved through direct monitoring, mass balance, or stoichiometry, such as a flue gas meter (Archer and Rahmstorf 2010). Voluntary carbon footprint mandates are systems that companies are not legally required to follow, but are strongly encouraged due to market pressure, investor concerns, or concerns about their company's reputation. Tracking occurs when a company chooses to disclose its GHG emissions using recognized reporting standards, even though there is no legal requirement to do so. Involuntary carbon footprint mandates are regulatory policies that require organizations to measure and report their GHG emissions. These mandates are non-negotiable and are established by governments or regulatory bodies. These mandates are legally binding and enforced by governments or regulatory bodies. If an organization fails to meet the established standards, it faces penalties ranging from fines to the loss of its operating license and legal action. Policymakers have a variety of policy approaches at their disposal to help companies reduce their contribution to climate change while promoting green growth. One commonly cited framework is the "5Ps," which include patrolling (monitoring emissions), prescription (laws and regulations), penalties (taxes), payments (incentives and fiscal support), and persuasion (corporate commitments and information). Together, these tools can encourage companies to curb emissions-intensive production, shift supply chains toward lower-carbon technologies, and support a transition to a low-carbon industrial structure by attracting green foreign direct investment and phasing out more polluting sectors. Each of these approaches employs multiple policy instruments that influence company behavior by altering production scale, technology choices, and industry composition (Saurave et al 2023). Meanwhile, many companies have developed AI-powered platforms to help companies accurately track and measure their Scope 3 emissions. These companies include, but are not limited to, PlanetFWD (2025), Watershed (2025), and Carbon Chain (2025). They use AI to measure and decompose the supply chain, uncover specific emissions-reduction opportunities, and offer customizable calculation methods (Watershed 2025 and PlantFWD 2025). Unfortunately, AI has a contradictory relationship with carbon emissions: it is a major emitter itself. While multiple studies indicate that AI could be the game changer in reducing climate change, driven by environmental deterioration and global warming.

Only a few studies have covered the negative environmental impacts of AI use in tracking carbon emissions. It has been found that deep learning (DL) is the main contributor to AI's carbon emissions. Therefore, before integrating AI technology, companies should consider ways to mitigate its use and carbon emissions (Gaur et al 2023).

2.5 Approaches to Estimate Scope 3 Emissions

Environmentally extended input-output (EEIO) analysis and life cycle assessment (LCA) are two widely used approaches for estimating Scope 3 emissions. EEIO methods link monetary transactions between economic sectors to emissions, making them useful for screening broad upstream and downstream impacts when supplier-specific data are limited. Process-based LCA, by contrast, traces emissions across the life cycle of a product or service using process-level data and can therefore provide greater specificity for individual materials, processes, and logistics pathways. The trade-off is that EEIO generally offers broader boundary coverage at an aggregated sector level, while LCA offers greater detail but can miss upstream activities if the system boundary is defined too narrowly. For this reason, hybrid approaches that use EEIO for broad screening and LCA for hotspot categories are especially relevant to Scope 3 estimations (Hendrickson et al 1998; Matthews et al 2008; U.S. Environmental Protection Agency 2026).

3. Conflicts of Reporting Full Carbon Footprint

A company's understanding and reporting of its full carbon footprint presents several challenges that complicate the accuracy and reliability of its assessments. These challenges arise from conflicts over transparency, standardization, and the inherent complexity of tracking emissions across vast, diverse supply chains.

3.1 Transparency Conflicts

In recent years, as the climate crisis has become increasingly dire, many companies have committed themselves to tracking their greenhouse gas emissions. In a survey conducted by The World Bank, companies from the automotive, food and beverages, IT services, textiles, and transportation sectors were asked whether they track their GHG emissions across their operations, with a large majority reporting that they do. When asked if they have independent verification of their emissions reports, only a small percentage of respondents answered yes (Saurav et al 2023). This lack of official monitoring and verification increases the risk of underreporting or misreporting to governments and investors and limits the scope for establishing formal programs that encourage companies to decarbonize their broader supply chains, such as through investment in or support for local firms. Moreover, companies that have confirmed they track and report their carbon footprint do not fully disclose their Scope 3 emissions, which account for the vast majority of their GHG emissions (World Bank 2023). The lack of true transparency in reporting leads to inaccurate records of emissions, leaving us to make, at best, an educated guess on the actual environmental impacts of a company's operations.

3.2 Standardization Conflicts

Standardization conflicts arise when a company reports its greenhouse gas emissions under multiple frameworks that apply different scopes, boundaries, and data requirements to the same underlying activities. These conflicts can reduce the consistency and comparability of reported information, complicating the interpretation of a company's full carbon footprint across its global supply chain (GHG Protocol 2011). Standardization conflicts also arise when principles such as relevance, completeness, accuracy, consistency, and transparency cannot be fully satisfied simultaneously in practice. Additionally, discrepancies between corporate GHG reporting standards and other policy instruments, such as carbon pricing systems and mandatory disclosure regulations, can create further conflicts in standardization. As a result, the same company may be required to prepare multiple emissions inventories, each using distinct methodologies and category definitions, thereby increasing reporting burdens and introducing inconsistencies that hinder comparison across jurisdictions and policy tools (GHG Protocol 2011). Finally, differences in how standards treat project-based reductions, avoided emissions, and biogenic CO_2 contribute to a lack of harmonization in reported results. Some programs allow netting project-based reductions against inventory emissions, while others, including the Corporate Value Chain Standard, require separate reporting of offsets, removals, and avoided emissions. These divergent approaches can lead to multiple "legitimate" representations of a company's carbon footprint, creating confusion for users of the information and complicating comparisons of performance across companies, sectors, and regions (GHG Protocol 2011). Another methodological complication is that value chain accounting and national inventory accounting do not aggregate in the same way. Within Scope 3 reporting, the same physical emissions can appear in multiple corporate inventories when the upstream emissions of one firm are reported as the downstream purchased-goods-and-services emissions of another. This form of double counting is inherent to value-chain accounting and does not necessarily indicate an error; however, it limits the interpretability of aggregated Scope 3 totals across companies, sectors, and countries (GHG Protocol 2011; Matthews et al 2008).

Scope 2 accounting introduces a different source of variation because the GHG Protocol Scope 2 Guidance requires reporting with both a location-based method and a market-based method. The location-based method reflects average grid emission factors, whereas the market-based method reflects contractual electricity procurement choices such as renewable energy certificates or supplier-specific products. As a result, firms with similar electricity consumption can disclose different Scope 2 totals depending on procurement structure and reporting practice, which complicates comparison (GHG Protocol 2015).

4. Data Analysis

In this section, several statistical analyses are presented to provide a better insight into emission 3 and contributing factors.

4.1 Study Design and Data Preparation

This study employs a comparative cross-country design using the most recent complete year of internationally comparable data available at the time of analysis. Emissions data were taken from the EDGAR 2025 release. From the full EDGAR country list, the study selected the five highest-emitting individual countries, excluding the EU27 aggregate, for comparison: China, the United States, India, Russia, and Indonesia. Sectoral values for industrial combustion and transportation were extracted from the EDGAR database and aligned to 2024 GDP data in current U.S. dollars for the sectoral GDP discussion. Data preprocessing consisted of filtering the database to the selected countries and sectors, harmonizing country names and units, and normalizing emissions by GDP to compare carbon intensity across countries. The year 2024 was selected because it is the latest year with a complete and internationally comparable EDGAR release available at the time of analysis, allowing a timely comparison without mixing reporting years. These countries collectively emitted 34743 million tonnes of carbon dioxide into the atmosphere in 2024, accounting for approximately 65% of global carbon dioxide emissions.

4.2 Data Analysis

Industrial combustion plays a crucial role in manufacturing processes, particularly in energy-intensive sectors such as steel, cement, and chemicals. High-temperature processes essential to production are typically powered by fossil fuels, notably coal and natural gas. This dependence on fossil fuels significantly contributes to greenhouse gas emissions. Consequently, countries with substantial manufacturing industries, such as China, tend to produce higher levels of carbon dioxide emissions from industrial combustion. Due to industrial combustion's impact on the manufacturing process, it significantly increases carbon dioxide emissions. Figure 1 shows emissions from the industrial combustion sector in the top five emitting countries.

Industrial combustion emissions are among the foremost contributors to global carbon dioxide emissions. Instead of simply reflecting total emissions output, the distribution of emissions relates to a country's place within global supply chains. China emerges as the leading producer, accounting for 63% of industrial combustion emissions among the top five countries. India follows at 16% and the United States contributed 10%. The gap between China, the United States, and India is not merely quantitative, as it reflects structural differences in their supply chains and in their emissions tracking and reporting frameworks. Discrepancies already arise between company-level disclosures and national reporting requirements, further complicating the reliability of emissions data. The absence of standardized reporting requirements at both the national and international levels significantly undermines data consistency, a challenge evident throughout this analysis. As a result, comparing countries that operate under different reporting standards makes it difficult to draw direct conclusions about the accurate scale, sources, and underlying drivers of their emissions. While these reports and numbers are accurate, given the methods used, it is difficult to gauge how the different methods compare globally. To truly identify the scope of a country's emissions within the global sector, universal tracking and reporting of emissions must be implemented.

From an emissions accounting perspective, transportation represents the transition point between Scope 2 emissions associated with purchased energy and Scope 3 emissions embedded in upstream and downstream logistics networks. Transportation is a key part of the supply chain, as it facilitates the movement of goods over short and long distances. A company's supply chain directly impacts costs, flexibility, and timelines, and in turn affects overall supply chain performance. Unlike industrial combustion, which reflects a country's production levels, transportation emissions indicate how supply chains and economies distribute goods. Improving transportation efficiency between technology or optimized operation analysis. Implementing efficient transportation methods can reduce logistics costs and lower a company's Scope 3 emissions. With a shifting focus on sustainability and technology integration, optimizing transportation procedures becomes essential to meeting both regulatory and consumer sustainability demands and market conditions.

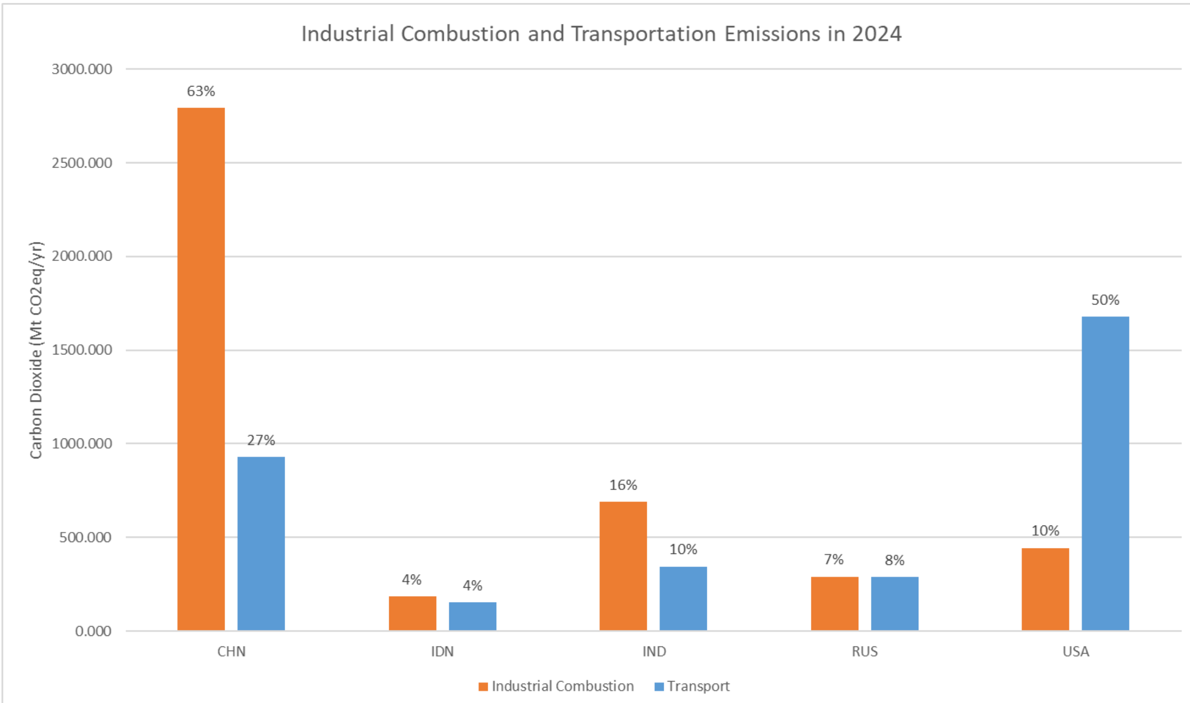

Figure 1. Industrial Combustion and Transportation Emissions in 2024

As illustrated in Figure 1, the United States leads in transportation-related emissions, accounting for 50% of total transportation emissions among the top-emitting countries. While personal vehicle use in the United States is comparatively high, passenger transportation represents only a small fraction (9%) of the overall transportation sector as seen in Figure 3, indicating that the majority of transportation-related emissions stem from freight movement, logistics, and broader supply chain activities rather than individual travel. Following the U.S., China had emissions accounting for 22% of the top emitters' emissions. This significant disparity between the United States and other nations underscores a heavy reliance on fossil-fuel-based transportation of goods. Still, these structural differences cannot be fully understood without considering the transparency and standardization challenges in the emissions reporting systems. Transparency gaps and conflicting reporting frameworks shape how supply chain emissions are recorded, attributed, and compared. Comparing the transportation sector emissions and industrial combustion emissions shows distinct structural differences among the highest-emitting countries. Russia also shows proportionally higher industrial combustion emissions than its transport emissions, implying a greater industrial contribution to its overall carbon profile. Meanwhile, India exhibits more moderate yet still significant contributions to emissions in both sectors. These differences highlight whether national emissions are more due to upstream or downstream emissions.

Gross domestic product (GDP) is derived from the value added at each stage of production within an economy. The supply chain comprises the interconnected processes of input extraction, partial products, logistics, and the final distribution of the good; each stage contributes value that is aggregated into GDP. Efficiency, technological advancement, and the industrial composition of a country's supply chain directly influence its levels of economic output and growth (Figure 2).

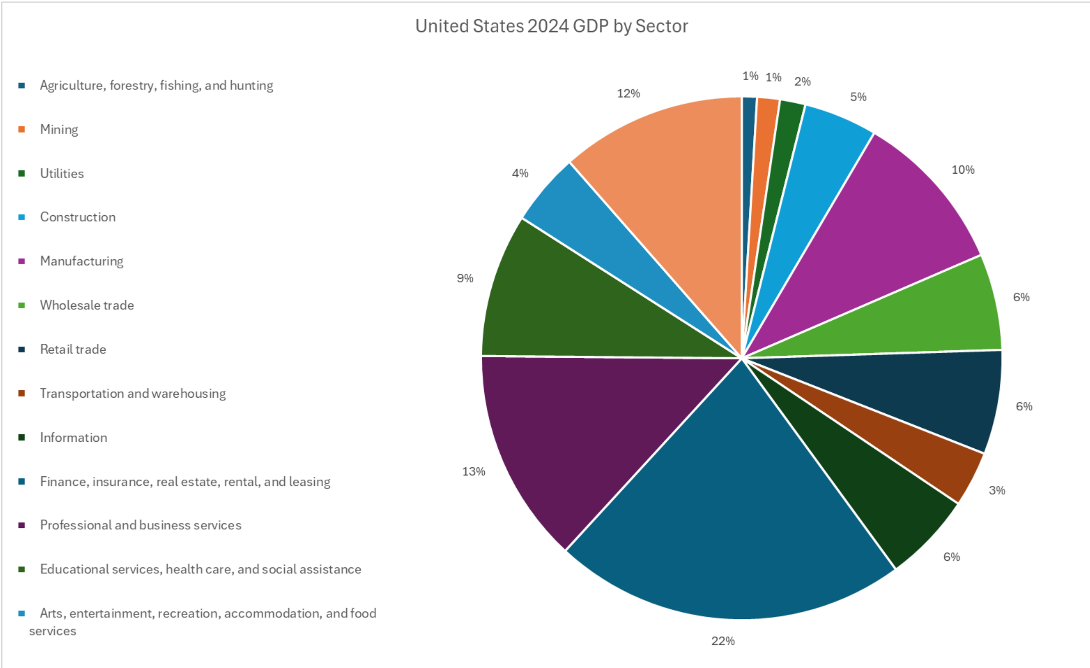

Figure 2. United States 2024 GDP by Sector

In other words, GDP is used as a macro-level proxy for value creation across extraction, production, logistics, and distribution stages, while the EDGAR emissions data capture the greenhouse gas releases associated with those activities. Dividing emissions by GDP therefore does not measure firm-level efficiency directly; rather, it provides an indicator of national carbon intensity relative to economic output. This ratio is useful for comparing structural differences among economies, but it should not be interpreted as a stand-alone measure of firms' performance or causality. An examination of sectoral contributions to GDP provides insight into how industrial structure shapes both economic output and associated emissions. As shown in Figure 2, the significant role of manufacturing in the economy is evident, as it represented approximately 10% of the total GDP. These elements are directly tied to industrial combustion and the emissions it produces. Although manufacturing is a significant contributor to the United States' GDP, it accounts for a smaller share than in China for a variety of reasons. Emerging technologies in reporting, such as AI and blockchain, improve reporting and tracking but have yet to be adopted universally. The discrepancy between tracking methods can be attributed to differences between reported and actual emissions. Transportation and warehousing accounted for 3.37% of annual GDP in 2024 (see Figure 2) (U.S. Bureau of Economic Analysis 2026). From another perspective, personal transit and group passenger transportation account for 9% of the transportation sector (Figure 3). This data demonstrates that passenger transportation accounts for only a small share of the overall transportation sector, with the majority of activity driven by supply chain and freight-related operations (Figure 3).

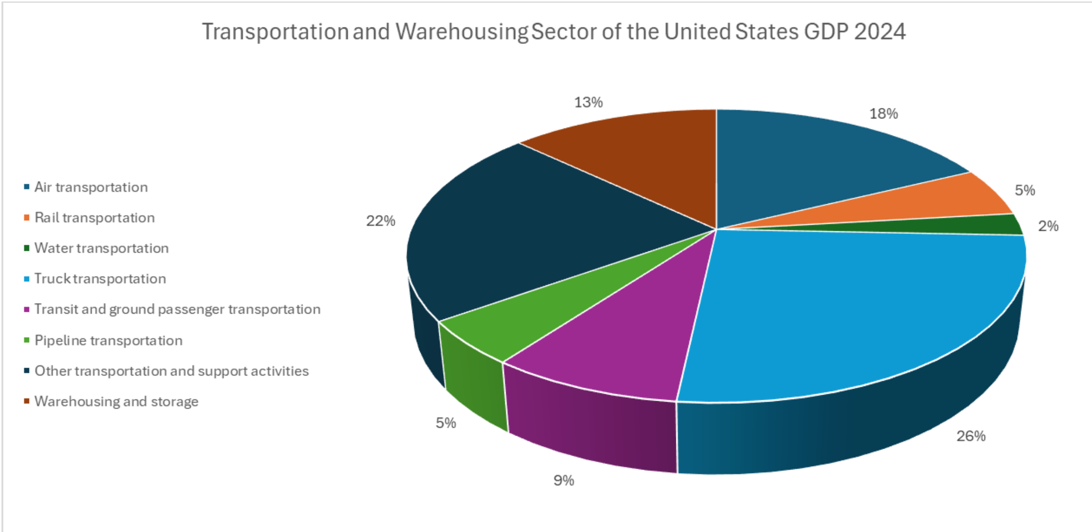

Figure 3. Transportation and Warehousing Sector of the United States GDP 2024

As shown in Figure 3, truck transportation is the largest contributor to the transportation sector of GDP, indicating its importance in logistics and the primary means of transporting goods. Due to the reliance on trucking, rail, shipping, and warehousing infrastructure to transport goods, this portion of GDP is directly linked to supply chain emissions, particularly those categorized under transportation-related greenhouse gas emissions. The data suggests that a measurable share of U.S. economic activity and its associated emissions is concentrated in the downstream stages of the supply chain (Figure 4).

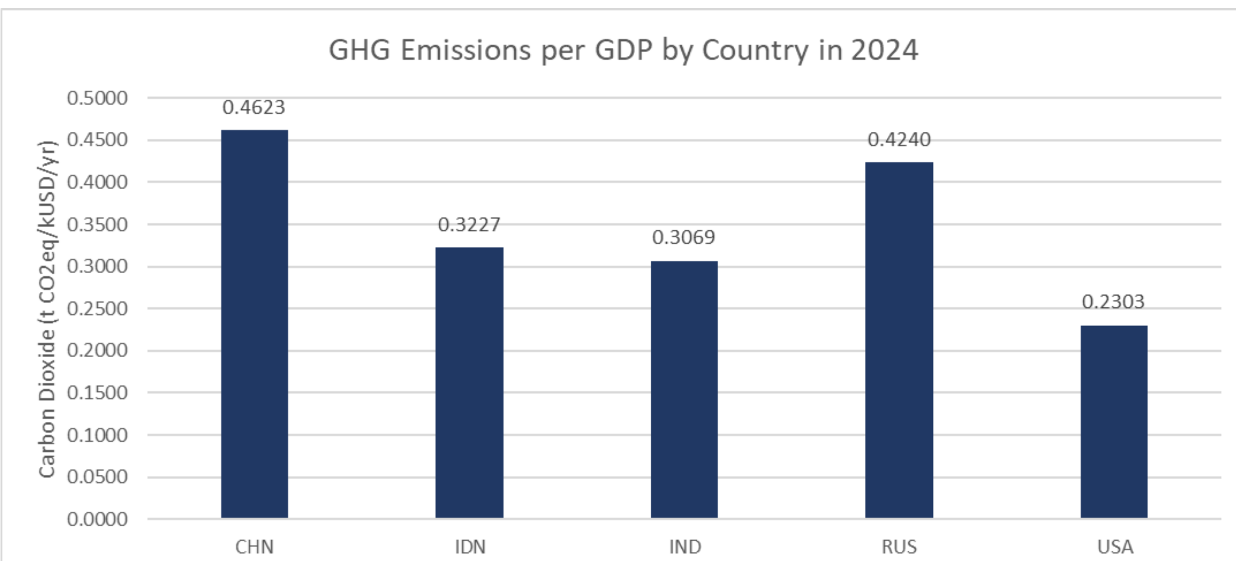

Figure 4. GHG Emissions per GDP by Country in 2024

While the United States and China account for the bulk of absolute carbon dioxide emissions, emissions per capita and relative to GDP offer a different perspective. Relating carbon dioxide emissions to economic output provides a monetary measure of carbon intensity. It allows for the evaluation of how efficiently a country's supply chain and industrial structure generate economic value relative to associated emissions. As seen in Figure 4, China emits the highest carbon dioxide intensity, approximately 0.46 tonnes per thousand USD of its GDP in 2024. This corresponds to the growth not only of their overall GDP but also of the industry portion of it, highlighting their reliance on energy-intensive processes. Following China is Russia, which produced 0.42 tonnes per one thousand USD of GDP. These higher intensities imply that value creation in these countries' economies is concentrated in energy-intensive supply chain activities. In contrast, the United States exhibits a substantially lower emissions intensity per unit of GDP, 0.23 tonnes per one thousand USD. This lower intensity suggests that the United States has a more diversified supply chain, where value is generated primarily by services, technology, or downstream supply chain activities, all of which add value without proportionally increasing emissions.

For further analysis, a correlation study was conducted between emissions and GDP for the five selected countries, as well as for the 50 countries with the highest emissions. For the five countries, the p-values from the Pearson and Spearman tests were 0.51 and 0.58, respectively. In the extended analysis of 50 countries, the corresponding p-values were 0.80 and 0.86, respectively. These results are consistent with above findings and suggest that countries with the largest absolute emissions are not necessarily those with the highest emissions intensity relative to economic output. But it is also important to note that correlation and causality are different concepts. From a supply chain perspective, this implies that countries with large-scale production systems may exhibit high total emissions while maintaining relatively lower emissions intensity due to diversified or service-oriented economic activity. Conversely, smaller or more resource-intensive economies may demonstrate higher emissions intensity despite lower absolute emissions.

5. Results and Discussion

Carbon dioxide emissions across the highest-emitting countries are shaped by their supply chains and the reporting standards to which they are mandated. By comparing industrial combustion and transportation emissions, the impact of Scopes 2 and 3 on the supply chain can be understood. Carbon emission totals and their relationship to a country's GDP can provide insight into the structure of a nation's supply chain. While these structural differences are evident in sectoral data, interpreting cross-country comparisons is constrained by significant reporting limitations. The observed emission data cannot be separated from each country's practices, accounting methods, reporting regulations, and transparency. Company-level reporting frequently lacks third-party validation, and Scope 3 emissions, despite efforts, remain inconsistently tracked and reported. Country totals reflect this and are, as a result, greatly impacted by this variation. There is no way to truly analyze the global impacts of carbon emissions without standardization. Therefore, because supply chain emissions are often estimated rather than directly measured, national totals may reflect methodological differences as much as actual differences in carbon intensity.

Improving the accuracy of carbon footprint accounts requires not only disclosure and transparency but also unified frameworks for tracking and reporting. Without consistent global standards, multiple valid accounts of the same supply chain emissions can exist, leading to inconsistency and confusion and limiting the effectiveness of carbon pricing and policy. Emerging technologies utilizing artificial intelligence offer potential solutions. Blockchain, digital twins, and IoT sensor networks can be adapted to enhance the traceability of emissions, automate data collection, and overall improve emissions visibility across global supply chains. Meaningful progress and sustainability efforts depend on standardizing emissions accounting frameworks and using technology to increase the accuracy of tracking and improve the transparency and reliability of emissions data across global supply chains.

6. Conclusion

This study examined the methodological challenges associated with carbon footprint accounting across global supply chains, with particular emphasis on Scope 2 and Scope 3 emissions, transparency limitations, and gaps in standardization. A comparative analysis of emissions from industrial combustion and transportation sectors, key components of supply chain systems, revealed significant cross-country differences. The correlation with a country's GDP demonstrates that the differences between different countries is influenced not only by their supply chain structure but also by variations in emissions reporting frameworks and account standards and methodologies. These findings confirm that inconsistent tracking and disclosure practices limit comparability and reduce the reliability of data within an already complex and difficult system to measure accurately. Overall, the study underscores the necessity of a consistent global reporting standard, improved transparency of emissions tracking, and the utilization of technology enabled tracking systems to strengthen accuracy and credibility of supply chain emissions accounting. From an industrial engineering perspective, improving carbon accounting requires integrating emissions measurement into process design, supplier management, facility planning, and transportation network optimization. Practical remedies include mapping emissions at the process, supplier, and logistics-node levels; building auditable data infrastructure that distinguishes location-based and market-based electricity accounting; and incorporating carbon criteria into procurement, routing, and capacity decisions.

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