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Abstract

This thesis presents a comprehensive analysis of global CO2 emissions attributed to international trade, marking a significant displacement of 16 GT since 2000, marking an increase of 45.5%. This work underscores the undeniable impact of international trade on CO2 emissions, highlighting a range of influence from -8% to $+20\%$ on national carbon footprints due to consumption. In particular, countries in BRIIAT (Brazil, Russia, Indonesia, India, Australia and Turkey) experience a substantial increase, particularly China, with a remarkable 200% increase in both imports and exports, potentially related to GDP growth and increased fossil fuel consumption. Rather, the EU, NAFTA, and OECD countries exhibit growth in trade-related emissions while reducing overall emissions, hinting at potential carbon leakage. Among climate policies and agreements, the integration of trade-related emissions into planning processes is crucial to effective climate action. This thesis advocates for standardized international practices in calculating CO2 emissions, using Input-Output models, to improve trend monitoring and policy formulation.

Kurzfassung

Diese Arbeit präsentiert eine umfassende Analyse der globalen CO2-Emissionen, die dem internationalen Handel zugeschrieben werden, und zeigt eine signifikante Verschiebung von 16 GT seit dem Jahr 2000, was einen Anstieg um $45,5\%$ bedeutet. Diese Arbeit unterstreicht die unbestreitbaren Auswirkungen des internationalen Handels auf die CO2-Emissionen und zeigt eine Bandbreite des Einflusses von -8% bis $+20\%$ auf den nationalen CO2-Fußabdruck durch den Konsum von Gütern. Insbesondere die BRIIAT-Länder (Brasilien, Russland, Indonesien, Indien, Australien und die Türkei) verzeichnen einen beträchtlichen Anstieg, vor allem China mit einem bemerkenswerten Anstieg der Importe und Exporte um 200%, der möglicherweise mit dem BIP-Wachstum und dem erhöhten Verbrauch fossiler Brennstoffe zusammenhängt. In der EU, der NAFTA und den OECD-Ländern ist dagegen ein Anstieg der handelsbezogenen Emissionen zu verzeichnen, während die Gesamtemissionen sinken, was auf eine mögliche Verlagerung von CO2-Emissionen hindeutet. Unter den Klimapolitiken und -vereinbarungen ist die Integration handelsbezogener Emissionen in die Planungsprozesse von entscheidender Bedeutung für wirksame Klimaschutzmaßnahmen. Diese Arbeit plädiert für standardisierte internationale Verfahren zur Berechnung von CO2-Emissionen unter Verwendung von Input-Output-Modellen, um die Trendüberwachung und die Formulierung politischer Maßnahmen zu verbessern.

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Acronyms

BTIO Bilateral Trade Input-Output

CBA Consumption-based accounting

COP Conference of Parties

EEBT emission embodied in bilateral trade

EEE Emissions embodied in exports

EEI Emissions embodied in imports

EEIOA Environmental Extended Input-Output Analysis

EET Emissions embodied in trade

GDP Gross Domestic Product

GHG Greenhouse Gases

IO Input-Output

IPCC International Panel for Climate Change

MRIO Multi-Regional Input-Output

PBA Production-based accounting

ROW Rest of the World

SRIO Single-Region Input-Output

TCBA Technology-adjusted consumption-based carbon accounting

UNFCCC United Nations Framework Convention on Climate Change

WIOD World Input-Output Database

1. Introduction

Climate change is an issue that transcends borders, and its effects are felt not only within the territories of individual nations, but also across international boundaries. The concept of trade-related emissions has emerged as a critical facet of this discussion [1]. It refers to the carbon emissions generated in the production of goods and services, which are subsequently traded between countries. As the global economy has become increasingly integrated, understanding these emissions is essential for designing effective climate policies and ensuring that international climate agreements are both equitable and impactful. Despite many mitigation efforts, annual worldwide CO_2 emissions have continued to increase from 22.75 billion tons in 1990 to 34.81 billion tons in 2020 representing a 56% increase [2]. At the same time, several international environmental agreements have been attempting to slow the significant rise in greenhouse gas emissions and the global average temperature on a collective basis. But until today, every global climate agreement has failed to reduce both.

This thesis aims to investigate the complex relationship between climate policies, international trade, and emissions by quantifying the share of trade emissions worldwide. To do so, two methods, which quantify CO_2 emissions from international trade, are applied and compared. To see how slightly different methods affect CO_2 emission levels. The comparison is performed by using an Input-Output (IO) model with updated data to provide a comprehensive assessment within the climate policy framework. In detail, this study merges the replication of [3] methodology in calculating emission levels per country with the application of [4] methodology, using more recent data focused on quantifying Emissions Embodied in Trade (EET) using updated data.

This comparative approach within the context of climate policy sheds light on the implications of employing IO modeling in climate research and policy formulation, specifically to evaluate emissions associated with international trade. The key contribution lies in utilizing an IO model with recent data and setting it in the context of the current climate policy framework. In Section 2, this work begins with an examination of climate policies, followed by an exploration of EET. The section introduces IO models and elucidates the methodologies involved in emissions accounting. Different models within the IO framework are discussed. Section 3 will provide an in-depth look at the methods and models that are used throughout this thesis. Hereby the two methodologies of the underlying studies are explained. Section 4 will thoroughly examine the data set we use, explaining where it is obtained. Section 5, the results of all accounting methods are presented. Identify which countries benefit the most from the current calculation method. When comparing the results using both methodologies, we highlight the differences and similarities of both methodologies. The final section will summarize the research findings and highlight conclusions for the development of more effective climate policies.

2. Background

2.1. Complexity of Effective Climate Mitigation

The transboundary of climate change underscores the interconnectedness of environmental systems and its profound implications for climate policies and international agreements [5]. It acknowledges that actions taken in one part of the world can have far-reaching effects on regions thousands of miles away, thus transcending geographical constraints [6]. Nations have formed climate agreements and protocols to address this issue, fostering shared responsibility and coordinated efforts. These agreements shape policy decisions by establishing common goals and objectives. The Stern Review, authored by Nicholas Stern, introduces the concept of an emission cap or carbon budget, setting a constraint on allowable greenhouse gas (GHG) emissions to minimize future economic damage [7]. The goal is to avoid exceeding this limit by 2050 to limit global warming below 2°C or even 1.5°C, as exceeding it poses severe environmental and economic risks [8, 7]. Current estimates suggest that a global carbon budget of no more than 400 GT CO_2 can be emitted until 2050, translating to approximately 7 to 8 years at the current pollution rate. Exceeding this budget could trigger irreversible environmental consequences and accelerate global warming, affecting critical ecological pillars such as the Amazon forest and Arctic Summer Ice [6].

The report of the International Panel on Climate Change (IPCC) report, released in January 2022, evaluated the global situation and effort in terms of climate conditions. The current scenario is rated as concerning by the report because the prevailing behavior leads to a considerable deviation from the path to achieve the temperature target [6]. The report discusses the everlasting use of fossil fuels, per capita consumption, the energy intensity of the Gross Domestic Product (GDP), and carbon intensity of the energy as the main drivers of the growth of emissions. Both developed and developing countries are showing this behavior [6]. But developing countries especially exhibit high emission growth rates due to rapid economic growth and industrialization during the last half century [6]. The problem is that most developing countries still rely on burning fossil fuels to generate electricity, and not on economic growth per se [9].

Historical data reveal a stark correlation between economic growth, measured by GDP, and CO_2 emissions. Over the past 200 years, average annual growth rates were 2.4% for GDP and 3.3% for CO_2 emissions [9]. Highlighting the intertwined relationship. The Asia-Pacific region, including China and India, for example, is responsible for an estimated 57% of global annual GHG emissions, replacing the EU-27 and the United States as the largest pollutant. For electricity generation, both countries still rely mainly on coal and their share comprises more than 60% of the total energy supply [10]. Meanwhile, they contribute more than 40% to the world GDP and both proportions are expected to grow [11]. Therefore, the development of emissions in both countries is expected to continue in the near future. Mostly, due to economic growth and higher living standards in urban areas, which are now limited in correlation with pollution [12]. According to government officials, CO_2 emissions are expected to peak in 2035 for China and around 2045 for India [8]. Similarly, a substantial number of fast-growing economies, such as Indonesia, the Philippines, Bangladesh, or Tajikistan, are following the example of China and India, both economically and environmentally [13]. The energy of sustainability is underlying the urge for sustainable economic growth that respects planetary boundaries.

The intersection of international trade with climate action is of great significance in our increasingly globalized and interconnected world. Over the past few decades, there has been remarkable growth in both global GDP and global international trade. The world GDP has grown from 22.7$ trillion in 1990 to an impressive 84.7$ trillion in 2020, representing an increase of 373%. According to data from the World Bank [11], global international trade has expanded from comprising 38% of the global GDP share in 1990 to around 60% in 2020. This tremendous growth emphasizes trade as the most significant contributor to global GDP, demonstrating its immense importance in a more interconnected and globalized world. It can be deduced that human-caused GHG emissions are mainly caused by consumption, global value chains are becoming more divided, and a large part of emissions around the world are created during the manufacture of goods that are traded internationally. It is reasonable to hold countries responsible for both the emissions produced within their borders and those imported from production from other countries that are consumed by their citizens. Recent research has taken into account the emissions associated with international trade to consider its impact. They discovered that developed nations' Emissions Embodied in Imports (EEI) have surged more than their Emissions Embodied in Exports (EEE). Therefore, the expansion of global trade weakens national initiatives to control emissions in countries where EEI increases faster than EEE [14]. Input-Output (IO) models have the ability to capture this economic complexity by successfully estimating trade-related emissions and their subsequent influence on national emissions levels. These models operate by systematically tracking the carbon content of goods as they navigate the complex network of global supply chains, encompassing various phases of manufacturing and crossing national boundaries. IO models provide a way to elucidate the many pathways through which emissions are distributed throughout the global economy. They reveal the interrelationships among consumption patterns, production networks, and emissions, providing insight into the actual origins of emissions linked to traded products and services. Equipped with this information, policymakers and stakeholders acquire valuable insights into the carbon footprint resulting from their trade endeavors, allowing the formulation of more focused and effective strategies for climate mitigation.

2.2. Key Climate Agreements

2.2.1. Introduction to Key Climate Agreements

The study of Emissions Embodied in Trade (EET) requires a focus on key international climate accords, such as the Montreal Protocol, the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the Paris Agreement. These agreements provide benchmarks for understanding global efforts to combat climate change and encompass various strategies, procedures, and objectives. They illustrate the dynamic nature of global climate policy and the complex network of negotiations and initiatives that have influenced our current state of affairs. Acknowledging the significance of these agreements is crucial in understanding emissions accounting intricacies and exploring potential solutions.

2.2.2. Objectives and Mechanisms of Climate Agreements

Each major international climate agreement has specific objectives and operational mechanisms to tackle the urgent challenge of climate change.

Starting with the Montreal Protocol of 1987, originally designed to address ozone depletion rather than climate change, it served as a groundbreaking precedent in international environmental diplomacy [15]. Its primary objective was to phase out ozone depleting substances, such as chlorofluorocarbons, through a gradual reduction in their production. The mechanism of this treaty involved countries agreeing to limit the production and use of these harmful substances [16]. In particular, the Montreal Protocol showcased the potential for international collaboration to effectively address global environmental challenges [15]. Scientific knowledge, diplomatic efforts, and industry cooperation converged to produce a historical agreement, demonstrating what can be achieved when these forces align [16].

The United Nations Framework Convention on Climate Change (UNFCCC) was created in 1992 with the purpose of preventing any human-induced interference that could be damaging to the global climate system [17]. Unlike the Montreal Protocol, the UNFCCC did not immediately impose binding emission reduction targets on countries. Instead, it created a framework for action, emphasizing the importance of international cooperation and consensus building [17]. Therefore, the Conference of the Parties (COP) was established as the highest decision-making body of the UNFCCC. [18]. The COP monitors the condition of climate change and the effectiveness of agreements. It analyzes the operations of the member countries, particularly by reviewing national emission inventories [19] [1]. The treaty also created the Annex System, which set the goals and objectives of three different types of signatory countries [17]: Annex I countries, industrialized nations and historically responsible for GHG emissions, are obligated to set emission reduction targets [17]. The countries in Annex II, a subset of Annex I, are economically advanced nations that also provide financial and technological support to developing countries [17]. Last, non-Annex I countries that have historically contributed less to emission growth are encouraged to take voluntary climate mitigation and adaptation actions. These categories are intended to assign various levels of responsibility and actions based on their economic situation and historical accumulation of GHG emissions [17].

In 1997, the Kyoto Protocol was adopted and enforced in 2005, introducing a more organized system with legally binding emission reduction objectives for developed countries (Annex I nations) [20]. To facilitate international cooperation, it introduced mechanisms such as emissions trading, a clean development mechanism, and joint implementation [13]. These mechanisms allowed countries to collaborate on emission reduction efforts and split the reduction gains [13]. One of the key achievements of the Kyoto Protocol was the introduction and quantification of cost-effective emission trading [21]. Although many greenhouse gases disperse rapidly in the atmosphere with minimal local environmental impact, the introduction of emissions trading had a limited direct effect on environmental outcomes. However, it substantially reduced the costs associated with emission reductions, which could be substantial depending on the level of ambition pursued. This cost-effectiveness, in turn, proved to be beneficial to the ecosystem, particularly considering the long-term nature of climate change [21]. However, the absence of major emitters such as the United States and China ultimately revealed limitations [5].

Lastly, the Paris Agreement, adopted in 2015, represents a significant shift in interna-

[1] COP3 in Kyoto and COP21 in Paris are the most well-known summits.

tional climate governance. It focuses on keeping global warming well below 2°C above preindustrial levels, with a target of 1.5°C [22]. Unlike the Kyoto Protocol, the Paris Agreement employs a bottom-up approach, where countries voluntarily submit nationally determined contributions [23]. These contributions reflect the efforts and possibilities of individual nations to mitigate and adapt to climate change [22]. The Agreement incorporates mechanisms for transparency and review to hold countries accountable, fostering a sense of shared responsibility. Furthermore, it acknowledges the importance of financial support from developed countries to help developing countries in their climate efforts [22].

2.2.3. Learnings from International Environmental Agreements

Examining the domain of international climate agreements and their role in tackling climate change, it is crucial to recognize that while these accords symbolize notable progress toward sustainability, they are not flawless. The Montreal Protocol's success was not solely due to unanimous intent but was influenced by various factors. The revelation of the ozone hole, along with an unanticipated increase in ozone depleting substances, such as chlorofluorocarbons, caused a shock wave in both the public and political realms, resulting in a sense of urgency for strict control measures [15]. Some researchers claim that the United States' superiority in scientific research, diplomatic skill, and chlorofluorocarbons production and consumption resulted in a success story in the negotiations of the ozone regime [24]. Scientific knowledge plays a significant influence on achieving political consensus [15]. Therefore, political and individual leadership had a vital role in breaking the gridlock and producing turning moments throughout the negotiating sessions. Another study stressed the significance of international institutions, as well as the role of the media and public concerns [25].

The UNFCCC framework has faced criticism for its lack of legally binding commitments, inadequately addressing historical emissions, and lack of well-defined emissions reduction targets [26]. Critics also stressed the convention's perceived timidity, lack of robust enforcement mechanisms, and allegations of influence by fossil fuel interests [27, 28]. The lack of meaningful inclusion and representation of indigenous and local communities in decision-making processes further sparked skepticism, emphasizing the need for improved inclusivity and equitable participation in global climate initiatives [27].

The Kyoto Protocol recorded both success and failure simultaneously. Critics have emphasized various critical components of the Kyoto Protocol to reduce global CO_2 emissions, including the base year, emission transfer, GHG coverage, and CDM [5]. From

2008 to 2012, the original signatories reduced CO2 emissions by 12.5%, exceeding the 2012 target of 4.7% [5]. This is a controversial achievement for two main reasons. First, global emissions increased by 4.3% each year [2]. Second, most of the reduction (11.2%) occurred in 1994, before the Kyoto Protocol was negotiated, primarily due to the decay of the Soviet Union and its impact on former Soviet states' emission inventories [5]. Additionally, when the Kyoto Protocol was signed but not yet implemented, exports from developing countries (Non-Annex I) to developed countries (Annex I) climbed considerably. Net emission transfer grew from $0.4GT$ in 1990 to 1.6 GT CO_2 in 2008, showing a 17% yearly average growth rate [14]. Throughout the whole time window, the authors discovered a total CO_2 displacement of 16 GT expecting an annual net emission transfer of 2.3 GT CO_2 in 2020 [14]. These results indicate that the change in emissions can be partially explained by the increase in emissions from international trade. This leads to the main problem. Namely, that the agreement is incapable of preventing emission transfers between countries as well [14]. Another weakness of the Kyoto Protocol lies in granting emission allowances to all Non-Annex 1 countries [5]. This led to the withdrawal of the US from the agreement. The withdrawal was primarily driven by concerns about its potential economic impact on the United States and the perceived unfairness of the agreement [26]. The Annex system led to the US withdrawing, leaving around 40% of global GHG emissions as voluntary efforts [19].

The Paris Agreement (PA) has faced criticism for its lack of enforceable mandates [29, 30]. While intended to be legally binding, not all elements are mandatory, making it less stringent compared to the Kyoto Protocol. One major drawback is the absence of country-specific emission targets [30]. The reliance on voluntary mitigation efforts and collective progress undermines equity and environmental justice, sidelining the responsibility of developed nations for their historical CO2 contributions [29]. Instead, it disproportionately burdens developing countries with future emission reduction expectations, leaving the most vulnerable nations exposed to the consequences of increasing GHG emissions for which they are not responsible [31]. Additionally, the aim of the Paris Agreement to secure financial assistance of 100$ billion per year from industrialized countries to support developing nations, has not been fully achieved, highlighting a shortfall in financial commitments [31]. In summary, these agreements vary in their objectives and mechanisms, showcasing the evolving strategies employed by the international community to combat climate change. From gradual phase-outs to binding targets and voluntary commitments, they demonstrate the flexibility and adaptability required to address this complex global challenge effectively. From the early success of the Montreal Protocol to the inclusive spirit of the Paris Agreement, these agreements emphasize that the interdependence of nations and the power of consensus are critical in the fight against climate change.

2.3. Emissions Embodied in Trade

2.3.1. Understanding Emissions Embodied in Trade

Globalization and decentralized production processes have a major influence on international trade, which has a significant impact on a nation's carbon footprint [14].It achieves this influence through various channels, including the importation and exportation of goods, together with the consumption patterns of countries [32]. When a nation imports goods, it effectively imports the emissions embodied in the production of those goods, contributing to its own carbon footprint. On the contrary, when exporting goods, it transfers a portion of its emissions to other countries, altering its emission profile in the process. In general, emissions can occur directly within the production process or are added by the global supply chain through transportation, power generation, or value addition [33, 4]. The concept of EET is crucial to understanding the global distribution of emissions and the environmental consequences of international trade. EET recognizes that the environmental impact of consumption is not limited to the country where the goods are consumed, but extends to the countries where they are produced [4]. It highlights the interconnectedness of production and consumption on a global scale and underscores the importance of accounting for emissions that occur along global supply chains. Quantifying EET is quite complex, one needs to capture the entire production structure of a single country [4]. Identifying all the sectors representing and connecting the produced output with the final and intermediate demand through international trade for each individual country [34]. Resulting in an emission matrix, which can be split into domestic and foreign emission.

2.3.2. Implications of Trade-Related Emissions on Climate Policies

The implications of trade-related emissions extend to the very core of climate policy formulation. Climate policies include the establishment of emission reduction targets, regulatory frameworks, and participation in international agreements. The intricate interplay between trade and emissions complicates the task of setting meaningful and equitable policies to mitigate climate change [35]. Traditional climate policies were designed primarily to address emissions generated within a nation's territory [36]. However, in a world characterized by globalized supply chains and international trade, this territorial focus becomes insufficient [14]. One pressing concern of International Trade is the risk of emission transfer. Restricting or limiting CO_2 emissions within a region can lead to a change in emissions in another region, where there are no restrictions [34]. Carbon leakage is the term used to describe this phenomenon [34]. It is defined as a "phenomenon in which the reduction in emissions in a jurisdiction associated with the implementation of mitigation policy is offset to some extent by an increase outside the jurisdiction/sector through induced changes in consumption, production, prices, land use, and/or trade across jurisdictions/sectors" in the IPCC's 5th Assessment Report [8]. The concept of carbon leakage raises questions about the effectiveness of individual climate actions when emissions are merely shifted rather than reduced globally [37, 34].

Generally, it is distinguished between Strong and Weak Carbon Leakage. Strong leakage, in this context, refers to the relocation of emissions caused by disparities in climate policy. Carbon-intensive businesses, for example, are being relocated to developing countries in direct reaction to a climate policy [34]. The latter refers to the expansion in such countries due to other factors outside of climate policy, such as wages or fixed costs [34]. In that sense, if a relocation takes place, the result of both cases are the same, only the reason for it can vary.

According to several authors of different studies, global emissions in international trade increased from 4.3 Gt CO_2 in 1990 to around 8.3 Gt CO_2 in 2008 [14]. A significant increase in emissions embodied in China's exports was observed, driven by the country's expanding manufacturing sector [38]. Their research highlighted a fundamental shift in responsibility for these emissions, highlighting the global impact of consumption-driven emissions from China's production activities [38]. To address these challenges, climate policies must evolve to embrace consumption-based emissions accounting, acknowledging the emissions associated with a country's consumption patterns, rather than just its territorial emissions [37].

Another challenge refers to the impact of climate policies on the competitiveness of industries. As countries implement stricter regulations, industries may face higher production costs, which could affect their ability to compete in the international market [3]. This challenge requires a delicate balance between environmental sustainability and economic competitiveness. The competitiveness of industries in countries with strict climate policies may be compromised [3]. This has been observed in industries facing higher production costs due to climate regulations that may relocate to countries with weaker regulations to maintain their competitive edge [3].

2.4. Emission Accounting, Input-Output Analysis , and Model Selection

2.4.1. Introduction to Measure Greenhouse Gas Emissions

Quantifying the environmental impact of individuals, groups, or a population represents an essential factor for climate policies [17]. It helps us to benchmark success, compare progress, and formulate targets for different entities over a specific time horizon. GHG emissions are effectively evaluated using the globally recognized Greenhouse Gas Protocol, established in 1998 by the World Resources Institute and the World Business Council for Sustainable Development [39]. This standard is crucial for accurately measuring, managing and reporting emissions, providing crucial guidelines and tools for organizations and governments to fully assess their environmental impact [39]. The classification of emissions into scopes is a key aspect of the Greenhouse Gas Protocol, categorizing emissions based on their origin and influence. Scope 1 emissions originate from sources directly owned or controlled by the organization, including fuel combustion on site and industrial processes [39]. Scope 2 involves indirect emissions from purchased energy, such as electricity and heat generation, while Scope 3 encompasses a wider spectrum of indirect emissions from the supply chain, business travel, and the product lifecycle [39].

Emission accounting is a systematic process that involves categorizing, allocating, and accounting for emissions [18]. It helps provide a comprehensive understanding of the environmental implications of emissions and offers information for informed policy decisions. Key aspects of emission accounting include categorizing emissions by source and sector, accurately assigning emissions to specific activities or regions, tracking emission trends, and evaluating emissions in the context of climate policies [18]. This helps identify areas that require additional attention and guide the modification of strategies for better environmental outcomes.

2.4.2. Limitations of Traditional Emission Accounting

For the most part, when one speaks about emissions, it is mainly referred to as territorial emissions or production-based accounting (PBA) [40]. According to the UNFCCC convention, any signatory country must follow the IPCC guidelines and submit annual emissions statistics based on that method [8]. PBA includes all GHG emissions from economic activities within a territory or jurisdiction area, as well as emissions from households. At the same time, each country recognized its own responsibility to ensure that no external effects were created that could cause environmental damage to other sovereign countries [8]. This opens the debate about the responsibility for GHG emissions from international trade, as each country has the responsibility of ensuring that no external effects cause environmental damage to other countries [36]. This leads to a controversial situation because no country is capable of measuring its environmental impact on third parties. But it is possible to measure the amount of trade between countries and their carbon footprint. Therefore, quantifying EET is essential to design climate policies [41]. Mainly because any climate policy that sets reduction targets targets any abatement in relation to a base year. Therefore, two crucial factors emerge as significant determinants: the selection of the base year and the accurate estimation of the related emissions [1]. In this context, any modification to established calculation rules has the potential to alter the reference year, thereby influencing the reduction objectives and the associated climate policy.

The literature has provided alternatives to PBA. Several studies have applied Consumption-Based Accounting (CBA) [42, 3]. Thus, one adds emissions of imported goods and subtracts emissions of exported goods. This approach counters the UNFCCC framework by making the consumer accountable for its action rather than the producer. If the UN used this technique, the world's power balance would be drastically altered [1]. The literature has shown that CBA is much higher for developed countries than for developing countries, resulting in a completely different public opinion for importing countries [3]. For PBA, the opposite is true [14].

The gap between PBA and CBA has been discussed for the past two decades in an attempt to explain this phenomenon [3]. Some authors explain this trend with economic motivations [43]. Namely, cost reductions through production outsourcing due to lower wages, taxes, or fewer restrictions. Despite negative motivations, it also brings positive effects such as GDP growth and job opportunities [43]. However, the authors find that outsourcing production drastically increases CO_2 emissions in the receiving country. Severe differences in production technologies, such as energy intensities, power generation, and transportation, are the main drivers behind this increase [43]. Another reason to outsource production could be the Clean Development Mechanism of the Kyoto Protocol, which was supposed to encourage cooperation between developed and developing countries [13]. Outsourcing represents economic growth for the Non-Annex countries. And cost and emission reduction for the Annex I and II initiator [43]. In addition to the motivations behind the different accounting methods, the implications for policies are essential. Both methods represent two extremes in terms of responsibility and in that sense do not represent a compromise [44]. Any climate strategy should aim to incentivize emission reductions while penalizing increased emissions.

When CBA and PBA are compared, advantages and disadvantages are given. Following the official recommendation to use PBA, the resulting emission data is much closer to statistical data. And therefore, much more transparent and inhabits less uncertainty [45]. PBA is said to be much more consistent with GDP, since most economic activities also generate monetary value [46]. And it is much easier to record the associated footprint for these activities. On the contrary, PBA does not eliminate potential carbon leakage [34]. Because it does not take into account imported consumption goods [46]. A country can outsource production and decrease its own emission level. Then import the same goods from a country with more energy-intensive production. Global emissions increase and individuals decrease, resulting in huge economic costs and leveraging future generations. Enabling the outsourcing country to gloss their National Emission Inventories.

The second method, CBA, shifts the responsibility back to the consumer by including import emissions [47]. Using CBA and tracing much more production steps, the resulting emission data exhibit less transparency due to big data requirements. But eliminating the carbon leakage effect is much better than PBA [46]. The biggest advantage of CBA is the ability to enumerate the consumption and amount of pollution that occurs in another country [46]. However, this poses some problems for policymakers because it is difficult to limit emissions outside their own jurisdiction. The downside here is that reductions in exports are not taken into account. These reductions can be in the form of emission intensities or an altered energy supply in the sending country. The problem is that the reductions in CO_2 emissions are credited to the importing country. Ignoring individual efforts to develop new technologies to absorb within the production process.

To account for technology differences, several studies have used Technology-Adjusted Consumption-Based accounting (TCBA). Adjusting for differences in energy and carbon intensities [3, 48, 49]. The results partially dissolve the gap between CBA and PBA in developed countries. For the USA and Canada, TCBA was still larger than CBA. However, for EU27 it was significantly lower. Given empirical evidence against emission outsourcing [49]. A problem of TCBA is that it shows a lack of scale. Using the world average emissions per sector only for imported goods. Therefore, treating imports and exports differently. In a study, the authors find that when using TCBA the sum of emissions from all EU27 countries differs compared to summing them individually [49].

2.4.3. Role of IO in Quantifying Emissions Embodied in Trade

Considering that the objective is to enumerate EET requires a model with the ability to capture direct and indirect GHG emissions. The literature has produced a model that fully captures resource consumption and connects various economies and sectors. In this sense, the Input-Output (IO) model appears to be the optimal accounting framework, since it allows variances in imported items and important technologies to be reported [50]. The IO model, developed by Nobel Prize winner Wassily Leontief in 1967, depicts the structure of production and final consumption within one or more economies [51]. For national accounting purposes, IO tables are generally constructed in monetary units, although the type of structure could also be represented in physical units of mass or energy [50]. IO is based on a set of sectorally disaggregated economic accounts, where inputs to each industrial sector and the subsequent uses of the output of those sectors are identified separately. The primary function of IO is to quantify the interdependence of different activities within the economy [51]. It uses straightforward mathematical routines to track all direct, indirect, and, where appropriate, induced, use of resources embodied within consumption [51, 50]. To accomplish this task, it is necessary to initiate the creation of the set of direct intermediate input requirements, commonly known as the Leontief Inverse. This matrix precisely computes the quantity of each intermediate good needed to produce a single final product [50]. The mathematical approach will be given in further detail in Section 3 3.

The IO model can also be applied in the context of environmental analysis, namely through the utilization of the Environmental Extended Input-Output analysis (EEIOA). This can be achieved by including physical accounting data, such as energy or material consumption, into the IO model [50]. Nevertheless, this process is quite complex because the extensions are in the form of physical units, making integration more difficult. It is necessary to make certain assumptions that will have a major effect on how the findings are interpreted [50, 52]. This approach is increasingly popular for analyzing material or energy needs, environmental effects, or amounts in terms of certain industries or components of the final demand, such as domestic and export demand. The IO table can be expanded to include material flows. This allows production sectors to be associated with material inputs, which can then be connected to final demand without completely satisfying it [53]. Regarding exports, the IO allows the estimation of upstream raw material requirements for the production of traded goods. The extraction of raw materials, wherever they occur in the world, is linked to the ultimate demand for goods and services in the country under study. The interpretation of models highly depends on the knowledge one has about them.

It can be used to trace the emissions associated with the production of specific goods and services through the supply chain [41, 50]. IO is a widely recognized and widely used methodology to assess the environmental consequences of international trade [54, 1].

It allows researchers and policy makers to enter the intricate web of global supply chains, identifying direct and indirect GHG emissions associated with the production of goods and services that cross borders [35]. While IO remains the dominant approach, alternative methods exist. Some of these include Life Cycle Assessment and Environmental Footprinting [55, 56, 41]. However, the prominence of EEIOA persists due to its ability to capture the complexity of global trade networks and offer valuable insights into the environmental impacts of consumption patterns on a global scale [50]. Alternative methods like Life Cycle Assessment and Environmental Footprinting, although valuable, are primarily equipped for evaluating the environmental impacts of individual products rather than providing a comprehensive view of complex supply chain dynamics.

2.4.4. Models and Model Selection for Quantifying Emissions Embodied in Trade

Three methodologies based on EEIOA are widely used to compute EET at the micro- and macro-scales: Single Region Input–Output (SRIO); Bilateral Trade Input–Output (BTIO), also known as Total Embodied Emissions in Bilateral Trade (EEBT); and Multi-Regional Input–Output (MRIO) models [57]. In terms of the boundary of the system, there are significant differences between the three models. The models span from closed economies to multiregional economies.

The SRIO model is the most basic and only focuses on one country. It investigates GHG emissions associated with final consumption while accounting for net exports to the rest of the world (ROW) aggregate. Note that here SRIO models assume the same production technology for domestic and foreign production [41, 1]. The BTIO is an extension of the SRIO model and basically splits up trade by trading partners. It is also able to account for differences in production technologies. The literature has provided several examples in which small groups of countries and trading partners have been investigated using BTIO. The MRIO is the most complex and represents an extension to a multiregional level. It is capable of differentiate not only between production technology, but also the allocation of imports. The model splits imports into intermediate and final consumption. Therefore, the model is able to capture re-exports of goods [57, 58].

Over the past two decades, research has highlighted the existence of two distinct models suitable for estimating CO_2 emissions within international trade using the EEIOA framework [1]. These methodologies have their respective advantages and drawbacks, depending on the specific objectives of the assessment [1]. Additionally, each model aligns with a particular accounting approach, while EEBT is regarded a hybrid of the initial two. These models include the BTIO or EEBT and the MRIO model. Both approaches share the common assumption that production technology operates in fixed proportions [42]. Regardless of the destination of the manufactured goods, all products within a given country are presumed to be manufactured using identical technology. These models employ EEIOA to calculate emissions per monetary unit, representing the predominant approach in contemporary research [50].

The BTIO model, an extension of the SRIO model [46], can be conceptualized as interconnected SRIO models. In this framework, foreign countries are treated as exogenous variables. Its main application is to determine the EET between domestic and foreign countries. Thus, it allows for the direct calculation of emissions based on bilateral trade data, particularly emissions originating from production within the home country for goods subsequently exported. Compared to the MRIO model, the BTIO model offers certain advantages and disadvantages. MRIO models excel at capturing multiple production steps embodied in international trade and addressing carbon leakage [46]. However, this complexity reduces transparency and accuracy because it involves amalgamating various data sets when analyzing multiple production steps. Moreover, constructing data sets for the use of MRIO requires a substantial amount of data [59].

The main difference between the two approaches is about the final allocation of emission. And it can reach up to 20% to 25% differences for a country depending on its trade characteristics [46]. EEBT models do not split the demand into intermediate and final demand. They just calculated emissions to meet the exported amount of goods. This results in a trade-off when deciding which approach to use, as the different approaches also favor different accounting methods. Overall, one can say that EEBT considers only emissions from exports, whereas MRIO considers emissions from exports and from imports to produced exports, and therefore captures not only direct final demand, but also intermediate demand and production. Similarly, EEBT favors production-based accounting (PBA) and MRIO consumption-based accounting (CBA). Here, in this thesis, MRIO will be used in both methods to capture trade-related emissions and the potential impact on emissions levels.

3. Methodology

3.1. Introduction to the Input-Output Model

3.1.1. Economic Representation

Input-Output (IO) tables are essential for understanding the structure of an economy, including the connections between industries and the composition of final demand. They record the inputs needed for each economic activity to produce output and meet the final demand [51]. It is difficult to find reliable data when constructing input-output tables in physical units [52]. Monetary figures are regularly collected by national statistical agencies and are used to calculate Gross Domestic Product (GDP) [52]. This adds issues to price changes, which may not properly reflect changes in the use of physical resources due to disparities in product types and prices [4]. Section 3.3 explains how this thesis accounts for price changes.

The general framework focuses on the dissecting of economic activity into different segments or industries [51]. The economy of an individual country is divided into n sectors. The total output of one sector x_i is given by

$$x_i = z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + y_i = \sum_{j=1}^{n} z_{ij} + y_i \;, \tag{3.1}$$

where $i \in \{1, \ldots, n\}$ and $j \in \{1, \ldots, n\}$. Here, the total final demand for the sector's product is represented by y_i. Inter-industry sales from sector i to all sectors j are represented by z_{ij}. This subdivision helps explain how each sector allocates its product to other sectors, a crucial aspect in understanding economic interdependencies [50]. Then, for all sectors of the economy of a country, we obtain the set of linear equations:

$$\begin{aligned} x_1 &= z_{11} + \cdots + z_{1j} + \cdots + z_{1n} + y_1 \\ &\vdots \\ x_i &= z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + y_i \\ &\vdots \\ x_n &= z_{n1} + \cdots + z_{nj} + \cdots + z_{nn} + y_n \ . \end{aligned} \tag{3.2}$$

Equations (3.2) can be written in matrix form, yielding

$$\mathbf{x} = \mathbf{Z} + \mathbf{y} \ . \tag{3.3}$$

Here $\boldsymbol{x} = (x_1, \ldots, x_n)$ is the vector of sectorial outputs and $\boldsymbol{y} = (y_1, \ldots, y_n)$ the vector of final demand.

$$\boldsymbol{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix}$$

is the input-output matrix. It reveals the total sales by each sector to intermediate and final demand.

Equation (3.3) is central in the IO analysis, it represents the sum of sectoral outputs ($\boldsymbol{x}$) through purchases from the producing sectors ($\boldsymbol{Z}$) and the final demand ($\boldsymbol{y}$) [50].

3.1.2. Direct Requirements: Technical Coefficient

It is important to understand the intermediate inputs associated with one unit of final demand. For example, one needs to know how much steel is needed, if one additional car is sold. Mathematical equivalence operations can be utilized to answer questions about direct and indirect inputs by applying two transformations. The initial step produces the matrix of direct intermediate input requirements, referred to as technical coefficients $\boldsymbol{A}$. Each element a_{ij} in $\boldsymbol{A}$ represents the direct input requirements to produce one final product in one sector. The calculation involves dividing each element of the matrix of inter-industry flows $\boldsymbol{Z}$ by the total output of that activity $\boldsymbol{x_j}$ to which it contributes [50].

$$a_{ij} = \frac{z_{ij}}{x_j} \ , \tag{3.4}$$

and yields the value of inputs of sector i to the value of outputs in sector j. From Equation, (3.4) one obtains $z_{ij} = x_j a_{ij}$ and can rewrite Equation (3.2) to:

$$\begin{aligned}
\mathbf{x}_1 &= a_{11}\mathbf{x}_1 + \cdots + a_{1i}\mathbf{x}_i + \cdots + a_{1n}\mathbf{x}_n + \mathbf{y}_1 \\
&\vdots \\
\mathbf{x}_i &= a_{i1}\mathbf{x}_1 + \cdots + a_{ii}\mathbf{x}_i + \cdots + a_{in}\mathbf{x}_n + \mathbf{y}_i \\
&\vdots \\
\mathbf{x}_n &= a_{n1}\mathbf{x}_1 + \cdots + a_{ni}\mathbf{x}_i + \cdots + a_{nn}\mathbf{x}_n + \mathbf{y}_n \; .
\end{aligned} \tag{3.5}$$

In order to transform (3.5) into a matrix, one needs to transform the vector $\boldsymbol{x}$ into a diagonal matrix [50]. Therefore, one is able to obtain the technical coefficients' matrix in matrix form as

$$\boldsymbol{A} = \boldsymbol{Z}\hat{\boldsymbol{x}}^{-1} \, . \tag{3.6}$$

3.1.3. Indirect Requirements: Leontief Inverse

A crucial point of the IO model is the second transformation to identify indirect inputs for production. The relationship between sector i and any sector j is the core of it. The production of sector j requires intermediate goods from sector i as inputs [50]. The total amount produced by a sector j, x_j, depends fully on the intermediate demand for goods between both sectors, given by z_{ij}. For example, cars need steel to be produced, which in turn require iron ore to be produced. To account for changes in cars on iron ore, we need to calculate the indirect inputs as well. To determine the indirect input related to any changes in final consumption, it is required to calculate a_{ij} repetitively for all sectors in an economy.

The Leontief Inverse provides a convenient alternative to repetitively calculation of $a_i j$ [51]. The Leontief Inverse enables the inclusion of both direct and indirect inputs, and is obtained from Equation (3.6). When the vector of total output $\boldsymbol{x_i}$ is multiplied by the matrix $\boldsymbol{A}$, the resulting vector represents the difference between total output $\boldsymbol{x_i}$ and final demand $\boldsymbol{y_i}$. This vector captures the inter-industry flows. Rearranging Equation (3.2) and inserting using the technical coefficient from Equation (3.6), one obtains

$$\begin{aligned}
\boldsymbol{A}\boldsymbol{x} &= \boldsymbol{x} - \boldsymbol{y} \\
\boldsymbol{x} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \\
\boldsymbol{x} - \boldsymbol{A}\boldsymbol{x} &= \boldsymbol{y} \\
(\boldsymbol{I} - \boldsymbol{A})\boldsymbol{x} &= \boldsymbol{y} \\
\boldsymbol{x} &= (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \\
\boldsymbol{x} &= \boldsymbol{L}\boldsymbol{y} \, .
\end{aligned}$$

Here,

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \, . \tag{3.7}$$

is the Leontief inverse.

A solution for (3.7) can be found when |I-A|!=0 [50].

Each component l_{ij} represents the quantity of input from sector j required to produce one unit of output in sector i. We can transform the economic representation from Equation (3.2) using the Leontief inverse, to obtain

$$\begin{aligned}
x_1 &= l_{11}y_1 + \cdots + l_{1j}y_j + \cdots + l_{1n}y_n, \\
&\vdots \\
x_i &= l_{i1}y_1 + \cdots + l_{ij}y_j + \cdots + l_{in}y_n, \\
&\vdots \\
x_n &= l_{n1}y_1 + \cdots + l_{nj}y_j + \cdots + l_{nn}y_n \, .
\end{aligned} \tag{3.8}$$

3.1.4. Assumptions IO Framework

To make the model tractable and applicable, two key assumptions are necessary. One fundamental premise are Fixed Technical Coefficients, which means that the ratios of inputs to outputs for each sector remain constant over a given period [50]. Although this assumption greatly simplifies calculations and allows for a systematic analysis of economic interdependencies, it may not always perfectly align with reality. Technological advancements and changes in production methods can introduce variations, challenging the stability of these fixed coefficients [51, 50]. Additionally, the model relies on the assumption of Constant Returns to Scale, asserting that if all inputs to a sector are multiplied by a certain factor, the outputs will increase by the same factor [51]. This concept suggests that doubling the input would result in doubling the output, highlighting the proportional relationship between the input and the output scaling [50].

3.2. Environmental Extended Input-Output Analysis

3.2.1. Extending IO Framework

In order to consider pollution generated from inter-industry activities, one considers pollution output vectors, also called direct impact coefficients, denoted by $\boldsymbol{q_i}$ [50]. The vector $\boldsymbol{q_i}$ is of dimension $n \times 1$ and describes the direct CO_2 emission intensities per sector in kilotons (kt) per year. The goal is to transform to use the Leontief Inverse $\boldsymbol{L}$ to calculate the total emission matrix. This emission matrix $\boldsymbol{E}$ represents the interindustry flow of direct and indirect emissions between endogenous and exogenous demand. Calculating indirect emissions is enabled by the technical coefficient a_{ij} contained in the Leontief Inverse. This enables the application and comparison of different emission accounting methods. Using the emission information represented by the row vector $\boldsymbol{q_i}$ for each sector, we adopt a hat notation to construct a diagonal matrix $\hat{\boldsymbol{Q}}$. The diagonal matrix $\hat{\boldsymbol{Q}}$ represents the total CO_2 emission per sector [50]. We then obtain the emission matrix as

$$\boldsymbol{E} = \hat{\boldsymbol{Q}}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} = \hat{\boldsymbol{Q}}\boldsymbol{L}\boldsymbol{y} \tag{3.9}$$

Each element e_i represents the total CO_2 emissions generated per dollar of final demand in the economy of a country i. Equation (3.9) is used for Environmental Extended Input-Output Analysis (EEIOA) and can be applied to pollution or energy [50]. An example illustrating the environmental extensions and application of the IO model is provided in the appendix A.2.

3.2.2. Calculating Emission Levels - Country Level

The two models compared in this study calculate the emissions per country and divide the world into a two-world perspective. Both utilize the MRIO framework, which enables the tracking of more than one production step. In this analysis, the region (1) and (2) refer to the domestic country and the foreign country, respectively. Each country comprises n sectors, each sector producing one product for intermediate users or final demand. Here, the demand can be domestic or foreign. Differences in production technology and pollution patterns between countries are also captured in the underlying data.

The first method uses the standard EEIOA Equation (3.9) to calculate the emission matrix $\boldsymbol{E}$ [1]. From a single country perspective, CO_2 emissions are perceived as:

$$\begin{bmatrix} e^{11} & e^{12} \\ e^{21} & e^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^2 \end{bmatrix} * \begin{bmatrix} L^{11} & L^{12} \\ L^{21} & L^{22} \end{bmatrix} * \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{3.10}$$

$$= \begin{bmatrix} \hat{q}^1 \ L^{11} \ y^{11} + \hat{q}^1 L^{12} y^{21} & \hat{q}^1 L^{11} y^{12} + \hat{q}^1 L^{12} y^{22} \\ \hat{q}^2 \ L^{12} \ y^{11} + \hat{q}^2 \ L^{22} \ y^{21} & \hat{q}^2 \ L^{21} \ y^{12} + \hat{q}^2 \ L^{22} \ y^{22} \end{bmatrix}. \tag{3.11}$$

PBA can be calculated by adding all the emissions resulting from domestic production that are finally consumed in country 1, (e^{11}), and the goods and services that are finally consumed in country 2, (e^{12}). This equation is given by [3]: $PBA = e^{11} + e^{12} + h^1$, where h^1 captures the emissions of households in country 1. On the contrary, Consumption-Based Accounting (CBA) uses a similar model according to [3]: $CBA = e^{11} + e^{21} + h^1$. The first part covers the emissions resulting from domestic production and consumption in country 1, and adds the emissions stemming from production in country 2, which are finally consumed domestically (e^{21}). To compensate for differences in technology, the world average emission intensity per sector is calculated q^{wa} [3]. This is done by summing the global CO_2 emissions for each sector and dividing these by the sector-specific global output: $q^{wa} = (q^1 + q^2)/(x^1 + x^2)$, referred to as the world average emission intensity CO_2 per sector (q^{wa}). This enables the calculation of Technology-Consumption Based Accounting (TCBA) emissions in Ref. [3]: $TCBA = e^{CB} + (e^{12} - e^{12}_{wa})$.

3.2.3. Calculating Emission Levels - Trade-Related

Rather than calculating national emission levels, the core of the second method is Ref. [4] is to quantify Emissions Embodied in Trade (EET), which is the sum of Emissions embodied in Export (EEE) and Emissions embodied in Import (EEI). The authors' approach begins similarly by splitting the world economy into a two-country perspective and utilizing the generalized environmental framework (3.9) as a basis. This approach uses the same notation as before with only one difference: The matrix $\boldsymbol{E}$ is generated in two steps. First, it is multiplied by the Leontief Inverse. Second, only the respective share of emission from the final demand is multiplied. A new variable k is introduced that refers to all different global emissions pollutants. The methodology used in [4] is based on earlier work by [44]. For the domestic country, the first part $\boldsymbol{EEE}$ can be calculated

[1] In [3], three levels per country are computed. Production-Based Accounting (PBA), accounting for territorial emissions. CBA including imports and subtracting exports. And TCBA using the global mean of emission intensities per sector. In summary, showing us the current declared emission levels and the influence of trade emissions.

using the following equation:

$$\boldsymbol{EEE}^r = \underbrace{\left[\sum_{k=1}^{n}(\boldsymbol{e^{kr}})'\right]\left(\sum_{s\neq r}^{n}\boldsymbol{y^{rs}}\right)}_{A} + \underbrace{\sum_{s\neq r}^{n}\left[(\boldsymbol{e^{rs}})'\sum_{k=1}^{n}(\boldsymbol{y^{sk}})\right]}_{B} \tag{3.12}$$

Part A represents the emissions necessary to produce a final good in the domestic country r, which is exported to a foreign country. For that. the domestic emissions. $\boldsymbol{e^{kr}}$, are multiplied with the demand of all foreign countries $\boldsymbol{y^{rs}}$. Part B gives us all indirect emissions abroad, $\boldsymbol{e^{rs}}$, that are necessary to produce a final good corresponding to intermediate demand, $\boldsymbol{y^{sk}}$.

The second part of the EET, EEI, can be calculated by :

$$\boldsymbol{EEI}^r = \underbrace{\sum_{s\neq r}^{n}\left[\sum_{k=1}^{n}(\boldsymbol{e^{ks}})'\right]\boldsymbol{y^{sr}}}_{C} + \underbrace{\left[\sum_{s\neq r}^{n}(\boldsymbol{e^{sr}})'\right]\left(\sum_{k=1}^{n}\boldsymbol{y^{rk}}\right)}_{D} \tag{3.13}$$

Part C encapsulates all emissions, $\boldsymbol{e^{ks}}$, to produce one final good in the foreign country, which is imported into the domestic country, $\boldsymbol{y^{sr}}$. Part D consists of emissions that come from producers in a foreign country $\boldsymbol{e^{sr}}$, which are imported for the final good domestic production, which is $\boldsymbol{y^{rk}}$.

3.2.4. Assumptions of EEIOA Framework

Successfully incorporating environmental aspects within the EEIOA analysis is contingent on certain assumptions that allow the integration of both physical and monetary data points. These include the assumptions of import substitution, feedback effects, and allocation of imports into intermediate and final demand. Import substitution states that both imported and domestic goods do not share the same technology and energy intensity [46, 60]. Inconsistent data may result when applying domestic emission intensity parameters without accounting for this heterogeneity. Feedback effects pertain to a model's ability to account for the re-export of products, essentially capturing alterations in production in one region due to shifts in intermediate demand in another [50]. The increasing prevalence of cross-border supply chains emphasizes the necessity of considering Feedback effects when assessing EET, particularly for economies that are heavily involved in production trade activities [61]. Other studies indicate that models considering multidirectional feedback can lead to differences exceeding 20% in terms of the net EET of countries [42]. Furthermore, an accurate allocation of imports to intermediate and final demand categories is crucial when considering technological disparities [56]. Sectors employing advanced technologies can exhibit lower emission intensities, and precise import allocation facilitates a detailed assessment of the environmental implications associated with trade.

3.2.5. Model Differences & Similarities

Both methods use the standardized EEIOA equation (3.9). The primary difference lies in their focus, with the first method focusing on domestic emissions and the second method extending it to understand emissions influenced by global trade. In the methodology proposed by [3], subsequent addition and subtraction operations derive PBA, CBA, and TCBA. On the contrary, [4] employs a more complex approach, involving post-multiplication of the final demand with the emissions matrix. Although both accounting methods serve different purposes, their composition should allow for comparison. Since both methods use the same emission matrix $\boldsymbol{E}$ for their calculation, one can set them equal. Then, for the 2-world perspective one derives

$$\boldsymbol{E} = \begin{bmatrix} e^{11} & e^{12} \\ e^{21} & e^{22} \end{bmatrix} = \begin{bmatrix} e^{kr} & e^{rs} \\ e^{sr} & e^{ks} \end{bmatrix} \tag{3.14}$$

The emission matrix $\boldsymbol{E}$ is divided into four parts, representing emissions that occur at home, abroad, or transferred between countries. Exports are represented by e^{12} and e^{rs} and imports by e^{21} and e^{sr}. In general, the trade balance of a country is calculated as $Exports - Improts$ In our case, we can compare the results of CBA and EET by comparing the percentage change in territorial emissions through the trade balance. According to our equality, they should theoretically be equal.

3.3. Accounting for Inflation

To ensure a meaningful comparison of environmental and economic data over time, it is essential to account for the influence of price changes [50]. In this analysis, economic changes are evaluated in terms of volume changes. The underlying IO tables are compiled annually, presenting data in both current and constant prices, facilitating a thorough assessment of volume changes between consecutive years. This is achieved by linking one year in current prices to the following year in constant prices [62]. The growth rate can be calculated

$$\text{Inflation Rate} = \left(\frac{\text{Current Year Value} - \text{Previous Year Value}}{\text{Previous Year Value}}\right) \times 100\,. \tag{3.15}$$

This inflation rate can then be used to adjust the data for a given year to the price level of the base year. However, revisions in economic standards can create gaps in data comparability, highlighting the importance of methodological consistency in the analysis of economic and environmental data [62].

4. Data

This research uses data from the World Input-Output Database (WIOD). The data set includes 44 major countries, including 28 from Europe, 15 other significant countries, and a Rest of the World (ROW) aggregate [63]. The data set covers 56 primary industry sectors, detailing their production of goods and services from 2000 to 2014. The tables in the data set give details about the goods produced and where they are ultimately used. This information is available free of charge [64]. It should be noted that the WIOD website does not have environmental accounts for the period in question. Therefore, we have obtained official environmental data from the European Commission [63]. This data set has been carefully compiled and updated by [65] for IO analysis.

Although WIOD data might not offer the highest level of detail in terms of country and product representation, they have a significant advantage. The WIOD combines tables presented in both current prices and previous year prices, enabling one to effectively account for volume changes over time and mitigate potential biases that could arise due to fluctuations in prices.

5. Results

For the purpose of this thesis and to condense the data, countries and various entities have been selected for the analysis. These include the BRIIAT countries (Brazil, Russia, India, Indonesia, Australia and Turkey), representing economies in transition. The next group is the developed OECD countries covered by officially ratified data [66]. Furthermore, China and the United States, being the two largest economies and major pollutants, are included [10, 67]. The Rest of the World (ROW) is aggregated to cover all other existing countries. Asia, Europe (including the UK) and North America to cover the available geographical regions from the dataset. Here, North America is represented by the NAFTA group (North American Free Trade Agreement), which covers the United States, Canada, and Mexico. The main reason for this selection is simple: Climate change is a global challenge that requires a global approach. Therefore, this thesis examines it from a holistic perspective. Detailed results for each country can be found in the appendix (A).

5.1. Emission Accounting Results using Jiborn Method

5.1.1. Production-Based Accounting Results

The results from Production-Based Accounting (PBA) reveal a balanced emission trend: Half of the observations increased, and the other decreased. In particular, Europe and NAFTA lowered PBA emissions by 20.5% and 12.4%. OECD countries showed a decrease of 11.7%, the US reduced emissions by 14.0%. On the contrary, substantial increases were observed. BRIIAT saw a significant 124% increase in PBA emissions, while Asia and ROW experienced significant increases, with increases of 122.1% and 75.6%, respectively. Meanwhile, China stood out with substantial growth, showcasing an impressive increase of 194% in PBA emissions.

5.1.2. Consumption-Based Accounting (CBA) Results

When using CBA, the results show a similar trend, though with some differences, especially in terms of reductions. Just like in PBA, approximately half of the entities saw an increase and the other half saw a decrease. In terms of reductions, EU emissions have fallen the most by 13.8%, while the United States reduced emissions by 11.8%. OECD countries reduced by 7.1%. NAFTA and the OECD also saw reductions, with 13.8% and 10.4%. On

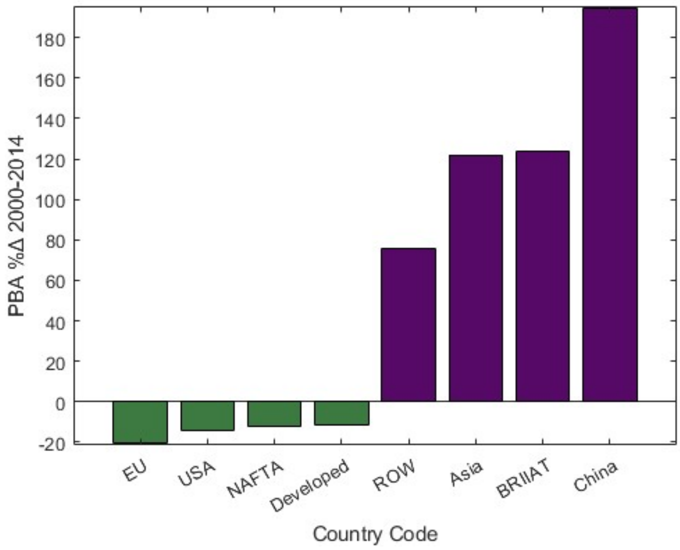

Figure 5.1.: Changes in PBA between 2000-2014

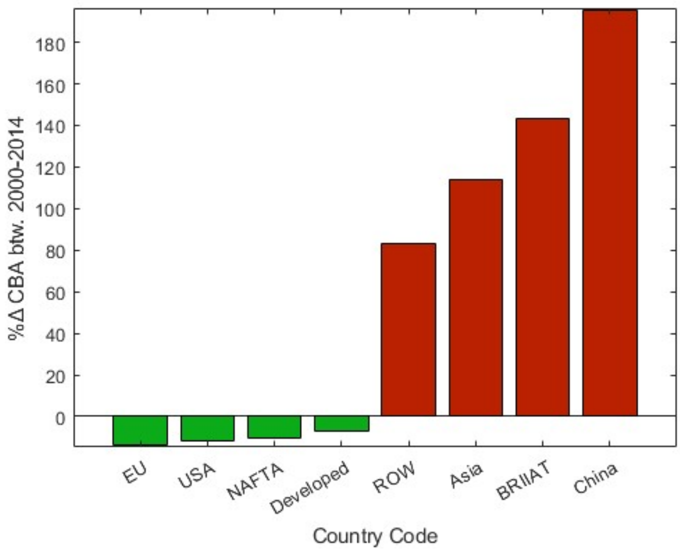

Figure 5.2.: Changes in CBA between 2000-2014

the other hand, Asia and the Rest of the World (ROW) experienced significant increases, with Asia at 114.1% and ROW at 82.9%. BRIIAT and China emerged with substantial increases, recording 143% and 195%, respectively.

5.1.3. Technology Adjusted Consumption-Based Accounting (TCBA) Results

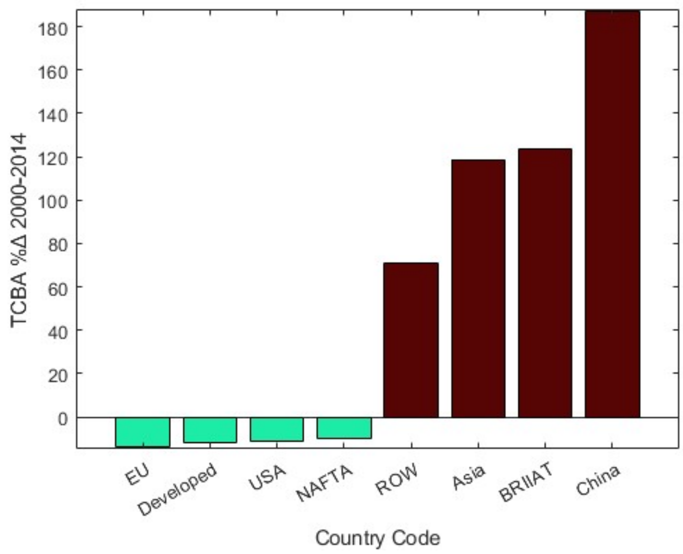

Figure 5.3.: Changes in TCBA between 2000-2014

When using mean emission intensities for TCBA, a similar pattern emerges: roughly half of the regions witnessed reductions, while the other half saw growth. In terms of reductions, Europe led with a significant decrease of 33.0%, followed by the OECD countries at 11.9%, the United States at 11.3%, and NAFTA at 10.0%. On the contrary, notable increases were observed in ROW, with a substantial increase of 71.0%, and even more striking increases in Asia at 118.8%, BRIIAT at 123%, and China at an impressive 187%.

5.2. Emission Results using Dietzenbacher Method

5.2.1. Global Development of Trade-Related Emissions

In general, the data show a displacement of more than 13.2 GT of Emission Embodied in Trade (EET) in 2014 for all countries. This represents an increase of 45.8% since

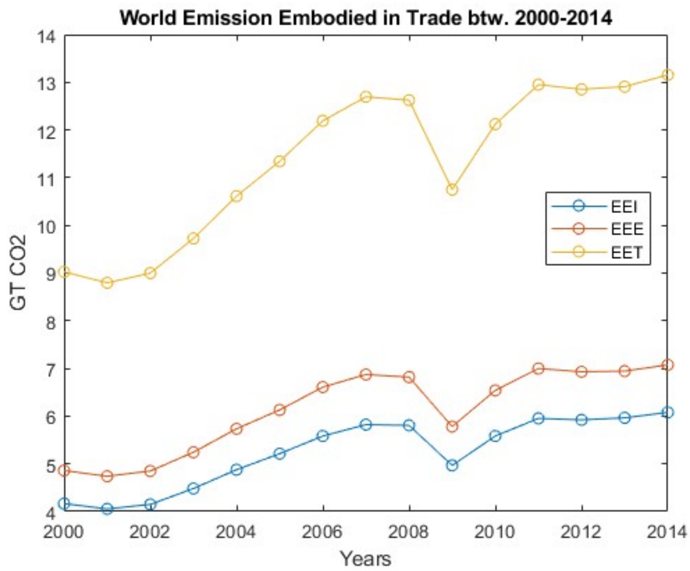

Figure 5.4.: Development of Emission Embodied in Trade

2000 for EET. Export emissions increased in total from 4.9 to 7.1 GT CO_2 emissions, representing an 45.6% increase. For imports, it increased from 4.2 to 6.1 GT CO_2 emissions, representing an 46.0% increase. In relation, annual CO_2 emissions in 2014 were 32.2 GT, EET accounting for 41.0% of annual emissions [10].

5.2.2. Emission Embodied in Trade Results (EET)

Following the global trend, all observed countries and groups show growth in Emission Embodied in Trade. The results range from minimal to exorbitant growth rates. The EU showed the smallest growth by 5.6%, the US by 8.2%, NAFTA by 10.9%, and the OECD countries by 12.7%. ROW by 70.0%, BRIIAT by 114.0%, Asia by 122.5% and China by strong 266.1%.

5.2.3. Emission Embodied in Import Results (EEI)

A similar picture can be observed with the EEI. All observations show growth. The EU exhibited a growth of only 6.0%, followed by the United States at 8.4%, NAFTA at 10.7%, the OECD countries at 12.4%, ROW at 77.2%, Asia at 99.2%, BRIIAT at 199.0% and China at a substantial 287.0%.

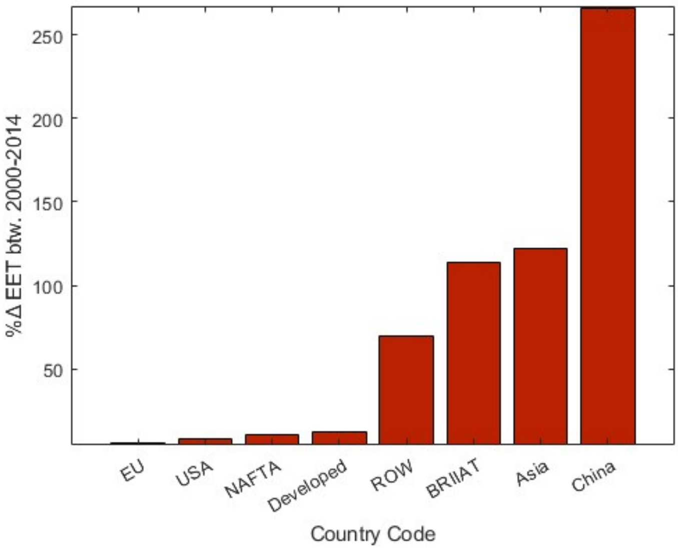

Figure 5.5.: Changes in EET between 2000-2014

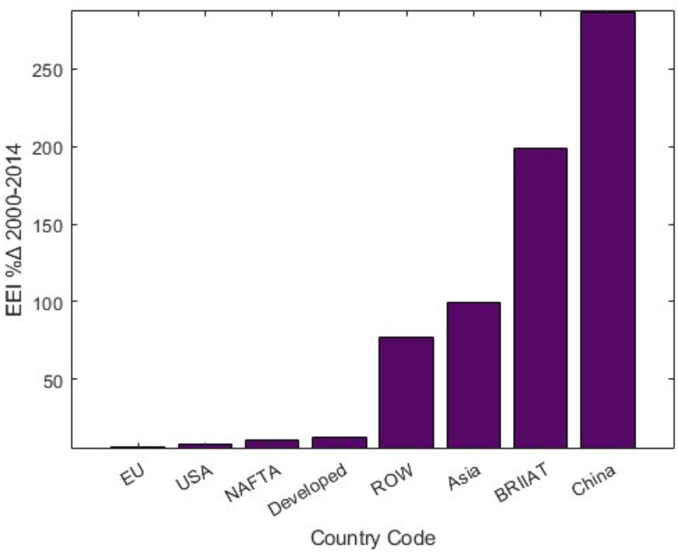

Figure 5.6.: Changes in EEI between 2000-2014

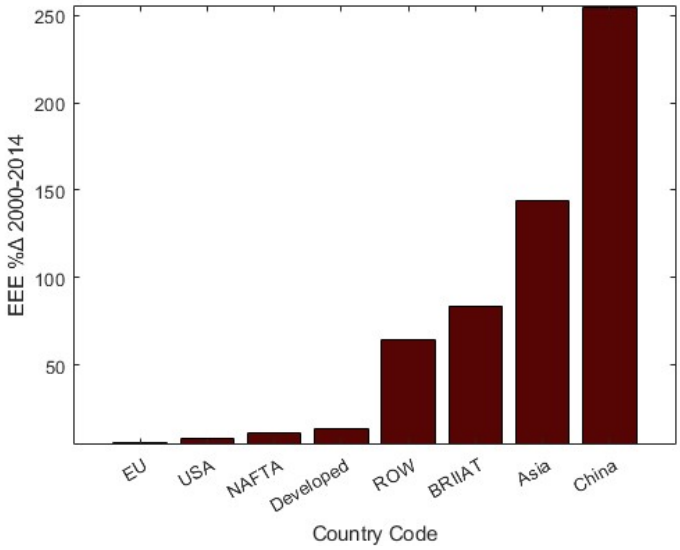

Figure 5.7.: Development of Global Emission Embodied in Trade between 2000 and 2014

5.2.4. Emission Embodied in EEE Results

Examining EEE reveals a scenario comparable to EEI, with growth observed: the EU at 5.2%, the US at 7.8%, NAFTA at 11.1%, OECD countries at 13.2%, ROW at 64.3%, BRIIAT at 83.6%, Asia at 143.7%, and China at impressive 254.8%.

5.3. Result Comparison of Both Methods

	Δ(PBA)	Δ(CBA-PBA)	Δ(TCBA-PBA)	Δ((EEE-EEI)-PBA)
BRIIAT	124.00	19.33	-0.35	8.63
NAFTA	-12.39	1.95	2.43	12.85
ROW	75.57	7.39	-4.55	62.66
CHINA	194.59	0.87	-7.45	162.36
ASIA	122.07	-7.97	-3.32	77.66
US	-13.99	2.18	2.68	14.57
OECD	-11.71	4.58	-0.20	12.46
EU	-20.46	6.70	-12.55	21.17

Table 5.1.: Influence of Alternatives Emission Accounting Methods on PBA

In this analysis, PBA is used as the primary benchmark for two compelling reasons. First, it aligns with the official methodology endorsed by the IPCC. Second, a direct comparison with the additional data provided by [3] shows identical results. To quantify the impact of trade-related emissions, the overall changes in percentages between 2000 and 2014 have been calculated for all methods. Subsequently, the results were subtracted from the benchmark to make the influence measurable. All results in table (5.1) are in %. Positive numbers signify that a country or entity would officially report higher emissions, while negative numbers imply lower emissions when using different accounting methodologies.

The first column presents the PBA results as previously listed. In the second column, the percentage change is presented, considering imports using the methodology by [3]. BRIIAT would exhibit 19.3% higher emissions, NAFTA 2.0%, ROW 7.4%, China 0.9%, the US 2.2%, OECD countries 4.6%, and the EU 6.7%. However, Asia would report lower emissions using CBA by 8.0%. Using the world mean of emissions intensities, all countries would report lower emission levels. Specifically, BRIIAT by 0.4%, NAFTA by 2.4%, ROW by 4.5%, China by 7.5%, Asia by 3.3%, the US by 2.7%, the OECD by 0.2%, and the EU by 12.6%. The fourth column represents the trade balance, defined as the difference between EEE and EEI, in relation to PBA calculated using the method of [4]. In this scenario, the emissions of BRIIAT would be 239.4% higher, for ROW by 88.5%, for China by 226.8%, and for Asia by 77.7%. In contrast, NAFTA would be lower by 12.8%, the US by 13.4%, the OECD by 12.5%, and the EU by 19.8%.

5.3.1. Limitations of the Results

Reproducing the result by [3] was successfully completed. In addition to slight differences for the CBA and TCBA results of around 3%, the results are very close to the results provided in the supplementary material provided by [3]. To understand the difference, it would be necessary to compare the exact codes and computation. It could be the case that [3] worked with rounded results for the plots and computation. The bias for TCBA results (5.3) may be due to the composition of the TCBA method. It shows a lack of scale by applying mean in emission intensities only for imports, as mentioned in section 2.4.2. The second method by [4] is successfully updated with new data. Since [4] did not provide detailed results and used an older dataset, the results cannot be compared. Nevertheless, it can be the case that a potential bias has led to higher results due to the fact that huge data sets are used within the MRIO framework.

6. Conclusion

The analysis of the data provided reveals a significant global displacement of 16 GT in CO_2 emissions related to trade, representing a substantial increase of 45.5% since 2000. This finding emphasizes the undeniable influence of trade on CO_2 emission levels. When viewed from a national or entity perspective, the study underscores a profound impact on a nation's carbon footprint. In particular, the results show an influence of consumption on territorial emissions within a range from -8% to $+20\%$ (5.1). Regarding the second method, the influence derived from the trade balance ranges from $+8\%$ to $+160\%$. Adjusting the data for technological differences refines this range to -12.6% to $+2.7\%$. This suggests a decline in emissions intensities on a global scale over time, accompanied by a decrease in trade influence.

The BRIIAT countries show a significant upward trajectory in emissions, with China showing a remarkable increase of more than 200% in both imports and exports. Possible explanations for this increase include GDP growth, higher living standards, and the burning of more fossil fuels. On the contrary, the EU, NAFTA, and OECD countries show growth in trade-related emissions while simultaneously reducing their overall emissions. This paradoxical behavior could signify a potential relocation of emissions from these countries to Asia, ROW, and BRIIAT, potentially involving outsourcing of emissions-intensive industries. Although this suggests a potential case of weak carbon leakage, the establishment of a causal link remains elusive. Despite the substantial reduction in territorial emissions by the EU and OECD, this achievement is partially counteracted when accounting for imports. In summary, it is imperative to recognize that CO_2 emissions continue to grow steadily on an annual basis, regardless of concerted reduction efforts. Furthermore, the influence of trade-related emissions is becoming increasingly pronounced, consistently hovering around 40% according to the data. In general, most trade-related emissions originate from BRIIAT and Asia. Continue the relations between economic and emissions.

From a methodological point of view, both approaches were successfully executed and share a similar methodology. The key discrepancy lies in the post-multiplication stage, which could potentially explain the observed variance in the results of the second method, as noted by [4]. However, both methods provide valuable information on the trajectory of trade-related emissions. The first method proposed by [3] yields more consistent data due to the preference of MRIO models for Consumption-Based accounting. However, it requires an extensive dataset and is more susceptible to deviations. A comparative analysis of the results for both methods has revealed discrepancies in the assumed equality.

In general, Input-Output (IO) models and analysis have become invaluable tools, especially considering that statistical offices already calculate such data for national accounting methods. Establishing current and previous year prices as an international standard would be highly beneficial for everyone. This standardization would allow for the continuous generation of CO_2 emissions data over time, aiding in target monitoring and the identification of net trends and patterns.

Regarding climate policies, the literature has indicated a mix of successes and failures within climate agreements 2.2. Various instruments, from binding targets to individualized plans, have been experimented with on a global scale. However, the overall impact of these efforts on effectively reducing CO_2 emissions remains limited. A crucial lesson drawn from this thesis for climate negotiations is the imperative of considering trade-related emissions and seamlessly integrating them into the planning process.

The next steps based on these findings are manifold. First, incorporating the most recent data up to the present would improve the continuous monitoring of trends and developments [3]. Second, decomposing the results of this work and identifying the main drivers behind the observed trends would provide invaluable information for effective climate action [4].

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A. Appendix

A.1. Country Level Emission Overview

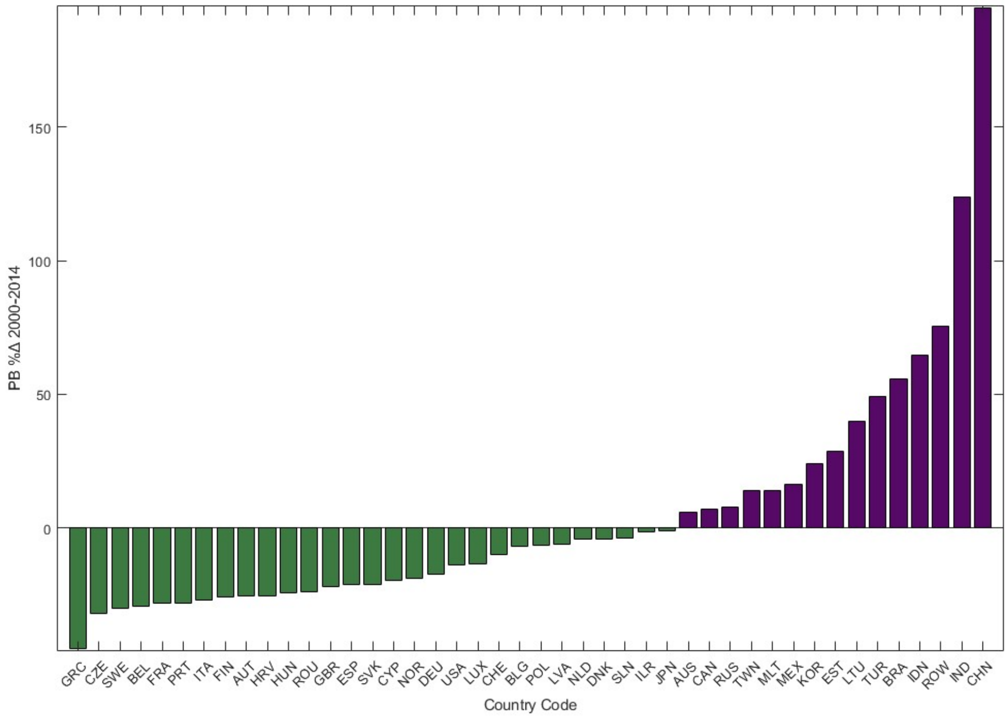

Figure A.1.: Changes in PBA between 2000-2014 for all Countries

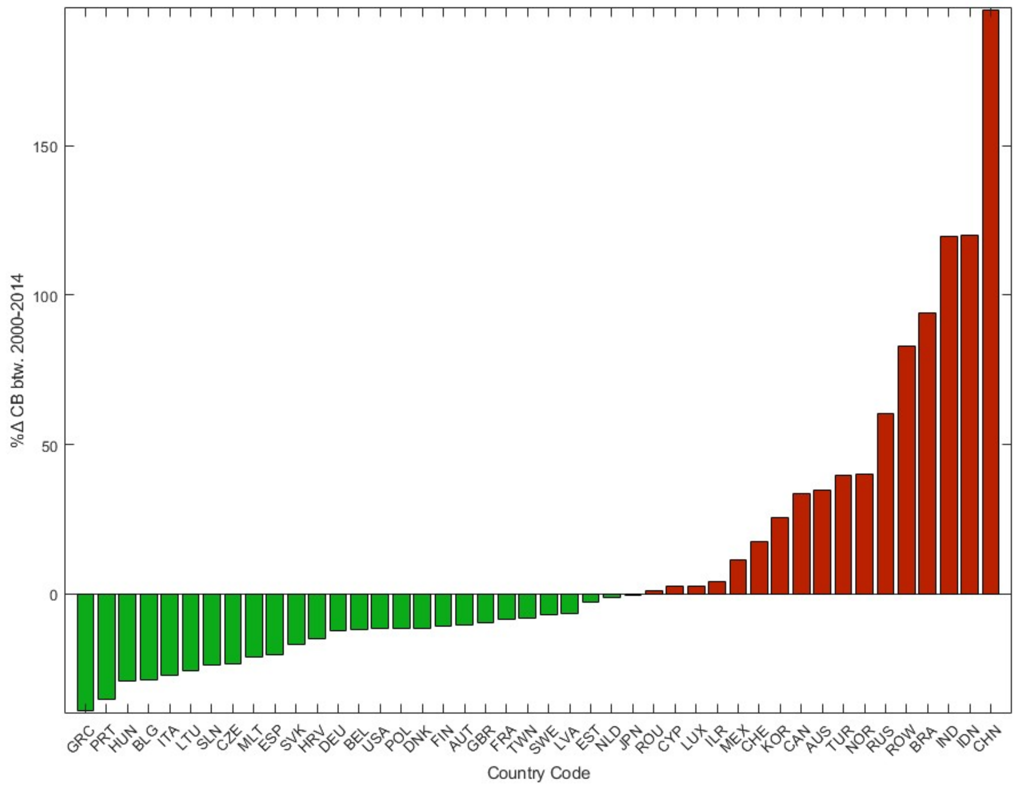

Figure A.2.: Changes in CBA between 2000-2014 for all Countries

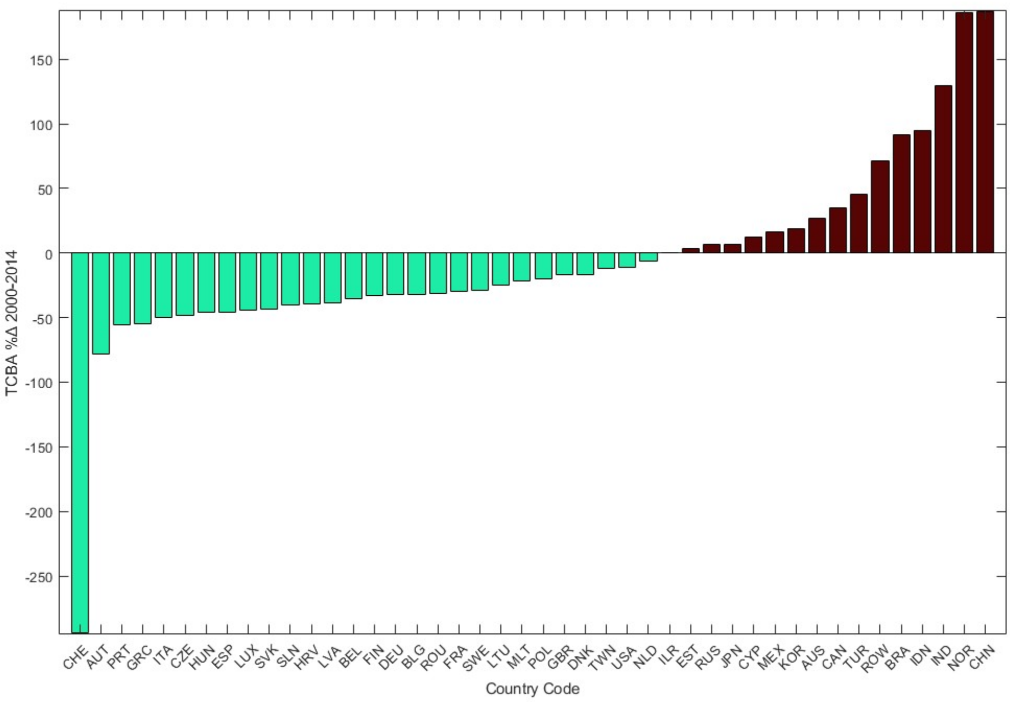

Figure A.3.: Changes in TCBA between 2000-2014 for all Countries

A.2. Input-Output Basic Example

	Iron Ore (i)	**Steel** (j)	**Cars** (k)	**Final Demand**	**Total Output**
Cars (k)	85	90	0	20	195
Steel (j)	10	10	90	200	310
Iron Ore (i)	5	5	20	500	530
Value Added	95	205	420		720
Total	195	310	530	720	1755

Table A.1.: Hypothetical 3 Sector Economy Example

Matrix Calculations

Interindustry Demand Matrix (Z)

The interindustry demand matrix Z represents the direct inputs required from one sector to another, denoted as z_{ij}.

$$Z = \begin{bmatrix} 85 & 90 & 0 \\ 10 & 10 & 90 \\ 5 & 5 & 20 \end{bmatrix}$$

Total Output Vector (x)

The total output vector x is the sum of the total output in each sector, denoted as x_i.

$$x = \begin{bmatrix} 195 \\ 310 \\ 530 \end{bmatrix}$$

Inverse of Total Output Vector (x^{-1})

The inverse of the total output vector (x^{-1}) is calculated element-wise as the reciprocal of each element.

$$x^{-1} = \begin{bmatrix} \frac{1}{195} \\ \frac{1}{310} \\ \frac{1}{530} \end{bmatrix}$$

Direct Requirement Matrix (A)

The direct requirement matrix A represents the proportion of output from sector i used as an input in sector j, denoted as a_{ij}. It is calculated as $a_{ij} = \frac{z_{ij}}{x_i}$

$$A = \begin{bmatrix} \frac{85}{195} & \frac{90}{310} & 0 \\ \frac{10}{195} & \frac{10}{310} & \frac{90}{530} \\ \frac{5}{195} & \frac{5}{310} & \frac{20}{530} \end{bmatrix}$$

Leontief Inverse (L)

The Leontief inverse L represents the direct and indirect inputs needed in each sector to produce a unit of output in each sector, denoted as L_{ij}. It is calculated as $L = (I - A)^{-1}$, where I is the identity matrix.

$$L = \begin{bmatrix} 2.066 & 0.478 & 0 \\ 0.058 & 1.034 & 0.305 \\ 0.018 & 0.032 & 1.041 \end{bmatrix}$$

Pollution Vector

The pollution vector q gives the total emissions per sector

$$q = \begin{bmatrix} 150 \\ 200 \\ 180 \end{bmatrix}$$

then in matrix form, we create am diagonal matrix,

$$Q_{\text{hat}} = \begin{bmatrix} 150 & 0 & 0 \\ 0 & 200 & 0 \\ 0 & 0 & 180 \end{bmatrix}$$

And L:

$$L = \begin{bmatrix} 2.066 & 0.478 & 0 \\ 0.058 & 1.034 & 0.305 \\ 0.018 & 0.032 & 1.041 \end{bmatrix}$$

And y:

$$y = \begin{bmatrix} 100 \\ 150 \\ 200 \end{bmatrix}$$

Emission Calculation

Now, let's calculate E using the formula

$$E = Q_{\text{hat}} \times L \times y$$

Calculating this, we get:

$$E = \begin{bmatrix} 3100.2 & 328.2 & 0 \\ 2072.0 & 3690.0 & 610.5 \\ 1860.0 & 216.0 & 187.2 \end{bmatrix}$$

The emission matrix ($\boldsymbol{E}$) represents the emissions for each sector, measured in metric tons. Essentially, it signifies the emissions associated with every dollar spent in each sector