The technology-adjusted balance of emissions embodied in trade: Assessing global carbon emission displacement from 1995 to 2009

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2017

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MASTER IN ECONOMIC DEVELOPMENT & GROWTH

The Technology-Adjusted Balance of Emissions Embodied in Trade: Assessing Global Carbon Emission Displacement from 1995 to 2009

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Abstract
Increasing global production fragmentation allows for emission displacement, which may counteract advanced nation's domestic reductions of production-related carbon emissions. Consequently, input-output analysis has become a common tool to measure countries' carbon footprint and emission trade balances based on national consumption instead of domestically produced CO_2 emissions. Nevertheless, traditional consumption-based indicators insufficiently account for cross-country discrepancies in production technologies or energy systems when quantifying actual emission displacement. By introducing the *technology-adjusted balance of emissions embodied in trade* we correct for these differences, identify global emission displacement from 1995-2009 and decompose it into the impact of its underlying drivers – trade specialization and the monetary trade balance. We find that Anglophone countries and particularly the USA have been net importers of carbon emissions as they specialized in carbon-heavy imports relative to less CO_2-intensive exports and – especially in the US-American case – showed a drastic monetary trade deficit from 1995-2009. Conversely, most European countries did not display suchlike trade specializations and – driven by monetary trade surpluses – have largely been net exporters of carbon emissions. Furthermore, China is – other than most emerging economies and mainly based on increasing specialization in more carbon-intensive exports than imports – identified as the major net exporter of emissions. These distinctions, suggesting that carbon trade patterns across the developed and developing world have recently been far from clear-cut, represent a novel finding in the emission displacement literature.

Key words: Emissions Embodied in Trade, Input-Output Analysis, Emission Displacement, Carbon Leakage, Carbon Footprint

EKHM52
Master thesis, Second Year (15 credits ECTS)
June 2017
Supervisor: Astrid Kander
Co-Supervisor: Viktoras Kulionis
Examiner: Kerstin Enflo
Word Count: 16,312

Acknowledgements

While a Master thesis only states the name of the authoring student, the process towards its successful completion involves the advice and encouragement of many different individuals. I feel honored and privileged for the support I have received throughout my academic career and dedicate these acknowledgements to those, who deserve my gratitude and appreciation.

I would like to thank my thesis supervisors Professor Astrid Kander and Viktoras Kulionis, who provided me with valuable and continuous feedback and guidance throughout the thesis-writing process. Moreover, I wish to express my gratitude to Prof. Dr. Bart Los, who ignited my interest in input-output analysis during preceding studies.

I am also incredibly thankful for the love and unconditional support of my family – in particular, Gudrun Baumert, Michael Reich, Hartmut Wolf, Heinke Hauschildt and Teresa Baumert – who have always been there for me when I needed them. Words cannot express how grateful I am to have them in my life.

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1. Introduction

The intensive media coverage and the noticeable relief after the sealing of the Paris Agreement in the end of 2015 illustrated the rising importance that large parts of the world ascribe to the danger of global warming – climate changes with increasing Earth temperatures due to anthropogenic greenhouse gas (GHG) emissions[1]. As part of the agreement, the participating countries decided to keep global warming distinctly below 2°C – possibly even 1.5 °C. This reflects the crucial significance of emission reductions in order to fight human-caused climate change, which governments attempt to address and translate into environmental policies (Aichele & Felbermayr, 2015; Peters et al., 2011).

Simultaneously, declining transaction costs of trade have led to increasingly global production processes for most final goods in recent decades. Consequently, it may not suffice to label a good as 'Swedish' or 'US-American' anymore as these national attributes veil the complexity of interconnected countries as well as industries, which may be involved in the production. Therefore, transnational trade agreements and the competitiveness of domestically realized production stages have emerged as major concerns of policy-makers. These developments, shifting both sustainability as well as global production fragmentation – defined as the 'disintegration of production structures across national boundaries' (Lopez-Gonzales, 2012, p. 24) – into the center of attention, emphasize the relevance of our study, which shall examine the interrelation of international trade and production-related carbon emissions[2].

As depicted in the exemplary and largely simplified Figure 1, a consumer demand for an US-American mobile phone may not exclusively induce economic activity in the domestic 'Telecommunication equipment' industry but may also imply increased demand for Chinese manufacturing. Furthermore, the assembling may draw on the production of batteries within Japan's 'Electrical parts' industry, which – in turn – may require lithium from Australia's mining sector. Therefore, the involved industries in Japan and Chile could possibly experience demand increases caused by the sale of a mobile phone in the USA, as well.

[1] The Paris Agreement terms an agreement aiming to reduce global warming and climate change's adverse impacts (United Nations Framework Convention on Climate Change [UNFCCC], 2015a). It was preceded by the Kyoto Protocol, which was adopted in 1997 and led to several developed countries' (so-called Annex I countries) agreements to emission reductions either during the first (until 2012) or the second commitment period (2013-2020) (UNFCCC, 2014)
[2] Throughout this study, the term 'emission' is used interchangeably with 'carbon emission'.

Figure 1: Linear Value Chain of a Mobile Phone

Nevertheless, not only the value added – denoting a given industry's contribution to a respective final product value (Timmer et al., 2013a) – but also the carbon emissions (with their related global environmental impact) associated with the production process of a final good are often partitioned across different industries in various countries (Xu & Dietzenbacher, 2014). Therefore, trade with intermediate goods concurrently implies trade with embodied emissions, which were required in order to produce these goods (Davis & Caldeira, 2010). Following this, a spatial discrepancy between the consumption and the production of a good's embodied emission may emerge (Aichele & Felbermayr, 2005; Barrett et al., 2013; Peters et al., 2011). This gave rise to an extensive academic discussion about the responsibility for recent global emission increases since it is often argued that large parts of the globally occurring carbon emissions are accounted for by advanced countries' consumption patterns (e.g. Andrew & Forgie, 2008; Munksgaard & Pedersen, 2001; Rodrigues et al., 2006; Serrano & Dietzenbacher, 2010). Moreover, the phenomenon has increasingly drawn public interest from a broader readership (e.g. The Economist, 2011; The Guardian, 2009 & 2014) highlighting the topicality of our study. In reference to the abovementioned exemplary case in Figure 1, the mining of lithium required in order to produce electrical components in Japan, which are assembled in China, may result in emissions accruing in Australia. However, the carbon emissions in Australia as well as those involved in the further processing in Japan and China only arise to serve final demand in the USA.

Consequently and drawing on the concept of multiregional input-output (IO) analysis, a large body of research, shifting the emission perspective from the producer countries to the countries of final demand, emerged – coining the term of consumption-based accounting (e.g. Davis & Caldeira, 2010). As IO analysis enables a clear distinction between product deliveries used to serve final demand (FD) and intermediate good supplies across industries, each industry's value added and the embodied emissions at the respective production stage may be traced along the (global) value chain (VC) – defined as the set of all value-adding activities needed in the production of a final good (Los, Timmer & Vries, 2015). Nevertheless, by employing matrix algebra not only the directly but also indirectly embodied emissions required at each production stage are considered. Therefore, summing these direct and indirect emissions arising from the production of a country's FD yields a given nation's carbon footprint (Minx et al., 2009).

Recently, such a 'consumption-based accounting' (CBA) approach has often been utilized (e.g. Ahmad & Wyckoff, 2003; Li & Hewitt, 2008; Nakano et al., 2009) to identify the degree to which advanced nations' FDs necessitate global production's emission. Nevertheless, despite the scholarly popularity of CBA studies, Kander et al. (2015) noted that even this approach may contain flaws as it insufficiently accounts for differences in the production technology among the trade partners when assessing the emission trade balance and the occurrence of emission displacement – shifts of carbon-intensive production capacities from countries with stringent climate policies to countries with less restrictive or non-existing emission constraints (Peters et al., 2011). Consequently, studies employing the CBA to identify evidence for emission displacement may mistake technology differences for specializations in more or less emission-intensive exports compared to the imports' carbon-intensity, which could result in biased findings about the existence or extent of trading countries' emission displacement.

This is where this paper shall fill in. First and building upon Jiborn et al.'s (forthcoming) study, which solely focused on Sweden and Britain, we introduce a novel approach to quantify consumption-based emissions. Second, our study employs this new approach for 40 countries (as well as a 'Rest-of-the-World' residual) yielding each nation's 'technology-adjusted balance of emissions embodied in trade (TBEET)' – thereby broadening the scope of examined countries to a global perspective. Third, this study analyzes the role of the monetary balance and specialization of trade for the all investigated countries' TBEETs. The generated findings may be considered relevant since they not only constitute a complement to the current approach of measuring emissions employed by the UNFCCC but also further advance the academically common measurement of consumption-based emissions. Moreover, country-specific studies on emission displacement are expanded by a substantially larger range of countries, which allows for further transnational generalizations.

In doing so, this analysis draws on a methodological approach, which introduces multiregional IO analysis and its environmental extension in general terms, before establishing the adjustment of the traditional CBA concept and applying it to IO and emission data from a renowned database. Thereby, this study aims to profoundly examine technology-adjusted emission displacement – a given country's reduction of domestic emissions coinciding with increased emissions abroad (Jiborn et al., forthcoming) – in global trade patterns while being guided by the research questions:

(1) *Have developed countries' domestic carbon emission reductions been counteracted by emission imports from developing countries when eliminating potential distortions resulting from technology differences across the trading countries?*

and

(2) *To what extent are surpluses and deficits in the examined countries' emission trade balance attributable to trade specialization or their monetary trade balance and may clear patterns for groups of countries with similar characteristics (e.g. emerging economies or advanced countries) be distinguished?*

As elaborated upon before, the answers to these questions are highly relevant as they may provide policy-makers with valuable insights required to assess the global environmental impact of national consumption patterns as well as enable the design of more suitable and effective policies to decrease a given country's carbon footprint.

The remainder of this paper is structured as follows. Chapter 2 presents an introduction to the emergence of interest in production-related environmental degradation, its interrelation with economic growth and traditional concepts to allocate responsibility for it. Furthermore, the advent of global VCs is presented, which resulted in the increased usage of IO analysis as a methodological tool to study VCs before this theoretical background is linked to a review of relevant literature contributions employing CBA as well as technology-adjusted emission accounting. This shall lead to the identification of this study's scope. Chapter 3 elaborates on the employed data while chapter 4 establishes the methodological approach of our analysis. Chapter 5 presents the results and translates these into the finding's implications and interpretation. By summarizing the main results, stating the paper's limitations and suggesting future research, chapter 6 concludes the study.

2. Literature Review

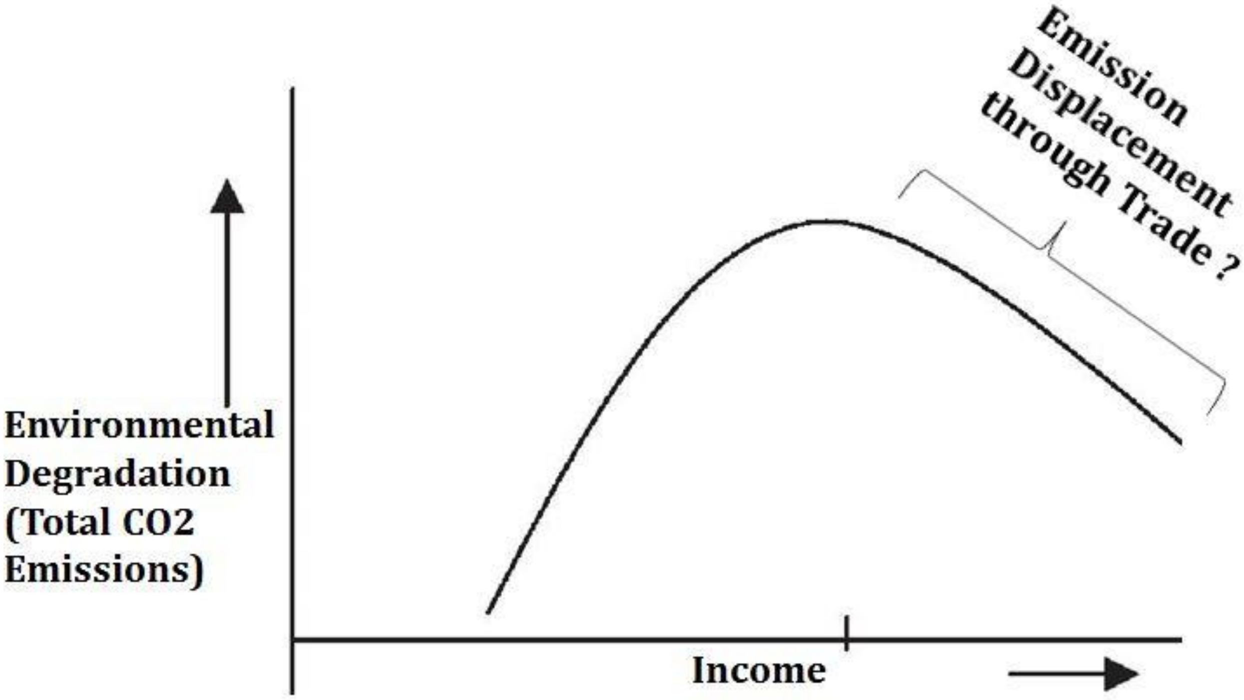
2.1. Economic Growth, the Environment & International Trade

The fact that the burning of fossil fuels such as coal, oil and gas for the purpose of energy generation involves a rise in the atmosphere's carbon dioxide (CO_2) concentration, which results in increasing global average temperatures (i.e. the greenhouse effect), is well established and acknowledged in academia (e.g. Le Treut et al., 2007, p. 115; MacKay, 2009, p. 5). While the onset of the industrial revolution(s) based on coal and oil extraction enabled an unprecedented population surge, an escape from the preindustrial, 'organic' economy (Kander, Malanima & Warde, 2014, p. 70) and the initiation of modern economic growth (Kuznets, 1973), it can also be considered as the beginning of the carbonization of energy systems. However, it took until the oil crises in the 1970s before major attention was drawn to the limited supply of fossil fuels[3] as well as the negative impact of emissions associated with the burning of fossil fuels (Meadows et al., 1972). Consequently, many scholars have since investigated the interdependency between economic growth and environmental degradation (e.g. Panayotou, 1993; Stern, 2004). For instance, the Environmental Kuznets Curve (EKC), which predicts the relationship between emissions and income in an inverted U-shape pattern, was empirically tested (Galeotti & Lanza, 2005; Stern, Common & Barbier, 1996). Figure 2 depicts this relation[4].

[3] A notable exception is represented by Jevons (1866, p. 123), who pointed out that increasing efficiency in the use of coal would likely imply an increased demand for the natural resource – thereby dismissing the presumption that energy efficiency improvements would reduce natural resource reliance.

[4] The EKC was termed by Panayotou (1993) and owes its name to Simon Kuznets (1955 & 1963) suggesting an inverted U-shape relation between economic growth and income inequality. While some studies use pollution intensity to measure relative environmental degradation on the y-axis (e.g. Roberts & Grimes, 1997; Sun, 1999; Tan, Wen & Chen, 2015), most academic contributions (e.g. Stern, 2004) aim to detect the relation of total emissions with income growth as illustrated in Figure 2 (Kander et al., 2017).

Figure 2: The Environmental Kuznets Curve



Source: Own construction based on Dinda (2004)

Theoretically, it is argued that, first, emission increases are caused by rapidly expanding industrialization at early development stages before, second, environmental concerns, a service transition, regulatory institutions and improving technology result in decreasing environmental pressure in relation to the growth of the Gross Domestic Product (GDP) (Dinda, 2004; Galeotti & Lanza, 2005). However, the evidence for the EKC is inconclusive and often contested, which is why it will not be discussed in-depth within this paper (see Dinda, 2004). Due to its relevance for the topic of this study, it is worth mentioning, however, that an additional and more recent argument for the existence of the EKC asserts that more developed countries' total emissions may decrease as these exploit the possibility of emission displacement through international trade (Cole, 2004). Therefore, as depicted in Figure 2 displaced emissions may be (part of) the reason for the decline in the EKC after the peak of a country's total emissions is reached.

This establishes a link to this study's research focus and re-emphasizes the topicality of our study, which aims to examine global emission displacement. However, it also calls for the introduction of related terms such as carbon leakage (i.e. emission displacement) and global production fragmentation (allowing for such displacement), which will be the subsequent sections' focal points.

2.2. Carbon Leakage and Traditional Indicators of Emission Responsibility

Despite a 'relative decarbonization in wealthy nations' (Afionis et al., 2017, p. 3), carbon leakage – a common synonym for (carbon) emission displacement – may actually increase global pollution, as the reduction of emissions in advanced nations could be substituted by more carbon-intensive imports from less regulated countries (Babiker, 2004; Kander et al., 2015). Moreover, the related literature distinguishes between 'weak' and 'strong' carbon leakage (Peters et al., 2011, p. 8907). Strong carbon leakage (also: policy-induced displacement) measures the increase of emissions in countries without given climate mitigation actions divided by emission reductions in countries implementing these policies (Barker et al., 2007; Peters et al., 2011). Thereby, it reflects a direct response to introduced emission mitigation policies (Peters & Hertwich, 2008a). In contrast, weak carbon leakage (also: demand-driven displacement) describes all aggregated flows of CO_2 embodied in imports from less to more restricted countries – irrespective of the motive (e.g. climate policies but also purely economic reasons)[5]. The rationale behind this is that climate emission regulations or production-related factor input costs (e.g. labor) may increase the relative prices of goods incentivizing shifts of (CO_2-intensive) production to countries without strict regulations in order to avoid global competitiveness losses (e.g. Copeland & Taylor, 2005; Azar, 2005).

This may either occur as a production reduction at home facilities with a simultaneous expansion of capacities abroad, the creation of new production plants in other countries or even in the form of the entire closure of domestic facilities and their substitution by production plants abroad (Helm, Hepburn & Ruta, 2012). As strong carbon leakage is more restrictive in its scope, it is often hard to estimate due to its strong assumptions and direct reference to relocation of production facilities (see Peters, 2008a). Therefore, the weak carbon leakage criterion is of more importance for this study as it comprises the emissions embodied in trade which shall be quantified in the course of our analysis.

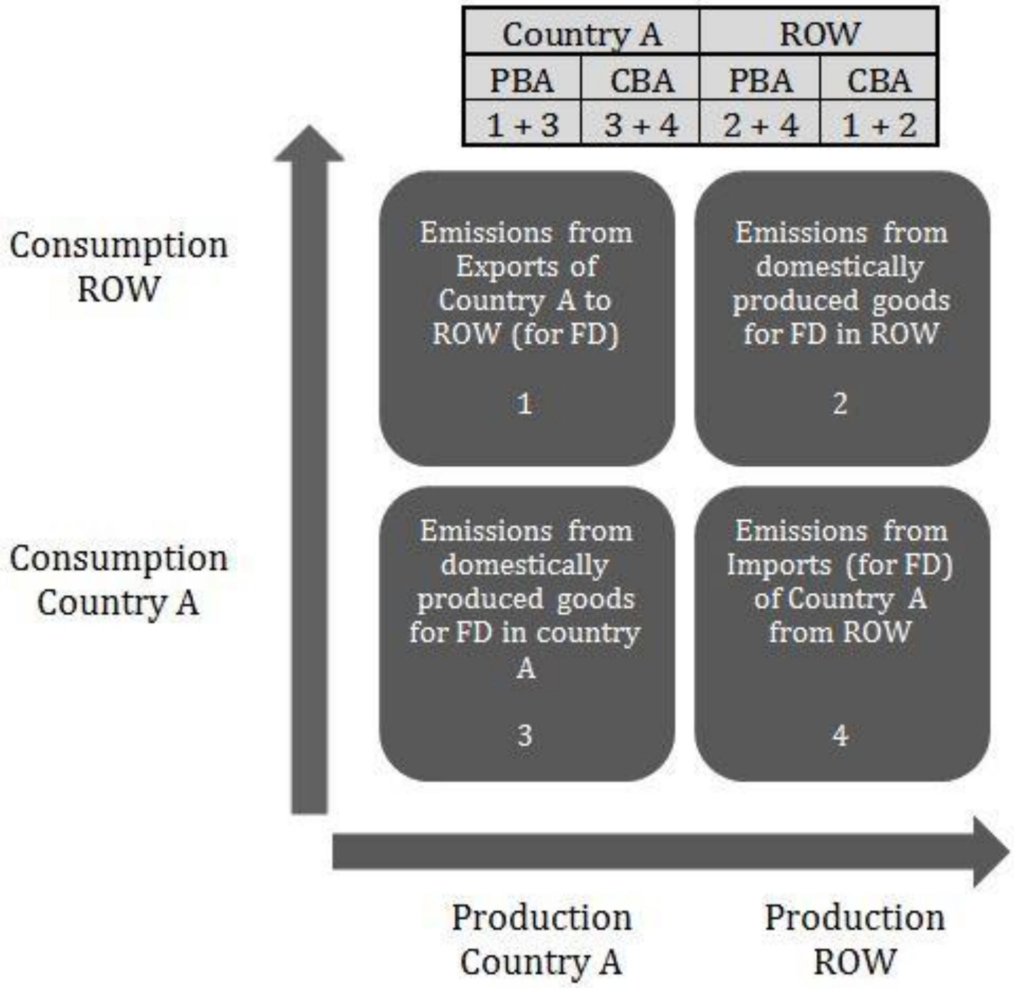
Furthermore, the possibility to displace emissions abroad gave rise to a discussion about the allocation of responsibility for emissions resulting from transnational production

[5] At an early stage of the phenomenon's academic examination, weak carbon leakage was also referred to as part of the 'displacement hypothesis' (e.g. Lucas, Wheeler &Hettige, 1993, p. 14) whereas the concept of strong carbon leakage is often investigated within the scope of the 'pollution haven hypothesis' (e.g. Cole, 2004, p. 73; Grether, Mathys & De Melo, 2012, p. 132). Throughout the remainder of this study, we will use the synonyms carbon leakage and (carbon) emission displacement interchangeably.

processes (e.g. Afionis et al., 2017; Kanemoto et al., 2013; Rodrigues & Domingos, 2008). While some scholars have undertaken attempts to share the responsibility between the producing and the consuming countries (e.g. Lenzen et al., 2007), two main perspectives are most common and hereinafter discussed. It is important to bear in mind, however, that both accounting schemes represent different approaches to allocate the national responsibility for production-related emissions while the total global emissions are, of course, equal in both concepts.

First, the production-based accounting (PBA) approach – used as a basis for climate mitigation policies impelled by the UNFCCC – assigns the (responsibility for) emissions involved in the production of a good or service to the country in which these emissions are generated (Afionis et al., 2017). While the USA has traditionally been the largest single-country producer of domestic emissions, China has – from 2006 onwards – taken over the inglorious title of the largest emitter of production-related emissions. However, the emissions produced for domestic consumption and those that are embodied in exports are not distinguished representing the possibility of carbon leakage and the main argument of PBA's criticism (Kulionis, 2014). In contrast, the CBA concept attributes all (responsibility for) emissions associated with the production and distribution of a final good to the location of consumption instead of production (Barrett et al., 2013). Therefore, insights from CBA may complement PBA by enriching it with information regarding consumption as a driving force of emissions (Peters, 2008b; Wiedmann, 2009). More specifically, while PBA burdens the producing country with domestic emissions regardless of the final products' destination, CBA considers a given country's emissions, which are produced and consumed domestically, but subtracts emissions embodied in exports and adds emissions embodied in imports (Suh, 2009, p. 535). The difference between countries' PBA and CBA is illustrated for a two-region example in Figure 3. As apparent from the Figure, PBA allocates country A with the carbon responsibility for all domestically produced CO_2 – irrespective of whether the CO_2-embodying goods are consumed at home (box 3) or abroad (box 1). In turn, CBA assigns country A with all emissions embodied in goods which are domestically consumed. These may be produced at home (box 3) or abroad (box 4).

Figure 3: PBA vs. CBA



Source: Own construction based on Suh (2009)

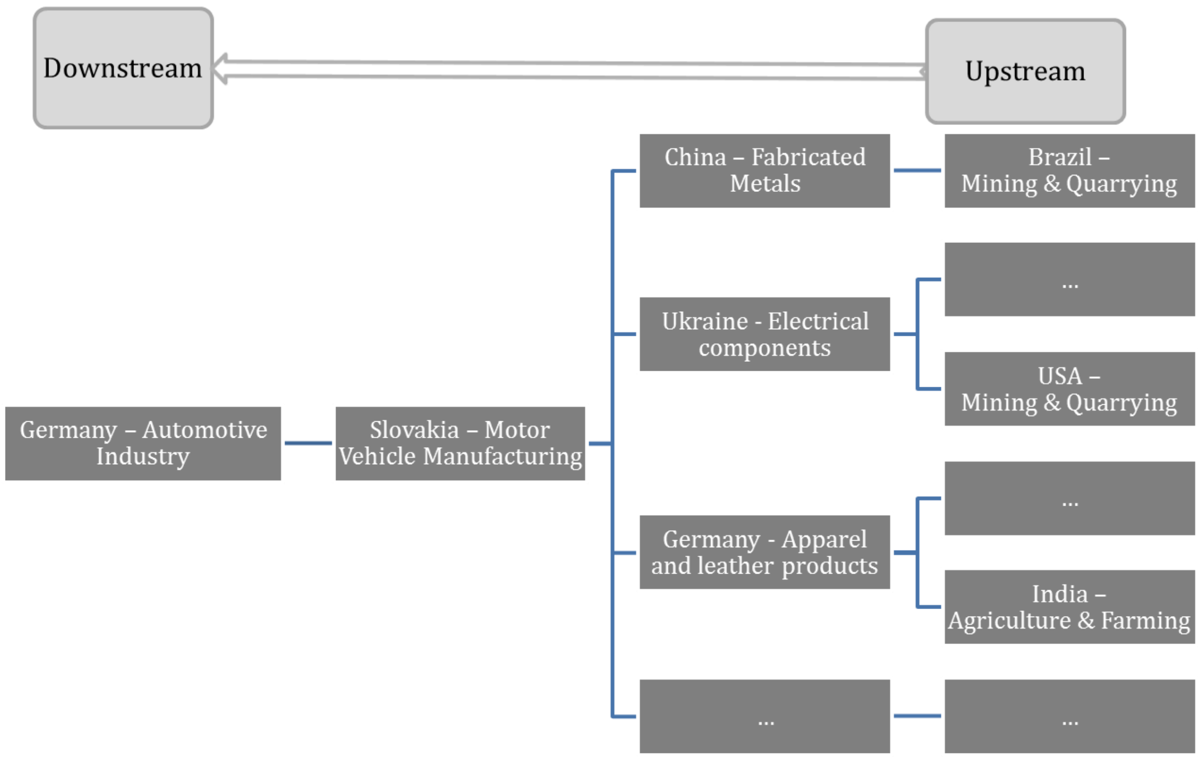
Due to improved data availability and increased interest in the drivers of the development of global emissions, many studies have compared the differences between the national results of production and consumption-based accounting. Consequently and due to the drastic discrepancies between countries' produced emissions and the CO_2 embodied in the consumption, which are often identified (e.g. Atkinson et al., 2011; Boitier, 2012; Wiedmann et al., 2010), the discussion about responsibilities for global emissions has recently also drawn the increased attention outside of academia (e.g. The Economist, 2011; The Guardian, 2009 & 2014). This, again, emphasizes the relevance of our study's analysis, which will refine previous results by implementing an adjustment to the common methodology to realize consumption-based accounting.

Moreover and to put the discussion about emission responsibility and displacement into context, it is worth mentioning that much attention was drawn to the phenomenon of carbon leakage when comparing the Kyoto protocol's so-called Annex I countries (with binding emission targets) and non-Annex I countries (without such emission targets) as it conceded the possibility of displacing emissions from the developed to the developing world (recall section 1). In light of the Paris Agreement – encompassing most of the world's countries and allocating Intended Nationally Determined Contributions (INDCs) to all of the signing nations (UNFCCC, 2015b) – the nature of potential carbon leakage has changed. While the Kyoto protocol allowed for emission displacement from countries with emission commitments to those without, the Paris Agreement may enable countries with absolute emission reduction targets (mostly advanced nations) to displace emissions towards countries with emission goals that are defined as relative to economic performance (commonly developing countries). However, as the employed data for our analysis only covers the years 1995-2009, we may only speculate about emission displacement in the Post-Paris Agreement period. Nevertheless, we may consider the distinction between Annex I and non-Annex I countries when quantifying the carbon leakage from 1995-2009 allowed for by the emergence of global VCs, which the ensuing section of this paper elaborates on.

2.3. Global Value Chains

In order to verify as well as quantify the assertion that production has increasingly globalized (Gereffi, 1989), many case studies have illustrated the fragmented nature of modern production processes. Among these, Dudenhöffer (2005) prominently examined the global VC of the 'Porsche Cayenne' – a German car – in order to determine the value added which (in 2005) had actually been contributed domestically to the sales price of the final product. While the car had still been completed in the German car industry, major parts of the production process had not been realized in Germany anymore. As elaborated upon by Dudenhöffer (2005), the German 'Automotive Industry' heavily relied on external components delivered from foreign companies, which themselves drew on supplies from more upstream industries dispersed regionally or globally. Consequently, while the production of the 'Porsche Cayenne' was still concluded in Germany, Dudenhöffer (2005) estimated that only around 30 per cent of the final car's value stemmed from domestic industries. Following this, large parts of the assembling took place in Slovakia's manufacturing sector, which – in turn – may have depended on domestic, Chinese or Ukrainian intermediate good deliveries. An exemplary and extended excerpt of Dudenhöffer's (2005) analysis is visualized in Figure 4.

Figure 4: Global Value Chain of Porsche Cayenne in 2005[6]



Suppose the sale of a Porsche Cayenne as illustrated in Figure 4 in which lines constitute intermediate deliveries of products (across or within countries) while boxes represent industries involved in the segmented production of a final good. As discussed by Dudenhöffer (2005), the demand for a car in Germany not only resulted in increased production within Germany but also required an expanded economic activity in Slovakia's manufacturing sector. Tracing the VC of Dudenhöffer's (2005) example even further upstream, Porsche's sale in Germany may have also implied additional demand for steel from China's 'Fabricated Metals' sector, switches from the Ukrainian 'Electrical products' industry or leather produced in the domestic 'Apparel and leather products' sector. These industries' intermediate good deliveries themselves, however, might have been enabled by Brazilian iron ore supplies to China, US-American copper mining serving the Ukrainian industry or animals skins occurring as by-products of India's

[6] Own construction based on Dudenhöffer (2005) but extended for illustrative purposes.

farming business, which are subsequently delivered to Germany for further processing to leather used in the Porsche Cayenne's interior. Obviously, this exemplary product case portraying the complex interdependencies of an unfolding globalized production network may largely be expanded by adding other intermediate deliveries – coining the term of the 'Global Factory' (Buckley & Ghauri, 2004, p. 88; Gereffi, 1989, p. 97).

Many more of such exemplary case studies emphasizing production fragmentation have been conducted. For instance, Dedrick, Kraemer and Linden (2010) disentangle the global production stages and the value added of contributing industries to the sales price of the iPod as a renowned consumer product. Despite establishing an improved understanding of global VCs, however, these microeconomic case studies did not allow for further generalizations regarding the fragmentation of production processes at an (inter-)national level. Moreover, the derivation of policy implications required economy-wide measures while common economic indicators became more contested in the course of advancing globalization[7]. These developments gave rise to the broader usage of IO analysis as a tool to measure countries' contribution to global VCs. However, the contribution to VCs may not only be traced in terms of value added but may easily be extended to an emission perspective. In other words, linking environmental accounts to the IO analysis also enables an examination of each involved industry's emissions, which are required in order to produce a final demand. In reference to Figure 4, one may expect that the Brazilian, US-American, Indian, Chinese, Ukrainian and Slovakian industries, which are involved in the production of a German car, generate emissions, which are ultimately consumed abroad – thereby exemplifying the spatial disconnect of consumption and production in globally fragmented VCs and reemphasizing the previously discussed question of responsibility for global emissions (section 2.2). As mentioned, CBA constitutes a method to reallocate emissions to the country where emissions are ultimately consumed. As it forms the prominent and traditional approach, which we aim to improve upon, it will be important to establish a clear understanding of prior findings attributable to CBA – as outlined in the subsequent section.

[7] For instance, many scholars have outlined the 'double counting problem' (e.g. Hummels et al., 2001; Koopman, Wang & Wei, 2012 & 2014; Wang, Wei & Zhu, 2014) causing trade statistics to be misrepresented and inflated relative to the good of the final product.

2.4. Prior Relevant Research on Emissions Embodied in Trade

While an in-depth elaboration on the large variety of studies which employ a CBA model in order to study potential emission displacement goes beyond the scope of this paper, several key findings shall be recognized.

First, several recent studies have found clear evidence for large emissions quantities, which are embodied in today's international trade patterns (e.g. Davis, Peters & Caldeira, 2011; Peters, Davis & Andrew, 2012). Among these, for instance, Davis & Caldeira (2010) conclude that 23 per cent of global CO_2 emissions were internationally traded in 2004 – amounting to 6.2 gigatoness (Gt) of CO_2. Similarly, Peters et al. (2011) estimate the emissions arising from the production of traded goods and services in 2008 at 7.8 Gt of CO_2 – equivalent to 26 per cent of total global emissions. Moreover, the authors stress the recent and continuous growth of emissions embodied in trade over time by indicating an annual rate of growth of 4.3 per cent when considering the substantially lower levels of 4.3 Gt of traded carbon emissions in 1990. This finding of continuous growth with major gross flows of traded emissions has also found academic support in many other recent publications (e.g. Davis & Caldeira, 2010; Nakano et al., 2009).

Second, academic contributions quantifying the difference between PBA and CBA have pointed to the large and increasing discrepancy, which arises when shifting from a production to a consumption-based perspective of allocating emissions to the respective responsible countries (e.g. Boitier, 2012; Peters et al., 2011). For instance, Boitier (2012) finds that while the EU-27[8] displayed 11 per cent higher consumption-based than production-based emissions in 1995, this share had risen to 24 per cent in 2008 (before decreasing as a result of the economic crisis in 2009). A similar trend is suggested for the OECD countries' total emissions. Moreover, it is claimed that major developing countries' (i.e. Brazil, Russia, India and China [BRIC]) production-based emissions exceed CBA estimations by 22 per cent in 2008. Finally, Boitier (2012) argues that this holds also true for the Rest-of-the-World (RoW) with PBA being 3.2 per cent above CBA.

Third, the detection of large discrepancies between CBA and PBA calculations highlights another often recognized pattern of international trade in emissions – the regional divide between advanced and developing countries with regards to their balance of

[8] The term EU-27 denotes all 27 member countries of the European Union (EU) in 2012.

emissions embodied in trade (BEET). Following this, a large amount of scholars (e.g. Peters et al., 2011; Xu & Dietzenbacher; 2014) has presented evidence for strong regional disparities in terms of net emission transfers. More specifically, Peters et al. (2011) quantify the net emission transfer from developing to advanced countries at 0.4 Gt in 1990 and 1.6 Gt in 2008. Consequently, this intensifying tendency to displace emissions to (non-Annex I) developing countries is often suggested to undermine carbon emission regulations (Davis & Caldeira, 2010).

Despite these numerous renowned studies enriching the traditional PBA perspective with insights regarding countries' consumption as a driving force of emission increases, the established method to realize CBA based on IO analysis has recently faced criticism. First and not far to seek, the PBA approach certainly distinguishes itself through simplicity in its construction, which remains unmatched by CBA (Afionis et al., 2017). Moreover, the interpretation of production-based emission accounting is easy to grasp for both the public and policy-makers. Second, Afionis et al, (2017) point out that – due to its transnational scope – policies resulting from CBA findings require not only almost universal cooperation but also bring about countries' liability for carbon emissions occurring outside their own jurisdiction, which may be difficult to communicate and implement. Third, while it is often acknowledged that CBA and IO analysis in general draw on large data requirements, the degree to which CBA is subject to data uncertainties as a consequence thereof is less commonly mentioned (Afionis et al., 2017; Peters & Hertwich, 2008b). Obviously, since the employed IO data needs to be consistent, it may require a harmonization of sector classification throughout all included countries as well as adequate currency conversions before being linked to emission data (another potential source of uncertainty) (Barrett et al., 2013; Peters & Hertwich, 2009). Moreover, information for countries with insufficient data quality is often aggregated to regional or residual accounts (e.g. 'Rest-of-the-World'), which – assuming fixed technologies and equal production structures for all included countries – may represent another source of error (Kulionis, 2014; Peters & Hertwich, 2009).

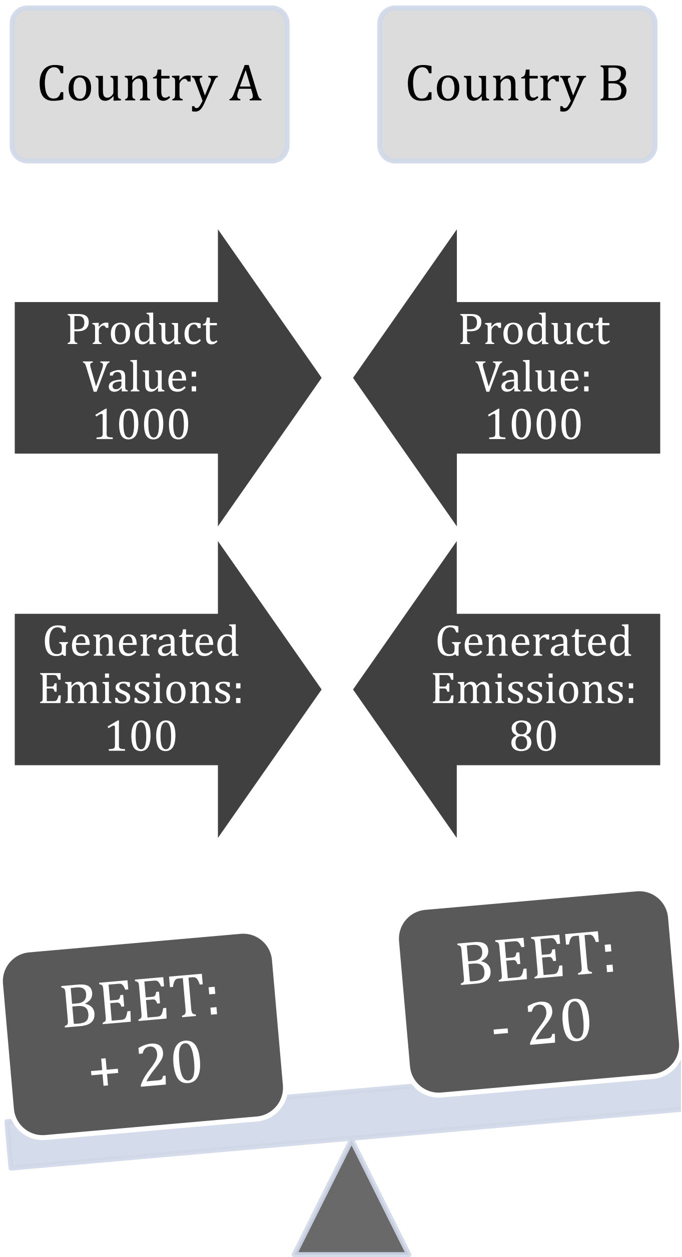
However, given the recently improved data availability and quality which can be expected to further enhance in the future, these caveats of rather practical nature are not expected to drastically challenge IO-based emission accounting' reliability (Barrett et al., 2013). Nevertheless, fundamental concerns about the method to compute the CBA as such have also been raised in recent years. As the related criticism and approaches to overcome it constitute the main objective of our analysis and thereby directly lead to the identification of the study's scope, we devote the subsequent section to this core issue.

2.4.1. Technology-Adjusted Emission Accounting

As mentioned, CBA is often considered to be superior to PBA due to its ability to attribute displaced emissions to consuming countries – thereby supposedly identifying carbon leakage (Afionis et al., 2017). However, as Kander et al. (2015) elaborate, CBA may confuse a country's relatively inferior production structures in terms of CO_2 emissions with specialization in a carbon-heavy export composition. More specifically, since the energy generation (e.g. from coal or renewables) and the production technology among trade partners may vary substantially in the amount of emitted CO_2, the trade specialization (e.g. in export of carbon-intensive industries such as chemicals or steel) may be indistinguishable from these differences in countries' technologies under CBA. Consequently, CBA may be unable to correctly identify whether a surplus in the balance of embodied emissions in trade stems from specialization in carbon-heavy export products (relative to imports) or from comparatively emission-intensive energy systems (i.e. electricity/energy generation). In turn, assuming an equal monetary trade balance, a deficit in the BEET could either be due to the specialization in carbon-heavy imports (relative to exports) or due to superior, less emission-intensive technologies and energy systems. This could result in misleading findings of international carbon transfer analyses and is argued to potentially challenge the reliability of CBA studies to identify emission displacement (Jakob & Marschinski, 2013; Jiborn et al., forthcoming).

For instance, the scenario depicted in Figure 5 (where arrows represent cross-border deliveries) supposes that a given country A incorporates a more emission-intensive energy system (e.g. by employing coal or oil instead of renewables or nuclear power sources to generate energy) and/or produces with comparatively more energy-intensive technology relative to its potential trade partners. If this country A would initiate trade of identical goods with country B that embodies less emission-intensive production structures, an analysis based on CBA would indicate a positive BEET labelling country A as a carbon exporter. This may hold true even though the regarded country A's production increases global emissions compared to a scenario in which its trade partner B serves its demands with domestic production (due to country B's lower carbon emission-intensity) (Jakob & Marschinski, 2013; Kander et al, 2015). The common

Figure 5: BEET and Technology Differences



interpretation of a scenario such as outlined above under the CBA concept would point to the existence of emission displacement by country B. Therefore, such countries with low carbon-intensity in their production (country B) may actually be termed net importers of embodied emissions and therefore penalized in the CBA scheme for exporting comparatively clean goods or services (Kander et al., 2015).

Consequently, CBA does not fulfill the entirety of conditions which Kander et al. (2015) attach to meaningful national emission accounting. These include, first, sensitivity, which is defined as the attribute of being responsive to factors that a nation itself may influence (e.g. the consumption level or carbon-intensity). Following this, the employed approach needs to account for the driving determinants of the emissions that a country causes. Second, effective accounting schemes should not allow for a country's carbon footprint reduction that ultimately leads to higher global emissions (i.e. monotonicity). Third and most intuitive, all national emissions should add up to the total global emissions (i.e. additivity) since it may otherwise be impossible to achieve global emission reduction goals even if national contribution targets are met. However, as elaborated on above and stated by Kander et al. (2015), the first two conditions may be violated not only by PBA but also by CBA. Moreover, it is crucial to stress that the lack of an adequate adjustment to account for trade partner's technology differences may lead to distorted results and the derivation of unsuitable implications for policy-makers – highlighting the relevance of studies such as this one –, which aim to overcome CBA's and therefor also the BEET's flaws when measuring emission displacement.

Consequently, by introducing the technology-adjusted consumption-based accounting (TCBA), Kander et al. (2015) correct for CBA's inability to meet all outlined requirements for a reliable national accounting scheme. In doing so, the authors suggest the harmonization of relative carbon intensities for the same industries across all different countries by computing each sector's world average based on the aggregation of output and emission data (with ensuing calculation of their global ratio) for all regarded industries. Furthermore, the authors conduct an empirical TCBA analysis based on IO and emission data from the World Input Output Database (WIOD; Timmer et al., 2015). Thereby, it is found that part of the apparent discrepancy between Europe's PBA and CBA may be explained by differences in the carbon intensity of Europe and its trade partners, which relativizes the prevalent interpretation of emission displacement as the sole source of the PBA-CBA divergence. In contrast, however, employing TCBA for the USA does not change its status as a net importer of embodied emissions. Following this, Kander et al. (2015) argue that – due to more carbon-efficient production in Europe compared to the world average – the common distinction between a carbon-importing developed and a carbon-exporting developing world may oversimplify and mask the variety of underlying patterns of international carbon trade. As our paper aims to realize a resembling correction for technology differences across countries, the intuition and academic inducement underlying our study can be considered similar to Kander et al.'s (2015). However, in line with Jiborn et al. (forthcoming), the focal point of this study is the refinement of the commonly employed BEET – thereby yielding the technology-adjusted BEET. Furthermore, the resulting refined emission trade balance is decomposed into its drivers and analyzes emission trade at a more subjacent level.

More specifically, based on Kander et al.'s (2015) previous insights, Jiborn et al. (forthcoming) adjust both imports and export by assuming globally uniform production technologies. This may be understood as the quantification of the amount of emissions that imports and exports would have caused if the traded goods had been generated with world average production technology. By subtracting the adjusted import-related emissions from the likewise corrected exported emissions, Jiborn et al. (forthcoming) introduce the 'technology-adjusted balance of emissions embodied in trade' of the UK and Sweden from 1995 to 2009 whereby the traditional BEET indicator is refined since the countries' technology differences are considered within their study. It is thereby found that while the standardization of production technologies mitigates the magnitude of the UK's consistently negative BEET over the regarded period, the Swedish TBEET appears positive despite its negative BEET throughout the entire time frame.

Moreover, the resulting TBEET for both countries is further decomposed into the monetary balance and specialization of trade to gain more profound insights regarding the emission balance's underlying determinants. The employed decomposition method of the emission trade balance is similar to Jakob & Marschinski's (2013) approach, which defines a country's emission export trade specialization in terms of relative differences in carbon intensities between its own sectors. Moreover, import specialization is understood as the imported goods' carbon intensity compared to the global economy carbon intensity. Thereby, again, Jakob & Marschinski's (2013) definition of trade specialization insufficiently accounts for technology differences, which may result in distortions when quantifying the trade specialization's contribution to a country's emission trade balance.

For instance, by alleging the Swedish economy as an example, one may argue that the country's relatively low overall carbon intensity may infer that it specializes in particularly emission-intensive exports. This occurs as carbon-intensive Swedish industries – even if these emit comparatively less per output than the same industry's world average – may display a higher level of carbon intensity relative to the remaining domestic economy (due to the above mentioned low overall carbon intensity) than other countries may exhibit. Nevertheless, when correcting for technology differences – thereby improving upon Jakob & Marschinski's (2013) decomposition of the non-adjusted BEET – and subsequently decomposing Sweden's TBEET, it is found that Sweden has increasingly specialized in more carbon-intensive imports compared to its export products over the regarded period.

It is worth mentioning that while Kander et al.'s (2015) calculation of the TCBA incorporates a technology adjustment for the export-related emissions of a country only, our computation of the TBEET and its decomposition involves the correction for technology-related emission differences both on the export and the import side. As pointed out by Domingos, Zafrilla and López (2016), a diverging method between allocating emissions to exports compared to imports will violate the desirable principle of ‘scale invariance’, which is part of a larger set of conditions to be fulfilled by national emission accounting outlined by Rodrigues, Domingos and Marques (2010, p. 31). While scale invariance implies that a group of countries’ carbon responsibility equals the summed carbon emissions which are caused by all included countries individually, the TCBA cannot ensure to satisfy this condition (Kander et al., 2016). For instance, the European Union (EU) may display a deviating carbon responsibility compared to the summation of all CO_2 caused by its members. This is due to the difference in allocating the emissions embodied in trade within the EU between regarding it as foreign or as domestic. As our paper aims to generate conclusive findings for different groups of countries (e.g. developing countries or Annex I countries), the technology-adjustment in this paper therefor refines both export and import-related emissions.

2.5. Scope of this Study

The preceding section aimed to establish a general understanding of the motive for –and the logic behind the technology-adjustment of imports and exports when examining countries’ traded emissions. Thus far, however, no study has internalized the methodology of Jiborn et al.’s (forthcoming) exemplary country case study in order to apply the approach to a broader range of countries. Therefore, thus far no generalizations linking the TBEET to countries’ characteristics (e.g. regions, emission regulations or development level) have been allowed for. Furthermore and in reference to the above mentioned rationale of carbon leakage in the light of climate agreements, previous studies have not been able to evaluate any potential connection between technology-adjusted emission displacement and (absolute) emission reduction commitments. By drawing on data for 40 countries and a RoW residual, the computation of the TBEET indicator and its subsequent decomposition into the underlying drivers, this contribution to the literature shall be accomplished within our paper, which gains relevance through its global perspective and the ability to allow for a distinction of characteristics which certain groups of countries may have in common in terms of trade-related emissions[9].

[9] While the underlying methodology of this study is based on the approach by Jiborn et al. (forthcoming), all data processing, calculations, illustrations and interpretations have been conducted independently by the author. Therefore, the mathematical calculation software Matlab with its proprietary programming language was employed. Moreover, Jiborn et al. (forthcoming) only examined two single countries, whereas this study examines all 41 available national accounts in individual but also in aggregated (i.e. country groups) form (see also Appendix A, B and C).

3. Data

Having established a more profound understanding of the nature of global VCs, their link to the environment and carbon leakage as well as an overview about previous findings making use of consumption-based emission accounting, it shall now be ascertained that the employed data for this study is adequate to generate insights which serve the research purpose. As elaborated on, the distinct rise in the complexity of global VCs with intensive intermediate good trade has created the imperative to study supply chains in more depth and therefor increasingly rely on IO analysis for the purpose of generating more meaningful trade-related indicators (including e.g. emissions embodied in trade) (Peters, Davis & Andrew, 2012). In order to establish a profound understanding of the concept which IO is based on, an introduction to the logic, representation and processing of IO data will follow before the extension with emission data will be elaborated on.

3.1. Input-Output Tables

The principle, which underlies IO data as well as its use to analyze the interaction of economies, industries and final consumers, is rather straight-forward. In general, a country's statistical institutions collect output data that enables the creation of national input-output tables as depicted in Table 1[10].

Table 1: Structure of a National Input-Output Table

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="4">Country N - Intermediate Inputs</th><th colspan="3">Country N - Final Demand</th><th rowspan="2">Total Output</th></tr>
<tr><th>Industry 1</th><th>Industry 2</th><th>…</th><th>Industry K</th><th>Final Demand 1</th><th>…</th><th>Final Demand S</th></tr>
<tr><td rowspan="4">Country N - Output</td><td>Industry 1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Industry 2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>…</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Industry K</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Value Added</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Total Output</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Source: Own construction based on Timmer (2015)

Within Table 1, the representation of a country n with k = 1, …, K industries (e.g. automotives) and s = 1, …, S final demand categories (e.g. private households) includes

[10] In line with the usual convention, Vectors are defined as columns while a prime indicates their transposed (row) form. Matrices are denoted with bold, upright capital letters, vectors are indicated by bold, upright lower-case letter, scalars are written as italicized letters. Finally, diagonal matrices with a vector's elements on the diagonal and zeros for all other entries are denoted by a circumflex (Serrano & Dietzenbacher, 2008 & 2010).

the intermediate matrix **Z** (check pattern) with K x K cells as well as the final demand matrix **F** (striped pattern) with S x S cells. Therefore, while a cell's column indicates the respective use of a good (either as an intermediate input for another industry or for consumption by one of the FD categories), the cell's row points out the delivering industry. Furthermore, each industry's value added in the considered time period is stated below the same industry's intermediate good input yielding the value added vector **w'** with the dimensions 1 x K. Finally, summing over the rows (or the columns) yields the vector of total output **x** with the dimensions K x 1 (and its transposed equivalent **x'**) (Dietzenbacher et al., 2013). Moreover, in accordance to the double entry bookkeeping principle, all industries' gross output included in IO tables must be equal to the same industries' sum of final and intermediate demand deliveries. Expanding the concept of IO tables to an international perspective encompassing all global production yields a World Input-Output Table (WIOT) as depicted in Table 2.

Table 2: The Structure of a Global Input-Output Table

		Country 1 Intermediate Input			**...**		**Country N Intermediate Input**			**Country 1 Final Demand**			**...**		**Country N FD**			Total Output
		Industry 1	...	Industry K	...	...	Industry 1	...	Industry K	FD 1	...	FD S	...	...	FD 1	...	FD S	
Country 1 Output	Industry 1																	
	...																	
	Industry K																	
...	...																	
	...																	
Country N Output	Industry 1																	
	...																	
	Industry K																	
Value Added																		
Total Output																		

Source: Own construction based on Timmer (2015)

A WIOT incorporates the same logic as embodied in a national IO table. However, all included countries' deliveries of intermediate as well as final goods are depicted by the rows' cells. Naturally, this also applies to the consuming industries (e.g. US American automotives) and FD categories (e.g. Swedish private households), which denote the columns of the WIOT (with n = 1, ..., N countries). Consequently, the dimensions of the **Z** matrix (KN x KN), the **F** matrix (KN x SN), the **w'** vector (1 x KN) and the **x** vector (KN x 1) differ in a WIOT when compared to a national table.

Within both a national IO table and a WIOT, every cell z_{ij} of the intermediate matrix **Z** contains the product value (in monetary units) which is delivered from industry *i* to industry *j*. Moreover, each element w'_j of the value added vector **w'** and each cell x'_j of the (transposed) output vector **x'** describe the value added and output which industry *j* generates, respectively. Finally, each value f_{ij} of the final demand matrix **F** denotes the value of final good deliveries from industry *i* to the final demand category *s*.

3.2. World-Input-Output Database (WIOD)

Logically, as our study will employ a globally encompassing IO analysis, the usage of WIOTs is inevitable. Therefore, we draw on the 2013 release of the WIOD (Timmer et al., 2015) consisting of IO tables based on national accounts and trade statistics from 1995 to 2011[11]. The employed data comprises 35 different industries for the EU-27 and 13 other major global countries complemented by a residual account for the RoW (Dietzenbacher et al., 2013). As such, the database has extensively been made use of for studies regarding global VCs (e.g. Baldwin & Lopez-Gonzales, 2015; Los et al., 2015).

Moreover, it includes various factor inputs such as total hours worked, capital compensation or energy use (Genty, Arto & Neuwahl, 2012). These diverse indicators obviously expand the scope and range of the database's applications substantially (Timmer et al., 2015). Furthermore and crucial for this study, each country's sectoral CO_2 emissions are listed, as well – which enabled many studies of emissions embodied in trade (e.g. Kulionis, 2014; Xu & Dietzenbacher, 2014) and are based on the EU-27 National Accounting Matrix with Environmental Accounts (see Eurostat, 2012), the UNFCC (2011) as well as EDGAR - the Emission Database for Global Atmospheric Research (EDGAR, 2011). Despite the availability of more recent and disaggregated IO data, this study is based on the WIOD'S 2013 release since it contains the latest carbon emission data with consistent WIOTs (both used for the years from 1995 to 2009).

Consequently, for all included years of the annual time series the WIOD quantifies the carbon emissions for 1435 country-sector combinations' (35 sectors in 41 countries incl.

[11] For a profound elaboration on the reasons for choosing the WIOD over other databases such as EORA (Lenzen et al., 2012a & 2013), EXIOPOL (Tukker et al., 2013; Wood et al., 2014) or GTAP (Aguiar, Narayanan & McDougall, 2016), please consult Tukker & Dietzenbacher (2013). Moreover, please note that Croatia was not included in the 2013 release of the WIOD which is why our study will elaborate on the EU-27 instead of all 28 current member states of the EU – thereby allowing for comparisons with other studies focusing exclusively on the EU-27 such as Boitier (2012), however.

RoW) and provides the inter-industry deliveries in a 1435 x 1435 intermediate matrix as depicted in Table 2. Moreover, it contains the demand of each country's five FD categories for each respective industry's good (1435 x 205). However, as the analysis that is aimed for does not distinguish between the diverse FD categories, the FD matrix may be simplified to a 1435 x 41 matrix. Finally, each year's output vector **x** with its dimensions of 1435 x 1 may be imported from the WIOD database for each regarded year, as well. Consequently, the hereby obtained data enables the calculation of relevant indicators (TBEET and its decomposition) which are necessary in order to answer the research question. This method will be elaborated on within the subsequent section.

4. Methodology

Drawing on the logic underlying an IO table as introduced in seminal contributions by Wassily Leontief (see e.g. Dietzenbacher & Lahr, eds. 2004; Leontief, 1936 & 1953), this section will introduce methods to determine meaningful emission indicators that may provide crucial insights about trade that can be derived from global IO tables. Subsequently, it will be shown how these methods may be linked to emission data in order to conduct analyses as presented in sections 2.4 and 2.4.1 Finally, the calculations underlying the TCBA and the related technology-adjusted balance of embodied emissions in trade (TBEET) will be established before an elaboration on the decomposition method employed to examine the TBEET in more depth will be given.

4.1. Input-Output Analysis as an analytical Tool

Based on the IO tables' structure and representation of the included industry-level data, the computation of IO coefficients forms a decisive part of IO analysis. First, one may calculate the input coefficient matrix **A** (also: technical coefficient matrix) with its dimensions *KN* x *KN*. The contained elements a_{ij} indicate the output value of a given (row) industry *i* which is delivered to (column) industry *j* in order to generate one single output unit in industry *j.* Therefore, the input coefficients are calculated by

(1) $$a_{ij} = z_{ij} / x_{ij} .$$

Following this, it may be worthwhile to employ matrix algebra to consider not only direct but also indirect supply requirements in order to assess the overall impact of occurring FD on a given industry or country (Timmer et al., 2013b). This is achieved by creating the so-called 'Leontief inverse' matrix **L** (also: total requirement matrix) with its dimensions *KN* x *KN* and where an included element l_{ij} quantifies the value of deliveries from industry *i* to industry *j* which is directly and indirectly embodied in the production of one (additional) unit of output in industry *j*. Thereby, the Leontief inverse distinguishes itself from the input coefficient matrix, which solely displays the direct production requirements of a given industry *i* required to generate an output unit in industry *j*. Consequently, the multiplication of **A** with a special final demand vector $\mathbf{f}_i$ (containing a single unit of demand in industry *i* and zeros for other industries' demands) yields a vector of all industries' direct output requirements to serve the final demand $\mathbf{f}_i$. Nevertheless, the production of $\mathbf{A}\mathbf{f}_i$ necessitates an additional output given by, again, multiplying with the input coefficient matrix **A** (, which in turn requires additional output). This geometric series may be simplified to the computation of the **L** matrix by

(2) $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$

in which the so-called *identity matrix* **I** with the dimensions *KN* x *KN* consists of ones on the matrix diagonal and zeros in all remaining cells (Miller & Blair, 2009, p. 58; Timmer et al., 2013b). Consequently, the multiplication of any final demand (vector) with the **L** matrix yields direct and indirect production requirements by each included industry in the IO table. This enables the assessment of final demand changes' impacts on every industry in all countries and disentangles complex production networks as in Figure 4.

Increased data availability has led to raised usage of IO analysis representing an indispensable tool to study the output distribution in trade-intensive production processes (e.g. Hummels, Ishii & Yi, 2001; Johnson & Noguera, 2012) Nevertheless, by integrating information on production-related emissions from industries' output into the quantitative model, IO analysis has become an adequate method to study embodied emissions along globally fragmented VCs, as well – the focal point of the next section[12].

4.2. Consumption-based Emission Accounting

While introducing the fundamentals of IO models, it became apparent that IO analysis allows for the illumination of each involved industries' value added contribution to a given final demand. Nevertheless, based on early insights from Leontief (1970), extending the model with environmental accounts enables the IO analysis to trace production-related emissions along fragmented production processes, as well. Therefore, with data on each industry's total emissions, one may determine how much CO_2 is directly emitted in the production of one (additional) unit of output in a given industry – aggregated to the vector (1 x *KN*) of emission coefficients **d'**. Consequently, its elements d'_j display the CO_2 emissions by industry *j* which are involved in the production of one additional gross output unit in the same industry as computed by

(3) $d'_j = c'_j \,/\, x'_j$

[12] Please note that – instead of emission data – many other production-related factor inputs such as labor (Timmer et al., 2013b), energy use (Machado, Scheffer & Worrell, 2001) or even biodiversity threats (Lenzen et al., 2012b) may be employed as an extension to the IO model.

where c'_j is the respective total emission value for industry j which forms part of the transposed total emission vector **c'** (1 x KN).

However, in order to consider direct but also indirect emissions embodied in the production, one must make use of the Leontief inverse. Consequently, if the FD vector **f** (KN x 1) would be determined as one given country's final consumption (i.e. with values for the regarded country's summed consumption over all FD categories and zeros for other nations' demands), the required emission vector **e** (KN x 1) may be calculated with

(4) $$\mathbf{e} = \hat{\mathbf{d}}'(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{f}$$

resulting in elements e_i indicating the directly and indirectly required emissions in industry i required to serve the demands of the given country as listed in **f**. Moreover, the aggregated sum of all elements of **e** would be equivalent to the country's carbon footprint in CBA (Davis & Caldeira, 2010; Jiborn, forthcoming). Thereby, it is worthwhile to emphasize that industry i could either be a domestic or foreign industry to the country which is investigated. This understanding is crucial as it highlights how intensive trade of (intermediate) goods may lead to a spatial disconnection of consumption and production of embodied emissions.

Therefore, CBA with an environmental extension may reassign production-related emissions to final consumers by tracing the demanded goods' VC throughout all involved trade or transformation steps in the production (Kander et al., 2015). Consequently, CBA consists of the domestic carbon emissions embodied in domestic consumption complemented by emissions incorporated in imported goods that are consumed domestically while domestic emissions resulting from the production of goods that are consumed abroad are subtracted (Kander et al., 2015; Peters & Hertwich, 2008b). In contrast, PBA only accounts for produced emissions within the boundaries of a given country – irrespective of the final demand location.

Following this, a given country's balance of emissions embodied in trade ($BEET_n$) may be defined as the discrepancy between the country's domestic emissions embodied in exports (EEE_n) and carbon emissions which are produced abroad but subsequently imported to serve domestic FD – termed emissions embodied in imports (EEI_n) (Jiborn et al., forthcoming; Kanemoto et al., 2013). Similarly, as EEE_n and EEI_n are incorporated in a country's CBA but disregarded in the same country's PBA, $BEET_n$ also represents the discrepancy between the two accounting approaches as elucidated for country *n* by

$$(5) \qquad BEET_n = EEE_n - EEI_n = PBA_n - CBA_n$$

As outlined in section 2.4, many studies investigating the BEET of single or multiple countries have been conducted (e.g. Peters et al., 2011) to provide evidence for emission displacement (i.e. carbon leakage; see section 2.2). However, the novel concept of the TBEET, which was designed in order to account for cross-country differences in the production technology of equivalent industries, has only rarely been employed thus far. Consequently, the subsequent sections describe, first, the adjustment it entails as well as, second, the decomposition method we use to analyze its underlying drivers.

4.3. Technology-Adjusted Balance of Emissions Embodied in Trade

In order to avoid mistakenly considering technology differences as proof of country's trade specializations in carbon-intensive products, we suggest the standardization of exported and imported goods' relative carbon intensities. By neutralizing differences in countries' production technologies or their prevalent energy systems, this paper analyzes the TBEET – a measure that unveils each examined country's emission displacement, which may then be further decomposed into the monetary balance and specialization of trade. In reference to the aforementioned conditions of meaningful national emission accounting as outlined by Kander et al. (2015), this measurement will not only meet the criteria of additivity but also the requirements of sensitivity and monotonicity that are not fulfilled by CBA and its related BEET indicator (recall section 2.4.1). Following this, TBEET will fully account for changes in a nation's consumption level as well as its carbon intensity (i.e. sensitivity) while carbon footprint reductions that imply higher global emission levels are not allowed for (i.e. monotonicity).

As direct and indirect value added contributions to final goods' values remain alike and only (relative) carbon intensities shall be harmonized in the calculation of the TBEET, the concept may draw on the Leontief inverse **L** as defined in equation (2). However, adjustments to the row vector **d'** as defined in equation (3) are necessary. While its elements d'_i assigned each country's industry with its individual coefficient indicating direct emissions involved in the production of one (additional) unit of output, the elements of the row vector $\mathbf{d'^{WA}}$ display the global average emissions caused by the production of such an output unit in a given industry (i.e. Textiles) irrespective of the industry's country location. Consequently, each industry is assumed to produce with the same carbon intensity in all regarded countries. This implies the quantification of direct emissions that the production of one output unit would have caused if it had been generated by using world average technology (Jiborn et al., forthcoming) defined as

(6) $$d'^{WA}_i = c'^{TOT}_i / x'^{TOT}_i$$

where c'^{TOT}_i indicates the total CO_2 emitted by a given industry i aggregated over all countries and x'^{TOT}_i equals the total output value generated by industry i summed over all regarded countries. The creation of suchlike average emission coefficients therefor results in the dimensions 1 x K of the vector $\mathbf{d'^{WA}}$ (as opposed to 1 x KN for $\mathbf{d'}$).

In accordance with the calculation of the required emission vector $\mathbf{e}$ (based on country-specific direct emission coefficients) as introduced in the preceding section, the computation of required emissions under the world average technology assumption ($\mathbf{e^{WA}}$) draws on the same logic but uses the diagonalized vector $\mathbf{\hat{d}'^{WA}}$ when multiplying with the Leontief inverse $\mathbf{L}$ and the FD vector $\mathbf{f}$ (both KN x 1)[13]. This yields the equation

(7) $$\mathbf{e^{WA}} = \mathbf{\hat{d}'^{WA}} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{f}$$

and elements e_i^{WA} describing the directly and indirectly generated emissions in industry i (domestic or foreign) which are necessary to serve the demands defined by $\mathbf{f}$. Including only a given country's FD in $\mathbf{f}$ would therefore result in this country's technology-adjusted carbon footprint when summing all elements of $\mathbf{e^{WA}}$.

Similarly, considering all global FDs and applying equation (7) yields sectoral emissions required to serve this FD when assuming standardized production technology. However, since we define the national TBEET as the discrepancy between the regarded country's technology-adjusted emissions embodied in exports ($TEEE_n$) and the likewise adjusted emissions embodied in imports ($TEEI_n$), we must disregard domestic emissions which ultimately serve domestic FD. Therefore, a country n's TBEET may be computed by

(8) $$TBEET_n = TEEE_n - TEEI_n \, .$$

[13] Please note that – in order to be able to realize the described calculation – the vector $\mathbf{d'}$ is, first, duplicated N times and, second, diagonalized in order to yield the (KN x KN) matrix $\mathbf{\hat{d}'}$.

While the TBEET of a given country quantifies the balance of technology-adjusted carbon trade, it does not illuminate the contribution of the monetary balance and specialization of trade to the TBEET. These insights may, however, be generated by further decomposing the TBEET, which the subsequent section elaborates on.

4.4. The decomposition of the TBEET

Since this paper aims to fully explain each country (group)'s TBEET by, first, the trade specialization and, second, the balance of trade, the sum of the two underlying determinants' impact for a given country will equal the country's TBEET – thereby being entirely additive (i.e. not leaving any residual) (Jiborn et al., forthcoming). Thus, the realized method draws on the additive and refined Laspeyres index decomposition introduced by Sun (1998) and used in line with Jakob & Marschinski (2013). Nevertheless, their paper distinguished not only the effects of trade specialization and balance but also a country's energy intensity – the energy necessary to generate one monetary unit of GDP – and its carbon intensity of energy, which they define as CO_2 emissions per energy unit. However, since the TBEET already corrects for differences in energy and carbon intensity, our decomposition deviates from Jakob & Marschinski's (2013) method by solely focusing on the remaining two drivers of the TBEET.

In doing so, a given country *n*'s export specialization is calculated by dividing a country's carbon intensity of exports assuming standardized world average (i.e. $TEEE_n$ divided by country *n*'s total export value) by the global carbon intensity. This may be elucidated by

(9) $$exp.sp_n^{WA} = \frac{\left(\frac{TEEE_n}{EX_n}\right)}{\left(\frac{E_W}{GDP_W}\right)}$$

where $exp.sp_n^{WA}$ describes the technology-adjusted export specialization of country *n*, EX_n is defined as the country's total export value while E_w denotes global emissions and GDP_w indicates the total global output value. Following the same logic, the technology-adjusted import specialization ($imp.\ sp_n^{WA}$) of country *n* is computed by

(10) $$imp.sp_n^{WA} = \frac{\left(\frac{TEEI_n}{IMP_n}\right)}{\left(\frac{E_W}{GDP_W}\right)}$$

with *n*'s total import value given by IMP_n.

Finally, the total contribution of both specialization (Δsp_n) and the trade balance (Δbal_n) to the TBEET of a country may then be calculated by

$$(11) \qquad \Delta sp_n = \left(\frac{TEEE_n}{EX_n} - \frac{TEEI_n}{IMP_n}\right) * IMP_n + \frac{1}{2} * \left(\frac{TEEE_n}{EX_n} - \frac{TEEI_n}{IMP_n}\right) * (EX_n - IMP_n)$$

and

$$(12) \qquad \Delta bal_n = \frac{TEEI_n}{IMP_n} * (EX_n - IMP_n) + \frac{1}{2} * \left(\frac{TEEE_n}{EX_n} - \frac{TEEI_n}{IMP_n}\right) * (EX_i - IMP_i)\,.$$

With the help of these equations, it will be possible to gain insights about whether and to what extent trade specialization and the monetary balance of trade contribute to countries' overall TBEET. Moreover, by employing a time series, it will therewith be possible to quantify whether countries may shift towards more (less) carbon-intensive imports or exports and to what extent this negative (positive) contribution to the overall national TBEET may be compensated for by their positive (negative) monetary trade balance. For instance, a country with a neutral trade balance and trade specialization in more carbon-intensive imports than exports will exhibit a negative TBEET (i.e. emission displacement). However, even if a given country's imports are more carbon-intensive than its exports, a positive monetary trade balance may result in the country's status as a net exporter of embodied carbon emissions (i.e. a positive TBEET). While the results will focus on major country groups like the EU-27, the emerging countries (represented by the BRIC countries consisting of Brazil, Russia, India and China) or the included Annex I countries in our dataset[14], major individual economies like the USA or China as well as some representative or exceptional cases shall be elaborated upon as well.

4.5. Assumptions of this Study

While the main uncertainties of national emission accounting – the large emission and IO data requirements with the related uncertainties in the collection and processing of the gathered information, the required currency conversion, the harmonized sector classification and the aggregation of residual accounts (e.g. RoW) – have already been elaborated upon (section 2.4), our study also rests on several assumptions. Therefore,

[14] As no segregated country data for some Annex I nations is available within the WIOD, the input, output and emissions of Belarus, Croatia, Iceland, Kazakhstan, Liechtenstein, Monaco, New Zealand, Norway, Switzerland and Ukraine are considered as part of the RoW residual and thereby as non-Annex I countries despite their emission targets. Moreover, South Africa is often mentioned as a major emerging country, as well, resulting in its common grouping with Brazil, Russia, India and China to form the BRICS countries. However, since no individual country WIOD data is available for South Africa, this study focuses exclusively on the BRIC to represent emerging economies while South Africa forms part of the RoW.

we complement the general assumptions as outlined by Christ (1955) and Lee & Mokhtarian (2004) with other assumptions necessary for the environmental extension employed in our study. All these assumptions simplify the model and aim to compensate for the lack in more disaggregated micro-data (Christ, 1955; Timmer et al., 2013b).

First, as Christ (1955) elaborates, IO analyses implicitly suppose that each country-sector combination only produces one homogeneous product which reflects the average output of each of the sector's firms (see also Timmer et al., 2013b). No distinctions in terms of a good's quality may be allowed for (Lee & Mokhtarian, 2004). Second, IO analyses assume constant returns to scale and thereby suppose that the input-output ratio of each sector remains constant. More specifically, were a sector's produced output to change by a certain percent, inputs to this sector would necessarily change by the same percent and vice versa (Christ, 1955; Lee & Mokhtarian, 2004). Third and closely related, it is assumed that the input coefficients (also: technical coefficients; section 4.1) and therewith the represented (global) production processes and VCs are fixed. Therefore, all companies within a given sector are expected to employ the same input proportions for the production of equal output. Moreover, it follows from the fixed input coefficients that technological progress within the individual regarded time periods (i.e. one year in the case of our study) is not allowed for (Lee & Mokhtarian, 2004). Finally, as our study links the gathered IO data to emission data while calculating emission coefficients, these coefficients are also assumed to be fixed for a given year and country-sector combination before this assumption is – as explained in section 2.4.1 – replaced by fixed emission coefficients per sector but across countries when creating the TBEET.

Obviously, these are strong general assumptions since it has often been found that for instance exporting companies exhibit different input structures than domestic producers (Timmer et al., 2013b). Furthermore, production inputs may change with the scale of a company's output, products are heterogeneous even within a sector and do in fact often largely differ in quality. Moreover, several sectors (e.g. Construction) may require major initial inputs before any output (i.e. a house) is generated (Christ, 1955). The same may obviously apply for the emission of CO_2 in the production process.

Nevertheless, with increasing sector disaggregation and due to the scale of the economy-wide data collection, the assumption's unrealistic nature can be expected to decrease, which allows for meaningful results of IO analysis in general and our study in particular.

5. Results

In order to emphasize the two-tier analysis of our study, we hereafter, first, display results for the TBEET as well as the PBA, CBA and BEET over time from 1995 to 2009 based on data from the WIOD. After these results have been commented on and interpreted, the TBEET is, second, decomposed into its drivers – trade balance and trade specialization. All quantitative results and their illustrations (including Appendix A, B and C) are, of course, based on the author's own calculations. It is worth highlighting that the single-country results obtained within this study are in line with Jiborn et al.'s (forthcoming) findings for Sweden and the UK – thereby pointing to the methodological accuracy of our study. However, our study broadened the perspective to a global dimension and allows for multi-country generalizations of emission trade patterns. Moreover, in order to emphasize the fact that the (technology-adjusted) balance of embodied emissions in trade equals zero globally as imported emissions must equal exported emissions by definition, Table 3 displays a detailed list of all TBEETs for each nation (with its related country code) included in the WIOD database in 2009.

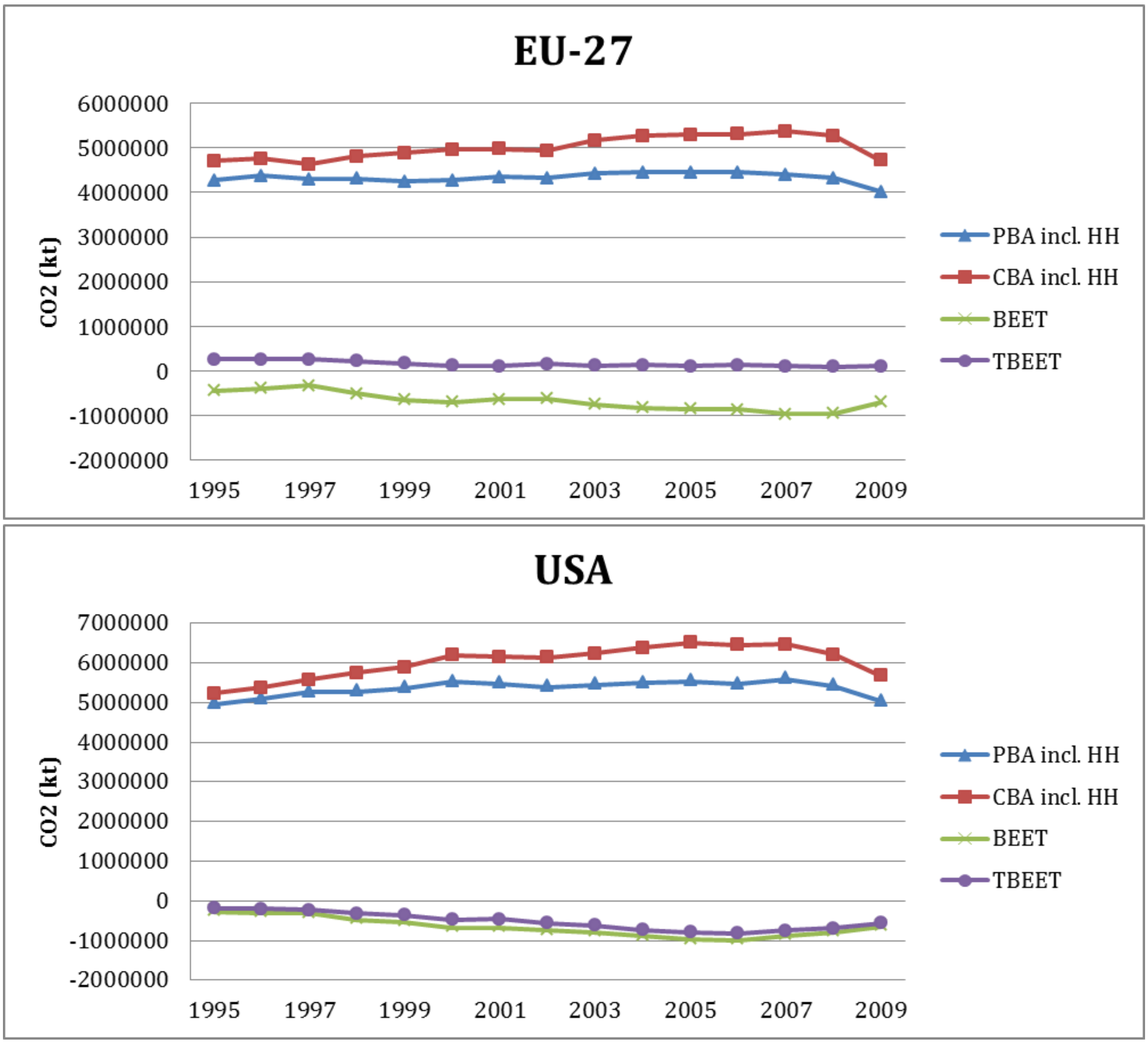
Table 3: TBEET of all WIOD Countries in 2009

Country	Country Code	TBEET in 2009 (in kt CO_2)
Australia	AUS	-24876
Austria	AUT	25180
Belgium	BEL	6316
Bulgaria	BGR	4589
Brazil	BRA	-5726
Canada	CAN	-29528
China	CHN	612720
Cyprus	CYP	-2610
Czech Republic	CZE	12766
Germany	DEU	86963
Denmark	DNK	33147
Spain	ESP	3558
Estonia	EST	1376
Finland	FIN	2049
France	FRA	-34575
United Kingdom	GBR	-79405
Greece	GRC	-11551
Hungary	HUN	-69
Indonesia	IDN	-17504
India	IND	-48758
Ireland	IRL	12260
Italy	ITA	-7172
Japan	JPN	57864
South Korea	KOR	94516
Lithuania	LTU	-1282
Luxembourg	LUX	4160
Latvia	LVA	-771
Mexico	MEX	-32228
Malta	MLT	133
Netherlands	NLD	58583
Poland	POL	5338
Portugal	PRT	-7363
Romania	ROU	-3682
Russian Federation	RUS	104862
Slovakia	SVK	6355
Slovenia	SVN	-727
Sweden	SWE	2168
Turkey	TUR	-3757
Taiwan	TWN	34169
United States of America	USA	-565017
Rest of the World	RoW	-292472
World (total)		0

5.1. Emission Trade and Responsibility from 1995 to 2009

Figure 6 compares production-based and consumption-based emissions for the EU-27 and the USA. As apparent from the graphs, our analysis' results confirm prior findings (e.g. Boitier, 2012; Peters et al., 2011) suggesting a large and mostly increasing discrepancy between advanced countries' carbon responsibility based on their domestic emissions and the emissions caused in order to serve their consumption (i.e. FD). The BEET quantifies the difference between the two indicators (recall Equation 5) and is therefore negative for both the EU-27 and the USA throughout the entire time frame. Furthermore, the observable trends for the EU-27 and the USA are very similar when regarding PBA, CBA and BEET reflecting an apparent pattern of advanced countries' consumption-based emissions significantly exceeding domestically produced emissions.

Figure 6: PBA, CBA, BEET & TBEET – Aggregated EU-27 and USA (1995-2009)[15]



[15] Both PBA and CBA consider household (HH) emissions, which are not part of international trade.

Nevertheless, when turning to the TBEET as the only displayed indicator in Figure 6 that accounts for technology differences across all global countries, it is found that, first, the EU-27's TBEET clearly contrasts the results obtained for the BEET as it is continuously positive throughout the entire period[16]. For the USA, however, the result does not change as substantially from the BEET to the TBEET since its status as a net importer of carbon emissions remains consistent even when adjusting for technology differences across countries. Consequently, the results suggest that while the EU-27's negative BEET may be caused by the European countries' carbon efficient production when compared to its trading partners and therefore becomes positive if production technologies are standardizes under TBEET, the USA's domestic carbon efficiency has not improved sufficiently over the regarded time period to be able to explain the negative BEET – resulting in a negative overall TBEET. Insofar, the different supranational findings for the EU-27's TBEET in comparison to the USA resemble the patterns found by Jiborn et al. (forthcoming) for the individual cases of Sweden (whose TBEET was continuously positive despite a negative BEET) and the UK (with a negative BEET, which is not compensated for by the technology adjustment in recent regarded years), respectively.

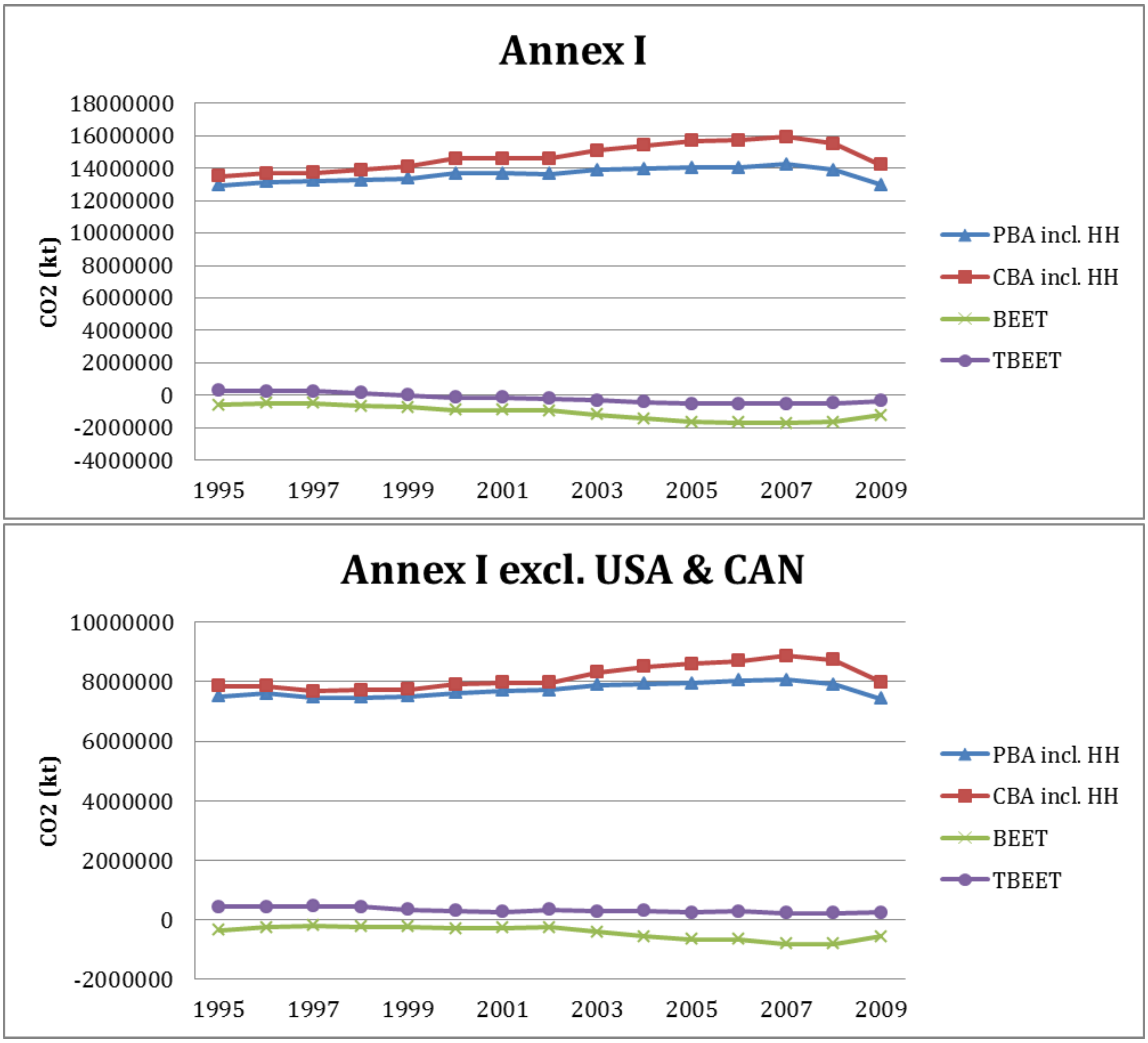
Finally, it may be acknowledged that – despite the EU-27's positive TBEET, its magnitude has been decreasing over time, which could give rise to some concerns by policy-makers since the EU-27 may eventually (have) turn(ed) into a net importer of carbon emissions in technology-adjusted terms. This may spur the previously discussed carbon responsibility question as it would imply that the EU-27's international trade leads to foreign-produced emissions required to serve the EU-27's consumption. For the USA, this adjusted carbon footprint already exceeds domestically produced emissions significantly. Due to the lack of more recent IO and emission data underlying our analysis, however, we may only speculate on more recent developments of the net trade balance on the supposition of standardized production technology in terms of emission intensity. However, it seems not far to seek that the trend of a slight decrease of the EU-27's TBEET over time has recently continued. Following this, the positive TBEET, which was maintained throughout the period, may have further decreased gradually or could have already reached negative levels – changing the EU-27's status from net exporter to net importer of emissions.

[16] The quantitative results and the illustrative representations of selected regarded countries can be found in Appendix A, B and C. Individual results for the remaining countries included in the WIOD can be obtained from the author on request.

In reference to the aforementioned Kyoto protocol and the consequent labelling of nations with binding emission targets as Annex I countries, it is worth highlighting whether extensive trade of countries with goals of emission reductions increased their technology-adjusted consumption-based emissions (, reflected in a negative TBEET).

While most major Annex I economies are found to have positive or only relatively mildly negative TBEETs in 2009 (with the possible exceptions of the UK, Australia, Canada and France; see also Appendix A.1), the USA contribute drastically to the overall negative TBEET of all Annex I countries as depicted in Figure 7. As illustrated, disregarding the USA (who never ratified the Kyoto protocol) and Canada (who withdrew from it in 2011) results in a positive TBEET for the aggregate of the remaining countries.

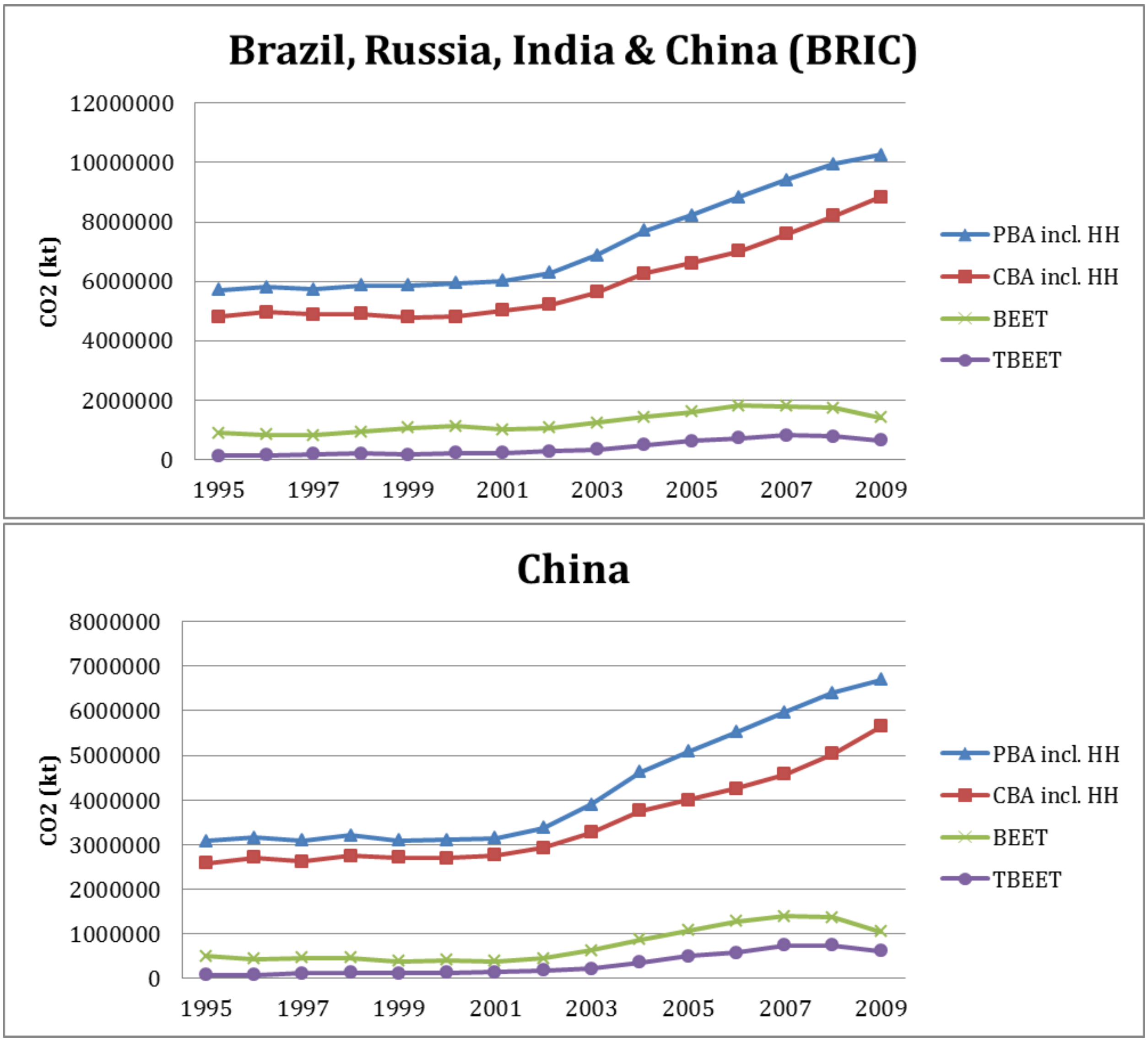
Figure 7: PBA, CBA, BEET & TBEET – Aggregated Annex I (1995-2009)



Consequently, assuming that Annex I countries' traded goods (excl. the USA and Canada) had been produced with global average technology, the initial status of the aggregate countries would change from net importer (in BEET terms) to net exporter of CO_2. Moreover, it is noticeable that the slightly positive level of the TBEET for the remaining Annex I countries is rather stable over the period. This suggests that these countries' mean production technology has – in terms of emission intensity – developed similarly to the world average while continuously maintaining a higher overall carbon efficiency.

Turning to countries that are often claimed to be emission displacement destinations, Figure 8 displays the PBA, CBA, BEET and TBEET results for BRIC countries and – due to its academic and public attention as the heart of the 'Factory Asia' (Dietzenbacher, Pei & Yang, 2012; Liu et al., 2016; The Economist, 2015a & 2015b) – for China individually.

Figure 8: PBA, CBA, BEET & TBEET – Aggregated BRIC and China (1995-2009)



As expected based on prior academic contributions by – among others – Davis & Caldeira (2010) and Peters et al. (2011), it may first be noted that – according to the traditional CBA approach – most major developing countries can be considered as net exporters of emissions (with the exception of Brazil) since both China's as well as the overall BRIC's (of which China forms a substantial part) production-based emissions are significantly higher than the emissions caused by their population's consumption resulting in a BEET that is significantly above zero throughout the entire period.

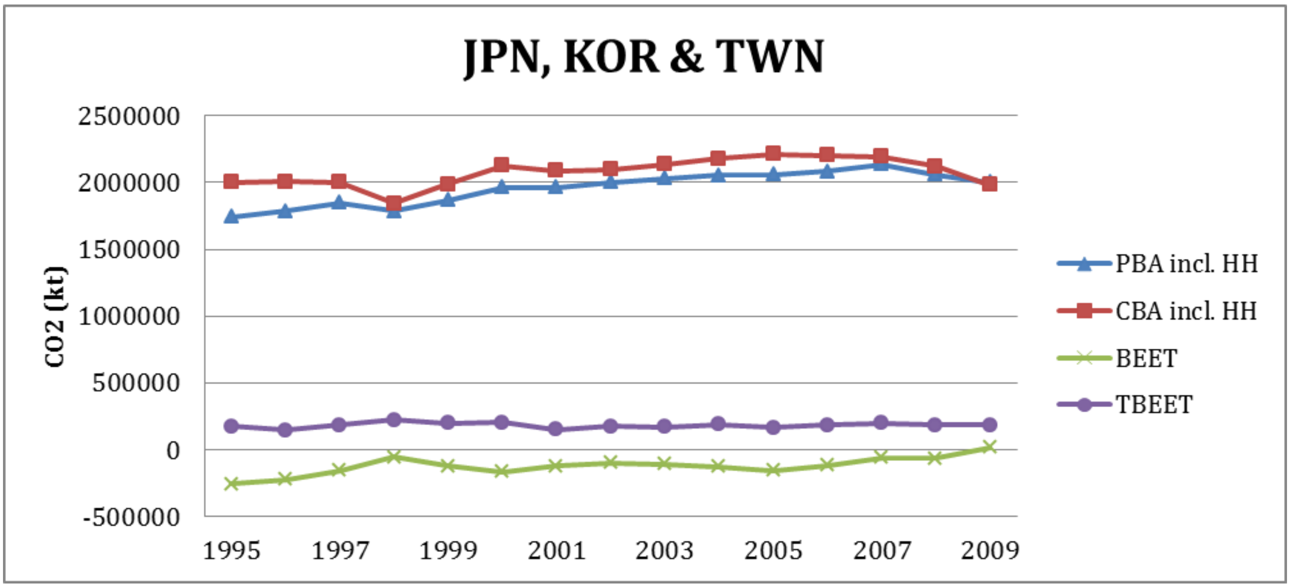
However, when correcting for technology differences and thereby regarding what these exported emissions would have caused if they had been produced with world average technology, two crucial findings can be distinguished. First, the BRIC's overall TBEET shrinks significantly compared to the BEET. Following this, the direction of the adjustment is clearly reverse to the correction observed for the EU-27 (and – to a lesser extent – for Annex I countries). While the summed TBEET for the BRIC remains positive throughout all regarded years, the selected developing countries' results suggest that their carbon efficiency is significantly below world average, which leads to an inflated BEET compared to the TBEET. Second and by examining the individual BRIC countries' TBEETs in more depth (see Appendix A.1 and B), it is found that China and Russia are the only BRIC countries that actually display a positive TBEET while – unlike the common perception of these emerging economies – Brazil and India are net importers of emissions when harmonizing the production's carbon intensities globally. This also emphasizes that the simplified categorization of emerging economies' role as net exporters of emissions is not clear-cut since China's exceptional TBEET is far from consistent with Brazil's or India's results. Finally, while Russia shows a positive TBEET, its magnitude – due to the significantly smaller population – differs largely from China's adjusted emission trade balance highlighting China's special status as emission exporter.

Again, we may only speculate about the TBEET development after 2009. However, it seems reasonable that – driven by China's economic upsurge and gross exports – the increasing discrepancy between BRIC countries' PBA and CBA may have broadened further after the slight convergence attributable to the temporary decrease in global trade in the course of the 2008 financial crisis and, subsequently, the 'Great Recession'.

Moreover, it may be worth asking which other countries – apart from China and Russia – have emerged as large-scale emission exporters, if major emerging economies such as

Brazil and India cannot be defined by this term. As displayed in Figure 9, our results suggest that the technology-adjusted emission trade surplus of high-developed and export-intensive Asian economies such as Japan and Korea contribute in offsetting negative TBEETs from the USA, the RoW aggregate and the UK (among others).

Figure 9: PBA, CBA, BEET & TBEET – Developed Asian Countries (1995-2009)



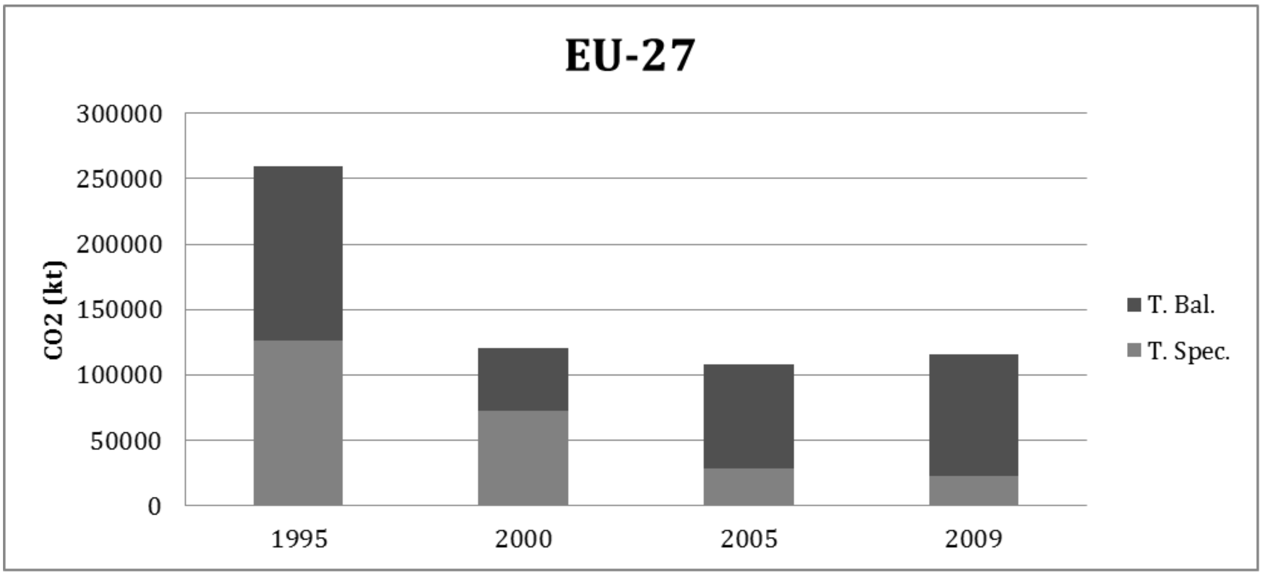
For most examined country (groups) – including the aggregate BRIC nations – it is rather challenging to predict how the TBEETs as well as their differences to the BEETs may have developed after 2009. Moreover, no assertion about whether or not the regarded countries display a pattern of specialization in importing more carbon-intensive products than are exported is possible, since this section's results for the TBEET illuminate national emission trade balances when assuming world average technology but cannot unveil and quantify the contribution of the two underlying driver – trade specialization and monetary trade balance. Consequently, the subsequent section displays the results of the decomposition analysis outlined in section 4.4.

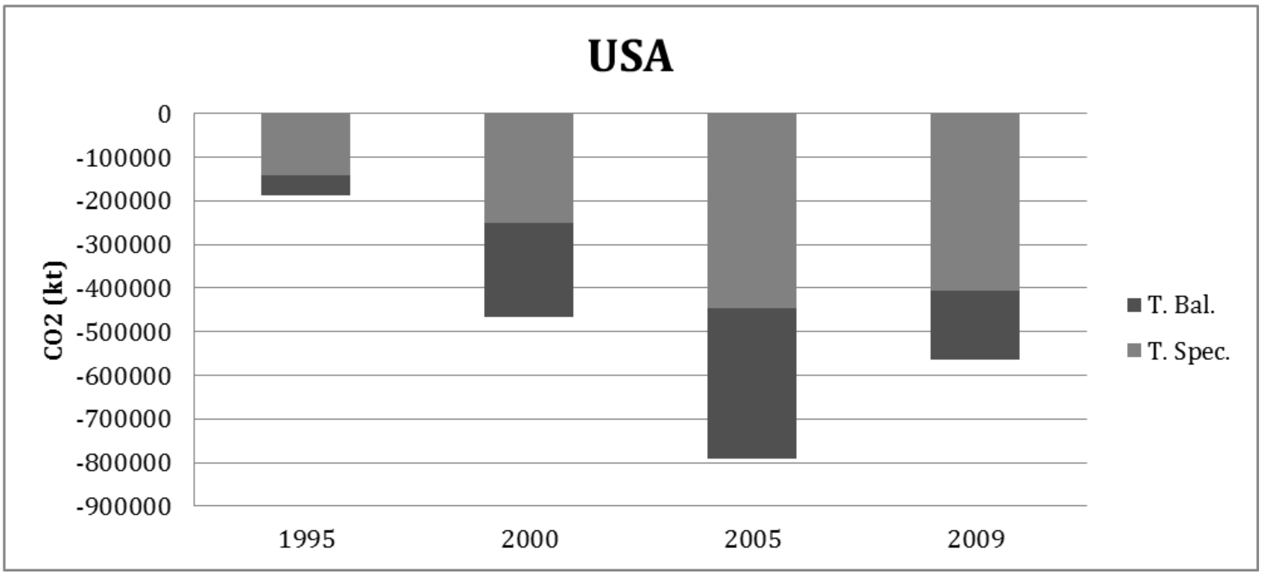
5.2. The Drivers of the TBEET

Figure 10 displays the contribution to the TBEET of trade specialization (T. Spec.) and the monetary trade balance (T. Bal.) of the EU-27 and the USA[17]. Thereby, standardized world average carbon intensities for each sector are assumed across the countries.

[17] In order to ensure a clear illustration of the TBEET's drivers (and due to its nature to depict a discrepancy between TEEEs and TEEIs), the scale of the hereinafter displayed graphs has been reduced significantly when compared to the graphs in Figure 6 – 9.

Figure 10: Decomposed TBEET – Aggregated EU-27 and USA (1995-2009)

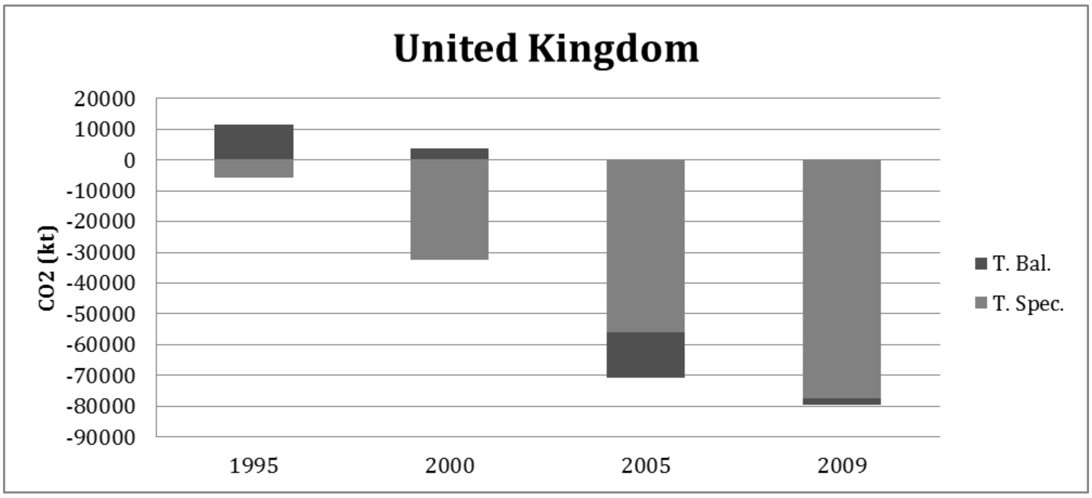




By turning to the EU-27 it is found that, first, the impact from trade specialization on the TBEET exhibits a decreasing trend but is positive throughout the regarded time frame. This is striking as it contrasts most major academic contributions that suggest that advanced countries are likely to outsource carbon emissions by importing more carbon-intensive products than are exported. As apparent from Figure 10, this presumption does not hold when technology differences in the production's carbon intensity are accounted for. Consequently, while technology differences between the EU-27 and the global average purport that this country group imports more carbon-intensive products than it exports, this cannot be confirmed by our analysis. Second, it may be noted that the positive impact of the EU-27's trade specialization has decreased from 1995 to 2009. Other than its positive overall impact on the TBEET, the trade specialization's trend – reflecting a shift towards more carbon-intensive imports and/or less carbon-intensive exports – largely complies with analyses by e.g. Davis & Caldeira (2010) who identified a similar development over time. This is true in a total sense (i.e. the overall contribution to the TBEET) as well as in a relative sense when compared to the contribution of the monetary trade balances on the TBEET. While more emission-intensive imports than exports accounted for around 60 per cent of the overall TBEET in 2000, the (positive) impact of trade specialization had decreased to roughly 20 per cent by 2009.

Based on this, one may expect a continuation of this trend, which could have resulted in the EU-27 as a displacer of carbon emissions also in technology-adjusted terms at some point in time after 2009, although the lack of more recent data prevents our analysis from verifying this assertion. Third, consulting the individual analysis of different EU-27 countries shows major differences in the impact of trade specialization to the TBEET across these countries (see Appendix A.2). While for instance the trade composition of Spain, Denmark, Greece, and the Netherlands display large positive contributions to the overall EU-27's import/export specialization, countries such as Germany, France and (particularly) the UK counter these contributions negatively – however not enough to result in an overall negative impact of the EU-27's trade specialization. Figure 11 highlights these large cross-country differences by showing the UK's decomposed TBEET (in line with the findings by Jiborn et al., forthcoming), which cannot be considered to resemble the equivalent graph for the EU-27 despite its significant share of the EU-27 overall production.

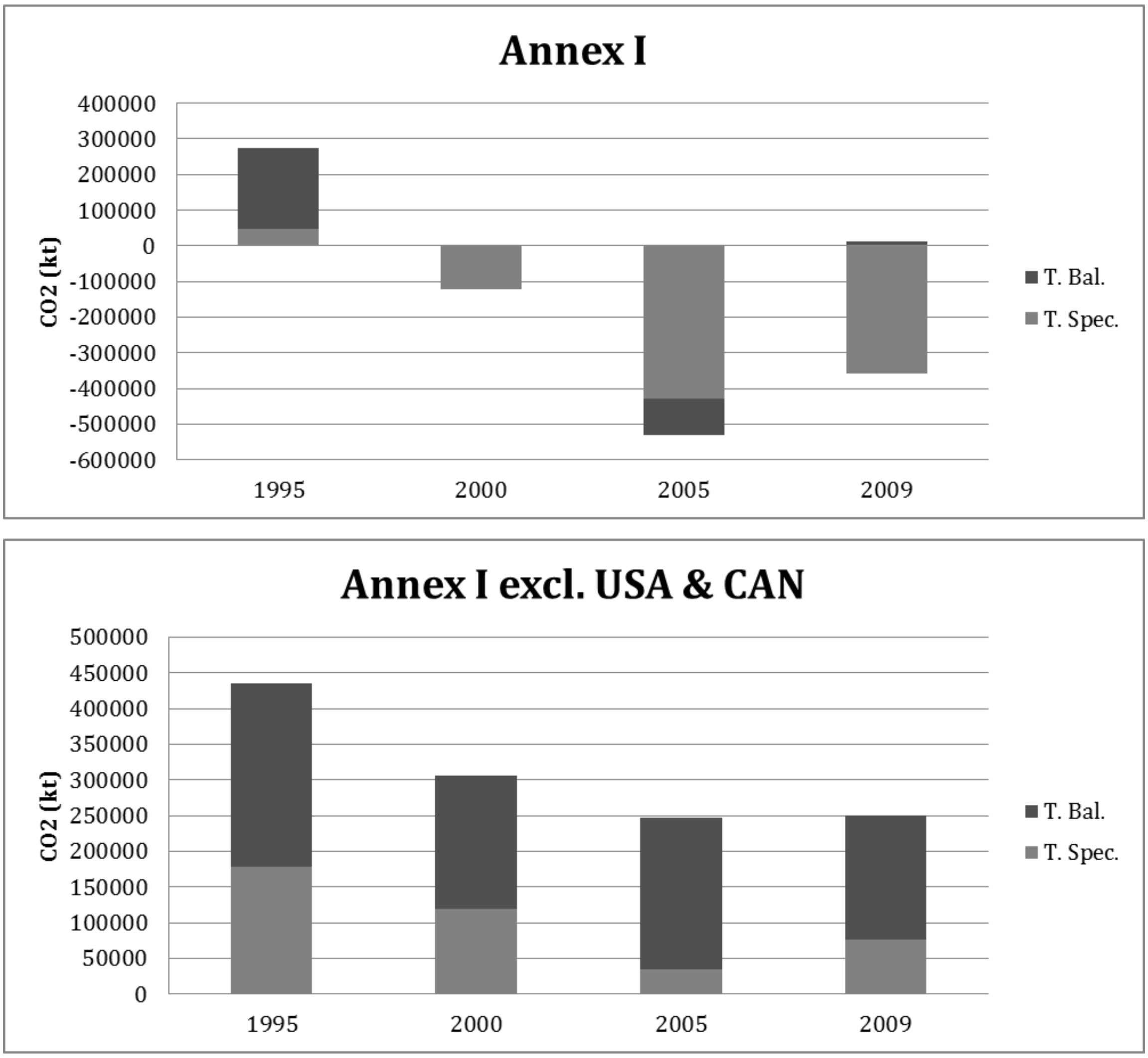
Figure 11: Decomposed TBEET – United Kingdom (1995-2009)



Instead, the pattern of the UK's trade composition seems akin to the development for the USA which is observable from the second graph in Figure 10. The illustrations as well as the underlying data results for the time period (Appendix A.2) display a consistently negative impact of the trade specialization on the TBEET for both countries which is intensifying over the regarded years. This can be interpreted as reinforcing emission displacement by changing the composition of imports and exports. However, as aforementioned section 4.4, countries or country groups could indicate a positive TBEET despite more carbon-intensive imports than exports since a monetary trade surplus could offset the trade specialization's negative impact. Nevertheless, Figure 10 does not correspond to this scenario. While the EU-27's positive trade balance clearly strengthens the positive overall TBEET further, the USA's trade deficit results in an amplification of the negative impact of trade specialization. Obviously, this leads to an even more distinct discrepancy between the EU-27's and the USA's TBEET (as was also shown in Figure 6).

In order to link the quantitative findings of this study to climate mitigation policies, Figure 12 displays results for Annex I countries (with and without the USA and Canada).

Figure 12: Decomposed TBEET – Aggregated Annex I (1995-2009)

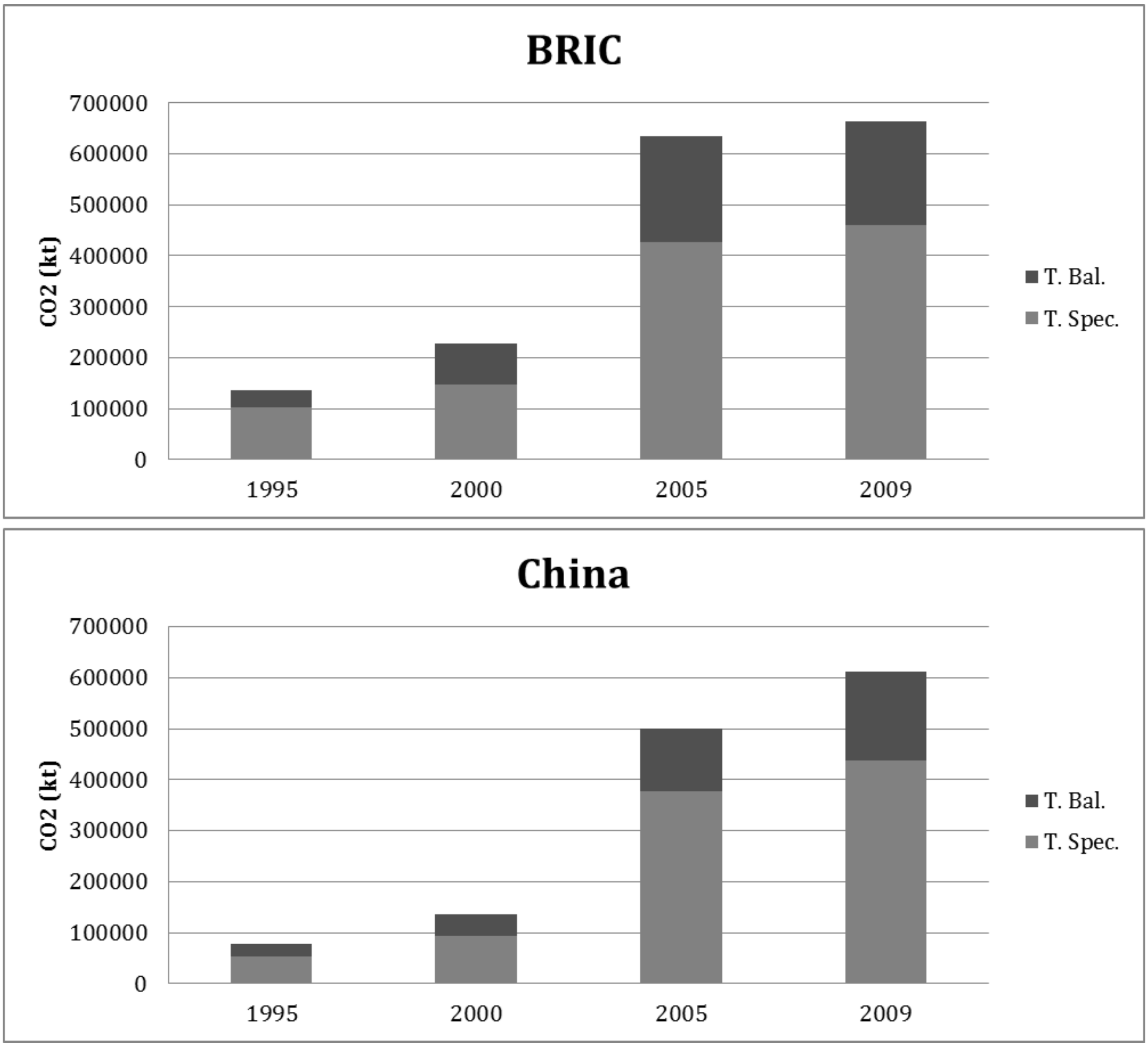


Here, too, the exceptional impact of considering the USA (and Canada) in the quantification of emission outsourcing becomes apparent. While all initial Annex I countries on aggregate exhibit a negative impact of trade specialization (after the first few years) on the TBEET, disregarding the two countries that did not ratify or eventually withdrew from the Kyoto Protocol still results in an increasing shift towards carbon-intensive imports or less carbon-intensive exports but also in an overall positive contribution of the remaining countries' trade specialization. Consequently, it should be emphasized that only the aggregated results for the sum of all Annex I countries included in our country sample seem to be in line with other findings such as by Peters et al. (2011). However, the presumption that this finding stems from a rather consistent pattern of emission displacement of the regarded countries cannot be supported by our study. Rather, we find that the majority of Annex I countries display a positive contribution of trade specialization to the TBEET as well as an even larger impact of most countries' monetary trade surplus to the adjusted emission trade balance over most of the regarded time period. Following this, the results do not suffice for generalizations that distinguish a certain pattern of emission displacement which all or at least most Annex I countries have in common when technology differences are corrected for. If anything, one may refer to an block of Anglophone countries within the Annex I nations since the USA, the UK, Australia and Canada can all be described as specialized in more carbon-intensive imports than exports (see Appendix A.2 and C).

Moreover, according to Figure 12 the trade balance does not appear to have an unambiguous contribution to the TBEET of the Annex I countries over the entire period. While it positively impacts the TBEET in the initial years (1995-2000) of the regarded time series, its contribution largely vanishes or becomes negative in more recent years.

Furthermore, it shall be examined whether a distinct pattern of emission trade specialization or monetary trade balance underlies the TBEET of BRIC countries and China in particular. Therefore, Figure 13 decomposes these emission trade balances.

Figure 13: Decomposed TBEET – Aggregated BRIC and China (1995-2009)



Again, the striking similarities between the BRIC's and China's graph reflect the importance of China as the country which is not only the largest emerging economy but also most involved in international trade. When focusing, first, on the trade specialization of the emerging economies, it becomes clear that a rather stringent pattern of increasingly positive contributions of the trade composition to the TBEET prevails. Since 1995, the total impact of trade specialization to the almost invariably and gradually increasing TBEET of both the aggregated BRIC countries and China individually has risen almost uniformly accounting for 64 to 76 per cent of the overall TBEET. Similarly, the aggregate trade surplus of the regarded emerging economies amplifies their overall (as well as China's) TBEET additionally by contributing 24 to 36 per cent of the technology-adjusted emission trade balance. This emphasizes that the

TBEET of the BRIC and China individually is driven more by what is imported and exported (in terms of carbon intensity) than by the trade surplus per se. Moreover, these developments may be directly translated into an intensifying manifestation of the BRIC countries' status as destinations for emission displacement represented by more carbon-intensive exports than imports and the country group's monetary trade surplus.

Nevertheless, the resemblance of the graphs for the BRIC countries and China also allows for a more nuanced interpretation, which was already signalized by the single-country TBEET results. By consulting each emerging country's decomposition of the TBEET (Appendix A.2), it is found that, again, China and Russia – with a clearly positive trade specialization – display a distinctly different pattern of (emission) trade specialization when compared to the remaining BRIC countries. More specifically, Brazil and India display either very small or negative contributions of trade specialization throughout the period (with unambiguous results for the trade balance). Consequently, their exported goods are not (significantly) more carbon-intensive than their imports while, of course, their trade volume is also substantially smaller than in China.

Certainly, these more detailed findings do not suggest a general pattern of trade specialization for emerging economies in general when technology differences are corrected for. They do, however, indeed point to China's exceptional role as the major net exporter of embodied emissions through both an increasing monetary trade surplus and more carbon-intensive export goods compared to their imports. Nevertheless, China and Russia (as well as the aggregate EU-27) are not the only countries with a positive contribution of trade specialization to the TBEET. As depicted in Figure 14, our results suggest that advanced Asian countries such as Japan and Korea or Taiwan exhibit a trade composition and monetary trade balance which are beneficial to their TBEET.

Figure 14: Decomposed TBEET – Developed Asian Countries (1995-2009)

Thus, it can be asserted that – when technology differences are accounted for – China and the most advanced major Asian economies emerge as the most popular destinations of displaced emissions with a specialization in more emission-intensive exports than imports as well as a monetary trade surplus. However, even the EU-27 display a declining yet positive trade specialization with a large monetary trade surplus.

Before turning to the concluding parts of this study, one important remark regarding the implication of emission displacement is in order. While the outsourcing of industrial production and the subsequent import of embodied emissions is generally associated with developed countries' attempt to circumvent climate regulations, it has rarely been noted that emission displacement may also have a positive effect on the global climate and that eliminating emission trade deficits and surpluses does not constitute the ideal scenario in order to limit the global emissions (Antweiler, Copeland & Taylor, 2001; Jiborn et al., forthcoming). If countries with less carbon-intensive production technologies and/or higher energy efficiency than the international average specialize in the production and subsequent export of relatively carbon-intensive goods while nations with lower carbon efficiency expand the production and export of less emission-heavy goods, this will result in a reduction of global emissions. In that sense, countries would trade in accordance to their comparative carbon advantage if nations that are well-endowed with accessible renewable energy sources (e.g. hydropower or wind) and embody less carbon-intensive production technologies would generate and export goods for which the (positive) technology discrepancy to the world average would be largest. Conversely, it would be most beneficial for the reduction of global emissions if relatively 'dirtier' countries would specialize in the production and trade of goods for which their respective (negative) discrepancy to the global average technology would be smallest. Nevertheless, since for instance China – with a largely coal-based energy system – is a major producer and exporter of energy-intensive products (e.g. steel), one cannot expect that this specialization according to the carbon comparative advantage is happening (on a broad scale) thus far.

Having outlined the results from our quantitative analysis we now proceed to answering the research questions, which were formulated at this paper's outset and, consequently, guided the realized examination of country (group)'s emission trade balances.

5.3. Discussion of Research Questions and Implications

Our analysis scrutinized patterns of trade in embodied emissions and thereby, first, questioned whether advanced countries' reductions of production-based emissions may have been counteracted by emission imports from developing countries when correcting for potential distortions stemming from technology differences among trade partners.

The answer to this question is far from unambiguous and straight-forward. While the traditional examination method of calculating the CBA and the resulting BEET indeed point to a large discrepancy between the advanced nation's domestic emissions and the global emissions produced to serve their demand, adjusting for technology differences yields drastic differences across the advanced countries. More specifically, the EU-27 (with notable exceptions such as the UK) was not found to be a net importer of emissions from developing countries, whereas this was indeed the case for the USA and other (particularly Anglophone) developed countries such as Australia, Canada or the UK. Of course, no causality of the common language for emission displacement may be derived, however. Rather, one may speculate whether the abundance of natural resources (especially coal and oil) in these particular countries may have resulted in some sort of path dependence with more carbon-intensive energy systems and less carbon-efficient technology compared to other advanced nations. Other than many EU-27 countries, the USA (in particular) as well as Australia, Canada and the UK have not been able to compensate for the composition of their traded goods by a positive monetary trade balance. Furthermore, when investigating a potential relation of the existence of binding emission targets and the import of embodied emissions, no such consistent relation could be distinguished as most Annex I economies do not display a negative emission trade balance when adjusting for technology differences. The reason for the overall negative TBEET of Annex I countries in the more recent years of the regarded time frame has instead largely been caused by the extensive import of embodied emissions of the USA in particular as well as of the UK, France, Canada and Australia at a smaller scale. Therefore, we cannot identify a clear pattern of emission import by Annex I countries when cancelling out technology effects from the emission trade balance. As far as the supply of embodied emissions is concerned, our results also do not support a consistent pattern of emission export from major emerging economies. Rather, it was found that China has indeed emerged as the most extensive exporter of embodied emissions while other advanced nations like Japan, Korea and Russia exhibit a similar pattern of technology-adjusted carbon export on a smaller scale from 1995 to 2009. Other emerging nations such as Brazil or India have not contributed as counterparts of the mentioned advanced nation's emission trade deficit, however.

By turning to the second research question, this study subsequently evaluated to what extent the adjusted emission trade balances were attributable to trade specialization and the monetary balance of trade. Here, again, our analysis delineated heterogeneous results for developed countries. While the overall impact of trade specialization on the TBEET was positive for the aggregate EU-27, the UK (and to a lesser extent France and Germany) showed evidence for more carbon-intensive imports than exports. This holds also true on a much larger scale for the USA, whose TBEET is clearly affected negatively by the country's trade composition. Moreover and different than for instance Germany, the USA have not been able to compensate for their trade specialization by an export surplus but rather experienced an amplification of their negative TBEET due to their unbalanced monetary trade statistics. By the same token, we find that few yet momentous country cases (e.g. the USA, UK, Australia or Canada) have exhibited a pattern of emission displacement, which leads to the overall negative adjusted trade balance for Annex I countries. A more systematic or homogeneous pattern of emission displacement shared among the countries with binding emission reduction goals could not be distinguished by our study for the regarded time frame. Similarly, no consistent pattern of (technology-adjusted) specialization in more emission-intensive exports than imports was found for the emerging countries, which could have been expected to be the primary destinations of displaced emissions. However, the striking magnitude of China's suchlike trade composition and its associated emergence as the main whereabouts of outsourced emissions as expected by prior scholars could be verified also in technology-adjusted terms. Other substantial (yet smaller when compared to China) destinations for displaced emissions were found to be developed Asian countries and Russia, which display more carbon-intensive exports than imports even when technology differences are accounted for.

Nevertheless, when complementing our analysis with a dynamic component by regarding the development over time in more detail, we could also find some evidence for gradual emission displacement from the aggregate EU-27 since its overall specialization in traded goods has continuously been shifting towards more emission-heavy imports and/or less carbon-intensive exports. While this has largely been counteracted particularly by China's increasingly carbon-heavy export orientation as well as by (comparatively smaller amounts of) displaced embodied emissions produced in for instance Korea and Russia, it should still raise policy-makers' concerns as it reflects an intensifying tendency towards emission displacement throughout most of the developed world – thereby counteracting the climate targets as defined in the Kyoto Protocol or, more recently, in the Paris agreement.

6. Concluding Remarks

This paper addressed the extent to which international trade in global value chains has enabled the displacement of embodied CO_2 emissions from 1995 to 2009. Moreover, the technology-adjusted balance of emissions embodied in trade was introduced as a novel input-output approach before being applied to data for 40 countries and a Rest-of-the-World aggregate from the World Input Output Database for the regarded time frame. Our approach represents a clear improvement to the production-based emission and consumption-based accounting as it cancels out technology differences which may pose a threat to the meaningfulness of conventional emission trade balances. Moreover, examining the TBEET for each country and over time enabled us to assess whether consistent transnational pattern of global emission export and import existed. Subsequently, a further decomposition of the TBEET was realized in order to distinguish the effects of trade specialization from the monetary trade balance. Thereby, we were able to examine whether developed countries (with emission regulations) have been displacing carbon emissions – either by specializing in less emission-intensive export products while importing carbon-heavy industrial goods or by a monetary trade surplus.

This can be considered relevant since our indicators may complement production-based emission accounting, which forms the basis for current climate mitigation efforts such as the Paris Agreement or Kyoto Protocol. Thereby, it may constitute a helpful tool for policy-makers seeking to develop effective climate mitigation regulations. Furthermore, by extending Jiborn et al.'s (forthcoming) study of two nations with a broad country range, a more profound and global understanding of CO_2 emission displacement from 1995 to 2009 was established by our study, which aimed to answer the questions:

Have developed countries' domestic carbon emission reductions been counteracted by emission imports from developing countries when eliminating potential distortions resulting from technology differences across the trading countries?

and

To what extent are surpluses and deficits in the examined countries' emission trade balance attributable to trade specialization or their monetary trade balance and may clear patterns for groups of countries with similar characteristics (e.g. emerging economies or advanced countries) be distinguished?

6.1. Main Results

On the basis of each country's TBEET within this study, we have not been able to find support for the presumption that developing countries have unambiguously emerged as large-scale net exporters of embodied emissions which, in turn, would be imported by advanced nations between 1995 and 2009. Rather, we find the aggregate EU-27 to be net exporters of embodied carbon emissions while the USA's substantial arising CO_2 trade deficit has largely been counteracted by China's immense surplus in the TBEET. Other major emerging economies such as Brazil or India were not found to export more emissions than their imports consist of. Moreover, no homogenous pattern could be distinguished across the adjusted emission trade balance of countries that are subject to climate mitigation regulations. While some developed (mostly Anglophone) countries with such emission reduction targets indeed imported embodied carbon emissions throughout the period, the majority of Annex I countries (i.e. with binding emission reduction goals) could be described by a positive TBEET.

Resting upon the results for the TBEET, the indicator's decomposition into trade specialization and the monetary trade balance neither unveiled any distinct patterns of global emission displacement across developed or emerging countries nor did it suggest a clear relation between emission regulations and a pattern of emission displacement. Instead, China could be found to have increasingly specialized in more emission-intensive exports than imports while the other emerging economies did not exhibit a similar development. Turning to the more advanced nations, the Anglophone countries included in our dataset were identified to progressively have shifted towards more carbon-intensive imports or less carbon-intensive exports while most of the EU-27 did not arise as displacer of emissions and even developed Asian countries such as Japan or Korea displayed more carbon-intensive exports than imports when technology differences were accounted for.

However, our analysis also observed all developed region's tendency towards comparatively more carbon-intensive imports than exports, which could cause policy-maker's concerns since an intensifying emission displacement of advanced nations (towards less technologically-advanced countries) may undermine current or future emission regulations aimed at the mitigation of the potential dangers of global climate change.

6.2. Limitations and Future Research

Despite the thorough processing and analysis of the employed data as well as the profoundly reasoned methodology, our study is subject to several caveats, which deserve attention. First, the quantitative results of this paper rely on the accuracy of the gathered data. The harmonization of different country's sectoral partition, the allocation of value added and emissions to these sectors and the homogenization of the underlying production structures for each sector's entire output can only depict an approximation of the global economies' value generation and trade patterns. Second, our study exclusively focuses on CO_2 emissions and thereby disregards other greenhouse gases such as methane, nitrous oxides or ozone (among others). However, as CO_2 constitutes the most important greenhouse gas caused by human activity and represents the focal point of the climate mitigation policies that our results were linked to, the findings of this study can still be considered meaningful. Third, it is worth acknowledging that while the examination of the Rest-of-the-World residual as such already embodies uncertainty due to the diversity of countries (and production structures) that it entails, the gathered account data from the WIOD also comprises some Annex I countries, which are subject to emission reduction targets. These countries – namely Belarus, Croatia, Iceland, Kazakhstan, Liechtenstein, Monaco, New Zealand, Norway, Switzerland and Ukraine – could not be distinguished from the Rest-of-the-World account and were considered to be non-Annex I countries in our study. Fourth, this study was limited to data for the time period from 1995 to 2009 while more recent years were not available in the employed database. Consequently, the development of the technology-adjusted emission trade balances since 2009 could be speculated upon but not substantiated with adequate data.

This leads to the identification of future research areas. Obviously, the design of adequate policies based on economic indicators relies on current data, which implies the need for a follow-up study based on our employed approach but with more recent data. In the light of the recently signed Paris Agreement and the related need to monitor the progress in limiting global emissions, this gains even more importance. Moreover, while the global scope of our study prevented detailed analyses of national or sectoral peculiarities in emission trade, future research may elaborate more profoundly on specific countries or sectors' relevance for global emissions. Finally, it may be worth replicating this study's approach while assessing technology-adjusted emission displacement for other important greenhouse gases.

References

Afionis, S., Sakai, M., Scott, K., Barrett, J., & Gouldson, A. (2017). Consumption-based carbon accounting: does it have a future?, *Wiley Interdisciplinary Reviews: Climate Change*, *8*(1)

Aguiar, A., Narayanan, B., & McDougall, R. (2016). An overview of the GTAP 9 data base, *Journal of Global Economic Analysis*, *1*(1), 181-208

Ahmad, N., & Wyckoff, A. (2003). Carbon dioxide emissions embodied in international trade of goods. [pdf] Available at: http://www.oecd-ilibrary.org/docserver/download/421482436815.pdf?expires=1496199630&id=id&accname=guest&checksum=923333EFADA4ABEF769579ABCCB9A5C0 [Accessed 24 April 2017]

Aichele, R., & Felbermayr, G. (2015). Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade, *Review of Economics and Statistics*, *97*(1), 104-115

Andrew, R., & Forgie, V. (2008). A three-perspective view of greenhouse gas emission responsibilities in New Zealand, *Ecological Economics*, *68*(1), 194-204

Antweiler, W., Copeland, B., & Taylor, M. (2001). Is Free Trade Good for the Environment?, *The American Economic Review, 91*(4), 877-908

Atkinson, G., Hamilton, K., Ruta, G., & Van Der Mensbrugghe, D. (2011). Trade in 'virtual carbon': Empirical results and implications for policy, *Global Environmental Change*, *21*(2), 563-574

Azar, C. (2005). Post-Kyoto climate policy targets: costs and competitiveness implications, *Climate Policy*, *5*(3), 309-328

Babiker, M. H. (2005). Climate change policy, market structure, and carbon leakage, *Journal of international Economics*, *65*(2), 421-445

Baldwin, R., & Lopez-Gonzalez, J. (2015). Supply-chain Trade: A Portrait of Global Patterns and Several Testable Hypotheses, *The World Economy*, *38*(11), 1682-1721

Barker, T., Bashmakov, I., Alharthi, A., Amann, M., Cifuentes, L., Drexhage, J., Duan, M., Edenhofer, O., Flannery, B., Grubb, M., Hoogwijk, M., Ibitoye, F.I., Jepma, C.J., Pizer, W.A., Yamaji, K. (2007) Mitigation from a cross-sectoral perspective. in: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (eds) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom & New York, NY, USA: Cambridge University Press

Barrett, J., Peters, G., Wiedmann, T., Scott, K., Lenzen, M., Roelich, K., & Le Quéré, C. (2013). Consumption-based GHG emission accounting: a UK case study, *Climate Policy*, *13*(4), 451-470

Boitier, B. (2012, April). CO2 emissions production-based accounting vs consumption: Insights from the WIOD databases *WIOD Conference Paper, April,* Available Online: http://www.wiod.org/conferences/groningen/paper_Boitier.pdf [Accessed 17 May 2017]

Buckley, P. J., & Ghauri, P. N. (2004). Globalisation, economic geography and the strategy of multinational enterprises, *Journal of International Business Studies*, *35*(2), 81-98

Christ, C. F. (1955). A Review of Input-Output Analysis, *NBER Chapters*, 137-182.

Cole, M. A. (2004). Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages, *Ecological economics*, *48*(1), 71-81

Copeland, B. R., & Taylor, M. S. (2005). Free trade and global warming: a trade theory view of the Kyoto protocol, *Journal of Environmental Economics and Management*, *49*(2), 205-234

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO2 emissions, *Proceedings of the National Academy of Sciences*, *107*(12), 5687-5692

Davis, S. J., Peters, G. P., & Caldeira, K. (2011). The supply chain of CO2 emissions, *Proceedings of the National Academy of Sciences*, *108*(45), 18554-18559

Dedrick, J., Kraemer, K. L., & Linden, G. (2010). Who profits from innovation in global value chains?: a study of the iPod and notebook PCs, *Industrial and corporate change*, *19*(1), 81-116

Dietzenbacher, E., & Lahr, M. L. (Eds.). (2004). *Wassily Leontief and input-output economics*. Cambridge, UK: Cambridge University Press

Dietzenbacher, E., Pei, J., & Yang, C. (2012). Trade, production fragmentation, and China's carbon dioxide emissions, *Journal of Environmental Economics and Management*, *64*(1), 88-101

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., & De Vries, G. (2013). The construction of world input–output tables in the WIOD project, *Economic Systems Research*, *25*(1), 71-98

Dinda, S. (2004). Environmental Kuznets curve hypothesis: a survey, *Ecological economics*, *49*(4), 431-455

Domingos, T., Zafrilla, J. E., & López, L. A. (2016). Consistency of technology-adjusted consumption-based accounting, *Nature Climate Change*, *6*(8), 729-730

Dudenhöffer, F. (2005). Wie viel Deutschland steckt im Porsche?, *ifo Schnelldienst*, *58*(24), 03-05

EDGAR (2011). Emissions Database for Global Atmospheric Research, v4.2 release, EDGAR project, European Commission. Available online: http://edgar.jrc.ec.europa.eu/overview.php?v=42 [Accessed 19 April 2017]

Eurostat (2012). Europe in figures – Eurostat yearbook 2012 [pdf] Available at: http://ec.europa.eu/eurostat/documents/3217494/5760825/KS-CD-12-001-EN.PDF/032ab046-5604-42cf-b0a5-7e63e1cda8bb [Accessed 22 April 2017]

Galeotti, M., & Lanza, A. (2005). Desperately seeking environmental Kuznets, *Environmental Modelling & Software*, *20*(11), 1379-1388

Genty, A., Arto, I., & Neuwahl, F. (2012). Final database of environmental satellite accounts: technical report on their compilation, *WIOD Documentation*, *4*

Gereffi, G. (1989). Development strategies and the global factory, *The Annals of the American Academy of Political and Social Science*, *505*(1), 92-104

Grether, J. M., Mathys, N. A., & de Melo, J. (2012). Unravelling the worldwide pollution haven effect, *The Journal of International Trade & Economic Development*, *21*(1), 131-162

Helm, D., Hepburn, C., & Ruta, G. (2012). Trade, climate change, and the political game theory of border carbon adjustments, *Oxford review of economic policy*, *28*(2), 368-394

Hummels, D., Ishii, J., & Yi, K. M. (2001). The nature and growth of vertical specialization in world trade, *Journal of international Economics*, *54*(1), 75-96

Jakob, M., & Marschinski, R. (2013). Interpreting trade-related CO2 emission transfers, *Nature Climate Change*, *3*(1), 19-23

Jiborn, J., Kander, A., Kulionis, V., Nielsen, H., Moran D. D. (forthcoming). Decoupling or delusion? Measuring emissions displacement in foreign trade.

Johnson, R. C., & Noguera, G. (2012). Accounting for intermediates: Production sharing and trade in value added, *Journal of international Economics*, *86*(2), 224-236

Kander, A., Malanima, P., & Warde, P. (2014). *Power to the people: energy in Europe over the last five centuries*. Princeton, USA: Princeton University Press

Kander, A., Jiborn, M., Moran, D. D., & Wiedmann, T. O. (2015). National greenhouse-gas accounting for effective climate policy on international trade. *Nature Climate Change*, *5*(5), 431-435

Kander, A., Jiborn, M., Moran, D. D., & Wiedmann, T. O. (2016). Reply to'Consistency of technology-adjusted consumption-based accounting', *Nature Climate Change*, *6*(8), 730-730

Kander, A., Warde, P., Henriques, S. T., Nielsen, H., Kulionis, V., & Hagen, S. (2017). International Trade and Energy Intensity During European Industrialization, 1870–1935, *Ecological Economics*, *139*, 33-44

Kanemoto, K., Lenzen, M., Peters, G. P., Moran, D. D., & Geschke, A. (2011). Frameworks for comparing emissions associated with production, consumption, and international trade, *Environmental science & technology*, *46*(1), 172-179

Koopman, R., Wang, Z., & Wei, S. J. (2012). Estimating domestic content in exports when processing trade is pervasive, *Journal of development economics*, *99*(1), 178-189

Koopman, R., Wang, Z., & Wei, S. J. (2014). Tracing value-added and double counting in gross exports, *The American Economic Review*, *104*(2), 459-494

Kulionis, V. (2014). CO2 Emissions Embodied in International Trade of the UK, 1995-2009: A Multi-Region Input–Output Analysis, Master thesis, Department of Economics, Lund University, Available Online: http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=4618953&fileOId=4622614 [Accessed: 13 March 2017]

Kuznets, S. (1955). Economic growth and income inequality, *The American economic review*, 1-28

Kuznets, S. (1963). Quantitative aspects of the economic growth of nations: VIII. Distribution of income by size, *Economic development and cultural change*, *11*(2, Part 2), 1-80

Kuznets, S. (1973). Modern economic growth: findings and reflections, *The American economic review*, *63*(3), 247-258

Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., Prather, M. (2007) Historical Overview of Climate Change., in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom & New York, NY, USA: Cambridge University Press

Lee, T., & Mokhtarian, P. L. (2004). An Input-Output Analysis of the Relationships between Communications and Travel for Industry, *Journal of Industrial Ecology*, *6*(2), 43-57.

Lenzen, M., Murray, J., Sack, F., & Wiedmann, T. (2007). Shared producer and consumer responsibility—Theory and practice, *Ecological Economics*, *61*(1), 27-42

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012a). Mapping the structure of the world economy, *Environmental science & technology*, *46*(15), 8374-8381

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., & Geschke, A. (2012b). International trade drives biodiversity threats in developing nations, *Nature*, *486*(7401), 109-112

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: a global multi-region input–output database at high country and sector resolution, *Economic Systems Research*, *25*(1), 20-49

Leontief, W. W. (1936). Quantitative input and output relations in the economic systems of the United States, *The review of economic statistics*, 105-125

Leontief, W. (1953). Domestic production and foreign trade; the American capital position re-examined, *Proceedings of the American philosophical Society*, *97*(4), 332-349

Leontief, W. (1970). Environmental repercussions and the economic structure: an input-output approach, *The review of economics and statistics*, 262-271

Li, Y., & Hewitt, C. N. (2008). The effect of trade between China and the UK on national and global carbon dioxide emissions, *Energy Policy*, *36*(6), 1907-1914

Liu, Z., Davis, S. J., Feng, K., Hubacek, K., Liang, S., Anadon, L. D. & Guan, D. (2016). Targeted opportunities to address the climate-trade dilemma in China, *Nature Climate Change*, *6*(2), 201-206

López González, J. (2012). Vertical specialisation and new regionalism, doctoral thesis, University of Sussex, Available Online: http://sro.sussex.ac.uk/43255/1/Lopez_Gonzalez%2C_Javier.pdf [Accessed: 17 March 2017]

Los, B., Timmer, M. P., & Vries, G. J. (2015). How global are global value chains? A new approach to measure international fragmentation, *Journal of Regional Science*, *55*(1), 66-92

Lucas, R. E., Wheeler, D., & Hettige, H. (1993). *Economic Development, Environmental Regulation, and the International Migration of Toxic Industrial Pollution, 1960-88* [pdf] Available at: http://documents.worldbank.org/curated/en/673921468765926548/pdf/multi-page.pdf [Accessed 24 April 2017]

Jevons, W. S. (1866). *The coal question: an enquiry concerning the progress of the Nation, and the probable exhaustion of our coal-mines*. London, UK: Macmillan

Machado, G., Schaeffer, R., & Worrell, E. (2001). Energy and carbon embodied in the international trade of Brazil: an input–output approach, *Ecological economics*, *39*(3), 409-424

MacKay, D. J. (2009). Sustainable Energy – without the hot air, *England: UIT Cambridge*, Available Online: http://www.withouthotair.com/cft.pdf [Accessed 10 April 2017]

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). The limits to growth, *New York*, *102*

Minx, J. C., Wiedmann, T., Wood, R., Peters, G. P., Lenzen, M., Owen, A. & Paul, A. (2009). Input–output analysis and carbon footprinting: an overview of applications, *Economic systems research*, *21*(3), 187-216

Munksgaard, J., & Pedersen, K. A. (2001). CO 2 accounts for open economies: producer or consumer responsibility?, *Energy policy*, *29*(4), 327-334

Nakano, S., Okamura, A., Sakurai, N., Suzuki, M., Tojo, Y., Yamano, N. (2009) The Measurement of CO2 Embodiments in International Trade: Evidence from the Harmonised Input-Output and Bilateral Trade Database, *OECD Science, Technology and Industry Working Papers*, No. 2009/03, OECD Publishing, Paris

Panayotou, T. (1993). *Empirical tests and policy analysis of environmental degradation at different stages of economic development* (No. 992927783402676). International Labour Organization

Peters, G. P., & Hertwich, E. G. (2008). CO2 embodied in international trade with implications for global climate policy, *Environmental science & technology*, *42*(5), 1401-1407

Peters, G. P., & Hertwich, E. G. (2008b). Post-Kyoto greenhouse gas inventories: production versus consumption, *Climatic Change*, *86*(1), 51-66

Peters, G. P., & Hertwich, E. G. (2009). The application of multi-regional input-output analysis to industrial ecology, *Handbook of input-output economics in industrial ecology*, 847-863

Peters, G. (2008a). Reassessing carbon leakage *Eleventh Annual Conference on Global Economic Analysis-Future of Global Economy* (pp. 12-14), Available Online: https://www.gtap.agecon.purdue.edu/resources/download/3751.pdf [Accessed 17 May 2017]

Peters, G. P. (2008b). From production-based to consumption-based national emission inventories, *Ecological economics*, *65*(1), 13-23

Peters, G. P., Minx, J. C., Weber, C. L., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008, *Proceedings of the National Academy of Sciences*, *108*(21), 8903-8908

Peters, G. P., Davis, S. J., & Andrew, R. (2012). A synthesis of carbon in international trade, *Biogeosciences*, *9*(8), 3247

Roberts, J. T., & Grimes, P. E. (1997). Carbon intensity and economic development 1962–1991: a brief exploration of the environmental Kuznets curve, *World development*, *25*(2), 191-198

Rodrigues, J., & Domingos, T. (2008). Consumer and producer environmental responsibility: Comparing two approaches, *Ecological Economics*, *66*(2), 533-546

Rodrigues, J., Domingos, T., Giljum, S., & Schneider, F. (2006). Designing an indicator of environmental responsibility, *Ecological Economics*, *59*(3), 256-266

Rodrigues, J., Domingos, T. M., & Marques, A. P. (2010), *Carbon responsibility and embodied emissions: Theory and measurement*. Routledge

Serrano, M., & Dietzenbacher, E. (2008). Responsibility and trade emission balances: two approaches for the same concept, *International Input–Output Meeting on Managing the Environment* (Vol. 9, No. 11), Available Online: https://www.researchgate.net/profile/Monica_Serrano2/publication/265075151_Responsibility_and_trade_emission_balances_two_approaches_for_the_same_concept/links/5562e5f408ae8c0cab333ecb.pdf [Accessed 19 May 2017]

Serrano, M., & Dietzenbacher, E. (2010). Responsibility and trade emission balances: An evaluation of approaches, *Ecological Economics*, *69*(11), 2224-2232

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve, *World development*, *32*(8), 1419-1439

Stern, D. I., Common, M. S., & Barbier, E. B. (1996). Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development, *World development*, *24*(7), 1151-1160

Sun, J. (1998). Changes in energy consumption and energy intensity: a complete decomposition model, *Energy economics*, *20*(1), 85-100

Sun, J. (1999). The nature of CO 2 emission Kuznets curve, *Energy policy*, *27*(12), 691-694

Tan, Q., Wen, Z., & Chen, J. (2015). The relationships between industrial pollution intensity and economic growth based on intensity environment Kuznets curve: study on China's pilot cities, *International Journal of Sustainable Development & World Ecology*, *22*(3), 231-241

The Economist (2011). Greenhouse gases – The cost of trade, *The Economist*, 26 April, Available Online: http://www.economist.com/blogs/dailychart/2011/04/greenhouse_gases [Accessed 29 May 2017]

The Economist (2015a). Global manufacturing – Made in China, *The Economist*, 12 March, Available Online: http://www.economist.com/news/leaders/21646204-asias-dominance-manufacturing-will-endure-will-make-development-harder-others-made [Accessed 29 May 2017]

The Economist (2015b). Manufacturing – Still made in China, *The Economist*,10 September, Available Online: http://www.economist.com/news/special-report/21663332-chinese-manufacturing-remains-second-none-still-made-china [Accessed 26 May 2017]

The Guardian (2009). West blamed for rapid increase in China's CO2, *The Guardian*, 23 February, Available Online:

https://www.theguardian.com/environment/2009/feb/23/china-co2-emissions-climate [Accessed 26 May 2017]

The Guardian (2014). CO2 emissions are being 'outsourced' by rich countries to rising economies, *The Guardian*, 19 January, Available Online: https://www.theguardian.com/environment/2014/jan/19/co2-emissions-outsourced-rich-nations-rising-economies [Accessed 26 May 2017]

Timmer, M., Los, B., Stehrer, R., & De Vries, G. (2013). Rethinking competitiveness: The global value chain revolution, *VoxEU.org*, 26 June, Available Online: http://voxeu.org/article/rethinking-competitiveness-global-value-chain-revolution [Accessed 12 May 2017]

Timmer, M. P., Los, B., Stehrer, R., & De Vries, G. J. (2013). Fragmentation, incomes and jobs: an analysis of European competitiveness, *Economic policy*, *28*(76), 613-661.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., & Vries, G. J. (2015). An illustrated user guide to the world input–output database: the case of global automotive production, *Review of International Economics*, *23*(3), 575-605

Tukker, A., & Dietzenbacher, E. (2013). Global multiregional input–output frameworks: an introduction and outlook, *Economic Systems Research*, *25*(1), 1-19.

Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J. & Kuenen, J. (2013). EXIOPOL–development and illustrative analyses of a detailed global MR EE SUT/IOT, *Economic Systems Research*, *25*(1), 50-70.

UNFCCC (2014). List of Annex I Parties to the Convention. Available Online: http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php [Accessed 13 May 2017]

UNFCCC (2015a). Adoption of the Paris Agreement [pdf] Available Online: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf [Accessed 22 April 2017]

UNFCCC (2015b). INDCs as communicated by Parties. Available Online: http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx [Accessed 20 May 2017]

Wang, Z., Wei, S. J., & Zhu, K. (2014). Gross trade accounting: A transparent method to discover global value chain-related information behind official trade data: Part 2, *Vox EU*, 16 April, Available Online: http://voxeu.org/article/learning-about-global-value-chains-looking-beyond-official-trade-data-part-2 [Accessed 13 May 2017]

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting, *Ecological Economics*, *69*(2), 211-222.

Wiedmann, T., Wood, R., Minx, J. C., Lenzen, M., Guan, D., & Harris, R. (2010). A carbon footprint time series of the UK–results from a multi-region input–output model, *Economic systems research*, *22*(1), 19-42.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A. & Simas, M. (2014). Global sustainability accounting—developing EXIOBASE for multi-regional footprint analysis, *Sustainability*, *7*(1), 138-163.

Xu, Y., & Dietzenbacher, E. (2014). A structural decomposition analysis of the emissions embodied in trade, *Ecological Economics*, *101*, 10-20.

Appendix A: Quantitative Results for Selected Individual Countries

Appendix A.1. PBA, CBA and BEET Results – Selected Countries

Table 4: PBA, CBA and BEET (AUS-IND) from 1995-2009 in kt CO_2

BEET	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IND
1995	4809	-30329	51327	497821	-214275	-35135	-100433	-47849	65755
2000	14073	-26637	49475	409738	-208956	-52968	-118506	-117631	93756
2005	-40574	-8562	119	1077888	-167857	-89409	-169375	-163201	20517
2009	-48080	-47737	-25806	1044610	-141432	-70767	-161752	-100188	47786
PBA incl. HH	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IND
1995	304708	229363	465258	3074350	949454	253767	405902	589734	806420
2000	357574	286963	527464	3100918	914816	305517	421465	602428	990336
2005	402300	310159	552329	5082700	898557	364889	427363	621585	1197920
2009	405468	322726	528885	6695928	816627	299987	385683	558629	1642719
CBA incl. HH	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IND
1995	299899	259692	413932	2576528	1163729	288902	506335	637583	740664
2000	343500	313599	477989	2691180	1123772	358485	539971	720060	896580
2005	442874	318721	552210	4004812	1066414	454298	596739	784786	1177403
2009	453548	370463	554691	5651318	958059	370754	547435	658817	1594933

Table 5: PBA, CBA and BEET (JPN-USA etc.) from 1995-2009 in kt CO_2

BEET	JPN	KOR	NLD	RUS	TWN	USA	EU-27	Annex I
1995	-272565	7447	-3131	379125	9418	-277014	-437080	-573942
2000	-235332	44744	-6349	660738	25706	-676331	-696024	-916341
2005	-239235	12891	-9852	517854	71500	-979461	-853502	-1643124
2009	-168526	85342	-5404	374571	102880	-644394	-697211	-1228326
PBA incl. HH	JPN	KOR	NLD	RUS	TWN	USA	EU-27	Annex I
1995	1141202	409041	193231	1608211	193957	4953562	4272833	12924916
2000	1204295	495222	198443	1569199	260930	5514270	4268154	13666365
2005	1206901	533906	206417	1635392	315883	5529034	4445798	14020652
2009	1101926	584059	204698	1598286	313741	5025427	4020253	12976686
CBA incl. HH	JPN	KOR	NLD	RUS	TWN	USA	EU-27	Annex I
1995	1413766	401594	196361	1229086	184539	5230576	4709913	13498858
2000	1439627	450478	204792	908461	235224	6190601	4964178	14582706
2005	1446136	521015	216269	1117538	244383	6508495	5299300	15663777
2009	1270451	498717	210102	1223716	210860	5669821	4717464	14205012

Appendix A.2. TBEET & Decomposition Results – Selected Countries

Table 6: TBEET and its Decomposition (AUS-IND) from 1995-2009 in kt CO_2

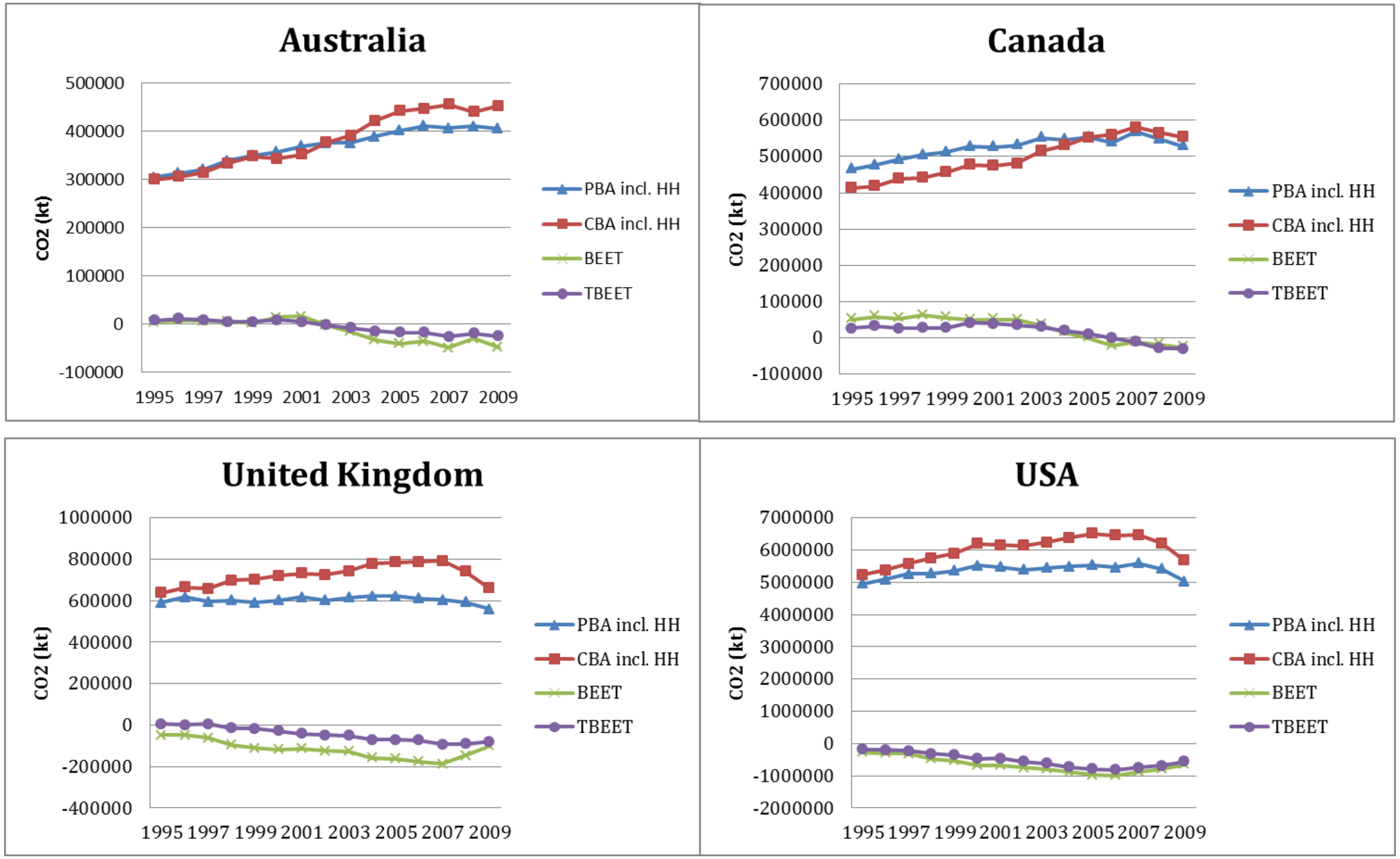
TBEET	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IND
1995	8227	-10491	27235	77189	-8054	-968	83795	5615	12418
2000	9020	-4803	42006	135907	-3685	-10538	14062	-28856	17641
2005	-16895	32005	11882	499717	74982	-32768	-17586	-70590	-24361
2009	-24876	-5726	-29528	612720	86963	3558	-34575	-79405	-48758
T. Spec.	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IND
1995	5411	-4218	10483	53601	-56432	10824	59008	-5696	14155
2000	3529	1110	10384	94078	-43206	14156	688	-32487	16652
2005	-15498	7291	-16827	376827	-37644	16011	-17403	-55915	-16198
2009	-29150	-9943	-27958	437401	-22745	32720	-20427	-77431	-27822
T. Bal.	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IND
1995	2816	-6273	16751	23588	48378	-11793	24787	11311	-1737
2000	5491	-5913	31622	41829	39521	-24694	13374	3631	990
2005	-1397	24713	28709	122890	112626	-48779	-184	-14676	-8164
2009	4274	4218	-1571	175319	109708	-29162	-14148	-1973	-20936

Table 7: TBEET and its Decomposition (JPN-USA) from 1995-2009 in kt CO_2

TBEET	JPN	KOR	NLD	RUS	TWN	USA	EU27	Annex I
1995	121648	28103	54882	57647	25432	-187215	219857	236122
2000	111344	67738	46066	79358	24927	-467335	85761	-155035
2005	51140	79386	62486	126663	37701	-790604	89370	-550635
2009	57864	94516	58583	104862	34169	-565017	112655	-347797
T. Spec.	JPN	KOR	NLD	RUS	TWN	USA	EU27	Annex I
1995	11974	22289	34769	39748	17964	-140824	118530	40514
2000	9227	49264	28745	35041	15422	-251701	47608	-147123
2005	-33632	52358	33492	58289	26231	-446558	16339	-440573
2009	15921	68925	33564	59536	19681	-405774	24626	-355174
T. Bal.	JPN	KOR	NLD	RUS	TWN	USA	EU27	Annex I
1995	109673	5814	20113	17899	7468	-46391	103322	197603
2000	102117	18474	17321	44316	9505	-215634	40153	-5912
2005	84771	27028	28994	68373	11470	-344046	75036	-108057
2009	41943	25591	25019	45326	14487	-159243	90038	9385

Appendix B: PBA, CBA, BEET and TBEET for selected Countries

Figure 15: PBA, CBA, BEET & TBEET - Anglophone Countries (1995-2009)[18]



[18] Again, please note the varying scale of the individual countries' graphs and as well as between Appendix B and C in order to ensure a clear illustration.

Figure 16: PBA, CBA, BEET & TBEET - BRIC Countries (1995-2009)

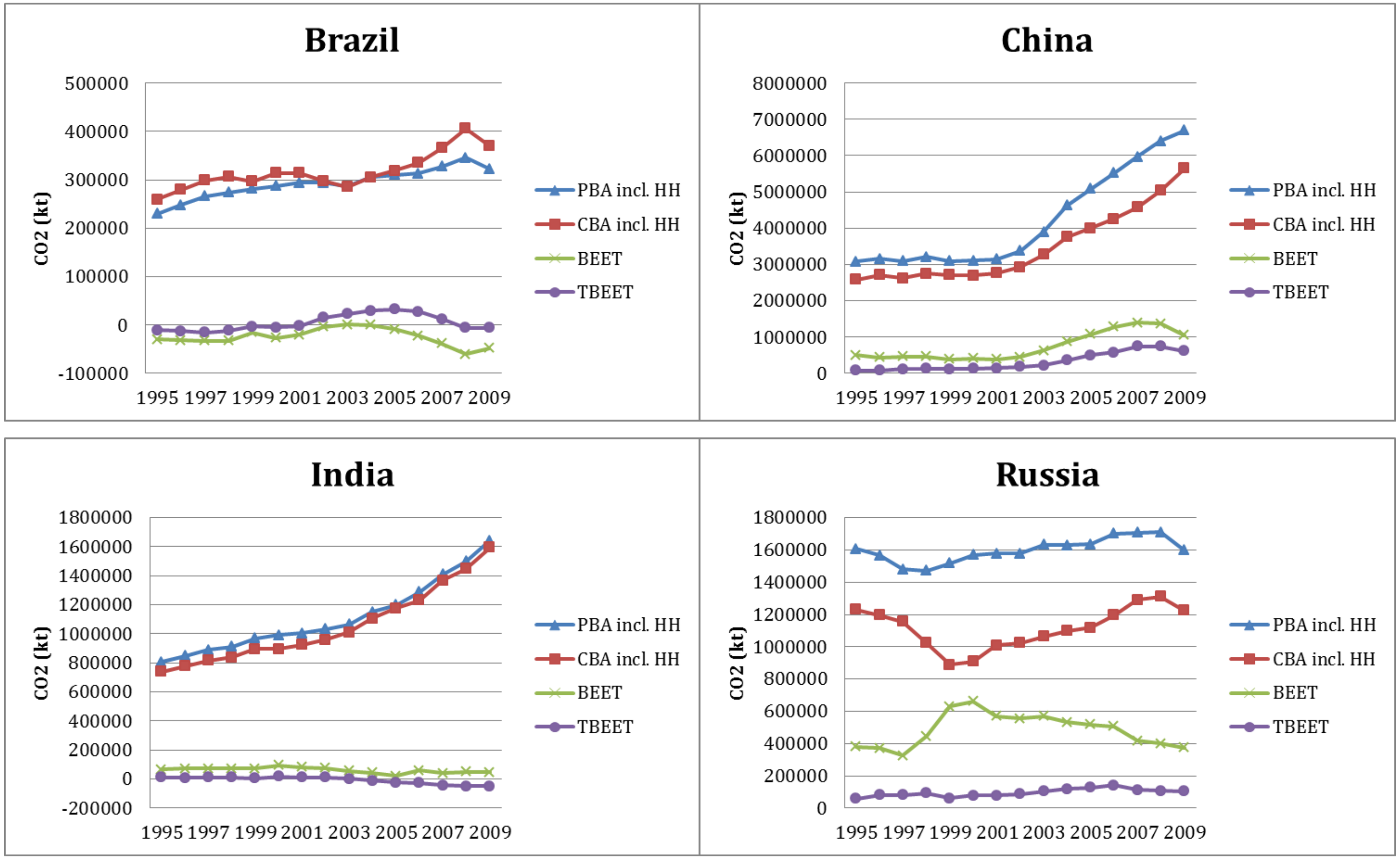
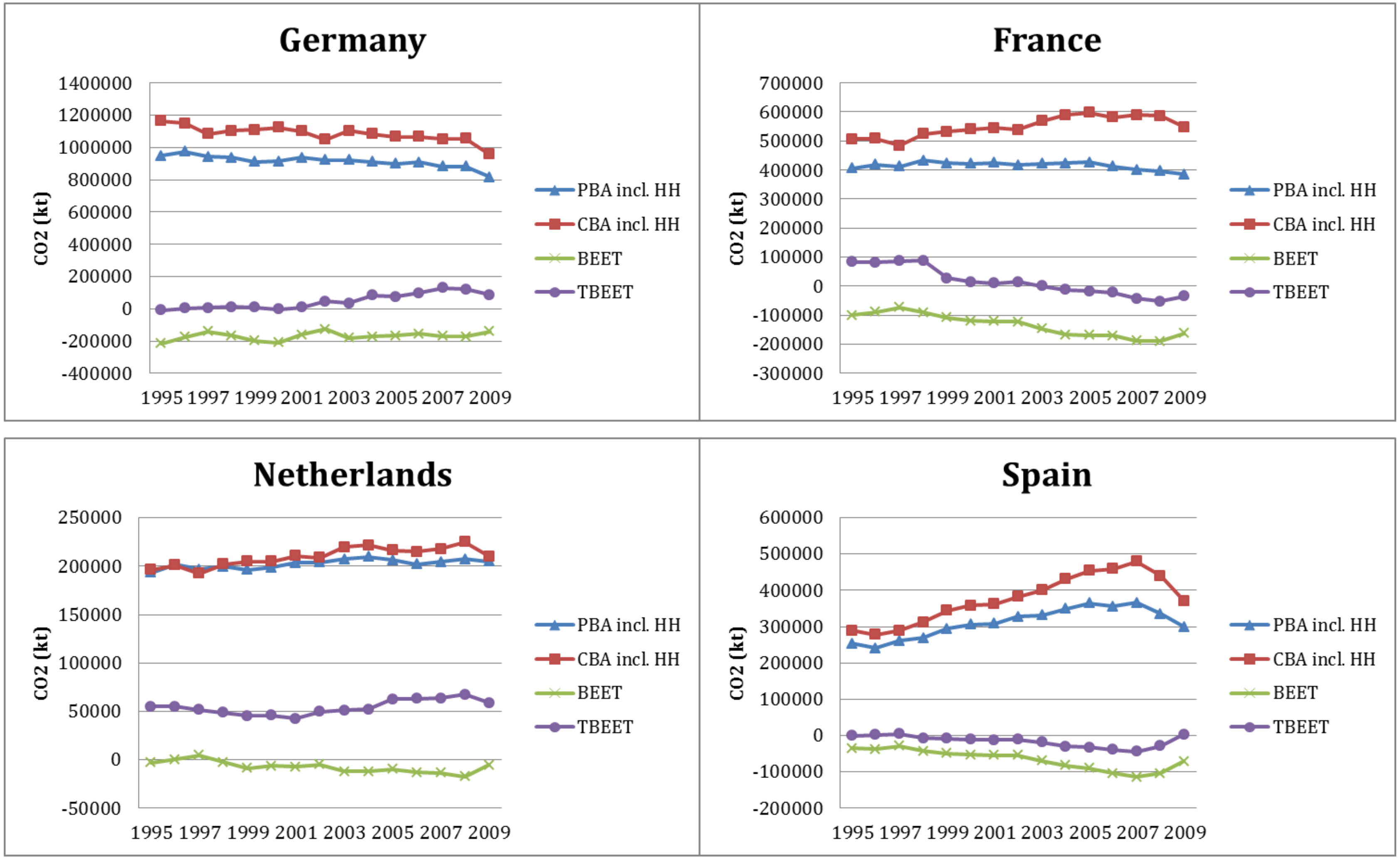


Figure 17: PBA, CBA, BEET & TBEET - Selected EU-27 Countries (1995-2009)



Appendix C: The decomposed TBEET for selected single Countries

Figure 18: Decomposed Individual TBEETs - Anglophone Block (1995-2009)

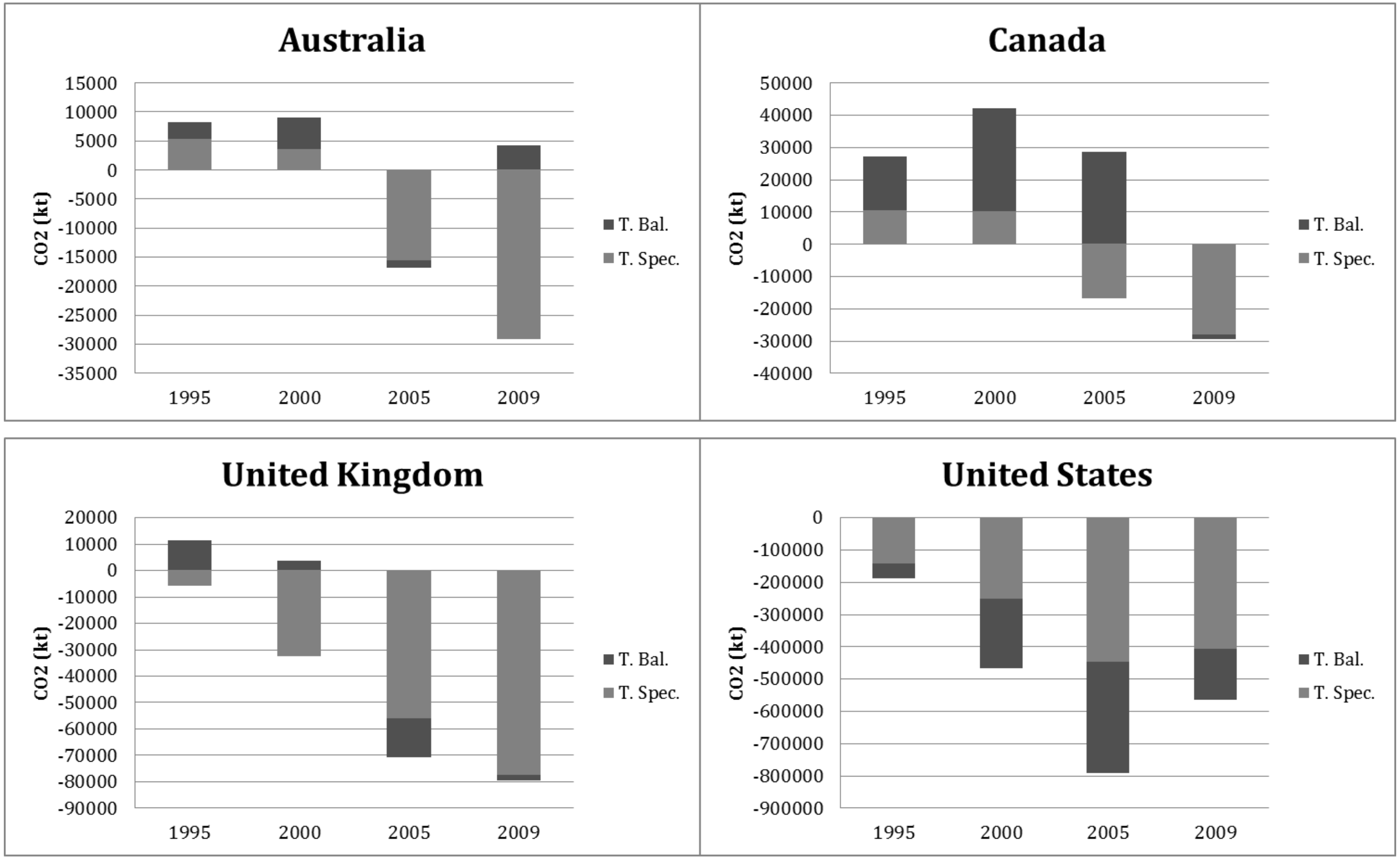


Figure 19: Decomposed Individual TBEETs – BRIC Countries (1995-2009)

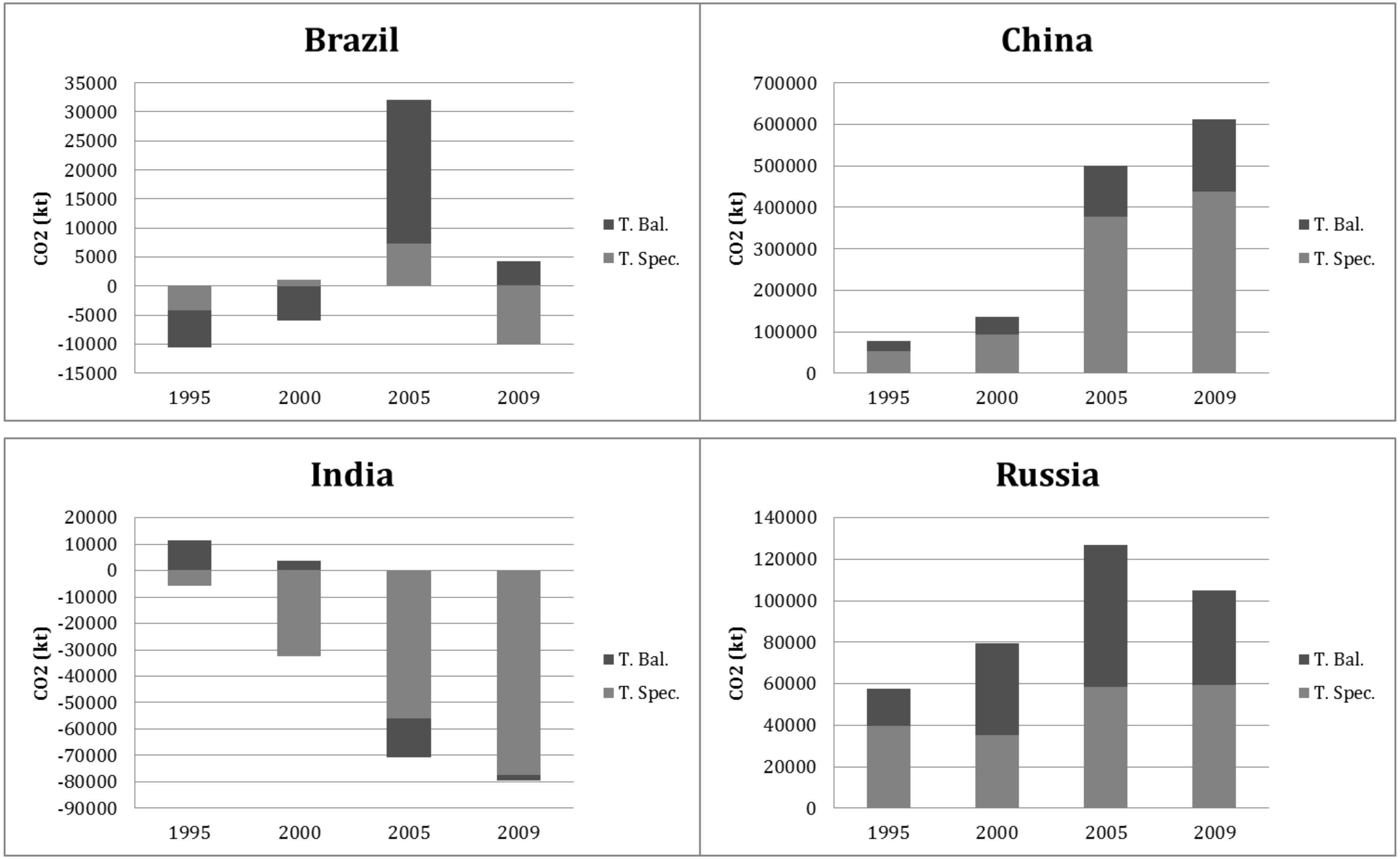
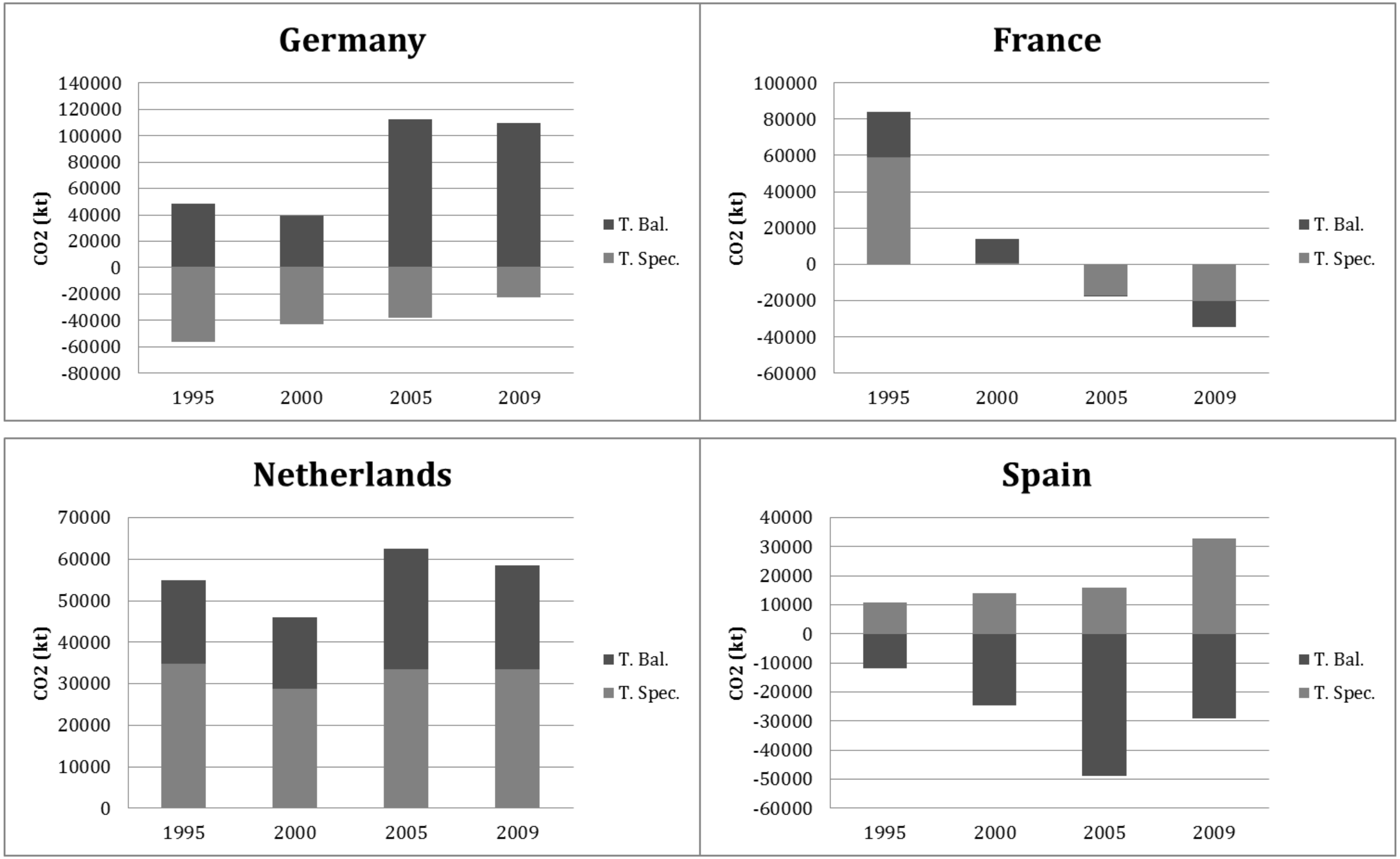


Figure 20: Decomposed Individual TBEETs – Selected EU-27 (1995-2009)



Appendix D: Glossary and Abbreviations

Annex I	Countries with emission reduction goals in the Kyoto Protocol
BEET	Balance of Emissions Embodied in Trade
BRIC	Brazil, Russia, India and China
CBA	Consumption-based Accounting
CO2	Carbon dioxide
EDGAR	Emission Database for Global Atmospheric Research
EEE	Emissions Embodied in Exports
EEI	Emissions Embodied in Imports
EKC	Environmental Kuznets Curve
EU	European Union
EU-27	All 27 member countries of the EU before 2013
FD	Final demand
GDP	Gross Domestic Product
GHG	Greenhouse Gas
Gt	Gigaton
INDC	Intended Nationally Determined Contributions
IO	Input-Output
kt	Kiloton
OECD	Organisation for Economic Cooperation and Development
RoW	Rest-of-the-World
PBA	Production-based Accounting
T. Bal	Monetary Trade Balance
T. Spec	Trade Specialization
TBEET	Technology-adjusted Balance of Emissions Embodied in Trade

TCBA	Technology-adjusted Consumption-based Accounting
TEEE	Technology-adjusted Emissions Embodied in Exports
TEEI	Technology-adjusted Emissions Embodied in Imports
UNFCCC	United Nations Framework Convention on Climate Change
VC	Value Chain
WIOD	World Input-Output Database
WIOT	World Input-Output Table