

Dynamic Technology-Adjusted Consumption-Based Accounting:

National emission responsibilities based on current consumption patterns and
production technologies

by

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Abstract

Effective global emission mitigation policies require accurate guidance in terms of a fair and comparable emission accounting framework. This thesis presents an indicator that acknowledges countries' technological differences as well as intertemporal capital dynamics. Accordingly, emissions associated with current consumption patterns are distinguished and less (more) polluting production compared to world averages are credited (punished). The novel contribution lies within the combination of two existing modifications to CBA for 40 countries using the World Input-Output Tables. The measure is created by deducting emissions embodied in exports based on world average sectoral emission intensities, and endogenizing capital dynamics as an approximation of inventory use following the augmentation method. Results impose considerable changes on emission responsibilities for a broad range of countries compared to conventional footprints, although not systematically in favor or disfavor of countries within similar development stages. Even if a measure capturing both of these features is interesting on its own, it should be further methodologically developed to differentiate between aims of capital investments.

Keywords: Emission Responsibilities, Consumption-Based Accounting, Technology-Adjusted Emissions, Intertemporal Capital Dynamics, Input-Output Analysis

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Abbreviations

CBA - Consumption-Based Accounting

CFC - Consumption of Fixed Capital

CO₂ - Carbon Dioxide

EEE - Emissions Embodied in Exports

E EI - Emissions Embodied in Imports

EET - Emissions Embodied in Trade

EKC - Environmental Kuznet's Curve

ETS - European Emission Trading Scheme

GDP - Gross Domestic Product

GFCF - Gross Fixed Capital Formation

GHG - Greenhouse Gas

IOT - Input-Output Table

MRIO - Multi-Regional Input-Output

PBA - Production-Based Accounting

TCBA - Technology-Adjusted CBA

UNFCCC - United Nations Framework on Climate Change

WIOT - World Input-Output Table

WIOD - World Input-Output Database

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1 Introduction

Rapidly increasing international economic interactions have improved living standards worldwide throughout recent decades, albeit largely to the cost of epochal environmental changes. Global warming will, most certainly, transcend 1.5°C above pre-industrial levels between 2032 and 2050 at the present pace, which causes long-term climatic effects including destroyed ecosystems and rising sea-level (Allen, Dube, Solecki, Aragón-Durand, Cramer, Humphreys, Kainuma, Kala, Mahowald, Mulugetta, Perez, Wairiu & Zickfeld, 2018). Anthropogenic emissions in the atmosphere need to be significantly reduced globally, preferably become negative, to not further aggravate the dystopic forecast of the future global climate.

Greenhouse gas (GHG) emission accounting is an essential tool to quantify emission responsibilities and, thus, to design effective climate mitigation policies. However, the creation of accounting frameworks and comprehension of drivers behind emission generating processes is not straightforward. Territorial emissions measured by a production-based accounting (PBA) framework have served and still conduct the baseline of climate science and several policy regimes, for example the Paris Agreement (Afionis, Sakai, Scott, Barrett & Gouldson, 2017), Kyoto Protocol, and the European Emission Trading Scheme (ETS) (Jakob, Marschinski & Hübler, 2013; Peters & Hertwich, 2008). These multilateral contracts accentuate strengthened efforts to combat climate change by targeting reductions of GHG emissions in primarily developed countries (the grouping of countries is motivated in Chapter 4) (UNFCCC, 2019a; UNFCCC, 2019b).

In contrast to PBA, a consumption-based accounting (CBA) framework determines national emission responsibilities based on consumption within each sovereign territory oppose to what has been produced in the same (Afionis et al. 2017; Peters & Hertwich, 2008). Davis and Caldeira (2010) provide a CBA inventory that deviates from territorial emissions, thus entails evidence of substantial amounts of CO₂ being traded internationally. They conclude that, in general, developed countries are assigned a rise in their emission responsibilities when determined by consumption. The prior ignorance to the divergence between PBA and CBA results enabled many developed countries to report decreasing territorial emissions, while several studies depicted a diametrical story of increasing emissions to satisfy their demands for consumption (Davis & Caldeira, 2010). As a consequence, CBA highlights the problems of

emission transfers that place impediments to global mitigation efforts (Peters, Minx, Weber & Edenhofer, 2011; Peters & Hertwich, 2008).

Conventional theories explain the discrepancy between PBA and CBA with a general pattern of developed countries to specialize within light industrial goods and import heavy industrial goods, which makes them become net importers of emissions (Afionis et al. 2017; Peters & Hertwich, 2008). Therefore, the territorial framework's neglect of, and tendency to induce, carbon leakage has been subject to frequent criticism since it does not adjust for emissions generated to serve their total amount of consumed goods and services (denoted as goods henceforth). Forasmuch as, without such adjustment, countries may fulfill climate goals even though no contribution to reduce global emissions has been generated in practice. The opposite also applies; nations may be punished for their generated emissions, although a substantial amount is caused by the production of export goods. Consequently, emissions generated to serve domestic consumption reflect the carbon footprint of a country more accurately (Jakob & Marschinski, 2013).

Nevertheless, CBA has also been subject to criticism. Namely, studies using this approach is criticized for exaggerating developed countries' trade specialization in light industrial goods as a result of neglecting technological differences between national energy systems and production technologies (Kander et al. 2015; Jakob & Marschinski, 2013). Reduced domestic emissions are not necessarily the result of trade specialization and emission displacement but perchance induced by improved energy efficiency and environmentally friendly technologies (Jakob & Marschinski, 2013). Videlicet, suppose enhanced climate policies in country A, which, reasonably, decrease emissions embedded in domestically produced goods for domestic consumption as well as in exports. Consequently, country A's net imports of emissions increase not due to enhanced carbon leakage but simply because of the cleaner production of exports. Drawing on these insights, country A could potentially be punished for ameliorating its production of exports.

As the research field has expanded, new measures allowing for technological differences have challenged the previously prevailing consensus on explanations to the gap between PBA and CBA. These suggest outsourcing of emissions to have been exaggerated by the conventional analyses. Furthermore, the results of several countries declare that emissions generated by imports are offset by the reduction of global emissions through more carbon efficiently

produced exports compared to their trading partners (Baumert, Kander, Jiborn, Kulionis & Nielsen). Kander et al. (2015) present technology-adjusted consumption-based accounting of emissions (TCBA). This measure allows for technological differences in production and energy systems within export sectors between different countries and thus reflects national impacts on global emissions more accurately (Kander et al. 2015).

Another criticized feature of CBA is its static character by merging current and future consumption. Through a modification to CBA, intertemporal capital dynamics are incorporated as an approximation of current consumption and investments for ditto in the future (Chen, Ohshita, Lenzen, Wiedmann, Jiborn, Chen, Lester, Guan, Meng, Xu, Chen, Zheng, Xue, Alsaedi, Hayat and Liu, 2018). This Dynamic CBA aims to capture the complexity of past capital being used to enable current production and, by extension, acknowledge that all currently produced emissions are not attributed to support current consumption. Multifold arguments may support this adjustment. For instance, surmounting present grand challenges and creating sustainable production processes and consumption patterns will require enormous investments, thus alter the picture of emissions embodied in current consumption (Pauliuk, Wood & Hertwich, 2015). Furthermore, initial stages of development are generally associated with rapid gross capital accumulation and hence place injustices between countries currently experiencing rapid growth and those post such a process (Chen et al. 2018).

This thesis aims to nuance the understanding of emission responsibilities associated with current consumption patterns. It is achieved by introducing an alternative indicator of consumption-based emissions that acknowledges technological differences as well as capital dynamics in one comprehensive measure; Dynamic TCBA. Accordingly, the thesis will be guided by the following research questions:

1) What are the effects on countries' emission responsibilities when technological differences and capital dynamics are acknowledged in a consumption-based framework?

and

2) Are there distinguishable patterns depending on countries' development stages?

The topic of this thesis positions itself in the research front and undertakes relevance in policy making in the sense that it contributes to nuance the contentious issue of quantifying emission responsibilities. Specifically, it provides input to understand drivers of environmental impacts from national consumption patterns while acknowledging technological differences and intertemporal capital dynamics.

The remainder of this thesis conforms to the following structure. Chapter 2 presents theoretical considerations regarding environmental degradation in relation to economic growth and the notion of stylized facts on capital dynamics. The topicality of this thesis is fortified in Chapter 3 by establishing a review of previously conducted research on differences between CBA and PBA and by presenting modifications to the CBA framework. Chapter 4 elaborates on the data that has been employed to generate results following the methodology presented in Chapter 5. The results of the combined measure are outlined in Chapter 6, which are interpreted in Chapter 7 that concludes the thesis.

2 Theoretical Context

This chapter presents theoretical considerations. Section 2.1 with sub-sections introduce a stylized fact regarding capital accumulation and continues with a theoretical cornerstone in environmental economics, namely the Environmental Kuznet's Curve (EKC) hypothesis.

2.1 Holistic interrelations of Economic Growth, International Trade, Environmental Impacts, and Capital Dynamics

2.1.1 Stylized Facts of Capital Accumulation

Kaldor (1960, 1961) presents six *stylized facts* that have become famous when describing the relationship between capital and GDP. Summers (1991) defines stylized facts as empirical regularities, or statistical tendencies, that are apparent even without advanced econometric techniques. Per definition, these do not necessarily hold for all countries in all periods but tend to reflect historical characteristics of data (Summers, 1991). One of the stylized facts provided by Kaldor in the 1960s suggests that capital eventually amounts to the size of the Gross Domestic Product (GDP) in the country under scrutiny, times three (Kaldor, 1960, 1961). Kander, Melanima, and Warde (2013) show that early industrializers, primarily Great Britain, seem to conform to this stylized fact with capital-output ratios of 3:1. They also suggest that latecomers, such as Sweden and Spain, commenced at much lower ratios between their respective capital stock and GDP in the 1870s. Nevertheless, capital investments grew substantially with time and composed ratios of 3:1 in Sweden and 3.6:1 in Spain by the shift of millenniums (Kander, Melanima & Warde, 2013), which conforms to the suggested stylized ratio. The pertinence of this stylized fact in this thesis lies within the apparent tendency for capital accumulation to stagnate and capital-output ratios to converge as countries develop.

2.1.2 The Environmental Kuznet's Curve

The close connection between energy generation through burning fossil fuels and rising carbon dioxide (CO₂) in the atmosphere, by extension resulting in the greenhouse effect, is profoundly established in the academia (MacKay, 2009; Davis & Caldeira, 2010; Liu, Jayanthakumaran & Neri, 2013; Jakob & Edenhofer, 2014). Several analyses of correlations between environmental

degradation and economic growth jointly provide a theoretical consensus on initially increasing emissions followed by stagnation and decline in later stages of economic development (Dinda, 2004). This phenomenon, first labeled as the Environmental Kuznet’s Curve (EKC) by Panayotou (1993), takes the shape of an inverted U, as illustrated in Figure 1.

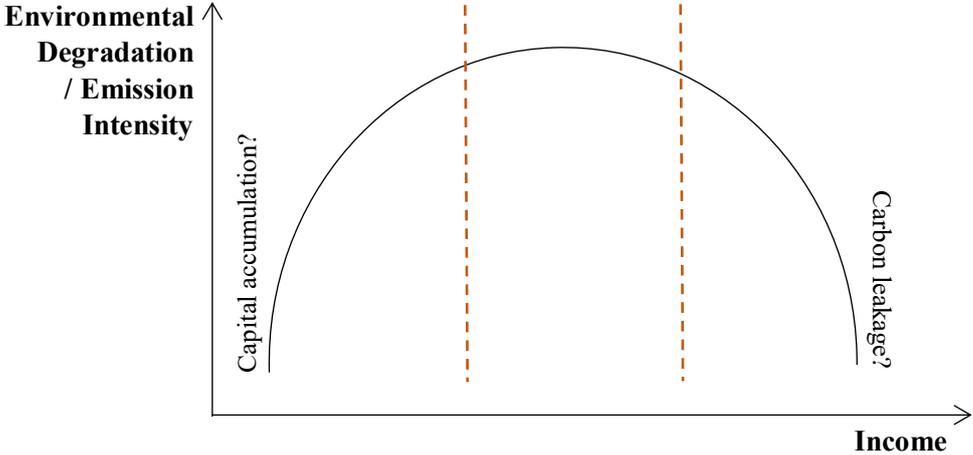


Figure 1: Visualization of the Environmental Kuznet’s Curve (EKC) hypothesis (adapted from Dinda, 2004)

Since its introduction, the hypothesis has sparked a large body of empirical work to test the EKC compliance with data, both with respect to total emissions as well as to energy intensity (CO₂/GDP). This field of research provides somewhat inconclusive results with contradictory explanations to the downward slope, which adopts either a technologically optimistic or a - pessimistic perspective (Kander, Mar Rubio-Varas & Stern, forthcoming). The former assumes effective mitigation policies to reduce energy intensities while the technologically pessimistic idea assigns developed countries’ emission reductions during their service transitions primarily to carbon leakage (Dinda, 2004; Peters et al. 2011; Steinberger, Roberts, Peters & Baiocchi, 2012). Peters (2010) presents two separate definitions of this concept; weak versus strong carbon leakage. The author suggests the weak (or demand-driven) version of the concept to encompass all international flows into the observed country. Thereby, it measures all foreign emissions that are brought about by consumption within its geographical territory. On the other hand, strong (or policy-induced) carbon leakage considers a subset of foreign emission increases due, explicitly, to climate policy of the country in question (Peters, 2010). Nevertheless, the discussion on EKC will not be extended in depth due to the ambiguous compliance with empirics.

3 Prior Relevant Research

This third chapter brings up prior conducted research related to the topic of this thesis. Section 3.1 describes the concept of emission displacement and the point of departure in measuring national emissions by traditional standards. Section 3.2 proceeds by explicating modified versions of CBA to quantify national emission responsibilities while the novelty and contribution of this thesis are highlighted in Section 3.3.

3.1 Emission Displacement and Traditional Indicators of Domestic Emissions

Aggregate measures of several developed countries suggest apparent compliance with the EKC due to seemingly decoupled interconnectedness of energy use and economic growth from the 1970s onwards (Kander et al. 2013). Hypothetically, such a reduction could solely be the result of emission displacement - a phenomenon of reducing emissions by increasingly import carbon-intensive goods from less regulated countries and specialize in the production of light industrial goods (Peters & Hertwich, 2008). Thereby, a possibility arises that national reductions may increase global emissions through these substitution effects (Henriques & Kander, 2010; Peters et al. 2011; Steinberger et al. 2012). For clarity, it should be noted that emission displacement and carbon leakage will be used interchangeably throughout this thesis.

Moreover, the occurrence of increasing fragmentation of production processes has initiated a discussion about emission responsibilities. Particularly, two attempts to quantify national emissions have progressed to become the most common, which are those that will be elaborated upon hereinafter. These accounting frameworks allocate the responsibility of emissions differently but aggregate equal levels of total global emissions (Afionis et al. 2017; Kanemoto, Lenzen, Peters, Moran & Geschke, 2011; Rodrigues & Domingos, 2008).

Firstly, the production-based accounting (PBA) framework assigns national responsibilities based upon generated emissions from all production within a sovereign territory (Davis & Caldeira, 2010). United Nations Framework Convention on Climate Change (UNFCCC) commonly employ such territorial emissions as a baseline in climate mitigation policies (Afionis et al. 2017). Traditionally, the US has occupied the title as the world's largest national

source of CO₂ emissions. Since 2006 however, China has surpassed the previous leader and is still the titleholder as the main production-related emitter (Schreurs, 2016). The Chinese emission rate more than doubled between 2001 and 2006, which, consequently, conducted 54 % of the global CO₂ emission increase during the same period (Gregg, Andres & Marland, 2008). China's economic development at expense of the global climate is inevitably a consequence of their rapidly expanding infrastructure and inefficient, carbon-intensive electricity system (Weber, Peters, Guan & Hubacek, 2008). Chinese emissions grew by a factor of 4.7 annually between 2006 and 2016, which accumulated into a global share of 27.9 % in 2017 (BP, 2018). Nevertheless, globalization of the world economy has spurred their growth of energy consumption and emissions (Guan, Peters, Weber & Hubacek, 2009; Liu et al. 2013). Goods produced in China for consumption in the US alone amounted to 14 % of Chinese CO₂ emissions in 2003 (Shui & Harriss, 2006). The discrepancies between emissions produced domestically and those embodied in trade are the primary source for criticism against PBA (Afionis et al. 2017; David & Caldeira, 2010; Peters & Hertwich, 2008).

Secondly, a consumption-based accounting (CBA) framework aims to reduce this possibility to displace emissions by reflecting total emissions generated to serve the demands of the country in question. Expressly, CBA relieves the responsibility of export goods by subtracting emissions embodied in exports (EEE) and adds those embodied in imports (EEI) to PBA as visualized by the filled or striped circular sectors in Figure 2 and 3. Naturally, countries become either net importers or -exporters of emissions depending on their transnational trade structure. To provide clarity for the sections that follow, the term traditional (carbon or emission) footprint is used synonymously with CBA and hence indicates the (CO₂ or GHG) emissions embodied in the supply chain to final demand calculated by the traditional CBA model.

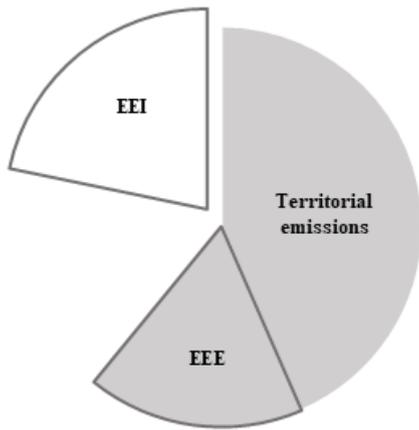


Figure 2: Visualization of PBA
(adapted from Davis & Caldeira, 2010)

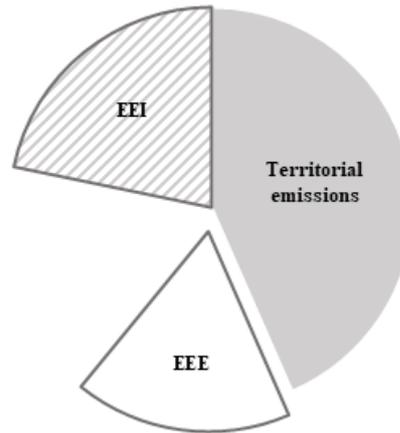


Figure 3: Visualization of CBA
(adapted from Davis & Caldeira, 2010)

Filled circular sectors represent emissions produced within the country while stripes indicate emissions that have been generated elsewhere. The detached circular sector is not included in the accounting framework that each figure illustrates. Note that the sizes of the three circular sectors do not necessarily represent their shares of emission responsibilities.

The difference between PBA and CBA aligns with the technologically pessimistic idea presented in Section 2.1.2, suggesting countries in more advanced development stages to have substituted domestic production of industrial goods with imports from less developed countries and therefore transform into service economies (Kander et al. forthcoming). Davis and Caldeira (2010) provide an inventory of countries' consumption based emissions that reveal substantial amounts of CO₂ - 6.2 gigatonnes (Gt) equivalent to 23 % of global CO₂ emissions in 2004 - being embodied in international trade. For instance, aggregated territorial emissions within OECD countries fell slightly between 1990 and 2010 while the consumption-based emissions rose by 5 % in the same period (Blanco, Gerlagh, Suh, Barrett, de Coninck, Diaz Morejon, Mathur, Nakicenovic, Ofosu Ahenkora, Pan, Pathak, Rice, Richels, Smith, Stern, Toth & Zhou, 2014).

In contrast to the widely identified shortcomings of PBA, weaknesses of CBA have generally been less recognized until recently. Despite the consideration of emissions embodied in trade (EET), CBA fails to encourage certain types of trade specialization by neglecting different carbon efficiencies (Kander et al. 2015). For instance, certain increases of national emissions could be beneficial on a global level if it substitutes alternative production that is less carbon efficient. Such contributions to reduce global emissions can even be penalized since EEI may very well exceed EEE due to different production technologies and energy systems.

Accordingly, CBA fails to promote mitigation efforts in export sectors simply because these are not considered.

By that means, the two most common accounting methods do not satisfy the requirements of appropriate measurements to penalize emission increasing behavior and credit efforts to its reduction, which is essential in order to compose effective climate mitigation policies. Contributions of prior research to correct for the deficiencies of CBA will be the focal point of the following section.

3.2 Modifications of CBA

3.2.1 Technology-Adjusted Accounting of Emissions

Building on the communicated insights of carbon leakage potential in preceding sections, different sectoral carbon efficiencies could promote a reduction of global emissions by exploiting such differences through international trade. Accordingly, increases of certain national carbon emissions could be beneficial if production is more carbon efficient compared to production elsewhere. PBA nor CBA recognize this, which thus highlights the importance to control for technological differences.

Kander et al. (2015) present a technology-adjusted CBA (TCBA) that allows for different production technologies in carbon accounting, originating from the previously described weaknesses of CBA. In order for emission accounting to provide accurate means of global or sub-global emission mitigation policies, the measures utilized should fulfill the following three necessary conditions (Kander et al. 2015). Firstly, a sensitivity condition implies that the measure needs to be responsive to factors that nations may influence, such as the level and composition of consumption as well as domestic carbon efficiency. The second condition corresponds to monotonicity, which abstracts the possibility of nations to contribute to increasing global emissions through its efforts of reducing national emissions. Thirdly, the accumulated national emissions should equal total global emissions to satisfy the additivity condition. Traditional accounting frameworks satisfy this latter condition, but not the first two (Kander et al. 2015).

While CBA subtracts export-related emissions from PBA using the average domestic emission intensity of the sectoral production in question, TCBA subtracts EEE based on the world average carbon intensity of the relevant sector (Kander et al. 2015). The reason behind this methodological difference is to control for alternative production without defining the supplier of the substitute. In the absence of alternative suppliers, TCBA assumes the alternative production to occur using the world average emission intensity for the relevant sector (Kander et al. 2015). Consequently, a country whose production is more carbon efficient relative the average world production of a substitute receives a larger deduction from PBA; hence, the country is credited. Reversely, a sectoral carbon intensity in exports that exceeds the world average will generate a larger remaining emission responsibility for the country in question once EEE are deducted; hence, the country is punished.

In the absence of technological adjustments, CBA has been assumed to explain Europe's compliance with the Kyoto protocol targets primarily as a result of outsourcing emission-intensive production (Peters et al. 2011). As displayed in Figure 4, TCBA calculates the emission responsibility of the EU27 to be below those suggested by PBA, which attributes parts of the gap between PBA and CBA to different carbon efficiencies in Europe and its trading partners rather than emission displacement (Kander et al. 2015).

Chinese emissions have increased substantially during the period studied regardless of the accounting framework used in the analysis. Moreover, its negative discrepancy between PBA and CBA highlights the advantage of CBA for a net exporter of emissions. Nevertheless, the placement of TCBA in between the traditional indicators displays the punishment to Chinese production, which largely depends on coal plants and high levels of pollution with respect to output. Accordingly, CBA underestimates the Chinese emission responsibility since it subtracts EEE irrespective of the carbon efficiency characterizing the relevant sector. Furthermore, in contrast to EU27 and China, TCBA indicates that US domestic carbon efficiency has developed neither faster nor slower than the world average. An explanation for this statement, however, is the US influence on world average technology. Lastly, TCBA intensifies Russia's emission responsibility substantially, which signals higher emission-intensive production in export sectors compared to the world average.



Figure 4: TCBA compared to traditional indicators of EU27, USA, Russia, and China (adapted from Kander et al. 2015), all vertical axes indicate GtCO₂.

TCBA corrected for the hitherto absence of a measure that penalizes and credits different carbon efficient export sectors. Thereby, the measure incentivizes countries to clean up industries producing export goods, which is not attained by the conventional standards of emission accounting.

3.2.2 Acknowledging Capital Dynamics in CBA

Chen et al. (2018) identify and maneuver another shortcoming of CBA, namely its merger of emissions stemming from current and future consumption. Emission growth increases substantially with structural change, which in turn primarily consists of capital investments and a carbon-intensive value chain (Minx, Baiocchi, Peters, Weber, Guan & Hubacek, 2011). In this regard, acknowledging changes of capital stocks in the CBA framework nuance the understanding of GHG emissions generated for current consumption and investment, respectively (Chen et al. 2018). Furthermore, transforming energy systems, production processes and consumption patterns to depend on energy carriers not emitting carbon require large capital investments (Kander et al. forthcoming; Pauliuk, Wood & Hertwich, 2015). For, as Jevon's paradox states, decreasing energy intensity is not sufficient if accumulated levels of emissions persist to increase in absolute terms due to steadily rising demand for consumption

(Alcott, 2005). Accordingly, fundamental changes are needed, and countries that invest heavily in such transformations generate more emissions in the present while aiming to reduce the same in the future. A fair measure of consumption-based emissions should acknowledge this phenomenon without placing punishments - thus the relevance of Dynamic CBA. Traditional accounting frameworks of consumption-based emissions implicitly assume constant amounts of emissions being embodied in capital; that is, capital formation and -depreciation embody equal quantities of emissions. By definition, this assumption disregards the dynamic nature of capital, which is essential to enable and maintain industrialized production (Jakob & Edenhofer, 2014) as well as to transform existing systems (Pauliuk, Wood & Hertwich, 2015).

In order to manage the static character of the traditional CBA, Chen et al. (2018) incorporate changes of the capital stock as an approximation for the temporal deviation between current emissions and future consumption. By considering capital dynamics, the gap between production- and consumption-based emissions can be decomposed into international trade and capital accumulation where the former redistributes emissions spatially and the latter over time (Chen et al. 2018). Accordingly, Dynamic CBA reflects differences in the capital stock in the sense that its level is below (above) the conventional footprint when there is a net increase (decrease) in emissions embodied in the capital stock.

As Chen et al. (2018) illustrate (see Figure 5), the Dynamic CBA (circle C) adjusts for emissions embodied in capital formation (EECF) and -depreciation (EECD) from the conventional carbon footprint (circle B). Thus, they claim that it cannot be surpassed that the dynamic effect varies depending on where countries are currently positioned in the development spectrum since these are characterized by different speeds of capital formation as also highlighted by Kaldor's stylized fact presented in Section 2.1.1. Correspondingly, they also state that traditional CBA represents a close approximation of the dynamic equivalent if EECD and EECF level each other out; when newly formed capital is only used to produce domestically utilized inventories. However, this balance is seldom the case in the real world. In particular, the disparity between the traditional and Dynamic CBA for several fast developing countries (China, India, Indonesia, Mexico, and Turkey) even exceeds the difference between territorial PBA emissions and the traditional CBA footprint (Chen et al. 2018). Therefore, approximations of dynamic footprints using the corresponding traditional footprint do not hold for countries with rapid capital accumulation, since the level of emissions embodied in capital formation substantially exceeds

those associated with capital depreciation, thus leading to a dynamic footprint well below the traditional one (Chen et al. 2018).

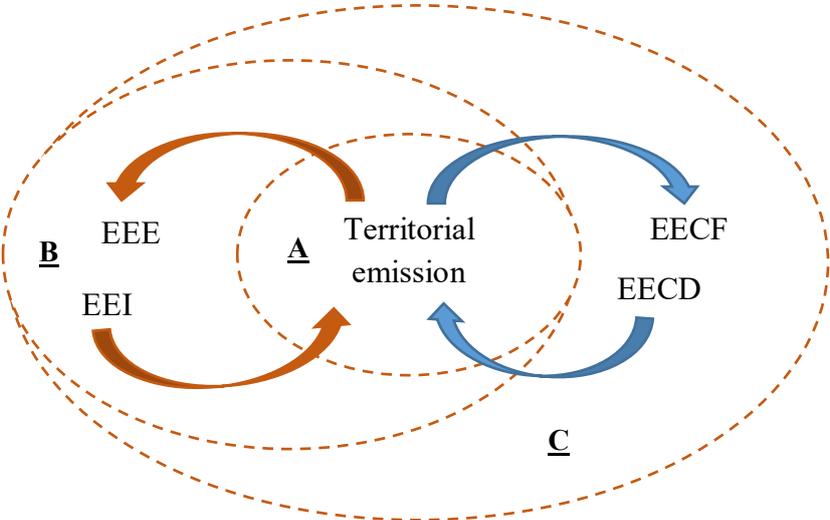


Figure 5: Conceptual illustration of flows associated with emission accounting (adapted from Chen et al. 2018)

By employing the dynamic measure to analyze consumption-based GHG emissions, Chen et al. (2018) provide evidence for the dynamic emission footprint to undercut territorial emissions by 7.4 % on a global level between 1995 and 2009. This is depicted by the difference between accumulated emissions embodied in current consumption and territorial emissions in Figure 6. Accordingly, this result suggests the conventional assumption that CBA equals PBA at the global scale to be inaccurate, which, by extension, might cause systematic errors while estimating national emission footprints (Chen et al. 2018). The gap is more pronounced for CO₂ compared to other types of GHG, partially due to its closer connection with capital formation and CO₂-emitting activities such as fossil fuel combustion and cement production (Chen et al. 2018).

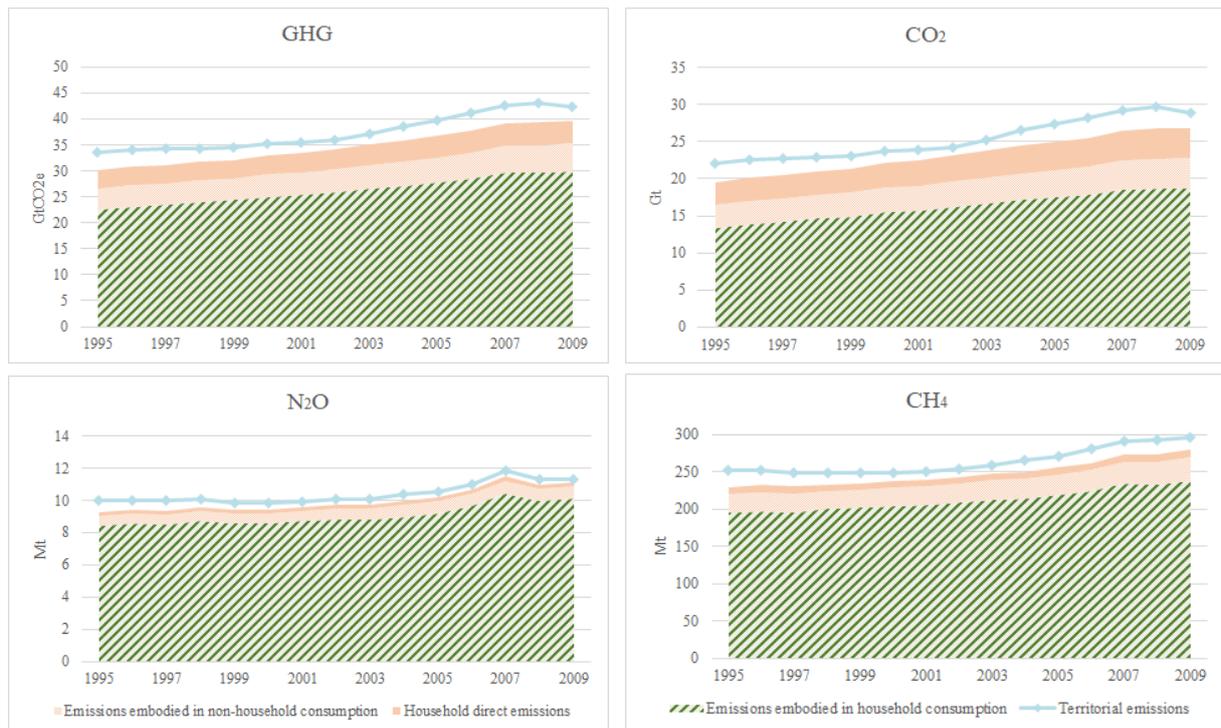


Figure 6: Globally accumulated territorial emissions and Dynamic CBA (adapted from Chen et al. 2018)

However, an essential angle to bear in mind connected to gross capital formation and climate mitigation is the different kinds of capital accumulation. Namely, whether investments solely result in increased consumption possibilities in the future (such as coal plants) or are aimed towards making production more sustainable (such as solar panels) (Pauliuk, Wood & Hertwich, 2015). Inertia strongly permeates energy systems and investment in non-renewable energy sources, thus, hamper the pace of which these systems can be altered to reduce energy intensity and become less pollutant (Kander et al. forthcoming). For instance, China still invests heavily in coal-fired electricity plants while also increasing investments in solar panels (Shearer, Brown & Buckley, 2019). Whereas the former induce increased consumption possibilities by no means of a more sustainable future energy system, the latter contributes to mitigate emissions. Nevertheless, the methodological construction in this thesis, as well as in Chen et al. (2018), does not distinguish between different types of capital formation.

3.3 Novelty of this thesis

GHG management is reliant on accurate measures and nuanced knowledge about the origin of emissions in order to maximize outcomes of mitigation efforts. The topic of this thesis positions itself in the academic front of research on emission accounting by combining recent modifications of CBA provided by Kander et al. (2015) and Chen et al. (2018). Its novelty lies within introducing a measure that acknowledges both technological differences as well as capital dynamics in a CBA framework. Furthermore, the results aspire to conduct a strong policy recommendation and emphasize the essentiality for national statistical institutes to more frequently update environmental accounts in order to enable effective global climate policies.

4 Data

Building upon the insights that have been established regarding theoretical considerations and frameworks to calculate emission responsibilities, this chapter will precise the adequacy of the employed data as well as describe its structure. The evident rise in the complexity of supply chains with intensified trade in intermediate goods has incentivized more thorough research within this field (Dutta, 2018). To achieve this, studies of supply chains have increasingly relied on so-called Input-Output (IO) analysis. For this reason, this chapter will profoundly describe the underlying concepts to IO, its execution, presentation of appropriate data and finally, incorporate the extension of environmental indicators.

4.1 Input-Output Tables

The introduction of IO analysis was made by Leontief in the 1930s and has conducted a pillar in analyzing economic-environmental relationships since the 1960s (Södersten, Wood & Hertwich, 2018b). Declining transport costs have drastically increased offshoring potentials thus also increasingly stimulated fragmentation of production processes across borders (Dietzenbacher, Los, Stehrer, Timmer & De Vries, 2013; Timmer et al. 2013), which has forced the collection of trade data to capture international transactions. Input-Output Tables (IOTs) enable one to trace such interdependent production structures through economic linkages. The method applies monetary expenditures to assess the direct as well as indirect, environmental impact generated per unit of output and the volume of goods produced and traded throughout value chains. This thesis applies IO analysis to map the GHG emissions embodied in final demand on national and international markets. Although, other environmental accounts have been analyzed in this respect as well such as embodied energy and land appropriation (Yunfeng & Laike, 2010).

Within the multi-regional IO (MRIO) framework, outputs are distinguished based on their use as either intermediate inputs or final consumption. By employing matrix algebra, direct and indirect emissions embodied in different stages of value chains aggregate to a countries' carbon footprint (Minx et al. 2011). Following conventional matrix algebra notation as proposed by Serrano and Dietzenbacher (2008, 2010), bold capital letters indicate matrices. Column vectors are denoted by bold lowercase letters while the addition of a prime indicates their transposed

form (row vectors). Italicized letters mark scalars and a circumflex denotes diagonalized matrices and vectors (Serrano & Dietzenbacher, 2008, 2010). The underlying principles of the IO identity are forthright in describing output (x) as a function of final demand (f) (Steen-Olsen, Owen, Barrett, Guan, Hertwich, Lenzen & Wiedmann, 2016). The IOTs are constructed on a territorial basis; including all activities taking place within a specified territory. A national IOT traces good flows of which the country under scrutiny is the origin or destination, as illustrated in Table 1, and is created using output data collected by the national statistical institution.

Table1: Schematic outline of national IO tables (adapted from Dietzenbacher et al. 2013)

		Country 1			Country 1			Total Output, x
		Intermediate use, Z			Final Demand, F			
		Industry 1	Industry \dots	Industry K	FD 1	FD \dots	FD S	
Country 1	Industry 1	z^{11}	$z^{1\dots}$	z^{1K}	f^{11}	$f^{1\dots}$	f^{1S}	x^1
	.....	$z^{\dots 1}$	$z^{\dots\dots}$	$z^{\dots K}$	$f^{\dots 1}$	$f^{\dots\dots}$	$f^{\dots S}$	x^{\dots}
	Industry K	z^{K1}	$z^{K\dots}$	z^{KK}	f^{K1}	$f^{K\dots}$	f^{KS}	x^K
	Value Added, w'							
Total Input, x'								

Table 1 represents intermediate transactions of a country with $k = 1, \dots, K$ industries and $s = 1, \dots, S$ final demand categories. The construction consists of the inter-industry transaction matrix Z ($K \times K$) whose elements (z^{ij}) represent intermediate sales *from* the industry in the corresponding row (i) to the one in the corresponding column (j) (with $i, j \in K$). The F matrix ($K \times S$) contains data on final demand for each industry's output by non-industry consumers (for example private households, government, exports or firms' gross fixed capital formation (GFCF)). Given an assumption of one homogenous good per industry, the economy consists of KS produced goods. On this note, rows show the supply by each industry while columns reflect the use of each good (intermediate input in Z or final consumption in F). The value added by other financial elements (for example reimbursements to workers, fixed capital, and taxes) within each industry is pointed out by the w' vector ($1 \times K$) below the corresponding intermediate inputs (Södersten, Wood & Hertwich, 2018a). Lastly, aggregated intermediate and final demand is given by the vector of total output (x) or its transposed equivalent x' (Dietzenbacher et al. 2013).

Aggregation of national accounts conducts World Input-Output Tables (WIOTs) that comprehend an international setting and trace fragmented supply chains, as displayed in Table 2.

Table 2: Schematic outline of International IO tables (adapted from Dietzenbacher et al. 2013)

		Country 1			...	Country N			Country 1			...	Country N			Total Output, \mathbf{x}
		Intermediate use, \mathbf{Z}				Intermediate use, \mathbf{Z}			Final Demand, \mathbf{F}				Final Demand, \mathbf{F}			
		Ind. l	Ind. ...	Ind. K	...	Ind. l	Ind. ...	Ind. K	FD l	FD ...	FD S	...	FD l	FD ...	FD S	
Country 1	Industry l	z^{ll}	$z^{l\dots}$	z^{lK}	...	z^{ll}	$z^{l\dots}$	z^{lK}	f^{ll}	$f^{l\dots}$	f^{lS}	...	f^{ll}	$f^{l\dots}$	f^{lS}	x^l
	.....	$z^{\dots l}$	$z^{\dots\dots}$	$z^{\dots K}$	...	$z^{\dots l}$	$z^{\dots\dots}$	$z^{\dots K}$	$f^{\dots l}$	$f^{\dots\dots}$	$f^{\dots S}$	...	$f^{\dots l}$	$f^{\dots\dots}$	$f^{\dots S}$	x^{\dots}
	Industry K	z^{Kl}	$z^{K\dots}$	z^{KK}	...	z^{Kl}	$z^{K\dots}$	z^{KK}	f^{Kl}	$f^{K\dots}$	f^{KS}	...	f^{Kl}	$f^{K\dots}$	f^{KS}	x^K
...
Country N	Industry l	z^{ll}	$z^{l\dots}$	z^{lK}	...	z^{ii}	$z^{i\dots}$	z^{in}	f^{ll}	$f^{l\dots}$	f^{lS}	...	f^{ll}	$f^{l\dots}$	f^{lS}	x^l
	.....	$z^{\dots l}$	$z^{\dots\dots}$	$z^{\dots K}$	...	$z^{\dots l}$	$z^{\dots\dots}$	$z^{\dots K}$	$f^{\dots l}$	$f^{\dots\dots}$	$f^{\dots S}$	...	$f^{\dots l}$	$f^{\dots\dots}$	$f^{\dots S}$	x^{\dots}
	Industry K	z^{Kl}	$z^{K\dots}$	z^{KK}	...	z^{Kl}	$z^{K\dots}$	z^{KK}	f^{Kl}	$f^{K\dots}$	f^{KS}	...	f^{Kl}	$f^{K\dots}$	f^{KS}	x^K
Value Added, \mathbf{w}'																
Total Input, \mathbf{x}'																

Country subscripts are left out for ease of exposition.

Hence, a WIOT is a comprehensive extension of national IOTs where bilateral international transactions connect these and the origins, as well as destinations, of good flows are made explicit. Expressly, these flows are split into the country and industry where the good has been produced as well as into the localization of its user (Yunfeng & Laike, 2010). This enables one to trace economic linkages between domestic and foreign industries. As previously, columns reflect production recipes and rows contain information on the distribution of each industry's output displayed over intermediate use and final consumption categories. Owing to the international perspective, the dimensions of the \mathbf{Z} matrix ($KN \times KN$) and the \mathbf{F} matrix ($KN \times SN$) expands to encompass the production processes and consumption of all N countries.

To assure accurate IO analyses, a market clearing condition needs to hold in order to account for all flows in the economic system. This necessitates equality between the gross output of each industry (last element of each column) and the accumulated intermediate and final use of the same (last element in each row) (Dietzenbacher et al. 2013).

4.2 World Input-Output Database

The international comparative nature of this thesis inescapably requires WIOTs, and the data employed is provided by the World Input-Output Database (WIOD). The WIOD combines detailed information on national production activities with data on international trade flows and is specifically designed and constructed for IO analyses (Timmer, Dietzenbacher, Los, Stehrer & De Vries, 2015). The 2013 release covers all 27 EU members (as of January 1st, 2007) and 13 other major advanced and emerging economies namely Australia, Brazil, Canada, China, India, Indonesia, Japan, Mexico, Russia, the Republic of Korea, Taiwan, Turkey, and the US, between 1995 and 2009. Jointly, the countries cover >85 % of the global GDP, measured in 2008 (Timmer, 2012). As adopted by Baumert et al. (2019), the notation of individual countries as developed aligns with the World Bank's classification of high-income countries. The only deviations regard Bulgaria, Lithuania, and Romania in order to refer to EU27 as an aggregation of developed countries. Accordingly, the EU27, Australia, Canada, Japan, the Republic of Korea, and the US are considered to be developed while the remaining is referred to as developing countries. Additionally, the dataset comprises an estimated residual labeled the rest-of-the-world (RoW), which is essential in order to satisfy the additivity condition presented in Section 3.2.1. All WIOTs published in the WIOD are aggregations of harmonized official statistics from national statistical institutions around the world, plus several other international statistical sources such as OECD, UN National Accounts, UN COMTRADE, and IMF trade statistics. The monetary values in the tables are expressed in millions of US dollars in current prices, and market exchange rates were used in the currency conversions (Dietzenbacher et al. 2013).

Despite the existence of more recent and detailed IO data, this thesis base upon the 2013 release of the WIOD since it provides GHG emissions in its environmental accounts next to consistent WIOTs as well as disaggregated capital stock data between 1995 and 2009. International production processes and energy systems have most certainly changed during the last decade, which would require more up-to-date data. Kulionis (2019) has contributed to extending the environmental accounts of the 2016 WIOD release, but these only constitute energy sources so far and hence are positioned outside the scope of this thesis. Therefore, estimations are bounded to the 2013 release although its current status is somewhat outdated. Nevertheless, the results still induce an approach to be further developed as updated statistical accounts are made available.

5 Methodology

Having established the fundamental principles of IO analyses, this chapter explicates IO modeling in more detail. After that, methodological modifications for extending the framework to incorporate environmental accounts as well as controlling for technological differences and capital dynamics are elucidated.

5.1 Analysis using the Input-Output method

As previously noted, IO analysis enables tracing of industries' production recipes in terms of amounts and types of intermediate inputs directly and indirectly needed in the production of one final good (Timmer et al. 2013). Owing to the composition of IOTs and their foundation on industry-level financial data, this type of analysis is appropriate to provide ex-post accounting rather than to possess any predictive power. Accordingly, IO modeling has become an expedient analytical tool to describe global value chains and their associated GHG emissions due to the increased fragmentation of production processes inherent in globalization (Kander et al. 2015; Steen-Olsen et al. 2016).

As originally formalized by Leontief in his groundbreaking work, the first step in IO analysis is to calculate technical coefficients (also called intermediate input coefficients), which display the output value of industry i (row) needed in order to produce one unit within industry j (column). These intermediate input coefficients may be defined as equation (1) while (2) shows that all a -elements create the \mathbf{A} matrix with the dimensions $KN \times KN$, which represents each industry's production structure. Put differently, this global intermediate input matrix show *direct* requirements per unit of output in one industry as it describes production processes using combinations of domestic and foreign intermediate goods (Timmer et al. 2013; Södersten, Wood & Hertwich, 2018b).

$$a_{ij} = \frac{z_{ij}}{x_j} \quad (1)$$

$$\mathbf{A} = [a_{ij}] \quad (2)$$

However, the impacts of a final demand change in one industry spill over to other parts of the economy due to *indirect* effects from interdependencies between different industries. A unit change in the final demand of a good imposes changes in the production of its required

intermediates, whose production, in turn, requires its inputs, which imposes additional production and so on. This geometric series may be converged to the famous Leontief inverse, \mathbf{L} , that constitutes a pillar in IO modeling (Södersten, Wood & Hertwich, 2018b). All contained interdependency coefficients (l_{ij}) in the \mathbf{L} matrix quantify the value of requirements from industry i , which is directly and indirectly associated with a unit change in industry j (Södersten, Wood & Hertwich, 2018b). The matrix is computed by inverting the difference between an identity matrix \mathbf{I} and the input coefficient matrix \mathbf{A} (Södersten, Wood & Hertwich, 2018b; Timmer et al. 2013), as in (3). The identity matrix, with its dimensions $KN \times KN$, consists of ones along its main diagonal and zeros elsewhere (Timmer et al. 2013).

$$\mathbf{L} = [\mathbf{I} - \mathbf{A}]^{-1} \quad (3)$$

Next, the total output vector \mathbf{x} ($KN \times 1$) is generated by multiplying the Leontief inverse with final demand, \mathbf{F} , quantifying direct and indirect production requirements from each industry in the IO table in order to satisfy final demand (Södersten, Wood & Hertwich, 2018b).

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \mathbf{F} = \mathbf{L}\mathbf{F} \quad (4)$$

With increased (MRIO) data availability, extensions of production related accounts have been introduced to the fundamentals of IO modeling such as labor (Timmer et al. 2013) and energy use (Liu, 2014). However, the extension related to this thesis and to be elaborated hereafter are the environmental accounts.

5.2 Emission Accounting in a Consumption-Based Framework

Extensions of basic IO analyses with information on industrial specific generated CO₂ emissions enable environmental accounts to be acknowledged in interindustry activities. Other pollutants are also acknowledged and may be calculated into CO₂-equivalent amounts by their 100-year global warming potential, or GWP100 (Södersten, Wood & Hertwich, 2018b). With such environmental information, a direct intensity vector (\mathbf{u}) with dimensions $KN \times 1$ can easily be calculated using element-wise right division (emissions divided by total output for each industry). Correspondingly, its elements (u'_j) reflect emission intensities, quantifying CO₂ emissions associated with one monetary unit worth of output for each industry as in (5),

$$u'_j = \frac{q'_j}{x'_j} \quad (5)$$

where q'_j is an element in the transposed vector \mathbf{q}' ($I \times KN$) showing total emissions generated in industry j . However, the Leontief inverse and final demand need to be considered in order to capture emissions embodied in all, directly as well as indirectly, linked economic activities:

$$\mathbf{E} = \hat{\mathbf{u}}\mathbf{L}\mathbf{F} \quad (6)$$

where $\hat{\mathbf{u}}$ is the diagonalized \mathbf{u} vector and contained elements of the \mathbf{E} matrix reflect industry-wise direct and indirect emissions generated in order to meet final demand.

Explicitly, conventional consumption-based emissions of country n are compiled and inspired by Kander et al. (2015) as:

$$CBA^n = \sum_{k,n} v_k + \underbrace{\sum_{k,r \neq n} x_k^{rn} \varepsilon_k^r}_{\text{imports}} - \underbrace{\sum_{k,r \neq n} x_k^{nr} \varepsilon_k^n}_{\text{exports}} \quad (7)$$

net trade balance

where v_k denotes territorial emissions of sector k , ε_k^n indicates the emission intensity in country n 's sector k , and x_k^{nr} reflects the production of output in country n 's industry k that is used in country r .

5.2.1 Technology-Adjusted Consumption-Based Accounting

Kander et al. (2015) put forward the feature of TCBA to control for emissions embodied in trade, while adjusting for different carbon efficiencies in the production of export goods. In practice, technological differences are accounted for by deducting EEE calculated with world sectoral average emission intensities, instead of domestic. This is the methodological difference to conventional estimations as has been described in Section 3.2.1. However, TCBA does not exclude the technology of the country in question to calculate world average emissions intensities. This is an easy way to maintain a valid additivity condition at the expense of the monotonicity condition (Kander et al. 2015). Consequently, the measures may underestimate technological differences since particular countries may conduct a substantial share of these averages.

TCBA practically replicates (7) with one exception; emissions embodied in exports are calculated and subtracted based on the weighted world average emission intensity, $\hat{\varepsilon}_k$, of each industry k :

$$TCBA^n = \sum_{k,n} v_k + \sum_{k,r \neq n} x_k^{rn} \varepsilon_k^r - \sum_{k,r \neq n} x_k^{nr} \hat{\varepsilon}_k \quad (8)$$

5.2.2 Endogenizing capital in CBA

Capital is most often treated exogenously in existing MRIO tables (Södersten, Wood & Hertwich, 2018a), thus also in measures based upon their regular intermediate IOTs. As a result of this, conventional CBA studies as well as TCBA, implicitly assume equal amounts of GHG emissions being embodied in newly formed capital and depreciated capital (used inventory), resulting in static amounts of emissions embodied in capital. Per definition, capital dynamics are ignored in this conventional framework despite their importance to enable production in industrialized countries and their features as sources as well as destinations of emissions (Chen et al. 2018). Since capital dynamics are used as indicators of differences between current- and future consumption, conventional accounting frameworks merge emissions generated in order to serve consumption regardless of its temporal occurrence. As conducted by Chen et al. (2018), this thesis incorporates dynamics of capital by endogenizing its formation and depreciation to final demand and intermediate use.

Lenzen and Treloar (2004) provide a comparison of two methods - the augmentation method versus the flow matrix method - to endogenize capital transactions in an IO system. While the former treats capital homogeneously, the latter acknowledges the destination and origin of different capital transactions. Södersten, Wood, and Hertwich (2018a) state that the flow matrix method describes total flows (capital as well as non-capital) by disaggregating and adapting capital to the structure of the regular \mathbf{Z} matrix. Correspondingly, this method yields more accurate results since it avoids systematic errors of the augmentation method by differentiating capital. Nevertheless, its application is less frequent in empirical studies due to the high data requirements (Lenzen, 1998, 2001). For the same reason, the augmentation method is adopted in this thesis and thereby adds a discrete, artificial industry with capital as its homogenous output. The corresponding production process uses inputs according to a GFCF vector, and consumption of fixed capital (CFC) is displayed by a row vector (Södersten et al. 2018a).

Chen et al. (2018) state that differences between static and dynamic carbon footprints originate from the different sources of emissions that are acknowledged. In particular, they suggest that the dynamic footprint differs in the sense that it contains capital input and a time dimension. They illustrate the different versions of emission accounting using the following equations, starting with a balance equation of the traditional static model of emissions in country n ,

$$g_i + \sum_j z_{ji} \varepsilon_j = x_i \varepsilon_i \quad (9)$$

Oppose to (7), Chen et al. (2018) define i and j as global sectors (that is, in a world consisting of two countries with three regions each, the indices would range from 1 to 6), g_i is direct sectoral emissions, z_{ji} denotes input used in sector i that has been produced in sector j , ε reflects emission intensities of sectoral outputs and x_i shows total output of sector i .

A vector \mathbf{e} containing sectoral emission intensities can be compiled from the following matrix expression, again following the methodology by Chen et al. (2018):

$$\mathbf{e} = (\widehat{\mathbf{X}} - \mathbf{Z}')^{-1} \mathbf{g} \quad (10)$$

of which $\widehat{\mathbf{X}}$ is a diagonalized vector of sectoral output, \mathbf{Z}' is the transpose of the MRIO matrix and \mathbf{g} is a vector of direct sectoral emissions.

Then, Chen et al. (2018) proceed by extending this framework to incorporate a time dimension, t , which enables the inclusion of capital input in the model and turns (9) into:

$$g_{i,t} + \sum_j z_{ji,t} \varepsilon_{j,t} + d_{i,t} \bar{\varepsilon}_{t-1}^n + c_{i,t} \varepsilon_{j,t-1} = (x_{i,t} + c_{i,t}) \varepsilon_{i,t} \quad (11)$$

where $d_{i,t}$ depicts capital depreciation by sector i in period t , $\bar{\varepsilon}_{t-1}^n$ is the emission intensity of country n 's capital stock in period $t-1$, and $c_{i,t}$ reflects the sum of negative inventory change in absolute terms (inventory use). Notice that this regresses to (9) when ignoring emissions embodied in capital.

Chen et al. (2018) continue by formulating a balance equation for the capital stock in country n as:

$$s_{t-1}^n \bar{\varepsilon}_{t-1}^n - \sum_{k,n} d_{k,t}^n \bar{\varepsilon}_{t-1}^n + \sum_j f_{j,t}^n \varepsilon_{j,t} = s_t^n \bar{\varepsilon}_t^n \quad (12)$$

where $d_{k,t}^n$ denotes the depreciation within country n 's sector k in period t , capital stocks are represented by s of which countries and time periods are indicated by the subscripts, and $f_{j,t}^n$ being output for capital formation in sector j of country n in period t . The emission intensity of the capital stock in period t_0 can then be reduced, according to Chen et al. (2018), to:

$$\bar{\varepsilon}_{t_0} = \sum_j f_{j,t_0+1}^n \varepsilon_{j,t_0+1} / \sum_j f_{j,t_0+1}^n \quad (13)$$

By applying equation (13) to (11), Chen et al. (2018) formulate the following equation for $t = t_0+1$:

$$g_{i,t_0+1} + \sum_j z_{ji,t_0+1} \varepsilon_{j,t_0+1} + d_{i,t} \sum_j f_{j,t_0+1}^n \varepsilon_{j,t_0+1} / \sum_j f_{j,t_0+1}^n = x_{i,t_0+1} \quad (14)$$

which they solve using matrix notation by:

$$\mathbf{E}_{t_0+1} = (\hat{\mathbf{X}}_{t_0+1} - \mathbf{Z}'_{t_0+1} - \mathbf{A}_{t_0+1})^{-1} \mathbf{G}_{t_0+1} \quad (15)$$

The components of \mathbf{A}_{t_0+1} can be obtained according to:

$$a_{ij,t_0+1} \begin{cases} d_{i,t} f_{j,t_0+1}^n / \sum_m f_{m,t_0+1}^n & (\sum_m f_{m,t_0+1}^n \neq 0) \\ 0 & (\sum_m f_{m,t_0+1}^n = 0) \end{cases} \quad (16)$$

with m also being a global sector identity. Owing to the inclusion of capital input (\mathbf{A}_{t_0+1}) and time dimensions, the computation of emission intensities differ between the traditional and dynamic accounting models. For t_0+2 , the following equation applies (Chen et al. 2018):

$$\mathbf{E}_{t_0+2} = (\hat{\mathbf{X}}_{t_0+2} - \mathbf{Z}'_{t_0+2} + \hat{\mathbf{C}}_{t_0+2})^{-1} (\mathbf{G}_{t_0+1} - \hat{\mathbf{D}}_{t_0+2} \bar{\mathbf{E}}_{t_0+1}^* + \hat{\mathbf{C}}_{t_0+2} \mathbf{E}_{t_0+1}) \quad (17)$$

where $\hat{\mathbf{C}}_{t_0+2}$ and $\hat{\mathbf{D}}_{t_0+2}$ are the diagonal of sectoral total inventory use and sectoral depreciation respectively in period t_0+2 , $\bar{\mathbf{E}}_{t_0+1}^* = [\bar{\varepsilon}_{i,t_0+1}^*]$ with $\bar{\varepsilon}_{i,t_0+1}^* = \bar{\varepsilon}_{t_0+1}^{*n}$ whenever sector i belongs to country n . Thenceforth, (10) can be solved for all countries in $t = t_0+2$, according to Chen et al. (2018) to reach:

$$\bar{\varepsilon}_{t_0+2}^n = s_{t_0+2}^n / (s_{t_0+1}^n \bar{\varepsilon}_{n,t_0+1} - \sum_k d_{k,t} \bar{\varepsilon}_{t_0+1}^n + \sum_j f_{j,t_0+2}^n \varepsilon_{j,t_0+2}) \quad (18)$$

Finally, emission intensities of sectoral output and capital stocks can be obtained by solving equations (11) and (12) sequentially (Chen et al. 2018).

Ultimately, Dynamic TCBA is composed based on the results of the methodological approaches to modifications that has been presented in this chapter. Namely, by combining technological adjustments of CBA and capital dynamics into one comprehensive measure. In practice, the combination is achieved by applying the dynamic effect between Dynamic CBA and conventional CBA in absolute terms to TCBA. Hereby, emissions associated with investments are deducted from the technology-adjusted measure.

6 Results

All chapters hitherto have contributed to establish the relevance and foundations of Dynamic TCBA. The following section will present results obtained from the calculations that have been conducted.

6.1 Dynamic TCBA

Graphs included in Figure 7 display the novel indicator of Dynamic TCBA in contrast to CBA and TCBA ranging from 1995 to 2009 for all countries included in the analysis. As previously indicated by Figure 4, technological efficiency depresses the amount of emissions that the aggregated EU27 should be held accountable for - due to considerably more emission-efficient production compared to world sectoral averages. Dynamic TCBA does not deviate considerably from its static counterpart, thus, emissions embodied in the combined European capital stock increase slightly over time. A similar interpretation can be drawn from the Brazilian results, although at lesser magnitudes. Brazilian emissions have risen throughout the period analyzed, but the responsibility for these are ameliorated with Dynamic TCBA on account of a less polluting energy system than the world average. Likewise, they are further pushed down by the temporal distinction of consumption. Japan also receives a substantial emission rebate on account of its carbon efficiency in export sectors. As one of the exceptions to the rule of positive net capital formations, Dynamic TCBA in Japan is positioned slightly above its static counterpart.

The technological adjustment does not alter the traditional footprint considerably for neither Canada, Mexico, Korea, nor Turkey. For these four countries, the separation between current and future consumption yields comparatively more extensive alterations to the measure than does TCBA. Australian results suggest a similar inference, although with a smaller dynamic effect. The nearly unaltered US results, regardless of the applied measure, imply no advancement of technology beyond the world average. Furthermore, the fact that Dynamic TCBA shows no considerable difference to its static equivalent suggests that emissions embodied in US capital formation as well as depreciation are similar in their magnitudes. Bear in mind though the impact US pose on world averages, which hampers the monotonicity condition and may underestimate the difference in production technologies.

China, a country principally advantaged by consumption-based accounting, is punished for its emission-intensive production and heavily polluting energy system resulting in a TCBA above CBA while the inclusion of capital dynamics depresses the level of emissions associated with current consumption. Both of these contrasting effects are captured by Dynamic TCBA, which approximately tracks both level and trend of the traditional Chinese footprint. Indonesia, India, and Russia are also penalized for more emission-intensive export sectors than world averages, with most distinct effects for Russia. These effects are then contrasted when separating current consumption from total production, which lowers the emission levels. The combined effects position Dynamic TCBA between the traditional footprint and its technology-adjusted counterpart for Indonesia and Russia. However, emissions embodied in Indian capital formation exceed those in depreciation more extensively resulting in a TCBA below both conventional CBA and TCBA.

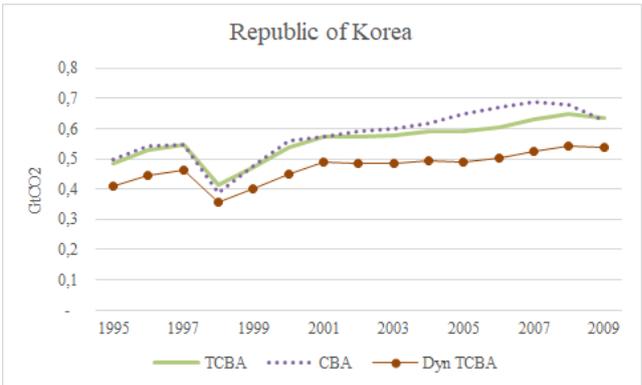
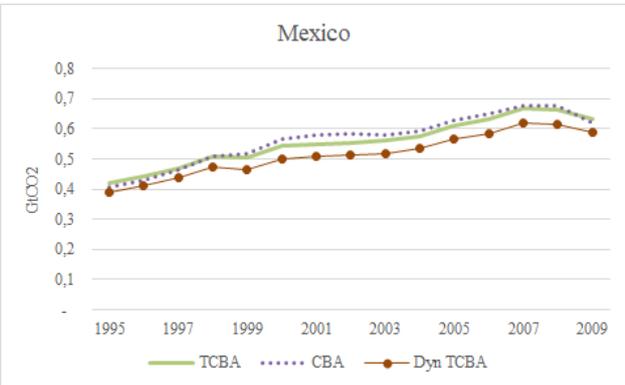
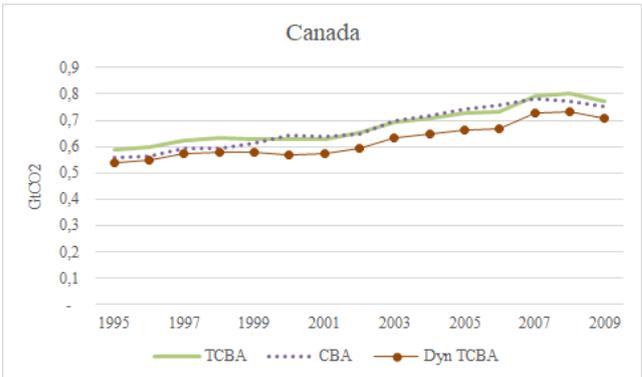
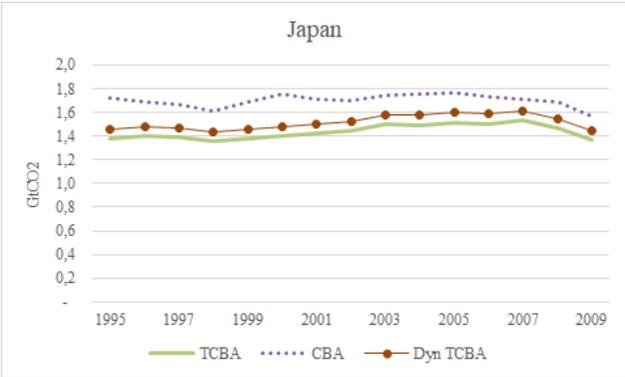
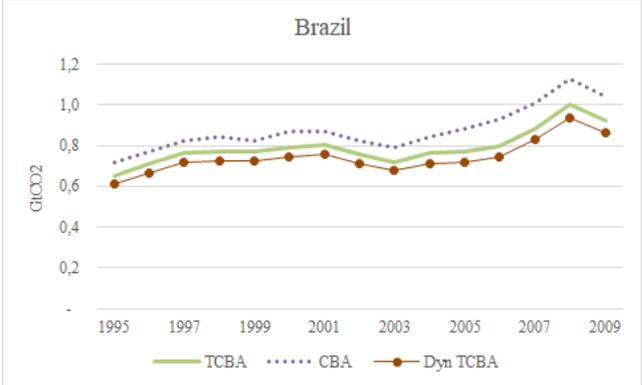
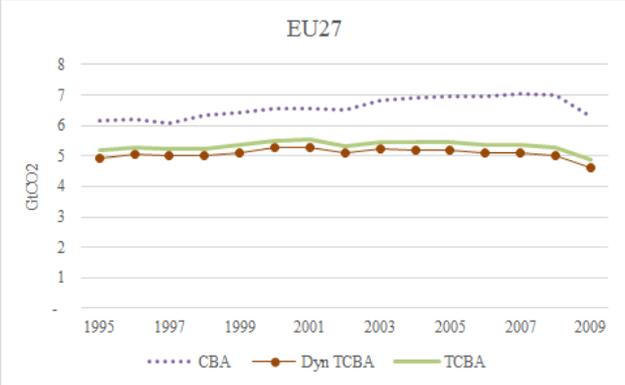




Figure 7: Dynamic TCBA compared to TCBA and Dynamic CBA

A dynamic character of applied measures amounts to lower levels of emissions compared to their static counterparts in all countries apart from Japan and the UK. For these two exceptions, the results indicate emissions embodied in capital depreciation (inventory use) to exceed those

in capital formation, which ultimately implies emissions embodied in the capital stock to reduce over time, although rather slightly. Their dynamic effects amount to 4,6 % (JPN) and 0,3 % (UK). For all other countries, accumulated emissions embodied in the capital stock tend to increase with time, thus place dynamic measures below their static counterparts. However, the magnitudes of these effects vary. The average discrepancies between static and Dynamic TCBA amount to less than 5 % for several developed countries, for example, the aggregated EU27, Japan, Australia, and the US. Other countries embody more copious amounts of GHG in gross capital formation as they are assigned significantly lower dynamic measures than their static equivalent; mainly China, India, and the Republic of Korea with dynamic effects of 14,5 %, 16,0 %, and 15,2 %, respectively. Brazil, Mexico, Turkey, Russia, Canada, and Indonesia are positioned in between the two extreme groups of countries regarding dynamic effects with averages ranging from 5,6 % (BRA) to 8,9 % (IDN) per annum.

As visualized in Figure 8, technological differences generally impact emission responsibilities to a greater extent than does differentiation between temporal deviation in consumption and production. The EU, Japan and Brazil are most advantaged by technological adjustments experiencing average declines of 19,1 %, 15,5 %, and 9,6 %, respectively, due to carbon-efficient export sectors. At the other side of the spectra are Russia (35,0 %), Indonesia (12,2 %), China (12,1 %), and India (8,0 %) with inferior production technologies and energy systems. Australia and USA, with the highest per capita averages, exhibit nearly unaltered emission levels (< 1 %) from the technological adjustment. Remaining countries' effects range from -3,0 % (KOR) to 1,5 % (CAN). Moreover, Figure 8 depicts deviating characteristics of per capita averages within the EU. For instance, Austria, Belgium, and Ireland benefit largely from the technological adjustment, while generally accumulating emissions associated with net capital formation of 4,8 %, 6,7 %, and 7,6 % respectively per annum. On the contrary, Bulgaria and Poland are punished for their inferior emission efficiencies resulting in Dynamic TCBA's above their traditional footprints.

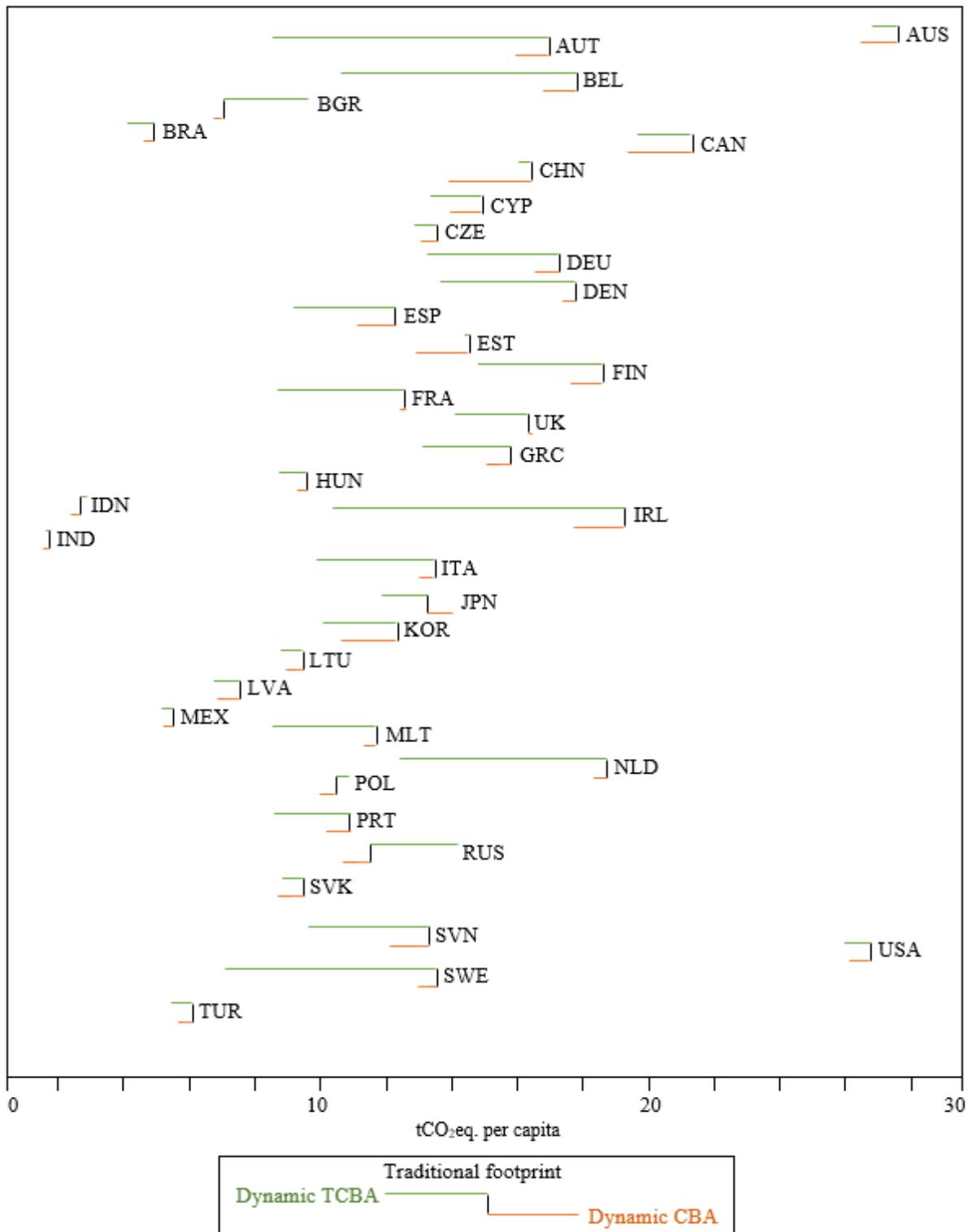


Figure 8: Change from traditional footprint to dynamic variants of CBA and TCBA (per capita averages 95-09). The position of the vertical line indicates per capita average of each specific country's traditional footprint; the free end of the upper versus lower line represents Dynamic TCBA and CBA, respectively.

Dynamic TCBA entails substantial changes to traditional footprints with most extensive average alterations for Russia, EU, the Republic of Korea, and Brazil, although with immense disparities between them. European emissions, as presented in this sample, are on average reduced from CBA by 22,8 % when both technology and capital dynamics are acknowledged. Brazil and the Republic of Korea exhibit reductions of 15,2 % and 18,2 %, respectively. For Russia and Indonesia, emission responsibilities increase when assessed by the new indicator with a Russian average effect of 26,2 %, and the significantly smaller effect of 3,3 % in the Indonesian case. Similarly, average discrepancies to traditional footprints amount to less than 5 % for Australia, USA, and China as well. Ultimately, Dynamic TCBA displays average reductions from CBA between 7,2 % (CAN) and 10,8 % (JPN) for the remaining countries.

Having presented the results of the novel indicator that incorporates a dynamic dimension to TCBA, the subsequent chapter will explicitly discuss and answer the research questions that were outlined in the incipience of this thesis.

7 Concluding discussion

This thesis has presented the methodological foundations of TCBA and Dynamic CBA leading up to a combined approximation of Dynamic TCBA, which captures emissions generated to serve current consumption while controlling for countries' emission efficiencies. With this, the newly proposed indicator eliminates the possibility of countries' emission responsibilities to disregard heavily polluting export sectors, and nuances the understanding of current consumption patterns. The overall aim has been to tackle the following questions:

1. *What are the effects on countries' emission responsibilities when technological differences and capital dynamics are acknowledged in a consumption-based framework?*

and

2. *Are there distinguishable patterns depending on countries' development stages?*

Results from Dynamic TCBA alter traditional footprints considerably for the majority of countries included in the sample. As presented, Russian emission responsibilities amount to substantially increased levels compared to conventional CBA. The aggregated EU experience a similar relative alteration in size, although of opposite direction; hence, considerably reduced emission responsibility resulting from less polluting production of exports as well as positive gross capital formation. Next to these two most affected countries are the Republic of Korea, Brazil, Turkey, Mexico, India, and Canada, in descending order. A noteworthy aspect is the relatively unaltered results of Dynamic TCBA compared to traditional footprints for AUS, USA, and China, which possess radically different inferences. Namely, while Dynamic TCBA is a combination of negligible effects for the former two, the Chinese dynamic and technological effects are equally extensive and counteract.

Correspondingly, Dynamic TCBA provides no evidence for apparent trends between developed versus developing countries. While the dynamic character mostly influences countries in earlier development stages, technological differences show no such distinct patterns, although implying substantial amendments to traditional emission responsibilities. Correspondingly, the newly proposed indicator affects trends and degrees of emission responsibilities of a broad range of countries, although not in a manner that systematically credits or punishes countries in

similar development stages. Therefore, acknowledging only one of the two modifications may lead to a skewed perception of emission responsibilities depending on either their current development stages (when assessed by Dynamic CBA) or production process characteristics (when assessed by TCBA). Nevertheless, both modifications contribute to nuance the implications of CBA, which enunciates the relevance of Dynamic TCBA in the sense that it is responsive to both aspects. Given the varying capital stock impacts depending on the development stage of the country under scrutiny, results of and comparisons with traditional footprint measures should be analyzed with cautiousness when the analysis includes developing countries.

The fact that static measures approximate their dynamic counterparts rather accurately (discrepancies of $< 5\%$) for several countries conforms to the implication of Kaldor's stylized fact. Because the original measure conducts a close approximation of Dynamic TCBA as one would expect given their classification as developed. Moreover, the dynamic character of the measure depresses its static counterpart for all but two (Japan & UK) economies in this analysis, thus confirming substantial amounts of emissions being associated with capital formation. Countries referred to as developing experience the most extensive dynamic effects (except for Canada as a developed country with an average dynamic effect of 8,8 %), thus also possibly aligning Kaldor's stylized fact. Accordingly, dynamic measures allow countries under development to undergo the transformation already made by further developed countries. According to the stylized fact, this generally corresponds to reaching the capital-output ratio of 3:1, implying increasing amounts of emissions embodied in the capital stock - of which the responsibility could be argued to burden not only the country under scrutiny.

By definition, the conventional assumption that production-based and consumption-based emissions amount to equal levels is contradicted; thus also the additivity condition. Conformably, parts of the responsibility for currently generated emissions are forwarded, which adds a caveat to the urgency associated with our grand challenges. Another aspect of the dynamic character is its leniency towards the large, crucial investments for transforming current energy systems. Conventional static measures would fail to incentivize such investments since associated emissions would burden current emission accounts. With this, the importance to differentiate between different capital investments arises, and also to support developing countries to experience green growth in their transformation.

The contributions of this thesis primarily serve as a strong policy recommendation in the sense that it enunciates the relevance to acknowledge capital dynamics and production technologies when quantifying emission responsibilities. Although a measure capturing both of these features is interesting on its own, it should be further methodologically developed. In order to eliminate the potential of dynamic measures to be an escape of responsibility, the aims of capital investments need to be differentiated. More particularly, whether these are targeted to enable more renewable energy sources, thus reduce emissions in absolute terms or merely enable further future consumption resulting in corroboration of Jevon's paradox. Correspondingly, if it follows that capital investments solely increase the inertia in the energy system or reduce economies' carbon dependence. Still, it is worthwhile to differentiate between current and future consumption in order to conduct more effective mitigation policies targeting consumption and investment behavior as well as to conduct a baseline for future modifications. Ultimately, the scope of this thesis also amplifies the need for national statistical institutions to update environmental accounts more frequently to enable up-to-date analyses and designs of climate policies.

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