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# Three essays on decomposition analysis of the territorial CO 2 emissions and the emissions embodiment in trade attributable to consumption of service-oriented economies

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# THREE ESSAYS ON DECOMPOSITION ANALYSIS OF THE TERRITORIAL $CO_2$ EMISSIONS AND THE EMISSIONS EMBODIMENT IN TRADE ATTRIBUTABLE TO CONSUMPTION OF SERVICE-ORIENTED ECONOMIES

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# ABSTRACT

Three Essays on Decomposition Analysis of the Territorial $CO_2$ Emissions and the Emissions Embodiment in Trade Attributable to Consumption of Service-Oriented Economies

Chairat Choesawan

With the pace of globalization, the rapid growth in international trade has led to a widespread perception of increasing $CO_2$ embodied emissions. As the fragmentation of international production has become a dominant feature of modern international trade, there is a vibrant debate over how embodied emissions should be attributed and allocated among economies. To contribute to the debate on emission allocations and mitigation effort comparisons, it is important to consistently investigate the structures of carbon transfers across global economies. The role of carbon transfer structures in affecting mitigation efforts can be explored as part of the consequences of various emission allocations. Thus, it becomes a fundamental theme of all three essays. Due to the leading economies in international trade in terms of volume and $CO_2$, extensive attention of this dissertation has been paid to the United States (U.S.), China, and European Union (EU) economies.

Emissions due to U.S. imports grew increasingly and contributed 31% of the worldwide imported emissions in 2012. Undoubtedly, taking emission responsibility for U.S. imports is important to gear up for a low carbon future. To integrate U.S. imports into the responsibility of global emissions, it is important to investigate the U.S. import effects and identify contributing factors behind imported emission changes. Two aspects are of interest for an understanding of imported emissions and the structure of carbon transfers: (1) the U.S. import demand can affect not only embodied emissions but also emissions at home; and (2) the sector coverage can determine the results of contributing factors. In this respect, the first essay entitled "Two-Stage Index Decomposition Analyses of Domestic and Import Related $CO_2$ Emission Changes for the U.S. Economy" utilizes a modification of multi-period logarithmic mean divisia index (LMDI II) to perform decomposition analyses of the import effects on both emissions for the U.S. economy during the period 1991-2012. It further employs an attribution technique of LMDI II in order to explore emission contributions of four industrial sectors (the utility, primary, secondary, and tertiary sectors). Dynamic changes in imported emissions are decomposed into five consumption factors: emission coefficient; energy intensity; structure of imports; final import composition; and final import scale. Dynamic changes in production emissions are generated based on three production factors of aggregate and disaggregated (real) carbon intensities: emission coefficient; energy intensity; and structure. The main findings of this essay are

presented in page 9. Analysis of the interplay of the contributing factors behind changes in emissions stimulated due to both import demand and domestic production become more critical for having a better understanding of the structure of carbon transfers. Also, it becomes important for seeking policy recommendations on emission responsibilities across economies as part of a transition to a low carbon future.

Global production fragmentation significantly affects the allocation of emissions embodied in international trade. Thus, differences between production-based emissions (PBE) and consumption-based emissions (CBE) increasingly produce uneven policy actions for targeting emission reductions between exporting and importing economies. These differences may impact mitigation efforts across economies given the current level of carbon transfers. As an alternative, a sharing-based emissions (SE) allocation is an approach that assigns exporters and importers responsibility for emissions based upon benefits linked to their production and consumption. The challenge facing the application of SE allocation is how to define a weighing procedure. In light of embodied emissions in international trade, Peters (2008) suggested that value-added should be used to define a weighting framework. However, no defined weighting procedure has been addressed so far in the literature. The second essay entitled "Sharing-Based $CO_2$ Emission Allocation with a Perspective on a Multilateral Border Tax Adjustment-the U.S. Economy" first aims to design a weighting procedure for establishing shares of the emission allocation.

Due to uneven distributions between emission and global trade intensities across economies, a change in emission allocations from the current PBE approach to an alternative approach that considers both production and consumption can result in a significant emission responsibility burden for specific industries. Thus, an impact evaluation is important to explore mitigation efforts and define the consequences of alternative emission allocations. To identify allocations, the applications of alternative allocations are empirically applied to the U.S. economy for the years 2005 and 2011. These alternative allocation are the SE and the consumption allocation with the application of a unilateral border tax adjustment. The main findings of this essay are presented in page 57.

In light of the current carbon transfers, a different allocation of mitigation efforts is needed across industries and economies throughout the world. However, an important challenge towards industrial responsibility is the identification of different policy measures appropriate for industries with different emission levels and type of linkages. It is critical to investigate the nature of emissions from different industries and their relationship with one another in regard to trade structures and embodied emissions across economies. In the third essay entitled "The Decomposition of Key Industries in Embodied $CO_2$ Emissions within the U.S., China, and EU15 Economies", I first construct a four-region environmentally-extended multi-regional input-output (EE-MRIO) model in order to examine the contributions of industrial import and export structures that mostly affect the calculation of embodied emissions. Then, I extend the concept of production-demand elasticity in order to identify roles of the different industries and emission relationships between industries. These roles are used to classify industries into four categories: a key industry; a relevant industry with own demand; a relevant industry with the demand from others; and non-relevant industry. The main findings of this essay are presented in page 116. The outcomes of this essay can be used for evaluating the practical applications of climate policies. In the respect of carbon transfers, three policy alternatives will be considered: (1) an emission standard of utility industry; (2) a unilateral border tax adjustment; (3) a multilateral border tax adjustment.

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# CHAPTER 1: INTRODUCTION

Climate change is one of the greatest threats faced by humans on this planet. It has raised concerns about what the global environment will be likes during the 21st century and beyond. In many regions around the world, changing precipitation and melting glaciers caused by the increase in global average surface temperature have seriously affected the quality and quantity of local water resources (IPCC, 2013). The repercussions include rising ocean levels, more intense heat waves, and severe droughts and floods. Mitigation patterns and species interaction of terrestrial, freshwater, and marine species are shifting (IPCC, 2014a). The effects of human health are more severe. In this respect, changing climate is anticipated to increase the displacement of people and increases the risks of social conflicts (IPCC, 2014b). All these impacts are projected to cause economic downturn at both national and global levels and eventually make world poverty reductions and decline in economic inequality[1] more difficult to address (Schor, 2015).

The scientific community expects that the significance of climate change impacts depends on the link between the concentration of greenhouse gases (GHGs) in the atmosphere and increases in global average surface temperature (IPCC, 2013). The largest contribution of the increasing concentration of GHGs has been anthropogenic carbon dioxide ($CO_2$) emissions (IPCC, 2013). There is a consensus that serious consequences of climate change can be mitigated if the global average temperature in the early 21st century due to anthropogenic emissions is constrained to no more than two degrees of warming compared to pre-industrial level (IEA, 2014). This implies that global emissions must be on track to decrease GHG concentration below 350 part per million (ppm) $CO_2$.

Recently, there has been welcome news that global $CO_2$ emissions are likely to stall or even decline slightly due to downward trends in emissions in many parts of the world (PBL, 2015). However, it is too early to conclude that this new trajectory of $CO_2$ and other global emissions will continue their decline. It is possible if emissions in China, the United States (U.S.), and the European Union (EU) drop faster than the increase of the rest of the world, particularly India and Southeast Asia (Schrag, 2015). Despite the slowdown, growth in the average global concentration of $CO_2$ has continued to increase and now stands above 400 ppm (Allen, 2015). Along this line, the National Oceanic and Atmospheric Administation (NOAA) and the National Aeronautics and Space Administration (NASA) recently released new data for

[1] Economic inequality refers to the differences of economic well-being among individuals in economy and among economy in an economic region (ET, 2015). There are three main econometric metrics of disparities: income inequality; consumption inequality, and wealth inequality (Lise and Seitz, 2011). Income inequality refers to the unequal distribution of household or individual incomes across a group of people. Consumption inequality is the extent to which a person's pay is different to its income. Wealth inequality is the unequal distribution of assets among a group of people. Along with risks of climate change, if people with different income and consumption are disproportionately affected by climate change, these impacts could cause them to become less well-off (Harvey, 2015). They may make the less well-off people poorer. In this way, climate change would be eventually exacerbating inequality and preventing reductions in world poverty (Schor, 2015).

2015 that indicates that our world is almost halfway (0.98) towards the two degrees of warming. Delaying stringent efforts to combat global emissions leads to less hope for a transition to a low carbon future.

The United Nations Framework Convention on Climate Change (UNFCCC) calls for a stabilization of GHG concentrations at 1990 levels to combat the repercussions of climate change (IPCC, 2013). Global climate agreements from Kyoto (1992) to Paris (2015) requires member countries to submit annual inventories of direct GHG emissions to address progress towards the long-term goals of the UNFCCC (IPCC, 2013). The boundary of this inventory includes GHG emissions and mitigations taking place within domestic territories, the so-called production-based emissions (PBE) perspective. In this perspective, most member countries of the Kyoto Protocol achieved their reduction commitments by a wide margin (Aldy, 2012)[2]. However, trends of per capita $CO_2$ emissions in many parts of the world are still increasing. (WDI, 2015a). Disparities in carbon production technologies (emissions per dollar of output) have been widening (Sato, 2013). There remains a gap between self-emission reduction commitments and mitigation actions necessary to limit warming to two degrees.

Reduction in trade barriers along with advances in transportation and communication technologies have contributed to the increased pace of globalization and are shaping the growth of trade in goods and services. For example, OECD export volume grew two-fold between 1990 and 2011 while import volume increased almost four-fold. Non-OECD export volume increased by seven-fold while import volume rose by over five-fold (WDI, 2015b). Globalization of trade has led to a fragmented production of goods and services, such that production of goods and services takes place at multiple locations around the globe.

This rapid growth in international trade has led to a widespread perception of increasing global $CO_2$ production (Peters, 2008; Peters and Hertwich, 2008a). Totals emission embodied in international trade have significantly increased over last two decades (Peters et al., 2011). This is relevant because direct and indirect emissions can be addressed in the production process of trade goods and services, so-called embodied emissions. When fragmented actions among economies are characterized by different abatements, the PBE can make a misleading view of worldwide mitigation efforts (Boitier, 2012), and eventually raise in quest towards carbon transfer (Sato, 2013).

Carbon transfer (i.e. carbon leakage) is broadly defined as the increase in emissions of exporting economies compared to the emissions mitigation achieved by importing economies (Peters and Hertwich, 2008b). In light of carbon transfer and distortions in embodied emissions, the consumption-based emissions (CBE) perspective is suggested as an alternative to PBE to mitigate significant risks of carbon transfer. It assigns an economy responsibility for all emissions generated from its consumption regardless of where the

[2] Kyoto Protocol assigns parties to reduce their emissions at least 5% below 1990 levels over 2008-2012.

products are produced. This perspective accounts for emissions embodied in imports, but not those in exports that are normally addressed in annual national inventories. There are many studies attempting to calculate CBE to provide policy recommendations relating to global reductions (Nakano et al., 2009; Chen and Chen, 2011; Foren et al., 2012; Narayanan et al., 2012; Wiebe et al., 2012; Kanemoto et al., 2014; Timmer et al., 2015). However, there is still a vibrant debate over how emissions should be attributed and allocated among economies. Figure 1.1 shows PBEs and CBEs of selected economies between 2005 and 2011. The calculation of these emissions was reported by International Energy Agency (IEA) (IEA, 2012; 2013). As clearly shown in Figure 1.1, the differences of emission allocations between these two perspectives can be large and may lead to uneven policy actions for targeting emission reductions between exporting and importing economies. The fairness of emission allocations remains a question.

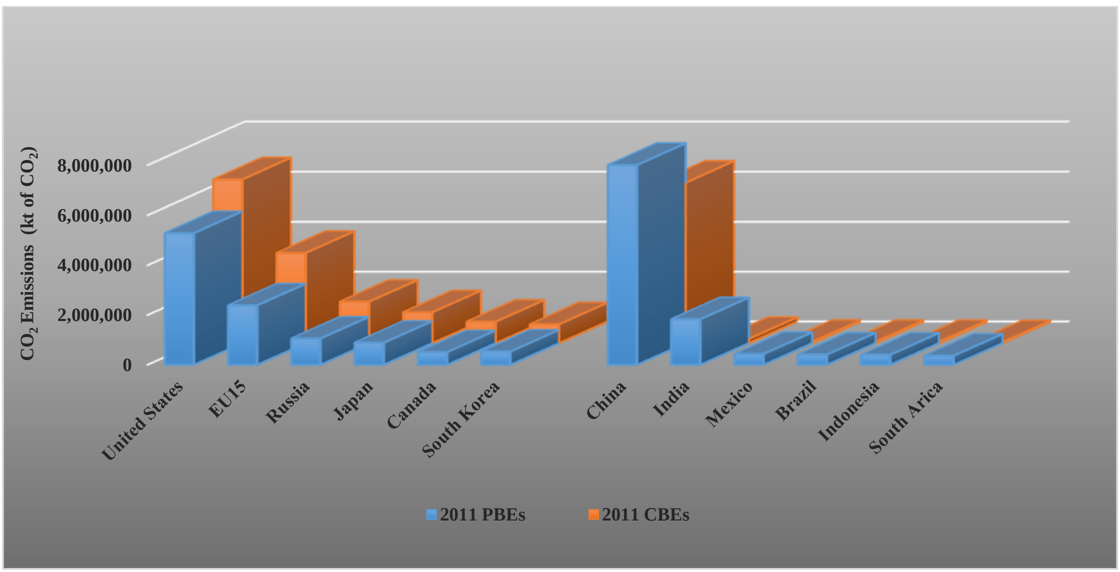


*Figure 1.1: Production-Based Emissions (PBEs) and Consumption-Based Emissions (CBEs) for Selected Economies, 2011*

Taking carbon transfers into consideration, there are three main channels through which goods and services are imported and embodied emissions flow through economies. As shown in Figure 1.2, assuming three economic regions and using economy A as an example, path A1 represents the emissions associated with products imported from economy B to deliver final demand of economy A. This path represents the emissions embodied in imports in response to the consumption occurring within economy A. Path A2 represents the emissions associated with intermediate inputs imported from economy B to supply domestic industries for producing products consumed in economy A. This path relates to the emissions embodied in imports in response to the production and consumption occurring within economy A. Path A3 is important and represents a dominant feature of modern international trade. This path shows the emissions involved in re-exports through processing trade. Paths A2 and A3 are named as the fragmentation of international trade. Path A3 is taken into account in global vertical specialization, meaning that emissions have occurred, potentially multiple time, in sequential trading chains across borders of several economies. In this respect, emissions along with international production fragmentation should be taken into consideration in the calculation of embodied emissions. It is important to note that exports from economy C can be a part of the production processes of economy B's re-exports. However, this study considers emissions occurring in this sense as spillover effects of embodied emissions in economy A. Consequently, they have not been included to the calculation of emissions embodied in international trade for economy A.

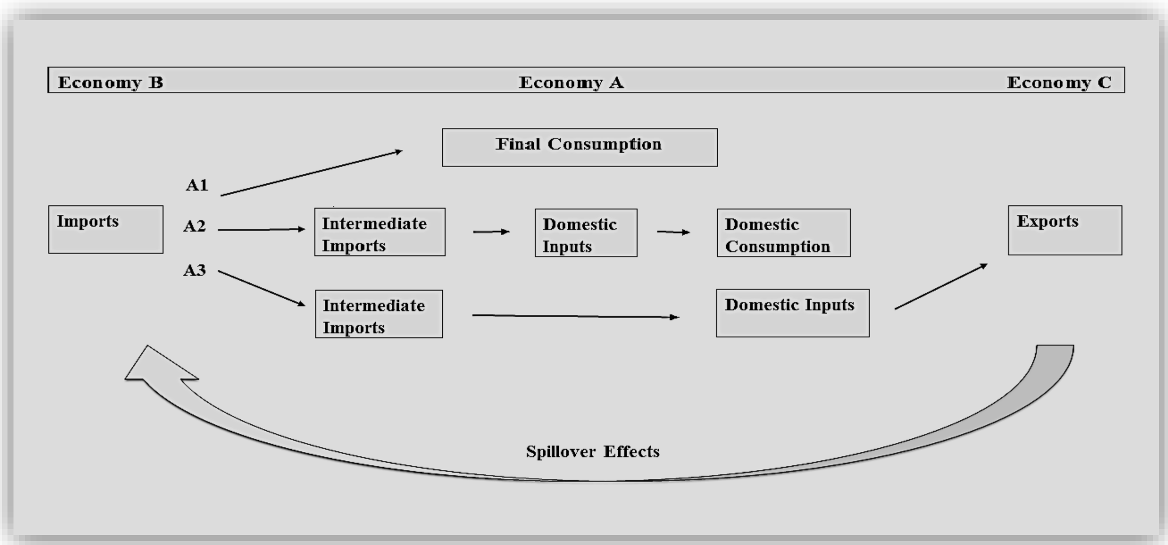


*Figure 1.2: Flows of Emissions Embodied in Imports*

Despite a sizable literature regarding the fragmentation of international production (Athukorala and Yamashita, 2006; Obashi, 2010; Falzoni et al., 2015), links between embodied emissions and international production fragmentation induced intermediate import has rarely been addressed in the literature. To contribute to the debate on the allocation of emissions and comparisons of mitigation efforts, it is critical to accurately and consistently investigate the structure of carbon transfers across global economies. As the leading economies in international trade in terms of volume and $CO_2$, extensive attention has been paid to the U.S., China, and EU economies. Along this line, the role of carbon transfers in affecting mitigation efforts can be explored as part of the identification of emission allocations and thus becomes a fundamental theme of all three essays.

Emissions due to U.S. imports have grown increasingly over the past decade and contributed 31% of the worldwide imported emissions in 2012. Under the CBE, the U.S. would be responsible for emissions from its imports. As a point of comparison, the estimates of U.S. imported emissions are equivalent to 34% of its production emissions. It is important to investigate the effects of U.S. imports on embodied emissions so that the structure of carbon transfer can be explored. Two aspects are of interest for an understanding of the structure of carbon transfer: (1) the U.S. import demand can ripple through not only embodied emissions but also emissions at home; and (2) the decomposition results can be determined by the sector coverage. For this reason, the analyses of contributing factors behind changes in both imported and domestic production emissions across industrial sectors have become important not only for having a better understanding of carbon transfer structures but also for seeking policy recommendations on how to allocate emission responsibility as part of a transition to a low carbon future. The first essay utilizes a modification of multi-period logarithmic mean divisia index (LMDI II) decomposition to identify the effects of imports behind dynamic changes in both emissions during 1991-2012. This essay employs an attribution technique of LMDI II to explore the contributions of four industrial sectors: utility; primary (e.g. agriculture, mining, etc.); secondary (e.g. paper, chemicals, etc.); and tertiary (e.g. hotels and restaurants, land transport service, etc.) sectors.

Global production fragmentation significantly affects the allocation of emissions embodied in international trade. Thus, differences between PBE and CBE allocations may impact mitigation efforts across economies given the current level of carbon transfers. As an alternative, a sharing-based emissions (SE) allocation is an approach distinct from either the PBE or CBE allocation that assigns exporters and importers responsibility for emissions based on benefits relating to their production and consumption. The challenge facing the application of this novel allocation is how to define a weighting procedure. The computation of SE requires an environmentally-extended multi-regional input-output (EE-MRIO) model. Many studies (Rodrigues et al., 2006; Lenzen et al., 2007; Peters, 2008) have recently proposed frameworks for SE allocation. However, no defined weighting procedure has been addressed so far in the research literature.The primary aim of the second essay is to design a weighting procedure for establishing shares of the emission allocation across economies.

Due to uneven distributions between emissions and global trade intensities across economies, a change in emission allocations from the current PBE approach to an alternative approach that considers both production and consumption could result in a significant emission responsibility burden for specific industries. Thus, an impact evaluation is important to explore mitigation efforts and define the consequences of alternative emission allocations. The application of alternative allocations (sharing-based allocation approach and consumption-based allocation with the application of a unilateral border tax adjustment) are empirically applied to the U.S. economy for the years 2005 and 2011. For importing economy like the U.S., these alternative allocations would be better than CBE allocation as demonstrated in essay 2.

In light of the current carbon transfers, a different allocation of mitigation efforts is needed across industries and economies throughout the world. However, an important challenge towards industrial responsibility is the identification of different policy measures appropriate for industries with different emission levels and type of linkages. It is critical to investigate the nature of emissions from different industries and their relationships with one another in regard to trade structures and embodied emissions across economies. In the third essay, I first construct a four-region EE-MRIO model in order to evaluate the significance of the international trade impact of the U.S., China, and EU15 economies and examine the contributions of industrial import and export structures that affect the calculation of embodied emissions. I then extend the concept of production-demand elasticity to embodied emissions in order to identify roles of the different industries and their industrial interdependencies. The outcomes of this essay provide an improved understanding of the nature of emissions played by different industries and their relationship to recommended policy measures that could be implemented to reduce emissions stimulated due to their economic activities.

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# CHAPTER 2: ESSAY 1 - Two-Stage Index Decomposition Analyses of Domestic and Import Related $CO_2$ Emission Changes for the U.S. Economy


## Abstract

U.S. imports grew significantly between 1991 and 2012, reaching 31% of worldwide $CO_2$ imported emissions by 2012. While taking emission responsibility for U.S. imports is important for a low carbon future, .two aspects are of interest for an understanding of imported emissions and carbon transfer structures. First, U.S. import demand can affect not only emissions embodied in imports but also emissions at home; and second the decomposition results can be determined by the sector coverage. This essay first utilizes a modification of multi-period logarithmic mean Divisia index (LMDI II) to perform decomposition analyses of the import effects on both imported and domestic emissions for the U.S. economy during the period 1991-2012. It further employs an attribution technique of LMDI II in order to explore emission contributions of four industrial sectors (utility; primary, secondary, and tertiary sectors). Dynamic changes in imported emissions were decomposed into five consumption factors (emission coefficient, energy intensity, structure of imports, final import composition, and final import scale). Dynamic changes in production emissions were generated based on three production factors of aggregate and disaggregated (real) carbon intensities (emission coefficient, energy intensity, and structure).

The most dominant contributor to the imported emissions was the increase in final import scale. However, this effect has slowly increased since 2004 and different sectors dominated over different sub-periods. The structure effect became more important and has surpassed the effects of emission coefficient and energy intensity to be the second largest contributor since then. The final import composition was the only one that drove down imported emissions. Comparing effects between emission coefficient and energy intensity, this analysis points out that the increase in emission coefficient of the secondary and primary sectors contributed to the rise in their energy intensity, but the reverse impact could not be made. Cross-over effects between the final import composition and final import scale revealed that the secondary sector affected imported emissions not only due to an effect of structural changes towards emission-intensive imports but also through a transform into intermediate imports. In the respect, with the substantial growth in imported emissions over 2003-2012, it is likely that the transformation towards intermediate imports contributes more to imported emissions than towards final imports. A similar situation can be observed in the primary sector, but cannot be made within the tertiary sector.

While the emissions from U.S. imports were growing, the aggregate carbon intensity slowed after 2006 and declined visibly in 2008. The main contributions were not only due to the decrease in the emission coefficient of the utility sector as a result of fuel switching towards natural gas but also the effect of structural change of the secondary sector carbon-intensive industries. The utility's and secondary's energy intensities gradually declined but remained positive influences on the aggregate carbon intensity. When the three contributing effects were combined, this analysis points out that the variation in industrial structure of the secondary sector was the major influence towards the smooth declines in energy intensity and the consistency of emission coefficient reductions of the utility and secondary sectors. In this respect, the aggregate carbon intensity was not consistent in the year-to-year declines during 2008-2012. Due to cross-effects of the structural change, this analysis indicates that the decrease in U.S. production emissions could be partially explained by the increase in emissions from its imports.

Policy implications of the decomposition and attribution results are discussed for establishing a transition towards a low carbon future by means of global mitigations of the emissions stimulated due to U.S. imports and improvements in the carbon intensity of the U.S. economy. The latter is the bases for the recommendations for achieving the goal under its INDC.

## 2.1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) has called for all members to submit an annual inventory of their emissions to address progress towards the goals of the UNFCCC since 2003 (UNFCCC, 2003). This inventory covers emissions and mitigations of direct greenhouse gas, primarily carbon dioxide ($CO_2$), taking place within their domestic territories. This is the production-based emissions (PBE) allocation. In this respect, emissions and mitigations associated with exports are generally included, but those associated with imports are not. With the pace of globalization and a growth of international trade, direct and indirect emissions along the production chain of trade in goods and services have significantly increased over the last two decades (Peters et al., 2011). When a fragmented actions across economies is characterized by unequal abatement, the PBE can give a misleading view of mitigation efforts within a specific territory (Boitier, 2012). It can also raise in quest about carbon transfers[3] due to disparities in carbon production technologies (Sato, 2013). The United States (U.S.) is currently the world largest net importer in terms of import volumes and $CO_2$. U.S. import demand accounted for 19% of the world imports ($2,736 billions) and contributed 31% of the global imported emissions (2,257,248 kilotons of $CO_2$) in 2012. By way of comparison, U.S. imported emissions are 34% of its production emissions and 150% larger than its exported emissions. The assignment of emission responsibility of U.S. imports is a critical components of meeting the goal of a low carbon future. However, this responsibility seems larger than the goal under its INDC regarding a pathway towards the 2015 Paris Agreement. The U.S. committed to curtails its $CO_2$ PBE by 26-28% below the 2005 level by 2025 (UNFCCC, 2015). To integrate U.S. imports into the responsibility of global emissions, it is important to investigate the effects of U.S. imports and identify the contributing factors behind dynamic changes in U.S. imported emissions and the structure of carbon transfers.

Three primary factors have been identified to explain an increased level of imported emissions according to trade theory (Copeland and Taylor, 2003). The first factor is an expanded level of economic activity (the scale effect). This expansion leads to higher levels of emissions due to greater fossil fuel use by exporting economies. A change in production share (the composition effect) is a second factor. This change depends on whether the emission-intensive sectors are expanding or contracting. A third effect relates to changes in carbon and energy methods by which products are generated (the technical effect). According to a new theory of fragmentation in trade, changes in the scale and structural composition of imports are highly relevant to competitive advantages between net importing and exporting economies (Onder, 2012). The potential of comparative advantages in response to levels of imported emissions is

[3] Carbon transfer (i.e. carbon leakage) is broadly defined as the increase in emissions of exporting economies compared to the emissions mitigation achieved by importing economies (Peters and Hertwich, 2008).

shaped by two forces: factor endowments (Baldwin, 2006); and environmental regulation (Mattoo et al., 2009). Examples include that with relative loose environmental regulations, if exporters are capital-abundant economies, international trade has led to an increase in imported emissions due to not only expanded levels of the scale but structural composition as well. At the same time, the effect of these expansions can be reflected in reduced PBE of importers as a result of relocations of capital-intensive sectors (Onder, 2012).

The reason for the change in imported and production emissions can be also due to modifications of carbon and energy efficiency methods. In the U.S., the Department of Energy (DOE) and the Environmental Protection Agency (EPA) have implemented a series of policies that incentivize industrial sectors to promote their highest carbon and energy standards. Examples include the Energy Policy and Conversation Standard Program (EPCP) and the Environmental Quality Incentives Program (EQUIP). Both were initiated in 2002 and have been in effect since 2004. The effects of these policies might be considerable but there is still need to assess whether the above policies plays a role in PBE mitigations. If carbon and energy efficiency methods are major contributors and there are large disparities of technological effects across economies, technological transfers may duplicate a similar trend between importing and exporting economies (Aldy et al., 2010). International policies that encourage technological transfers may turn out to promote a participation of exporters regarding a control of emissions from U.S. imports. The modification of carbon and energy efficiencies associated with the industrial sector performance and the performance of industrial sectors that produce imports to the U.S. needs to be investigated (Voigt et al., 2014). However, the different size of industrial sectors can determine variations of the influencing factors due to factor manipulation from different activities (Gonzalez et al., 2014). The sector coverage becomes an important issue. In this way, analysis of the interplay of the contributing factors behind dynamic changes in both emissions across industrial sectors have become more crucial not only for having a better understanding of carbon transfer structure but also for seeking policy recommendations on how to allocate emission responsibility across economies as part of a transition to a low carbon future.

Index decomposition analysis (IDA) is an analytical tool for exploring factors behind changes in energy consumption and greenhouse gas emissions. In recent years, IDA has been widely used for studying energy usage and energy-related $CO_2$ emissions in the U.S. economy (Lee and Oh, 2010; EERE, 2010; Vinuya et al., 2012; Feng et al., 2014). However, existing studies have not yet explored the contributions of different levels of aggregation regarding interplay analyses across emission attributions and industrial sectors. It is important that index decomposition of imported emissions also requires consumption factors in regard to consumption-based emissions (CBE) allocation. This perspective provides an alternative allocation of emissions in response to consumption occurring within economy, rather than production.

Therefore, the objectives of this essay are to examine the contributions of consumption factors influencing dynamic changes in U.S. $CO_2$ imported emissions as well as to investigate the contributions of production factors behind dynamic changes in $CO_2$ production emissions. These are applied at both the economy-wide and industrial sector levels. The industrial sectors are the utility, primary (e.g. agriculture, mining, etc.), secondary (e.g. manufacturing), and tertiary (e.g. services) sectors. Specifically, two-stage multi-period logarithmic mean Divisia index (LMDI) decomposition is used to: (1) provide overviews of real carbon intensity trends in imported emissions and domestic production emissions during 1991-2012; (2) determine the effects of imports on $CO_2$ emissions by means of analyzing the contributions behind dynamic changes in emissions stimulated due to U.S. imports based on five consumption factors (the emission coefficient, energy intensity, structure of imports, final import composition, and final import scale); and (3) gain better insights into the contributions influencing dynamic changes of U.S. production emissions based on three production factors of carbon intensity (the emission coefficient, energy intensity, and structure). This essay first uses a modification of LMDI decomposition (LMDI II) by Ang et al. (2010) to perform a decomposition analyses of aggregate $CO_2$ emissions, and further uses an attribution technique of LMDI II by Choi and Ang (2012) in order to explore the contributions of four industrial sectors.

The remainder of this essay is structured as follows. The second section examines the importance of index decomposition methods and reviews current findings of existing studies. The third section presents the LMDI method and the extension to attribution techniques. The fourth section discusses the data used in the analysis. The fifth section provides overviews of U.S. $CO_2$ emissions from imported and domestic production as well as a clear review of carbon intensities of both emissions with respect to four industrial sectors. Sector six presents the multi-period decomposition results and discussions at both economy-wide and industrial sector levels. The last section concludes the main research findings and provides policy strategies that are recommended to reduce emissions from U.S. import demand and to improve carbon intensities of the U.S. economy.

## 2.2 Index Decomposition Analysis: Present Studies

Decomposition analysis is an analytical tool for exploring factors behind changes in energy consumption and greenhouse gas emissions. It is a means to evaluate the effects of associated policies and measures in energy usage and energy-related greenhouse gas emissions. The structural decomposition analysis (SDA) and the index decomposition analysis (IDA) are two board categories of decomposition. SDAs have been conducted that show large variations in the estimates given by different characteristic factors (no-factor reversal). They are also limited by the availability of input-output tables for selected years (Su and Ang, 2012). Conversely, when data for intervening years are available, IDAs are conducted using a multiplicative formula which has been adopted by different applications using a variety of constraints (Ang et al., 1998). They are supported by theoretical decomposition foundations (Xu and Ang, 2014). One of the concerns in the application of IDAs is the method used to link to indexs (Ang et al., 2009). Popular methods can be divided into two groups: (1) methods linked to Laspeyres indices[4] (percentage-based change); and (2) methods linked to Divisia indices (log-based change). Many studies during the 1980s and 1990s applied the Laspeyres index including those by Jenne and Cattell (1983), Reitler et al. (1987), Howarth et al. (1991), Park (1992), and Sun (1998). Ang and Choi (1997) argued that the results of IDAs based upon the Laspeyres method faced many index number problems that can raise questions about the desirability of using a specific index number. Properties related to the desirability include factor reversal (no variation of estimates given by a number of factors), time reversal (a chaining implementation), proportionality (a perfect decomposition), and aggregation (a consistency in aggregation). The Divisia index has been recommended based on desirability of the index number properties. The logarithmic mean Divisia index (LMDI) was proposed by Boyd et al. (1998), and Ang et al., (1998). The criteria for evaluation were discussed by Ang (2004).

There are two different versions of the LMDI: (1) Montgomery-Vartia index (LMDI-I) [5], and (2) Sato-Vartia index (LMDI-II) [6]. LMDI-II has been the preferred index for the multiplicative decomposition as the proportional distribution is more reasonable when a large number of factors (more than 3 factors) are considered (Ang et al., 2009). Also, LMDI-II has an advantage for consistency in aggregation where a set of industrial sectors is considered as disjoint subsets of the entire economy. It has proved useful that price and quantity indices for industrial sectors i can be computed through several stages of index calculations with respect to the subset of their group (Ang and Liu, 2001). In recent years, LMDIs have been widely

[4] The Laspeyres index is known as the concept of percentage change using weights that rely on the value of a base year chosen (Sun, 1998).

[5] See Montgomery (1937) and Vartia (1976)

[6] See Sato (1976) and Vartia (1976) and the application for this index includes De Boer (2008).

used for studying energy usage and energy-related $CO_2$ emissions in the U.S. economy. LMDI examples include Lee and Oh (2010); EERE (2010); Vinuya et al. (2012), Choi and Ang (2012); and Feng et al. (2014). Lee and Oh (2010) utilized the arithmetic mean and the logarithmic mean Divisia index methods to analyze the driving forces of $CO_2$ emissions in APEC countries. EERE (2010) and Choi and Ang (2012) used the LMDI-II method to track the drivers of an economy-wide energy efficiency trends. Vinuya et al. (2012) used LMDI-II with the chain method to account for $CO_2$ emission changes in each state between 1990 and 2004. Feng et al. (2014) quantified the drivers behind changes in the economy-wide $CO_2$ emissions from 1997 to 2011 by using LMDI-II method. They found that the growth in emissions was mainly due to economic growth whereas decreased emissions were a result of economic slowdown. Changes in fuel mix (replacing coal with natural gas) has played a minor role in U.S. emission reductions.

Even though a number of studies have used LMDI-II to analyze energy-related $CO_2$ emissions in the U.S., no existing studies have deeply explored the contributions of different levels of aggregated $CO_2$ emissions across sectors. The LMDI-II can be used to decompose changes in aggregated $CO_2$ emissions in a sector given by two different ways: (1) the weighted sum (disaggregation) (Ang, 2004; Ang, 2005); and (2) sum for all sub-sectors (aggregation with no weight) (Ang, 2006). Ang et al. (2010) demonstrated that while the second were obtained, variations of the influencing factors exist among sector disaggregation levels. For example, differences have likely been greater for the service sector since different activities may be used to represent emission drivers. In addition, levels of disaggregation may be very important for capturing real carbon and energy efficiency changes, but cannot be judged in isolation (Lu et al., 2012; González et al. (2014). LMDI disaggregation tends to be used to compute estimates of some relevant effects when a sector whose activities are given by mixed activity measure (a mixture of physical and economic indicators) (González et al., 2014), not accounting for the case of sum for all sub-sectors.

However, the weighted sum is determined by not only aggregate value but also growth rate (Ang et al., 2010). In regard to LMDI-II method, both can be decomposed into the contributions of each component (Choi and Ang, 2012). The decomposition of the growth rate is limited to the quantity index, which is determined by an additive decomposition (Ang et al., 2010). In a recent study, Choi and Ang (2012) transformed a geometric index (a basis of LMDIs) into a Laspeyres index (a basis of national account) by exploiting a useful identity in Reinsdorf et al. (2002) and Balk (2004). They also devised single period and multi-period attribution methods to generalize additive decomposition in national accounting. This application of the LMDI to national accounts is called attribution analysis of LMDI-II. In this way, decomposition obtained by this technique can be quantified by different levels of disaggregation (e.g. industrial sectors) as well as a measure in physical activity that provides the links between real economic activity and $CO_2$ emissions (Choi and Oh, 2014; Liu et al., 2015). Ang et al. (2010) indicated that the contributions derived by physical activity provide better estimates of energy usage and energy-related emission changes than those derived by economic activity with the importance of price effects. In this respect, the contributions will be quantified by the real term (Choi and Oh, 2014).

Another concern is that existing LMDI studies have focused on the contribution of changes in $CO_2$ emissions with the production-based perspective. Recently as part of a paradigm shift towards consumption-based emissions, decomposition analyses of changes in production emissions may be a less reasonable guide to a low-carbon economy because imported goods and services have a high proportion of carbon occurring along global supply chains (Peters et al., 2011). Levinson (2009) suggested that the contributing factors be explained in terms of an index decomposition. These factors include emission coefficient, energy intensity, structural composition of imports, final import composition and final import scale. Su and Ang (2012) reviewed the literature in this area and supported the conclusions that demand scale should take into account energy-related emission changes when LMDI methods are applied. Until now, existing studies in index decomposition have paid less attention to the contributions to changes in consumption-related emissions.

## 2.3 Logarithmic Mean Divisia Index (LMDI) Decomposition: Methodology and Procedure

Among the index decomposition methods, the LMDI-II has been the preferred Divisia index due to properties of index number desirability. This essay applies conventional LMDI II analysis to the contributing factors behind changes in imported emissions (EI) and domestic production emissions (PE) at both the economy-wide scale and for different sector levels. Aggregate carbon intensity (CI) can be used as a proxy for investigating a characteristic of changes in domestic production emission (Lee and Oh, 2010). This section first presents the LMDI II decomposition behind changes in the economy-wide imported emissions, and then presents the LMDI II decomposition of the aggregate carbon intensity in relation to the importance of the economy-wide domestic production emissions. Drawing on Choi and Ang (2012), the conventional LMDI II decomposition of different n sectors underlying the changes in imported emissions and carbon intensity is presented in the last subsection. Table 2.1 summarizes important notations used in this essay.

### 2.3.1 The Aggregate Imported Emissions ($EI$)

Based on Levinson (2009), the aggregate imported emissions of the U.S. economy in year t ($EI^t$) can be expressed as:

$$EI^t = \sum_s EI_s^{\,t} = \sum_s \frac{EI_s^{\,t}}{F_s^t} \frac{F_s^t}{M_s^{\,t}} \frac{M_s^{\,t}}{M^t} \frac{M^t}{ym_s^{\,t}} ym_s^{\,t} \tag{2.1}$$

where $EI_S^t$ represents the emissions from imports of sector s in year t, $F_S^t$represents the primary energy use for imports of sector s in year t, $M_S^t$ represents the value of sector s' s imports in year t, $M^t$ represents the total value of imports in year t, and $ym_S^t$ represents the value of sector s' s final import in year t.

Methods used by Levinson (2009) are applied with the choice of LMDIs (Ang et al., 2009). The imported emission change from year t-1 to year t ($D_{mtot} = \frac{EI^t}{EI^{t-1}}$) can be decomposed as:

$$D_{mtot} = D_{mc} D_{me} D_{mstr} D_{mgy} D_{my} \tag{2.2}$$

In the above equation, the imported emission change can de decomposed into the following five factors: $D_{mc}$ is the emission coefficient effect for imports which refers to the change in imported emissions induced by the variation of emission coefficient of imports ($\frac{EI_i}{F_i}$); $D_{me}$ is the energy intensity effect for imports which refers to the change in imported emissions induced by the change in energy intensity of imports ($\frac{F_i}{M_i}$); $D_{mstr}$ is the structure effect for imports which refers to the change in imported emissions induced by the shift in sectoral structure ($\frac{M_i}{M}$); $D_{mgy}$ is the final import composition effect which refers to the change in imported emissions induced by the shift in sector final import ($\frac{M}{ym_i}$); and $D_{my}$ is the final import effect which refers to the change in imported emissions induced by the change in final import ($ym_i$). According to Ang (2005), the total effect on the left-hand side equals the product of all effects on the right-hand side. Effects will be expressed in indices such as greater than 1 (increases in the emissions), equal to 1 (no change), and less than 1 (decreases in the emissions).

### 2.3.2 The Aggregate Carbon Intensity ($CI$)

The challenges of the U.S. to curtail production emissions by 26-28% below 2005 levels in 2025 are how to maintain industrial activity while achieving improvements in carbon and energy efficiencies (EPA, 2015b). In this respect, efficiency improvements may become an even more important support for the expansion of emission reductions. As carbon intensity is taken as the reciprocal of carbon efficiency, it is frequently used to represent energy and environmental performances of industrial sectors (Choi and Oh, 2014). Based on a reduced form of Kaya identity, the aggregate carbon intensity proves to be useful in the decomposition of domestic production emissions (Lee and Oh, 2010). The aggregate carbon intensity of the U.S. economy in year t ($CI^t$) can be written as:

$$CI^t = \sum_s \frac{PE_s^t}{F_s^t} \frac{F_s^t}{V_s^t} \frac{V_s^t}{V^t} \tag{2.3}$$

where $PE_S^t$ represents the domestic production emissions of sector s in year t; $F_S^t$ represents the primary energy use for domestic production of sector s in year t; $V_S^t$ represents the added value of sector s in year t; and $V^t$ represents the total added value of the economy in year t. It should be noted that the added value takes the place of the output value in order to quantify a measure of physical activity that can link between real economic activity and sector $CO_2$ performances regardless the significance of price effects (Choi and Ang, 2012; Choi and Oh, 2014).

Through the LMDI theoretical foundation, the aggregate carbon intensity change from year t-1 to year t ($D_{tot} = \frac{CI^t}{CI^{t-1}}$) can be decomposed as:

$$D_{tot} = D_c D_e D_{str} \tag{2.4}$$

The above equation expresses the following three factors: $D_c$ is the emission coefficient effect which refers to the change in aggregate carbon intensity induced by the variation of emission coefficient

($\frac{PE_i}{F_i}$); $D_e$ is the energy intensity effect which refers to the change in aggregate carbon intensity induced by the change in energy intensity ($\frac{F_i}{V_i}$); and $D_{str}$ is the structure effect which refers to the change in aggregate carbon intensity induced by the shift of domestic sectoral structure.

Assume that there are S sectors, the terms on the right hand side of Equations (2.2) and (2.4) from year t-1 to year t can be computed by using LMDI II weights (Ang et al., 2010) as follows:

(1) The Imported Emissions

$$D_{mc}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{EI,s} \ln \frac{mc_s^{\ t}}{mc_s^{\ t-1}}\right) \tag{2.5}$$

$$D_{me}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{EI,s} \ln \frac{me_s^{\ t}}{me_s^{\ t-1}}\right) \tag{2.6}$$

$$D_{mstr}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{EI,s} \ln \frac{mstr_s^{\ t}}{mstr_s^{\ t-1}}\right) \tag{2.7}$$

$$D_{mgy}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{EI,s} \ln \frac{mgy_s^{\ t}}{mgy_s^{\ t-1}}\right) \tag{2.8}$$

$$D_{my}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{EI,i} \ln \frac{my_s^{\ t}}{my_s^{\ t-1}}\right) \tag{2.9}$$

(2) The Carbon Intensity

$$D_{c}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{\mathrm{CI,s}} \ln \frac{c_s^{\ t}}{c_s^{\ t-1}}\right) \tag{2.10}$$

$$D_{e}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{\mathrm{CI,s}} \ln \frac{e_s^{\ t}}{e_s^{\ t-1}}\right) \tag{2.11}$$

$$D_{str}^{\mathrm{t-1,t}} = \exp\left(\sum_{s\varepsilon S} w_{\mathrm{CI,s}} \ln \frac{str_s^{\ t}}{str_s^{\ t-1}}\right) \tag{2.12}$$

where $w_{EI,s}$ and $w_{CI,s}$ denote the Sato-Vartia weights (LMDI-II) that are defined by the logarithmic mean such that $L(a, b) = \frac{(b-a)}{(lnb-lna)}$ (Ang et al., 2009). In this way, $w_{EI,s}$ and $w_{CI,s}$ can be written as follows:

$$w_{\mathrm{EI,s}} = \frac{L(EI_s^{\ t-1} / EI^{t-1}, EI_s^{\ t} / EI^{t})}{\sum_{s\varepsilon S} L(EI_s^{\ t-1} / EI^{t-1}, EI_s^{\ t} / EI^{t})} \tag{2.13}$$

$$w_{\mathrm{CI,s}} = \frac{L(PE_s^{\ t-1} / PE^{t-1}, PE_s^{\ t} / PE^{t})}{\sum_{s\varepsilon S} L(PE_s^{\ t-1} / PE^{t-1}, PE_s^{\ t} / PE^{t})} \tag{2.14}$$

*Table 2.1: Some Notations and Definitions Used in This Essay*

| Notations | Description |
|---|---|
| **Imported Emissions** | |
| $\boldsymbol{EI^t}$ | Economy-wide imported emissions in year t |
| $\boldsymbol{EI_s^t}$ | Emissions from Imports of sector s in year t |
| $\boldsymbol{F_s^t}$ | Primary Energy use of sector s in year t |
| $\boldsymbol{M_s^t}$ | Value of sector s's imports in year t |
| $\boldsymbol{M^t}$ | Total value of imports in year t |
| $\boldsymbol{ym_s^t}$ | Value of sector s's final imports in year t |
| $\boldsymbol{D_{mc}^{t-1,t}}$ | Emission coefficient effect for imports in period [t-1,t] |
| $\boldsymbol{D_{me}^{t-1,t}}$ | Emission intensity effect for imports in period [t-1,t] |
| $\boldsymbol{D_{mstr}^{t-1,t}}$ | Structure effect for imports in period [t-1,t] |
| $\boldsymbol{D_{mgy}^{t-1,t}}$ | Final import composition effect in period [t-1,t] |
| $\boldsymbol{D_{my}^{t-1,t}}$ | Final import effect in period [t-1,t] |
| $\boldsymbol{D_{z,s}^{t-1,t}}$ | Contribution of sector s to the change of influencing factors z behind imported emission changes in period [t-1,t] |
| $\boldsymbol{d_{z,i}^{t-1,t}}$ | Contribution of industry i to the change of influencing factors $z$ behind imported emission changes in period [t-1,t] |
| $\boldsymbol{z_i^{t-1}}$ | Influencing factors of industry i in year t-1<br>where $z$ denotes emission coefficient of imports ($mc$), energy intensity of imports ($me$), structure of imports ($mstr$), final import composition ($mgy$), final import ($my$) |
| $\boldsymbol{z_i^t}$ | Influencing factors of industry i in year t |
| **Carbon Intensity** | |
| $\boldsymbol{CI^t}$ | Aggregate carbon intensity in  year t |
| $\boldsymbol{PE_s^t}$ | Domestic production emissions of sector s in year t |
| $\boldsymbol{V_s^t}$ | Added value of sector s in year t |
| $\boldsymbol{V^t}$ | Total added value in year t |
| $\boldsymbol{D_c^{t-1,t}}$ | Emission coefficient effect in period [t-1,t] |
| $\boldsymbol{D_e^{t-1,t}}$ | Energy intensity effect in period [t-1,t] |
| $\boldsymbol{D_{str}^{t-1,t}}$ | Structure effect in period [t-1,t] |
| $\boldsymbol{D_{q,s}^{t-1,t}}$ | Contribution of sector s to the change of constituent factors q behind carbon intensity changes in period [t-1,t] |
| $\boldsymbol{d_{q,i}^{t-1,t}}$ | Contribution of industry i to the change of constituent factors q behind carbon intensity changes in period [t-1,t] |
| $\boldsymbol{q_i^{t-1}}$ | Constituent factors of industry i in year t-1<br>where $q$ = emission coefficient ($c$), energy intensity ($e$), and structure ($str$) |
| $\boldsymbol{q_i^t}$ | Constituent factors of industry i in year t |

## 2.3.3 The Attribution of LMDI II

In regard to LMDI, decomposition of sector levels to changes in imported and domestic production emissions can be quantified by two different ways: the weight sum and sum for all sub-sectors. Variations over the sum for all sub-sectors tend to be far larger than those over the weighted sum of sector disaggregation since energy use and $CO_2$ emissions are dependent on different activity indicators (i.e. economic and physical activities) (Ang et al., 2010). Levels of sector disaggregation are important for contributions to the change of each factors, but cannot be judged in isolation (Lu et al., 2012). The sum of weights to be unity is required, which has an advantage of the Sato-Vartia index (LMDI II). Choi and Ang (2012) recently introduced a new technique that can be used to quantify the attribution of the contributing factors (e.g. the emission coefficient, the energy intensity, etc.) to the specific attributes (e.g. industrial sectors). Using this technique and assuming that i industries can be grouped into s specific sectors, LMDI II of the influencing factors for the sector attribution associated with the changes in imported emissions and carbon intensity can be expressed as follows:

(1) Imported Emissions

$$D_{z,s}{}^{t-1,t}-1=\sum_{i\varepsilon s} d_{z,i}{}^{t-1,t}=\sum_{i\varepsilon s}\frac{\dfrac{w_{EI,i}}{L(z_i{}^{t-1}D_z{}^{t-1,t},z_i{}^{t})}z_i{}^{t-1}}{\sum_{i\varepsilon s}\dfrac{w_{EI,i}}{L(z_i{}^{t-1}D_z{}^{t-1,t},z_i{}^{t})}z_i{}^{t-1}}\left(\frac{z_i{}^{t}}{z_i{}^{t-1}}-1\right) \qquad (2.15)$$

where $D_{z,s}^{t-1,t}$ represents the contribution of sector s to the change of influencing factors (z) behind imported emission changes from year t-1 to t. $d_{z,i}^{t-1,t}$ represents the contribution of industries i to the change of influencing factors $(z)$ behind imported emission changes from year t-1 to t. $z$ denotes $mc$, $me$, $mstr$, $mgy$, and $my$ respectively. Following these expressions, the product of $D_{z,s}^{t-1,t}$ for each sector is equal to $D_{z}^{t-1,t}$ for an entire economy when the sum of $w_{EI,s}$ is unity (Choi and Ang, 2012). The Sato-Vartia weight for the sector attribution behind changes in imported emissions $(w_{EI,i})$ is $\frac{L(EI_i^{t-1}/EI_s^{t-1},EI_i^{t}/EI_s^{t})}{\sum_{i\varepsilon s}L(EI_i^{t-1}/EI_s^{t-1},EI_i^{t}/EI_s^{t})}$.

(2) Carbon Intensity

$$D_{q,s}{}^{t-1,t}-1=\sum_{i\varepsilon s} d_{q,i}{}^{t-1,t}=\sum_{i\varepsilon s}\frac{\dfrac{w_{PE,i}}{L(q_i{}^{t-1}D_q{}^{t-1,t},q_i{}^{t})}q_i{}^{t-1}}{\sum_{i\varepsilon s}\dfrac{w_{PE,i}}{L(q_i{}^{t-1}D_q{}^{t-1,t},q_i{}^{t})}q_i{}^{t-1}}\left(\frac{q_i{}^{t}}{q_i{}^{t-1}}-1\right) \qquad (2.16)$$

where $D_{q,s}^{t-1,t}$ represents the contribution of sector s to the change of constituent factors (q) behind carbon intensity changes from year t-1 to t. $d_{q,i}^{t-1,t}$ represents the contribution of industry i to the change of constituent factors $(q)$ behind carbon intensity changes from year t-1 to t. $q$ denotes $c$, $e$, and $str$

respectively. The Sato-Vartia weight for the sector attribution behind changes in domestic production emissions ($w_{PE,i}$) is $\frac{L(PE_i^{t-1}/PE_s^{t-1}, PE_i^t/PE_s^t)}{\sum_{i\varepsilon s} L(PE_i^{t-1}/PE_s^{t-1}, PE_i^t/PE_s^t)}$.

The multi-period sector attribution to each influencing factor reflects the dynamic behavior of changes in imported and domestic production emissions over time (Ang et al., 2010). Since the industrial sector can be affected by a series of emission mitigation policies and energy efficiency measures in different phases, the analysis of multi-period sector attribution has been useful for policy recommendations (Ang et al., 2010). According to Choi and Oh (2014), the multi-period change of an influencing factor can be derived from the single-period one as follows:

(1) Imported Emissions

$$D_z^{0,T} - 1 = \sum_{s\varepsilon S}\left(D_{z,s}^{0,T} - 1\right) = \sum_{s\varepsilon S}\sum_{i\varepsilon s}\sum_{t\varepsilon T} D_{z,s}^{0,t-1}\, \mathrm{d}_{z,i}^{t-t,t} \qquad (2.17)$$

;$z = mc$, $me$, $mstr$, $mgy$, and $my$

(2) Carbon Intensity

$$D_q^{0,T} - 1 = \sum_{s\varepsilon S}\left(D_{q,s}^{0,T} - 1\right) = \sum_{s\varepsilon S}\sum_{i\varepsilon s}\sum_{t\varepsilon T} D_{q,s}^{0,t-1} d_{q,i}^{t-1,t} \qquad (2.18)$$

;$q = c$, $e$, and $str$

where $D_z^{0,T} - 1$ and $D_q^{0,T} - 1$ refer to the multi-period change of an influencing factor from year 0 to year T. $D_{z,s}^{0,T}$ and $D_{q,s}^{0,T}$ refer to the contribution of sector s to the multi-period change of the influencing factor from year 0 to year T.

## 2.4 Data

The primary data required for this essay were collected from the Eora input-output database (worldmari.com). The Eora's country tables can be derived through national and international input-output tables and the various extensions to environmental accounts (Lenzen et al., 2012). The strength of this economy table is that the interactions between trading partners can also be viewed (Lenzen et al., 2013). The full set of Eora table for the U.S. contains 142 industries. However, due to the available data of energy use and $CO_2$ emissions, the industries are consistently reported in only 60 industries. Further, 60 industries are grouped into four specific industrial sectors rather than pulled up into a single aggregation. Four specific sectors consist of the utility, primary, secondary, and tertiary sectors. A breakdown of industries by sector is presented in Table 2.2. In addition, the study period spans 1990 to 2012 which covers the most recent data set.

*Table 2.2: A Breakdown of Industries by Sector*

| Sector ($s$) | Industry ($i$) |
|---|---|
| **The Utility Sector** | (1) Production, collection, and distribution of electricity industries; (2) Manufacture gas industry; and (3) Steam and hot water supply industries |
| **The Primary Sector** | (1) Agriculture and farm industries; (2) Forestry, fishing, and related activity industries; (3) Oil and gas extraction industry; (4) Mining industry; (5) Support mining activity industry; and (6) Construction |
| **The Secondary Sector** | (1) Food, beverages, and tobacco industries; (2) Textile and textile product industries; (3) Apparel and leather industries; (4) Paper industry; (5) Printing and related support activity industries; (6) Petroleum and coal industries; (7) Chemical industry; (8) Pharmaceutical industry; (9) Plastic and rubber industries; (10) Wood industry; (11) Nonmetallic and non-mineral industries; (12) Primary metals industry; (13) Fabricated metal industry; (14) Machinery industry; (15) Computer and electronic industries; (16) Electrical equipment industry; (17) Radio, television, and communication industries; (18) Medical and optical instrument industries; (19) Motor vehicle and trailer industries; (20) Building and repairing industries of ships and boats; (21) Aircraft and spacecraft industries; (22) Railroad and transport equipment industries; and (23) Other manufacturing industries |
| **The Tertiary Sector** | (1) Wholesale trade; (2) Hotel and restaurants; (3) Land transport; (4) Water transport; (5) Air transport; (6) Pipeline transport; (7) Support and auxiliary transport; (8) Post and telecommunications; (9) Finance and insurance; (10) Real estate; (11) Legal services; (12) Renting of machinery and equipment; (13) Computer and related activities; (14) Research and development; (15) Management of companies and enterprises; (16) Administrative and support services; (17) Waste management and remediation services; (18) Other business services; (19) Education; (20) Ambulatory health care service; (21) Hospitals; (22) Nursing and residential care services; (23) Social assistance; (24) Performing arts, spectator sports, museums, and related activities; (25) Amusements and recreation industries; (26) Accommodation; (27) Food services and drinking places; and (28) Other services, excluding government |

The monetary value data were collected from national input-output and international input-output tables. Both tables are present in one main valuation sheet with four extensions. The main sheet is basic prices of transaction while the other extended sheets represent trade margins, transport margins, taxes, and subsidies. It is important to note that the 1990-1999 national input-output tables are purchaser prices. The added values by industry and the total added value of the U.S. over this time period were recomputed by four extensive sheets[7]. The import values by industry and total values of U.S. imports were taken from a main sheet of national input-output tables. It is important to note that monetary import values are nominal prices. According to Lenzen et al. (2012), the price effects could be managed by applying a constant format of 2005 which is already contained in this database.

The Eora database provides a consistent and harmonized environmental account, covering energy use tables and pollutant emission tables. The energy use by industry were from the Eora energy tables. Thirteen types of fuels were considered, including hard coal, lignite, coke, crude oil, gasoline, kerosene, diesel oil, jet-fuel, light fuel oil, heavy fuel oil, naphtha, natural gas, and other petroleum. Only two types of non-fossil fuel were considered in electricity generation such as hydro and nuclear. $CO_2$ emissions focus in this essay are the energy-related $CO_2$ emissions, excluding the emissions from the other sources such as landfill waste. The domestic production emissions by industry were taken from U.S. $CO_2$ emissions table while the imported emissions by industry were from a table of $CO_2$ emissions embodied in U.S. imports. However, it should be noted that the Eora database provides the emissions data with no full separable $CO_2$ estimated by energy type. For this reason, an energy analysis breakdown has not been a desired objective of this essay. Table 2.3 summarizes data specific sources for decomposition analyses.

*Table 2.3: Data Sources for Two-Stage LMDI Decomposition*

| DATA | SOURCE | PERIOD | EXPLANATIONS |
|---|---|---|---|
| **Added value by industry and total added value** | The extended sheets of national input-output tables | 1990-2012 | Millions of dollars |
| **Import value by industry and total import value** | National input-output tables | 1990-2012 | Millions of dollars |
| **Final import by industry** | International input-output tables | 1990-2012 | Millions of dollars |
| **Energy use by industry** | Energy tables | 1990-2012 | Terajoule (TJ) |
| **Domestic production emissions by industry** | U.S. $CO_2$ emission tables | 1990-2012 | Kiloton (kt) |
| **Imported emissions by industry** | $CO_2$ emissions embodied in U.S. imports | 1990-2012 | Kiloton (kt) |

[7] Purchaser prices equal to the sum of basic prices, taxes on products, trade and transport margins, and non-deducible added value taxes. Then, they are subtracted by subsidies on products. To get basic prices, there is a need to convert from the above approach.

## 2.5 $CO_2$ Emissions and Carbon Intensity Trends for U.S. Economy

This section provides an overview of U.S. imported and domestic production emissions from 1990 to 2012. It first presents the performance of an entire economy and then introduces the performance of specific sectors. Carbon intensity taken as the reciprocal of carbon efficiency is frequently used to represent the emission performance of industrial sectors (Choi and Oh, 2014). Further, this section presents the percentage changes of real carbon intensities associated with the industrial sector performance and the performance of industrial sectors that produce imports to the U.S. over the period 1991 to 2012. Industrial sectors specifically refer to the utility, primary, secondary, and tertiary sectors.

### 2.5.1 Imported Emissions

Emissions attributable to U.S. imports gradually increased by 31% between 1990 and 1997. They continued to grow from 649,142[8] kt (Gg) of $CO_2$ in 1998 to 1,001,118 kt in 2002, representing a cumulative increase of 72% since 1990. Between 2003 and 2007, aggregate imported emissions showed an increasingly rapid growth compared to the previous period, reflecting an annual growth rate of 13% compared to the previous period of 6.4%. The period between 2007 and 2012 saw a steady growth even though 2009 brought a slight decline in the overall imported emissions, representing an annual rate of change of 11.7% and accounting for 2,257,248 kt in 2012. The reasons for the increase during the period 1998 to 2012 include the influence of North American Free Trade Agreement (NAFTA) in 1998, the new opportunity for trade with China in 2002, and the temporary reduction due to global economic slowdown in 2008. Given this, the analysis highlights four periods: (1) 1990-1997; (2) 1998-2002; (3) 2003-2007; and (4) 2008-2012.

Figure 2.1 shows imported emission trends in response to the performances of four industrial sectors during 1990-2012. The secondary sector represents the largest source of imported emissions, contributing about 44% of overall emissions in 2012. Emissions from the primary sector contributed 26% of total imported emissions whereas those from the tertiary sector contributed 18%. Emissions from the utility sector represented about 12% of the aggregate imported emissions in 2012.

[8] According to Figure 2.1, aggregate emissions can be calculated by the sum of emissions across four economic sectors.

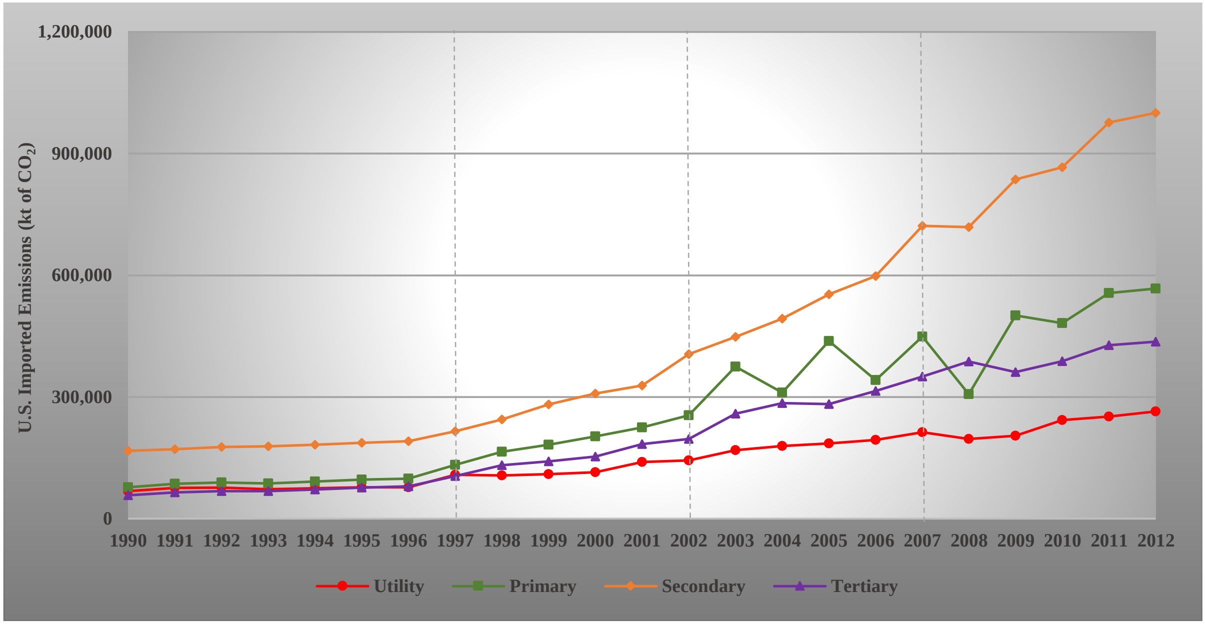


*Figure 2.1: U.S. Imported Emission Trends for Four Industrial Sectors, 1990-2012*

During the first period, emissions across all sectors gradually increased with the average annual growth rate of 2.4%. Beginning in 1998, emissions from the secondary and primary sectors showed large increases compared to those in period one. Emissions from the secondary sector increased by 66% between 1998 and 2002 whereas emissions from the primary sector grew by 55%, reflecting an annual growth rate of 8% and almost 6% respectively. These could be partially explained by the influence of NAFTA starting in 1998. Agriculture imports to the U.S. from Canada and Mexico started to climb with changes of 78% and 82% between 1998 and 2002 (FAS, 2008). Manufacturing imports (e.g. vehicles, machinery, and plastic) and mining imports (crude and natural gas) from Canada also grew quickly from 12.5% of the total U.S.-Canada imports in 1998 to 37% in 2002 (USTR, 2010). During the same period, emissions from the tertiary and utility sectors went the same pace but relatively small.

Between the 2003 to 2007 period, emissions from the secondary sector grew very fast as new growth relied heavily on carbon-intensive industries. Shares of these industries increased significantly (Figure 2.7 in Appendix 2-A) in conjunction with the open opportunity for trade with China. Carbon intensive industries refer to industries that produce relatively more emissions in comparison with other industries. Examples of carbon intensive industries include chemicals, fabricated metals, and plastics plus rubber. The emissions associated with the secondary sector showed a rapid increase from 405,413 kt in 2003 to 722,231 kt in 2007, reflecting an almost 230% increase since 1997. Consistent increases were also observed in emissions of the utility sector. This sector's emissions rose by 48% between 2003 and 2007, which was almost three times the amount of its emissions in 1990. Emissions from the primary sector grew by 76% during the same period (from 255,168 kt in 2003 to 448,782 kt in 2007), but experienced slight fluctuations with upward surges. As shown in Figure 2.6 in Appendix 2-A, these fluctuations could be partially explained by import volumes of oil-natural gas and other mining from Canada and Mexico as a result of volatilities of the Henry Hub spot price during 2003-2007 (EIA, 2010). In regard to the tertiary sector, its emissions went to the same pace as the secondary sector and increased about 65% from 2003 by 2007. Contributions of this sector include expanded emissions of water transport service, air transport service, computer and related activities, renting of machinery and equipment as well as post telecommunications, which were observed on Figure 2.8 in Appendix 2-A.

During the last period, overall emissions across four industrial sectors have continued to grow even through 2009 brought about slight declines in emissions due to the global economic recession. Emissions from the secondary sector increased steadily to 1,000,568 kt in 2012. The largest contribution from this sector remains the outsourcing of carbon-intensive industries (e.g. chemicals, fabricated metals, plastic and rubber, plus motor vehicles and trailer parts). A share of these industries in the total value imports increased from 25% in 2007 to 37% in 2012 (Han and Soroka, 2013), which was six times their import share in 1997. Conversely, emissions associated with the primary sector showed a big difference. The previous period saw great fluctuations in emissions, but this period between 2007 and 2012 had a slight upward trend. The reasons for the difference include an increased import share of agriculture from 17% of total import in 2003 to 32% in 2010[9] (Han and Soroka, 2013) as well as the Henry Hub price volatility declined due to innovation of hydraulic fracturing technology (EIA, 2013). Emissions of the tertiary sector have become increasingly important. Its share in imported emissions increased from 11% in 2002 to 18% in 2012. The contributions have remained almost the same over the previous period, including health services.

### 2.5.2 Production Emissions

In contrast to the structure of imported emissions, aggregate emissions attributable to domestic production substantially increased during the first two periods, grew steadily during the third period, and then declined during the last period. They reached a minimum of 5,356,966[10] kt in 2012, 9% lower than 2007 levels and almost 7% lower than 2005 levels. This recent decline may pave a way for a transition to low-carbon economy. However, further declines will be required to achieve 26-28% reductions below 2005 levels in reference to U.S. INDC. A clear view of U.S. production emissions regarding sector performances may contribute a higher change of reductions in the upcoming future.

[9] At the same time, import shares of oil and gas declined from 36% in 2003 to 29% in 2010 (EIA, 2012).

[10] According to Figure 2.2, aggregate emissions can be calculated by sum of emissions across four economic sectors.

Figure 2.2 shows production emission trends in response to four sector performances during 1990 -2012. Emissions associated with the utility sector constituted about 41% of the aggregate emissions in 2012. Emissions from the secondary sector contributed almost 25% whereas those from the tertiary sector contributed to 21% in 2012. Emissions from the primary sector represented close to 13%.

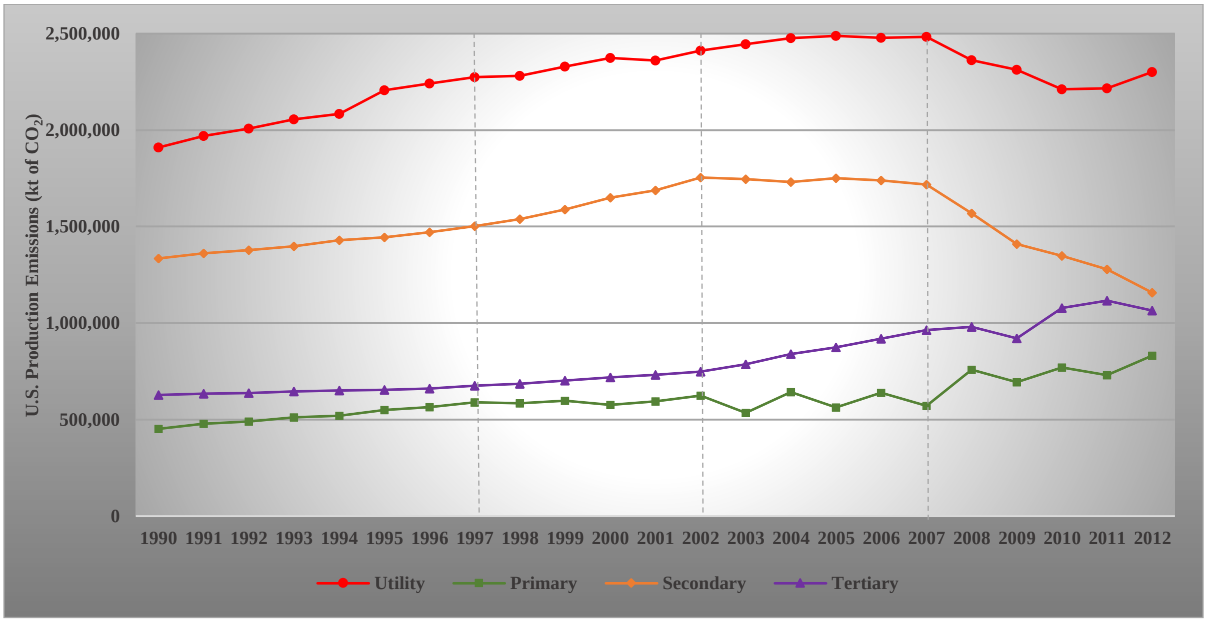


*Figure 2.2: U.S. Production Emission Trends for Four Industrial Sectors, 1990-2012*

During the first two periods, the utility and secondary sectors brought about continuous growth of the aggregate emissions. In the utility sector, emissions grew by an annual rate of 3.7% changing from 1,909,695 kt in 1990 to 2,411,756 kt in 2002. Over this same time period, the secondary sector's emissions increased from 1,334,684 kt to 1,754,700 kt, growing by an average 2.4% per year. These expansions were due to increased volumes of sector activities, accounting for an average annual growth rate of 1.46%. Emissions from the primary sector showed a slight increase during 1995-2002, which an annual rate of change of 0.74%. This is due in part to the influence of NAFTA. While U.S. agriculture exports to Canada and Mexico grew modestly during this time period, agriculture imports from those partners grew at a much faster rate (USTR, 2010). In this sense, NAFTA had a smaller effect on U.S. domestic production of the primary sector compared to that on its imported emissions. Regarding the tertiary sector, emissions gradually increased, reflecting an annual growth rate of 0.89%.

Beginning in the third period, both the utility and secondary sectors experienced small increases in emissions. The emissions associated with the utility sector increased by roughly 3% in 2007 greater than 2003 levels whereas the emissions associated with the secondary sector remained relatively constant in the early years of this period before declining by about 3.4% in 2007. However, these trends showed no sign of stopping production emissions increases at the aggregate level. In turn, the aggregate emissions were offset by a rapid increased volume of the tertiary sector. The emissions associated with the tertiary sector increased by 29% above 2002 levels, which was 53% greater than 1990 levels. This substantial increase was due in large part to increases in energy used by transport services in accordance with a change in emissions share within this sector. The primary sectors displayed relatively small year-to-year volatility of associated emissions. The variation was due to changes in added values of oil-gas extraction and mining, in replace of added values of agriculture over the previous period according to a change in their emissions (Figure 2.10 in Appendix 2-A).

During the fourth period, downward trends in emissions associated with both the utility and secondary sectors were observed. Emissions associated with the utility sector declined by 12% in 2012 below 2007 levels and 11% below 2005 levels. This decline was due in large part to economic downturn and a shift of fuel use from coal to natural gas. Nevertheless, utility sector's emissions were not in constant decline during the last period, increased from 2,212,084 kt in 2010 to 2,301,089 kt in 2012. A return to coal of the utility sector was due to a temporary decline in coal prices between 2010 and 2012 (EIA, 2014). The emissions associated with the secondary sector declined by 18% below 2007 levels and 22% below 2005 levels. This decline was due to a change in the added value shares of various carbon intensive industries. Example includes fabricated metal, non-metallic and non-mineral, motor vehicles and trailer parts, plus computer and electronic equipment. In turn, the upward trends in emissions associated with the primary and tertiary sectors were found.

This analysis points out that supposing no more changes in emissions outside the utility sector, emissions within the utility will have to decline a further 19% in 2030 below 2012 levels in order to reach a goal of the 2015 CPP and anticipated to meet an initial goal of U.S. INDC (EPA, 2015a). Longer-term fuel switching may be more inevitable. It is important that a shift of fuel use can technically affect a decrease in production emissions through two main effects: (1) the emission coefficient effect; and (2) the energy intensity effect (EIA, 2012). However, there are no clear indications of which effect indeed determines the decrease in emissions despite a decline in natural gas price volatilities. This aspect will be discussed further in section 2.6.

### 2.5.3 Carbon Intensities for Imported and Domestic Emissions

As growing aggregate emissions generally correlate with economic growth, aggregate emissions are commonly used in reference to national plans for addressing voluntary reduction targets (Aldy et al., 2010). However, carbon intensity, which reports the amount of emissions weighted by industrial sector activity, may become more useful implications if emission changes in response to different sizes of industrial sectors are considered. Figure 2.3 shows percentage changes in carbon intensities with respect to imported and domestic production of $CO_2$ by sector. Overall, percentage changes in emission intensities indicate the same pattern of changes occurring in the aggregate emissions as shown in Figures 2.1-2.2, but display a unique set of explanations.

The annual carbon intensity of U.S. imported emissions (M-Emissions in Figure 2.3) displayed an increasing trend over the study period and showed greater increases than that of its production emissions (P-Emissions in Figure 2.3) since 2005. This intensity increased in a range of 1.4-3.8% between 1991 and 2012 period. Regarding percentage change, the percentage changes started considerably increasing in 2005, representing 30% of increase from 2005 to 2012. Contributions include rapid increases in carbon intensities of secondary's and tertiary's imported emissions after 2005, and consistent increases in carbon intensity of utility's imported emissions beginning in 2003. Example include that the secondary's carbon intensity grew in a range of 1.2-2.9%. Tertiary's carbon intensity rose in a range of 0.4-2.1% while utility's carbon intensity increased in a range of 0.3-1.8%. Among them, the carbon intensity of primary imported emissions was relatively constant over the first two periods. It showed large year-to-year fluctuations during period three before increasing slightly over the last period. However, despite a dominant contribution of carbon intensity of imported emissions, the discrepancy in percentage changes between specific secondary sector's and economy-wide carbon intensities has been widening over the last two periods. This analysis finds that reducing carbon intensity with respect to U.S. import demand may not further be limited by the secondary sector's carbon intensity decline alone. Carbon intensities of others should take into consideration as they has increased.

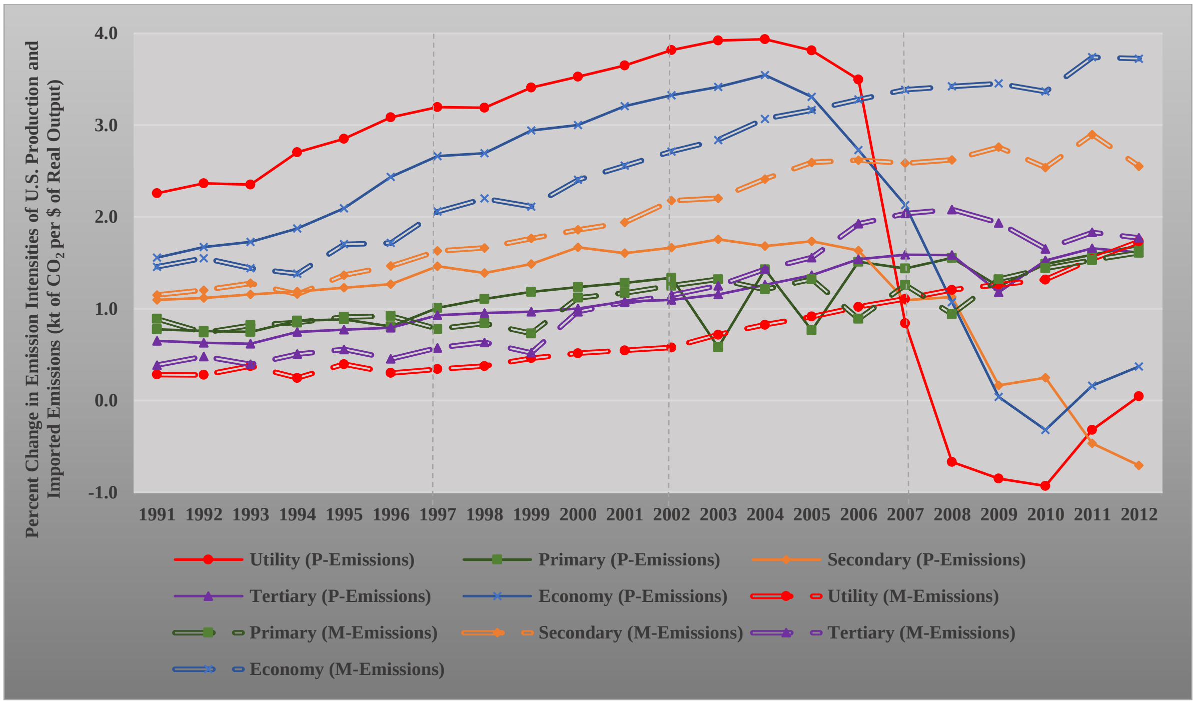


*Figure 2.3: Percentage Changes in Carbon Intensities of U.S. Imported and Production Emissions Attributable to Four Industrial Sectors, 1991-2012*

While the domestic economy continued to grow during first three periods, the annual carbon intensity of U.S. production emissions (P-Emissions) increased steadily in a range of 1.7-3.5% until 2004, which represented an average of 2.36% per year. Contributions include substantial changes in carbon intensities of the utility and secondary sector's production emissions, and gradual increases in carbon intensities of primary and tertiary production emissions. At the end of period three, carbon intensity for the entire economy declined by more than 3% in 2009 to a negative growth rate. These changes were due to considerable declines in utility and secondary carbon intensities, about an average of 4% and 2% decreases respectively. However, examination shows that percentage increases in utility carbon intensity were almost 34% on average greater than those in carbon intensity for the entire economy during periods one to three. Even though utility carbon intensity showed percentage decreases over the last period, differences were uneven, accounting for an average of 46% of the discrepancy. This analysis indicates that given the carbon intensities of other sectors, the carbon intensity for the entire economy will need much more aggressive efforts by the utility sector to further reduce emissions. A big challenge for reducing the utility sector's carbon intensity may be posed by the goal to reduce emissions by 30% below 2005 levels in reference to the 2015 CPP. This analysis also highlights that the difference of carbon intensities with respect to imported and domestic production emissions seems to become another significant challenge for the U.S. to address to meet its consumption responsibility for $CO_2$.

## 2.6 Multi-Period Decomposition Results and Discussions

This section provides a two-stage decomposition of the results of dynamic changes in U.S. imported emissions and production emissions during 1991-2012. The driving forces of imported emissions can be divided into five consumption factors drawing on Levinson (2009): emission coefficient ($mc$); energy intensity ($me$); structure of imports ($mstr$); final import composition ($mgy$); and final import scale ($my$). Following this setup and using the input-output database, these analyses can implicitly investigate an adjustment of import pattern regarding dynamic $CO_2$ emission changes. In turn, the driving forces of production emissions can be examined through three production factors of carbon intensity: the emission coefficient ($c$); energy intensity ($e$); and structure ($str$). It is important to note that multi-period decomposition results of economy-wide and four industrial sectors are presented in figures and tables as well as explained in the text. Those of industrial sub-sectors which are always included in a part of attribution calculation are partially explained in the text only. The index decomposition of both economy-wide and four industrial sectors are fully presented on Tables 2.6-2.7 in Appendix 2-B.

### 2.6.1 Decomposition Analyses of Imported Emissions

#### Multi-Period Decomposition

Emissions stimulated due to U.S. import demand grew consistently from 399,036 kt in 1991 to 2,257,248 kt in 2012, reflecting an average annual growth rate of 20%. Figure 2.4 shows the results of imported emission decomposition by means of conventional LMDI-II (see Equations (2.5)-(2.9)). These results display effects of contributing factors on changes in imported emissions compared to the year 1990. The effects can be expressed by an increase in emissions (greater than 1), no change (equal to 1), and a decrease in emissions (less than 1). Changes in the final import scale was the most important contributor, driving the emissions up by 152% between 1990 and 2012 (an index of 1.152 in 2012). Changes in the emission coefficient effect showed no big influences on imported emissions until the U.S. started to benefit from NAFTA beginning in 1998. The emission coefficient change led to an imported emission increase of 14% during period two (where an index increased from 1.033 in 1998 to1.047 in 2002). It continued to have major influence on imported emissions and displayed a rapid increase of 27% over the third period and a 43% over the last period. In 2012, the emission coefficient effect led to a 92% increase of imported emissions relative to 1990 levels. The main reason for these increases was the growth of carbon-intensive imports from China which relied heavily on coal as the fossil fuel used for Chinese industries (Peters et al., 2011). The short-term decline in international coal prices in 2006 was another reason for the increased emission coefficient effects (EIA, 2012).

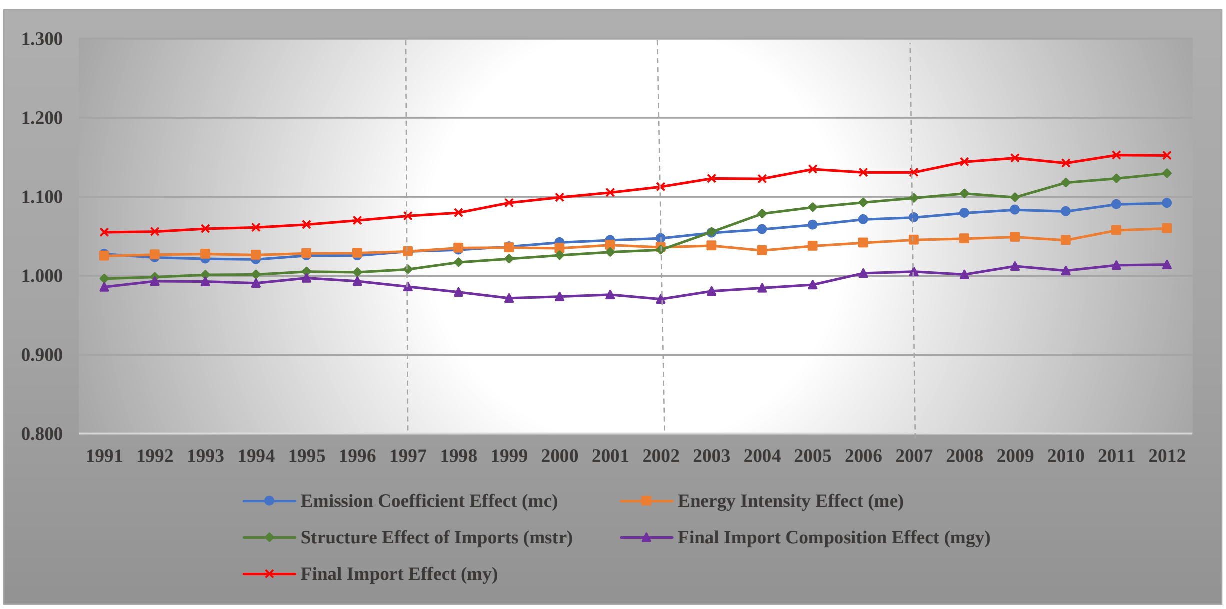


*Figure 2.4: Index Decomposition of U.S. Imported Emissions, 1991-2012*

Changes in the energy intensity exerted modest upward influences on imported emissions over the study period. As shown in Figure 2.4, the energy intensity effect remained relatively constant between 1991 and 1996 as the rapid growth of import values overwhelmed the increase in energy use for imports. Import values increased by an average annual growth rate of 14% while energy use for imports grew annually by only 8%. The energy intensity effect gave rise to a 7% increases of imported emissions between 1997 and 2002 (from an index of 1.031 in 1997 to 1.036 in 2002) before increasing to 32% over the last two period (from an index of 1.038 in 2003 to 1.060 in 2012). In 2012, the energy intensity effect led to a 60% increase of imported emissions relative to 1990 levels. These changes in the energy intensity were due to the short-term volatility of international coal prices in 2006, 2008, and 2011 (EIA, 2012) as well as due in part to the growth of energy use by carbon-intensive industries. In this way, this analysis indicates that increases in the emission coefficient can contribute to rises in energy intensity. However, this analysis finds that the short-term decrease in the energy intensity during the 2001-2004 period led to no sign of decreases in the emission coefficient.

A shift in the structure of imports acted as an additional increase in imported emissions during period one. This structural effect turned out to be more important for imported emissions over the remaining periods. The structural shift brought about a mild emission increase of 12% during the first period (from an index of 0.996 in 1991 to 1.008 in 1997) and moved imported emissions up by 13% during the second period before urging up imported emissions by 43% during the third period. In 2012, the shift in import structure led to a 130% increase of imported emissions compared with 1990 levels. In this respect, the structure effect surpassed the effect of the emission coefficient since 2004 and became the second largest contributor to imported emissions.

With an index number under 1, the final import composition was the only factor that drove down imported emissions. However, the upward influences of other factors completely overwhelmed the final import effect. Changes in the final import composition led to a small decrease in imported emissions of 6% during the first period and a greater decrease of 12% during the third period. This effect started to turn a positive influence in the end of last period. Evidence includes that the final import composition drove imported emissions up by 6% between 2006 and 2012 (from an index of 1.003 in 2006 to 1.014 in 2012). Particularly, the final import composition effect in 2012 led to a 14% increase of imported emissions relative to 1990 levels.

## Multi-Period Attribution

Using Equation (2.15), the multi-period attribution shows the percentage changes of each of the five influencing factors within the four industrial sectors (Table 2.4). It is important to note that regarding this attribution technique of LMDI-II, the product of the influencing factors is equal to the influencing factors of the entire economy such that $D_z^{t-1,t} = \prod_{s\varepsilon 4} D_{z,s}^{t-1,t}$ where z is mc, me, mstr, mgy, and my.

As shown in Table 2.4, the multi-period attribution of influencing factors through four industrial sectors provides an enhanced understanding of what sectors were the main contributors to changes in imported emissions. The attribution results of final import reveal that the final import scale effect for all sectors was the largest contributor to an imported emission increase during periods one to four, but different sectors dominated over different periods. The primary sector dominated the increase in final import scale over period one with the cumulative increase of 28%[11] while the secondary sector dominated periods two and three, which were 27% and 33% of increase respectively. The tertiary sector came to govern the increase over the last period (36%). The final import scale of the utility sector affected imported emissions with relative constant impact over all four periods. This reflects that the final import scale effect of the tertiary sector influences imported emissions larger than that of the primary and secondary sectors over the last period.

The multi-period attribution of emission coefficient factor indicates that the effect of emission coefficient on imported emissions was similar to the effect of energy intensity, but the magnitude of contributions was much larger by period. During the first two periods, the emission coefficient effects of four sectors did not show significant increases in imported emissions. At the third period, the emission coefficient effects of the primary and secondary sectors moved up very fast due in part to the degradation of fuel quality as a result of the increasing share of carbon-intensive imports from China. The emission coefficient effect of the utility consistently increased to support import activities of primary and secondary sectors. The primary sector showed cumulative increase of 6% while the secondary sector showed cumulative increase of about 9%. The examples of industries include agriculture and farm (14% of increases between period three and period four), oil-gas extraction (15%), mining (14%), chemicals (14%), paper (12%), non-metallic and non-mineral (14%), plastic and rubber (13%), plus primary metals (15%). The primary and secondary sector's emission coefficient effects drove imported emissions up over the last period along with the strong increase in the tertiary sector's emission coefficient effect. The reason for the tertiary sector's increase could be partially explained by the rapid growth in final demand scale. However,

[11] It could be calculated by the sum of percentage changes of the final import scale associated with the primary sector. From 1991 to 2002, primary's final import scale changed by 28% such that 3.90+3.92+3.93+…+4.01.

despite the slowdown of the final import scale effects, the primary and secondary sector's emission coefficient effects showed no sign of improvements over the last period.

The multi-period attribution of the energy intensity factor reveals that energy intensity varied significantly by period in accordance with performances of four sectors. The magnitude of its effect was smaller than that of the emission coefficient. The primary sector showed the largest increase in the energy intensity effect over the first period with the cumulative increases of 7%. The secondary sector took the place of energy intensity effect during periods two and three. Its energy intensity effect increased by 4% in period two and 7% in period three. At the same time, the primary's energy intensity showed a decrease of 2% over period two and an increase of 1% over period three compared to that of period one. The utility sector contributed additional increases in the energy intensity effects over the periods studied even though the utility sector's energy intensity effect showed slight variations in year-to-year over period two. During the last period, the tertiary sector showed a rapid increase in the energy intensity effect, with a cumulative increase of 5%. However, despite a slowdown in the final import scale effect, the energy intensity effects of the primary and secondary sectors constantly increased and a dominated the changes in energy intensity over the last period. Specifically, the reasons for the increases over the last period were due to the increases in energy intensities of oil-gas extraction (4%), mining (5%), chemicals (5%), non-metallic and non-mineral (6%), and primary metals (5%). In this respect, comparing emission coefficient and energy intensity effects attributable to four industrial sectors, this analysis emphasizes that the increases in primary's and secondary's emission coefficient factors contributed to the rise in their energy intensities. But, the slowdown in primary's energy intensities over period two did not show improvements in emission coefficient within this sector.

The multi-period attribution for the structure of imports indicate no large effects on imported emissions except for the primary and secondary sectors. The structure of the utility sector contributed imported emission decreases over each of the first three periods, but turned to positive effects on emission increases over the last period. This change was attributed to increases in electricity use to support emission-intensive imports. The structure of the tertiary sector acted as additional increases in imported emissions over all periods. This could be explained by little changes in real import values between emission-intensive and non-emission-intensive industries within the tertiary sector. Examples of major emission-intensive industries include air transport service and water transport service. The main of non-emission-intensive industries include computer and related activities, renting of machinery and equipment, post telecommunications, plus health services.

The structure of the secondary sector increased imported emissions substantially from a cumulative increase of 12% in period three to 25% in period four. The reason for the rapid shift was due to the significant changes in real import values of chemicals, non-metallic and non-mineral, plastic and rubber, plus primary metals industries. The structure of the primary sector also largely affected imported emissions from 13% in period three to 18% in period four. However, this sector showed large year-to-year fluctuations over the last period. The variation of import values between agriculture-farm and mining was the key reason. Due to the fact that agriculture has less emission intensity than mining (EIA, 2012), an increasing share of agriculture's import values brought about decreases in the structure effect within this sector. In turn, a decreasing share of mining import values brought about the opposite effect.

When the effects of the final import composition are combined with the final import scale effects, these results provide a better understanding of how adjusting import consumption patterns influences U.S. imported emissions. This combination reveals that while the effects of secondary import structure were increasing, there had an upward influence of the final import composition (2% increase in 2003 to 16% increase in 2012) along with a mid-influence of the final import scale (from 8% increase in 2003 to almost 10% increase in 2012). When the final import composition effect grew faster than the increase in final import scale effect, the secondary sector affecting imported emissions was not only due to increases in real import values of emission-intensive industries but also a shift of import consumption towards intermediate import. A similar situation was observed in the primary sector.

However, this observation was not made within the tertiary sector. It was due to a shift of the tertiary sector's import structure towards final import of non-emission-intensive industries. This could be evidenced by a downward influence of its final import composition along with an upward influence of the final import scale over period four. In this respect, this analysis demonstrates that increasing volumes of final import demand greater than total import value growth ( $gy$ less than 1) lead to a downward influence of the final import composition and a modest upward influence of the import structure. In turn, the opposite situation ( $mgy$ greater than 1) leads to a mild influence on the final import composition, but a sharp influence on import structure. However, this analysis contributes a more robust understanding that a shift of import structure towards intermediate import affects imported emissions more than a shift towards final import according to the rapid increases in imported emissions over the last two periods.

*Table 2.4: Decomposition of U.S. Imported Emissions Attributable to Four Industrial Sectors, 1991-2012*

| Factor | Sector | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Emission Coefficient ($mc$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | 0.26 | 0.26 | 0.35 | 0.23 | 0.37 | 0.28 | 0.32 | 0.35 | 0.43 | 0.48 | 0.51 | 0.54 | 0.67 | 0.77 | 0.85 | 0.95 | 1.04 | 1.13 | 1.18 | 1.23 | 1.44 | 1.62 |
| | Primary | 0.98 | 0.41 | 0.18 | 0.10 | 0.15 | 0.17 | 0.21 | 0.18 | 0.30 | 0.38 | 0.28 | 0.38 | 0.48 | 0.58 | 0.79 | 0.89 | 0.99 | 1.29 | 1.63 | 1.96 | 1.99 | 2.22 |
| | Secondary | 1.02 | 1.06 | 1.14 | 1.12 | 1.34 | 1.55 | 1.83 | 1.97 | 2.08 | 2.16 | 2.37 | 2.41 | 2.73 | 2.74 | 2.83 | 2.86 | 2.76 | 2.86 | 3.01 | 2.77 | 3.16 | 2.78 |
| | Tertiary | 0.45 | 0.56 | 0.46 | 0.59 | 0.65 | 0.53 | 0.67 | 0.74 | 0.84 | 1.13 | 1.25 | 1.34 | 1.46 | 1.67 | 1.82 | 2.25 | 2.38 | 2.43 | 2.26 | 1.93 | 2.14 | 2.07 |
| **Energy Intensity ($me$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | 0.67 | 0.71 | 0.70 | 0.70 | 0.76 | 0.77 | 0.82 | 0.91 | 0.70 | 0.75 | 0.91 | 0.73 | 0.70 | 0.40 | 0.71 | 0.62 | 0.87 | 0.76 | 0.80 | 0.94 | 1.13 | 1.28 |
| | Primary | 1.07 | 1.07 | 1.09 | 1.03 | 0.96 | 0.92 | 0.99 | 1.19 | 1.28 | 1.22 | 1.37 | 1.31 | 1.19 | 1.20 | 1.22 | 1.27 | 1.22 | 1.26 | 1.13 | 1.24 | 1.20 | 1.28 |
| | Secondary | 0.51 | 0.56 | 0.60 | 0.63 | 0.66 | 0.71 | 0.76 | 0.86 | 0.95 | 1.12 | 1.14 | 1.19 | 1.21 | 1.29 | 1.34 | 1.39 | 1.42 | 1.53 | 1.36 | 1.56 | 1.67 | 1.72 |
| | Tertiary | 0.22 | 0.28 | 0.34 | 0.23 | 0.42 | 0.44 | 0.48 | 0.50 | 0.57 | 0.36 | 0.40 | 0.33 | 0.64 | 0.54 | 0.44 | 0.63 | 0.73 | 0.85 | 0.96 | 0.87 | 1.03 | 1.28 |
| **Structure of Imports ($mstr$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | -2.91 | -2.82 | -2.69 | -2.59 | -2.61 | -2.74 | -2.53 | -2.56 | -2.45 | -2.20 | -1.98 | -1.67 | -1.48 | -1.23 | -1.03 | -0.73 | -0.64 | -0.43 | 1.33 | 1.36 | 1.58 | 1.31 |
| | Primary | 1.78 | 1.78 | 1.73 | 1.67 | 2.12 | 2.07 | 2.06 | 2.42 | 2.53 | 2.61 | 2.58 | 2.04 | 2.32 | 3.02 | 3.11 | 2.66 | 3.64 | 2.83 | 4.35 | 3.27 | 4.26 | 4.71 |
| | Secondary | 0.67 | 0.74 | 0.96 | 1.04 | 1.02 | 1.10 | 1.18 | 1.48 | 1.63 | 2.00 | 2.12 | 2.83 | 3.50 | 3.51 | 3.70 | 4.31 | 4.66 | 4.40 | 4.64 | 5.17 | 5.29 | 5.71 |
| | Tertiary | 0.15 | 0.20 | 0.15 | 0.10 | 0.05 | 0.08 | 0.15 | 0.40 | 0.50 | 0.20 | 0.30 | 0.10 | 1.15 | 0.95 | 0.85 | 0.95 | 0.85 | 0.74 | 0.95 | 1.35 | 1.25 | 1.19 |
| **Final Import Composition ($mgy$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | -0.86 | -0.48 | -0.38 | -0.38 | -0.29 | -0.38 | -0.38 | -0.57 | -0.67 | -0.67 | -0.67 | -0.57 | -0.57 | -0.57 | -0.67 | -0.57 | -0.57 | -0.57 | -0.38 | -0.38 | -0.57 | -0.71 |
| | Primary | -1.70 | -1.35 | -1.26 | -1.26 | -0.90 | -0.99 | -1.48 | -1.42 | -1.54 | -1.61 | -1.28 | -1.14 | -1.28 | -1.01 | -0.27 | 0.34 | 1.49 | 0.69 | 1.15 | 0.35 | 1.38 | 1.52 |
| | Secondary | -0.63 | -0.27 | -0.18 | -0.18 | 0.18 | 0.09 | -0.01 | 0.08 | -0.20 | 0.15 | 0.59 | -0.22 | 0.70 | 0.80 | 0.85 | 1.16 | 1.50 | 1.69 | 1.86 | 2.05 | 2.24 | 2.42 |
| | Tertiary | 1.80 | 1.40 | 1.10 | 0.90 | 0.70 | 0.60 | 0.50 | -0.16 | -0.48 | -0.56 | -1.08 | -1.08 | -0.83 | -0.76 | -1.37 | -1.23 | -1.32 | -1.37 | -1.37 | -1.41 | -1.55 | -1.60 |
| **Final Import Scale ($my$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | 3.56 | 3.57 | 3.59 | 3.60 | 3.62 | 3.63 | 3.66 | 3.68 | 3.71 | 3.77 | 3.76 | 3.76 | 3.85 | 3.89 | 4.19 | 4.60 | 4.87 | 4.59 | 4.58 | 4.59 | 5.26 | 5.33 |
| | Primary | 3.90 | 3.92 | 3.93 | 3.95 | 3.97 | 3.98 | 4.01 | 4.23 | 4.19 | 4.43 | 4.67 | 4.98 | 5.22 | 4.75 | 5.08 | 4.34 | 6.45 | 5.06 | 6.78 | 5.14 | 5.59 | 6.07 |
| | Secondary | 3.07 | 3.17 | 3.33 | 3.49 | 3.62 | 3.90 | 4.21 | 4.37 | 4.81 | 5.10 | 5.38 | 5.69 | 6.24 | 6.60 | 6.07 | 6.44 | 6.79 | 6.48 | 6.48 | 6.46 | 6.80 | 7.24 |
| | Tertiary | 3.42 | 3.36 | 3.51 | 3.48 | 3.67 | 3.88 | 4.06 | 4.03 | 4.84 | 4.90 | 4.98 | 5.05 | 5.15 | 5.19 | 5.53 | 6.03 | 6.26 | 6.83 | 6.73 | 6.66 | 7.12 | 7.27 |

## 2.6.2 Decomposition Analyses of Carbon Intensities

### Multi-Period Decomposition

The trend in aggregate carbon intensity indicates a consistent increase during the first three periods before declining substantially in period four. However, aggregate carbon intensity was not in constant year-to-year decline during period four. The dominant contributions to increased carbon intensity were the emission coefficient and energy intensity. Most of the declines in carbon intensity came from structural change. Figure 2.5 summarizes the decomposition of U.S. carbon intensity by means of conventional LMDI-II (see Equations (2.10)-(2.12)).

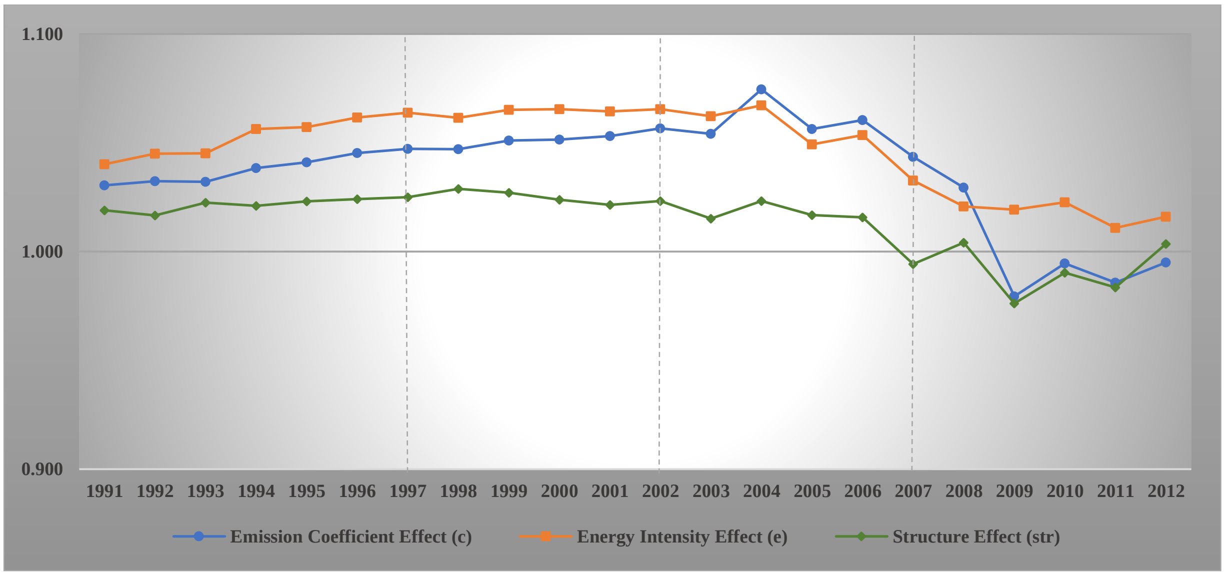


*Figure 2.5: Index Decomposition of U.S. Aggregate Carbon Intensities, 1991-2012*

During period one and two, energy intensity was the most influential factor on aggregate carbon intensity. For example, increased energy intensity worsened aggregate carbon intensity by 64% above 1990 levels in 1997 and 66% in 2002. In comparison, the emission coefficient effect increased aggregate carbon intensity by 47% and 57% respectively. However, after 2004 the energy intensity effect was overwhelmed by the effect of emission coefficient. Increased emission coefficient worsened aggregate carbon intensity by 44% at period three while energy intensity contributed an increase in aggregate carbon intensity by 33% at the same period. This reflects that emission coefficient and energy intensity slightly improved over period three. It could be partially explained by short-term volatility of coal prices during 2004-2006 (EIA, 2010). However, their effects were all positive (above 1) and did not yet lead to the decreases in aggregate carbon intensity.

Beginning in 2008, the emission coefficient improved very rapidly and led to a 21% decrease below the 1990 level by 2009. Energy intensity also contributed a slight improvement and reached 19% above 1990 levels by 2009, which accounted for 48% of the decrease from 2004 (from an index of 1.067 in 2004 to 1.019 in 2009). Both the emission coefficient and energy intensity declined to improve aggregate carbon intensity. However, their effects showed no consistent year-to-year decreases. Example include fluctuation in emission coefficient indices of 0.995 in 2010, 0.986 in 2011, and 0.995 in 2012. The energy intensity effect remained positive and the magnitude of its improvement was too small to contribute significantly to the declines in aggregate carbon intensity.

When the structure effect was considered, the structural change additionally increased aggregate carbon intensity over the first three periods. However, changes in structure contributed a substantial decline in carbon intensity over the last period. For example, the structural change contributed the decline in aggregate carbon intensity by 24% in 2009 compared with 1990 levels. However, its effect has not led to year-to-year declines as a result of a small variation in the U.S. carbon-intensive industry shares.

## Multi-Period Attribution

The multi-period attribution calculated from Equation (2.16) shows the percentage changes of emission coefficient, energy intensity, and domestic structural change that impact real carbon intensities attributable to four specific sectors. Real carbon intensities refer to carbon intensities performed by different sectors in accordance with differences in their activities. Table 2.5 summarizes decomposition of carbon intensities attributable to four industrial sectors.

The multi-period attribution of the energy intensity explores that the increased energy intensities of four industrial sectors worsened their real carbon intensities during periods one and two. Energy intensity effect of the utility sector contributed its real carbon intensity by a cumulative increase of 12% over period one and 18% over period two. Increased energy intensity of the primary sector worsened its real carbon intensity by 6% over period one and 10% over period two. Energy intensity effect of the secondary sector contributed a further increasing of real carbon intensity by 5% over period one and 9% over period two. The energy intensity of the tertiary sector had small impacts of real carbon intensity over the first two periods with a cumulative increase of 3% and 5% respectively. During the last two periods, the energy intensities of the utility and secondary sectors improved substantially. Utility energy intensity effect contributed the slowdown of real carbon intensity with a cumulative increase of 10% over period three and 7% over period four. Secondary energy intensity effect contributed a decline in real carbon intensity by 8% and 5% respectively. The reason to the decreased utility energy intensity was partly due to high volatilities of coal prices during 2010-2012, reflecting the fact that coal price variations were 20% greater than those of natural gas (EIA, 2014). This is relevant because natural gas is on average 26% more energy efficient than coal (IEA, 2012). The reasons to the decreased secondary energy intensity were due in part to the amendment of energy policy and conversation programs (EPCP) launched in 2002 and the decline in energy use by carbon-intensive industries as a result of a shift in industrial structure. This program requires manufacturing industries to improve energy conversation by associating amended procedures to estimate their annual operating costs, including an operation of a device piece of machine and equipment to their maintenance costs in order to promote the highest energy conservation standards.

However, these improvements were not effective enough to reduce aggregate carbon intensity, meaning that the energy intensity factor for the entire economy remained positive. Despite improvements in real energy intensity within the utility and secondary sectors, there were no signs of year-to-year consistent improvements occurring. This analysis points out that given the use of natural gas, consistent improvements in the utility sector's energy intensity is an important challenge for the future of additional carbon intensity declines. This analysis also raises the question that improvements in energy intensities within the food and beverages, paper, non-metallic and non-mineral, fabricated metals, machinery, and transport equipment industries may enhance the consistent declines in the secondary sector's energy intensity because of the high energy intensity within these industries.

The energy intensity of the primary sector has remained relatively constant over the last two periods. This consistency has occurred even with programs such as Natural Resources Conservation Service (NRCS) environmental quality incentive program (EQIP) launched in 2002. This program provides funding for agriculture and mining companies to implement energy conservation practices (EERE, 2008). The energy intensity of the tertiary sector substantially increased over period four due to increases in energy use of inland and water transport service industries. Its effect induced real carbon intensity by a cumulative increase of 8%.

The multi-period attribution of the emission coefficient reveals that the emission coefficient effects of four sectors contributed increased real carbon intensities over periods one and two in similar to the effects of their energy intensities. The magnitude of emission coefficient effects on real carbon intensities was smaller during two periods. Example includes the emission coefficient effect of the utility sector contributed real carbon intensity by a cumulative increase of 9% over period one and 11% over period two. Emission coefficient effect of the secondary sector worsened real carbon intensity by 4% and 7% respectively. However, emission coefficient of the utility and secondary sector improved greatly at the end of period three. Their effects dominated decreases of aggregate carbon intensity during the beginning of period four. The utility sector's emission coefficient effect contributed a decrease of real carbon intensity by 5% over period four while the secondary sector's emission coefficient effect contributed to a decrease in real carbon intensity by 1%. The main reason to the decrease was due solely to fuel switching towards natural gas as a result of the innovation of hydraulic fracturing technology. This analysis points out that despite a substantial decline in the utility sector's emission coefficient, its effect was not sufficient to reduce real carbon intensity. The reason for the inconsistent decline was due in part to the high volatility of coal prices during 2010-2012 (EIA, 2014).

The emission coefficient of the primary sector showed a slight decline with small fluctuations during the last period. The fluctuation was due in part to a different energy share between agriculture and mining. Technically, the agriculture industry is highly dependent upon natural gas used for process heating whereas mining industry depends on diesel and other petroleum products used for machine drives and vehicles (Beckman et al., 2013). In this respect, reducing dependency on fossil fuel is a major challenge for the consistent declines of aggregate carbon intensity. The emission coefficient of the tertiary sector was the only factor that consistently increased real carbon intensity over the last period. It was due solely to increases in the energy share of inland and water transport service industries.

The multi-period attribution of the structure indicates that the structure effects of four sector showed small positive effects on real carbon intensities during the first three periods. In the last period, the structure of primary and secondary sectors played an important role in real carbon intensity declines. Then, these contributions dominated decreases in aggregate carbon intensity. The primary sector's structure effect reduced real carbon intensity by 1% while the secondary sector's structure effect dropped real carbon intensity by almost 8%. The reason for the decline was changes in the added values of emission-intensive industries. For example, added values of chemicals and non-metallic and non-mineral industries decreased by an average annual rate of 4% during 2008-2010 and 2% per year during 2011-2012.

When the three influencing factors were combined, this analysis points out that mild influences of energy intensity and emission coefficient on secondary carbon intensity were mostly due to the effect of a structural shift in carbon-intensive industries rather than the effect of EPCP because most of the influences occurring at the end of period three, not the beginning which was EPCP in effect. However, the variation in industrial structural changes can partly influence the smooth improvements in secondary energy intensity and the consistency of emission coefficient improvements within this sector.

In addition, this analysis finds that some industries could have partial benefits from this program. Example of industries include textile and textile product, apparel and leather, printing, plastic and rubber, wood, primary metals, computer and electronic, plus electrical equipment. However, this program did not establish a consistent improvement of their energy intensities and emission coefficients. In this sense, it is important that above industries and other industries with no improvements (food and beverages, paper, non-metallic and non-mineral, fabricated metals, machinery, and transport equipment industries) should be highlighted for enhancing the effectiveness of this program.

*Table 2.5: Decomposition of U.S. Aggregate Carbon Intensities Attributable to Four Industrial Sectors, 1991-2012*

| Factor | Sector | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Emission Coefficient ($c$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | 1.05 | 1.13 | 1.16 | 1.26 | 1.41 | 1.64 | 1.79 | 1.87 | 2.04 | 2.08 | 2.22 | 2.31 | 2.37 | 2.46 | 1.44 | 0.90 | 0.55 | -1.92 | -1.97 | -2.57 | 0.21 | 1.09 |
| | Primary | 0.46 | 0.45 | 0.45 | 0.60 | 0.54 | 0.55 | 0.69 | 0.76 | 0.81 | 0.85 | 0.88 | 1.49 | -0.26 | 1.50 | -0.22 | 1.51 | -0.45 | 1.72 | -1.75 | 1.29 | -1.81 | 1.43 |
| | Secondary | 1.15 | 1.23 | 1.14 | 1.45 | 1.58 | 1.70 | 1.54 | 1.34 | 1.47 | 1.37 | 1.33 | 0.95 | 1.29 | 1.19 | 1.24 | 1.17 | 1.10 | 1.07 | 0.16 | 0.54 | -1.35 | -0.70 |
| | Tertiary | 1.36 | 1.40 | 1.44 | 1.49 | 1.53 | 1.57 | 1.64 | 1.67 | 1.70 | 1.77 | 1.80 | 1.83 | 1.93 | 2.11 | 2.21 | 2.34 | 2.42 | 1.88 | 1.53 | 1.61 | 1.54 | 1.66 |
| **Energy Intensity ($e$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | 1.85 | 2.04 | 2.15 | 2.34 | 2.11 | 2.49 | 2.12 | 2.68 | 2.85 | 2.87 | 2.78 | 2.82 | 2.78 | 2.56 | 1.96 | 1.36 | 1.02 | 0.72 | 0.16 | 0.16 | 0.14 | 0.16 |
| | Primary | 0.90 | 0.98 | 1.15 | 1.20 | 1.32 | 1.35 | 1.34 | 1.19 | 1.22 | 1.23 | 1.24 | 1.32 | 1.02 | 1.12 | 1.01 | 1.21 | 1.00 | 1.14 | 0.99 | 0.88 | 0.79 | 1.05 |
| | Secondary | 0.15 | 0.78 | 0.67 | 1.02 | 1.10 | 1.13 | 1.14 | 1.12 | 1.16 | 1.27 | 1.21 | 1.25 | 1.28 | 1.10 | 0.76 | 0.21 | -0.01 | -1.28 | 0.67 | 1.43 | 0.86 | 1.22 |
| | Tertiary | 0.58 | 0.63 | 0.68 | 0.97 | 1.08 | 1.07 | 0.98 | 1.03 | 1.05 | 1.03 | 1.06 | 1.02 | 1.20 | 1.26 | 1.12 | 0.93 | 1.21 | 0.91 | 0.75 | 0.94 | 1.01 | 1.14 |
| **Structure Effect ($str$)** | | | | | | | | | | | | | | | | | | | | | | | |
| | Utility | 0.64 | 0.26 | 0.74 | 0.25 | 0.32 | 0.45 | 0.58 | 0.85 | 0.54 | 0.32 | 0.14 | 0.32 | 0.23 | 0.14 | 0.27 | 0.35 | 0.12 | 0.06 | 0.14 | 0.02 | 0.32 | 0.29 |
| | Primary | 0.36 | 0.43 | 0.38 | 0.43 | 0.47 | 0.36 | 0.44 | 0.52 | 0.54 | 0.49 | 0.46 | 0.55 | -0.36 | 0.47 | -0.15 | 0.24 | -0.44 | 0.36 | -0.89 | 0.36 | -0.90 | 0.33 |
| | Secondary | 0.65 | 0.71 | 0.76 | 1.08 | 1.21 | 1.20 | 1.10 | 1.16 | 1.17 | 1.15 | 1.18 | 1.14 | 1.29 | 1.35 | 1.18 | 0.87 | 0.65 | 0.74 | -1.01 | -0.88 | -1.38 | -0.53 |
| | Tertiary | 0.24 | 0.26 | 0.35 | 0.32 | 0.29 | 0.38 | 0.36 | 0.33 | 0.42 | 0.39 | 0.35 | 0.29 | 0.36 | 0.34 | 0.37 | 0.10 | 0.90 | 0.74 | 0.65 | 0.47 | 0.32 | 0.26 |

## 2.7 Conclusions

U.S. import demand grew increasingly between 1991 and 2012, and contributed 31% of worldwide imported emissions by 2012. Undoubtedly, taking emission responsibility for U.S. imports is critical to gear up for a low carbon future. However, this responsibility is likely to be larger than the U.S. commitment under INDC. To integrate U.S. imports into the responsibility of global emissions, this essay determined the effects of import demand on $CO_2$ emissions by means of analyzing the contributing factors behind dynamic changes in imported emissions from 1990 to 2012. Five consumption factors were evaluated (the emission coefficient, energy intensity, structure of imports, final import composition, and final import scale). Drawing on a theory of fragmentation trade, increasing international trade has created networks of production that have repercussions on global emissions and can affect emissions at home (Onder, 2012). Ignoring these connections may lead to a misleading picture of contributors.

This essay investigated the contributions influencing dynamic changes of U.S. production emissions based upon three production factors of carbon intensity (emission coefficient, energy intensity, and structure). The interplay of contributing factors behind dynamic changes in both emissions has become more crucial not only for having a better understanding of carbon transfer structure but also for seeking policy recommendations on how to allocate emission responsibility across economies as part of a transition to a low carbon future. In this respect, this essay first utilized a modification of LMDI decomposition (LMDI II) to perform decomposition analyses of $CO_2$ emissions stimulated due to both import demand and domestic production. It further used an attribution technique of LMDI II to investigate the contribution of four industrial sectors: the utility; primary; secondary; and tertiary sectors. The main findings of this essay are presented below.

The U.S. imported emission grew increasingly from 1990 to 2012 more than doubling during this time period. The most dominant contributor to this growth was the increase in final import scale. The attribution analyses indicate that different sectors dominated over different sub-periods. Evidence showed that the primary sector dominated the increase over period one (1991-1997) while the secondary sector dominated over periods two (1991-1997) and three (2003-2007). The tertiary sector came to drive the increase during the last period (2008-2012).

Emission coefficient and energy intensity effects showed no significant influences on imported emissions until the U.S. started to trade with China during period three. As shown in Figure 2.4, the emission coefficient effect led to a 27% increase of imported emissions over period three and a 43% increase over the last period. The energy intensity effect brought about 14% of increased imported emissions and 16% respectively. The attribution analysis reveals that the primary and secondary sectors dominated the increase over two periods. Oil-gas extraction, mining, chemicals, non-metallic and non-mineral, paper, rubber and plastics, plus primary metals were the main contributors. The emission coefficient and energy intensity of the tertiary sector also played an important role in imported emissions over the last period due to the rapid growth in import demand scale. Comparing emission coefficient and energy intensity effects attributable to four industrial sectors, this analysis emphasizes that an increase in primary and secondary emission coefficients contributed a rise in their energy intensities. This is relevant because coal for process heating is on average 26% worse energy efficient than natural gas (IEA, 2012). However, the slowdown in primary energy intensities over period two did not show much improvement in emission coefficient within this sector.

A shift in the structure of imports became more important over the last two periods. The structure effect surpassed the effect of emission coefficient to become the second largest contributor since 2004 as shown in Figure 2.4. The attribution analysis reveals that the structure effect of the secondary sector was the main contributor. It was due to the considerable change in real import values of chemicals, non-metallic and non-mineral, rubber and plastics, plus primary metals. The structure effect of the primary sector was another contributor that drove imported emissions up. However, it showed large year-to-year fluctuations over the last period. The variation of import values between agriculture-farm and mining was the key reason.

The final import composition was the only factor that drove down imported emission due to an index number less than 1 (see Figure 2.4). However, the upward influences of other factors completely overwhelmed this downward effect. When effects of the final import composition are combined with the final import scale, this can provide a better understanding of why the influence of final import scale reduced over period four as well as how the import pattern could influence the emissions. The attribution analysis reveals that the secondary sector affecting imported emissions was not only due to increase in real import values of emission-intensive industries but also a shift of import consumption towards intermediate import. This can be observed by an upward effect of the final import composition along with a mild influence of the final import scale. In the respect with the substantial growth in imported emissions over the last two periods, it is likely that the adjustment towards intermediate import contributes more influence on the imported emissions than that towards final import. A similar situation was observed in the primary sector, but not made within the tertiary sector.

While the emissions from U.S. imports were growing increasingly, the aggregate carbon intensity, which is taken to represent emission performances of the U.S. domestic production, slowed in the middle of the third period and declined visibly in the last period. As shown in Figure 2.5, the dominant contributions to decreased carbon intensity were the structure and the emission coefficient. The energy intensity improved but remained a positive influence on the increased aggregate carbon intensity. That means that the magnitude of its improvement was too small to contribute declines in the aggregate carbon intensity.

The attribution analysis revealed that the structure effects of the primary and secondary sectors played the most important role in the aggregate carbon intensity declines over period four. The energy intensities of the utility and secondary sectors declined greatly during period three, but slowly during the last period. The reason for the slow decline of the utility sector was due in part to high volatilities of coal prices during 2010-2012 while the contribution of the secondary sector was due to the variation in energy use of carbon-intensive industries. At the end of the third period, these effects was compensated by the substantial decreases in emission coefficients within the utility and secondary sectors. As the emission coefficients of the utility and secondary sectors declined substantially, these effects surpassed the effects of energy intensities to become the second largest contribution to decline the aggregate carbon intensity. The reason for the decrease in utility's emission coefficient was due to fuel switching towards natural gas whereas the contribution of the secondary sector was solely due to declines in added values of carbon-intensive industries (e.g. chemicals and non-metallic and non-mineral industries).

However, aggregate carbon intensity did not reflect consistent year-to-year declines. When the three contributing factors attributable to four industrial sectors were combined, this analysis points out that the variation in industrial structural change was the major influence the improvements in the secondary sector's energy intensity and the consistency of emission coefficient improvements within this sector. In this respect, these findings reflect that the main contribution to the decline in U.S. production emissions was not only the effect of fuel switching towards natural gas as a result of the innovation of hydraulic fracturing technology but also due in part to the importance of structural change effects of carbon-intensive industries. With respect to the cross-effects of structural changes, the decrease in U.S. production emissions could be partially explained by the increase in emissions from its imports.

Based upon the decomposition and attribution results, a number of policy strategies are discussed for establishing a transition towards a low carbon future due to improvements in the profile of U.S. import consumption and modifications of the aggregate U.S. carbon intensity. The latter is important to recommend for achieving the U.S. goal under INDC. Due to the increasing importance of the structure effect, climate policies to deal with emissions embodied in U.S. imports (in reference to carbon transfers) should grow out of the use of domestic policies (i.e. voluntary national reductions). It is relevant because a shift in the structure of imports can be regarded as the reduction of the emission burden at home. The U.S. should ensure that its cooperation covers a significant share of carbon transfers.

As the import demand has been moving towards not only intermediate imports but also carbon intensive imports, a share of emission responsibility between trading partners should be established by international trade rather than by a focus on low-carbon and energy technology transfers. Example of trade measures in carbon transfers includes border adjustments. It is important that a policy design on border adjustments should be flexible to allow both exporters and importers to take actions along the process of carbon transfers.

Despite declines in U.S. domestic production emissions due to effects of the emission coefficient and structural change, in the future, decreases in production emissions would be limited by the benefits from natural gas. Given the use of natural gas, improvements in energy intensity remain an important issue. When the effect of the Renewable Portfolio Standards (RPSs) was not remarkable, natural gas in the only substitute for the use of coal but also the growth of renewable energy (e.g. solar and wind) (Feng et al., 2015). The effectiveness of RPSs should be significantly enhanced if attention is given to the continuity of natural gas.

Some industries could have partial benefits from the EPCP program. Example of industries include textiles and textile products, apparel and leather, printing, plastics and rubber, wood, primary metals, computer and electronic, plus electrical equipment. However this program did not establish a consistent improvement of their energy intensities and emission coefficient. As the key reason for smooth improvements in the secondary sector's energy intensity and consistency in emission coefficient improvements within this sector was due to an effect of the structural shift in carbon-intensive industries. It is important that carbon-intensive industries with no improvements (food and beverage, paper, non-metallic and non-mineral, fabricated metals, machinery, and transport equipment industries) should be highlighted to establish consistent declines in energy intensity and emission coefficient within this sector as well as enhancing the effectiveness of EPCP program.

Even though the decomposition and attribution results of this essay can suggest a number of policy strategies to reduce emissions from U.S. import demand and further improve carbon intensity for the U.S. economy, it has limitations. First, an increase in the disaggregation analysis by the maximum number of sub-industrial sectors or products may provide more in-depth policy strategies for future emission reductions. In particular, emission changes are driven by and compensated for by shifts in structural composition. With the lack of more disaggregated data, this essay is limited to the analyses for 60 sub-industrial sectors. Second, since IDA generally does not take into account of an indirect effect of the contributing factors, such evidence can be implicitly observed through the relationships between import composition and final imports.

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# Appendix 2-A

## Imported Emissions

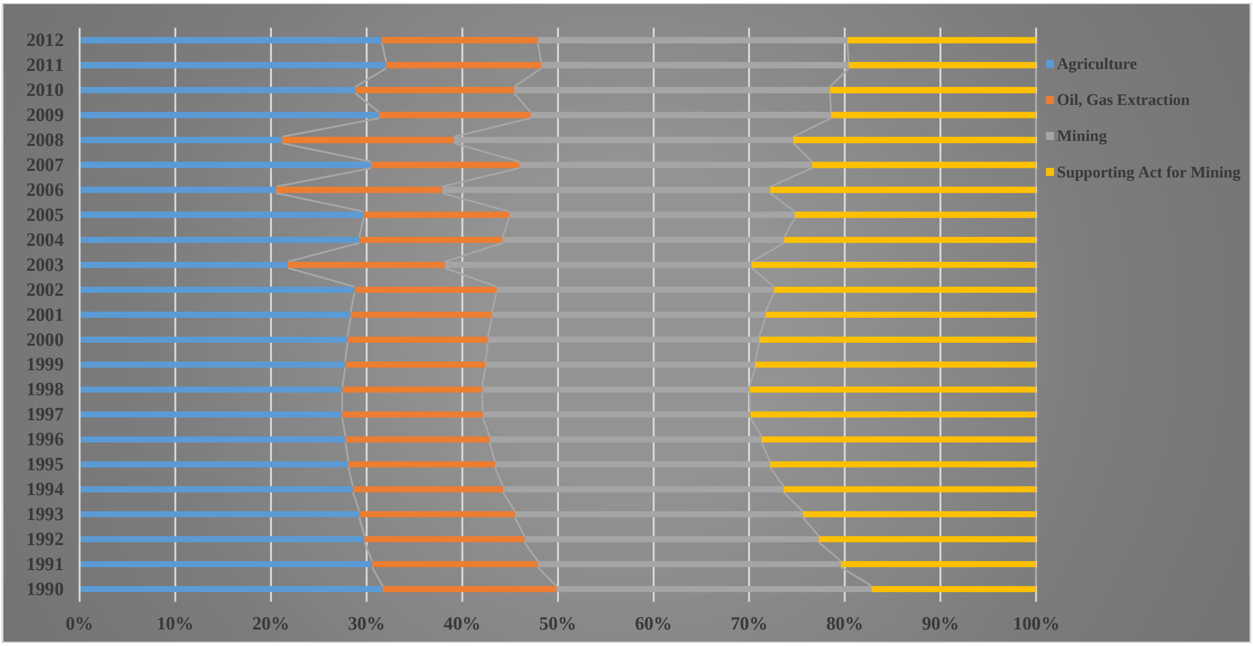


*Figure 2.6: Share of U.S. Imported Emissions by Industry within the Primary Sector, 1990-2012*

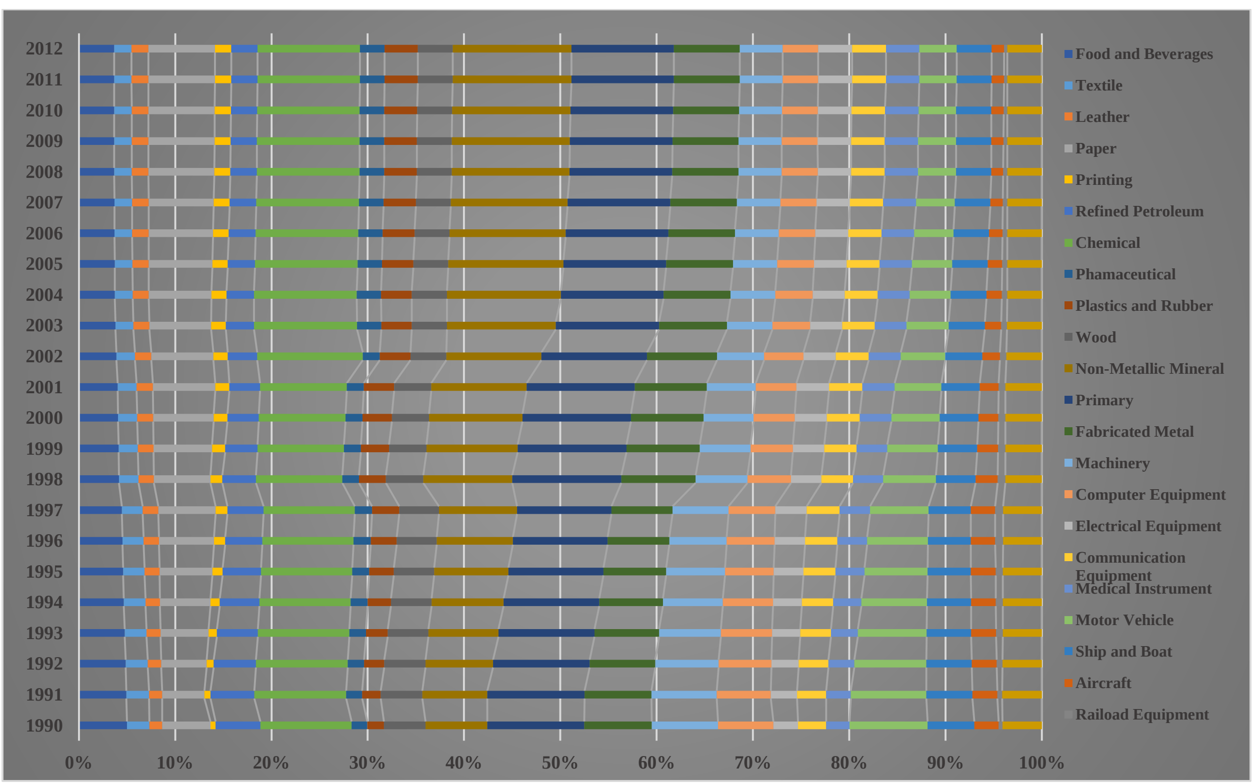


*Figure 2.7: Share of U.S. Imported Emissions by Industry within the Secondary Sector, 1990-2012*

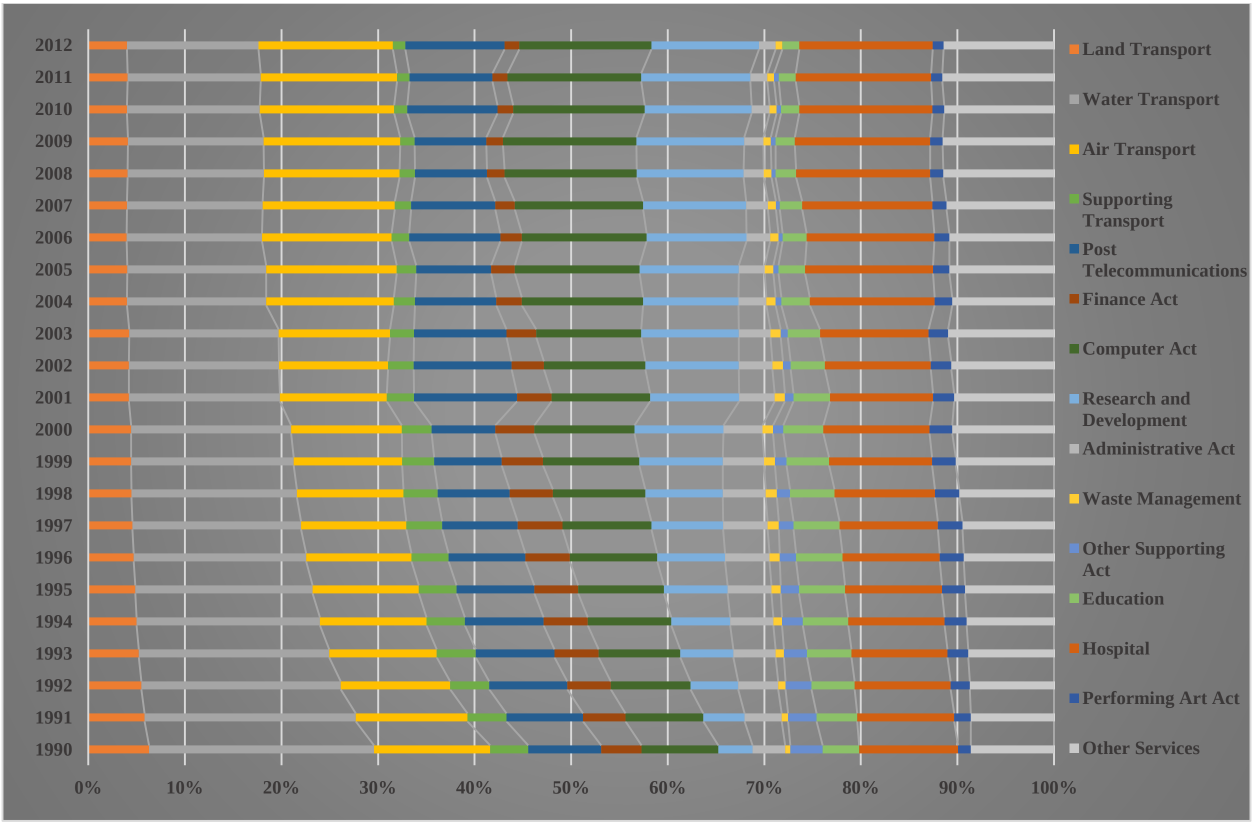


*Figure 2.8: Share of U.S. Imported Emissions by Industry within the Tertiary Sector, 19902-2012*

## Production Emissions

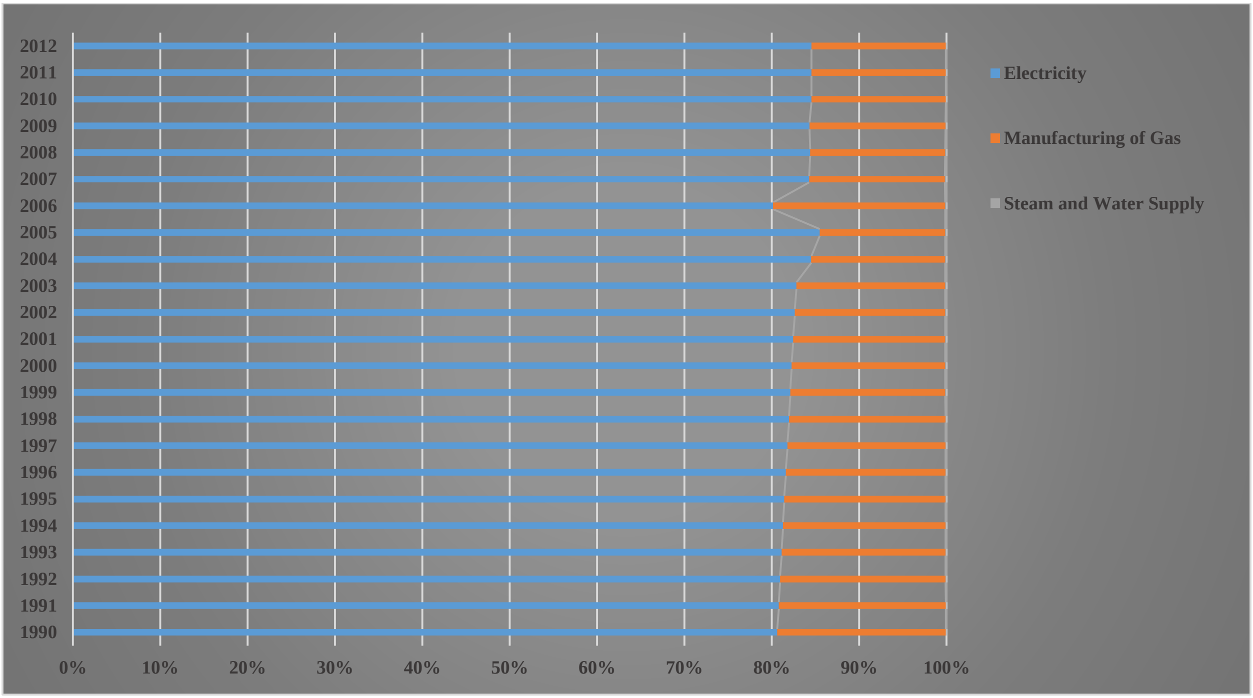


*Figure 2.9: Share of U.S. Production Emissions by Industry within the Utility Sector, 1990-2012*

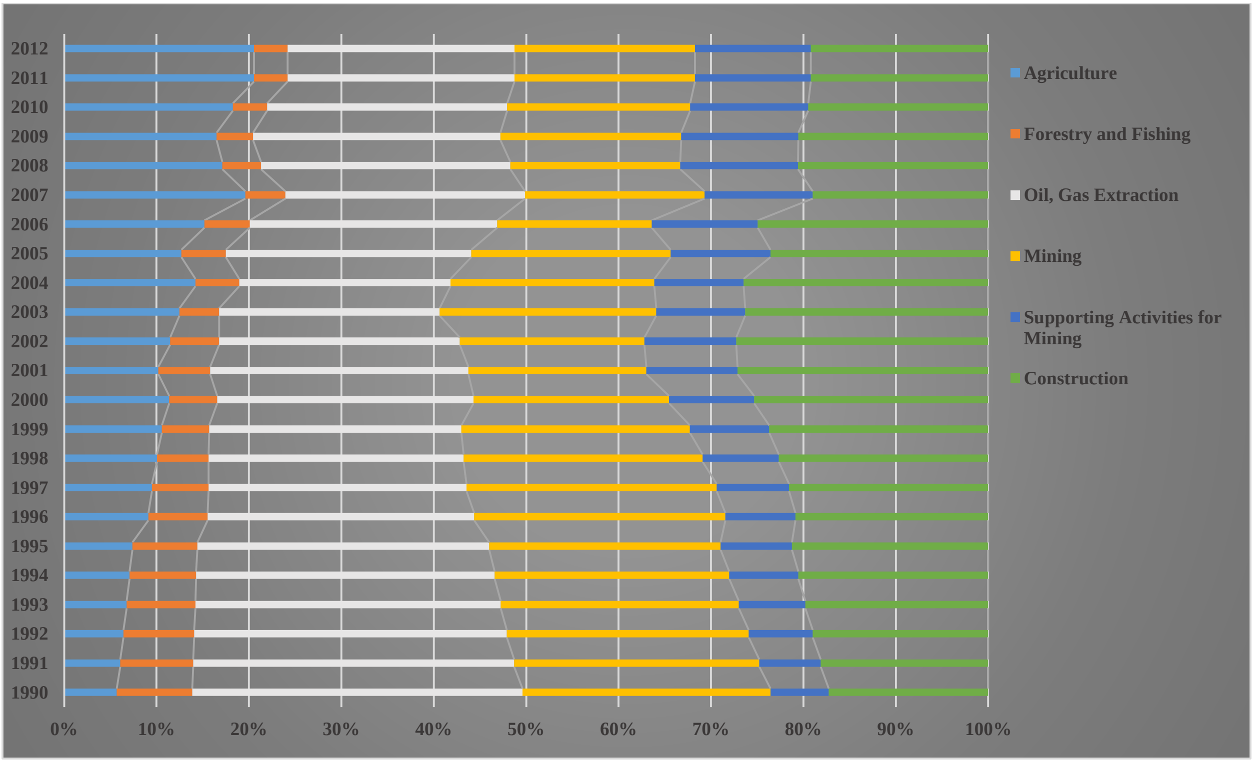


*Figure 2.10: Share of U.S. Production Emissions by Industry within the Primary Sector, 1990-2012*

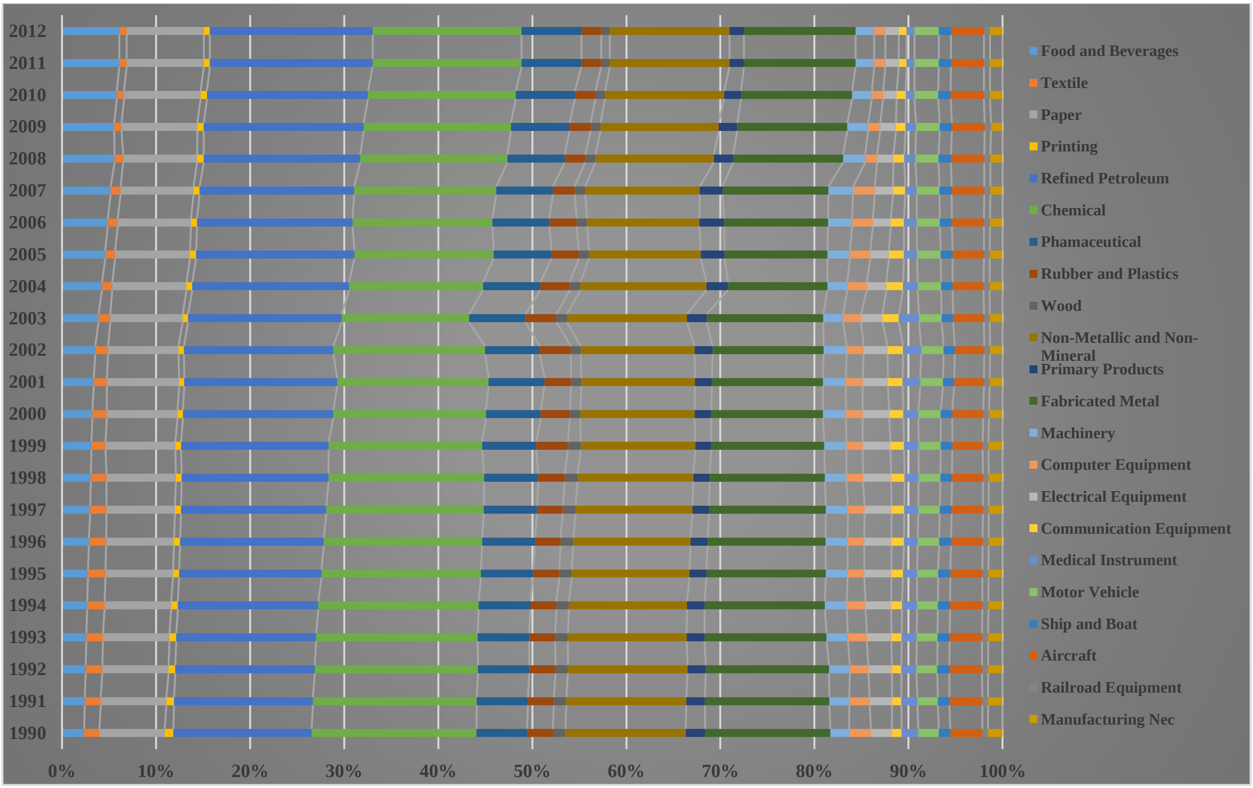


*Figure 2.11: Share of U.S. Production Emissions by Industry within the Secondary Sector, 1990-2012*

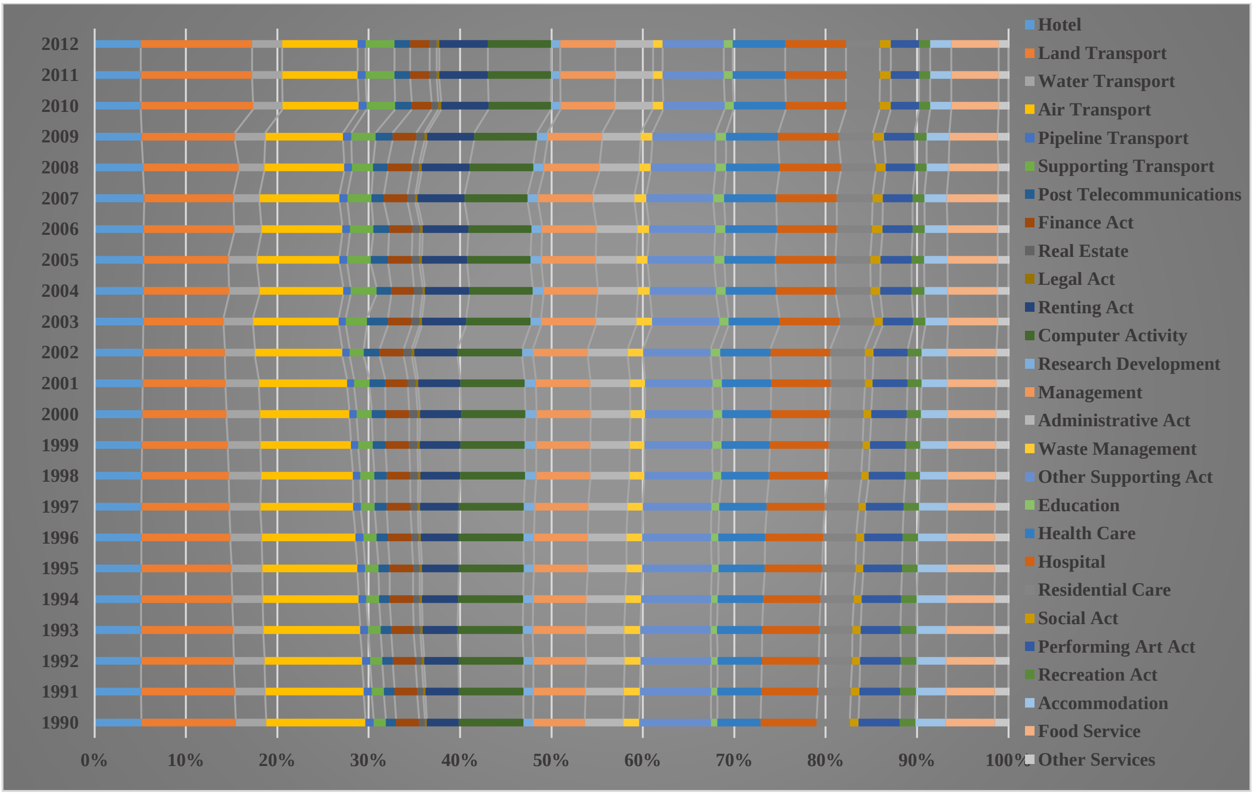


*Figure 2.12: Share of U.S. Production Emissions by Industry within the Tertiary Sector, 1990-2012*

# Appendix 2-B

*Table 2.6: Decomposition of the U.S. Imported Emissions by Industrial Sector, 1991-2012*

| Level | Factor | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Economy** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.091 | 1.099 | 1.105 | 1.103 | 1.125 | 1.126 | 1.136 | 1.149 | 1.164 | 1.183 | 1.205 | 1.210 | 1.271 | 1.302 | 1.346 | 1.383 | 1.401 | 1.429 | 1.452 | 1.452 | 1.511 | 1.527 |
| | mc | 1.027 | 1.023 | 1.021 | 1.021 | 1.025 | 1.025 | 1.031 | 1.033 | 1.037 | 1.042 | 1.045 | 1.047 | 1.054 | 1.059 | 1.064 | 1.071 | 1.073 | 1.079 | 1.083 | 1.081 | 1.090 | 1.092 |
| | me | 1.025 | 1.026 | 1.028 | 1.026 | 1.028 | 1.029 | 1.031 | 1.035 | 1.035 | 1.035 | 1.039 | 1.036 | 1.038 | 1.032 | 1.038 | 1.042 | 1.045 | 1.047 | 1.049 | 1.045 | 1.057 | 1.060 |
| | mstr | 0.996 | 0.998 | 1.001 | 1.002 | 1.005 | 1.004 | 1.008 | 1.017 | 1.022 | 1.026 | 1.030 | 1.033 | 1.055 | 1.078 | 1.086 | 1.093 | 1.098 | 1.104 | 1.099 | 1.118 | 1.123 | 1.130 |
| | mgy | 0.986 | 0.993 | 0.993 | 0.991 | 0.997 | 0.993 | 0.986 | 0.979 | 0.971 | 0.973 | 0.976 | 0.970 | 0.980 | 0.985 | 0.989 | 1.003 | 1.005 | 1.002 | 1.012 | 1.007 | 1.013 | 1.014 |
| | my | 1.055 | 1.056 | 1.059 | 1.061 | 1.065 | 1.070 | 1.076 | 1.080 | 1.092 | 1.099 | 1.105 | 1.113 | 1.123 | 1.123 | 1.135 | 1.131 | 1.131 | 1.144 | 1.149 | 1.143 | 1.152 | 1.152 |
| **Utility Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.006 | 1.012 | 1.015 | 1.015 | 1.018 | 1.015 | 1.018 | 1.017 | 1.016 | 1.020 | 1.025 | 1.027 | 1.031 | 1.032 | 1.040 | 1.049 | 1.056 | 1.055 | 1.077 | 1.079 | 1.091 | 1.090 |
| | mc | 1.003 | 1.003 | 1.004 | 1.002 | 1.004 | 1.003 | 1.003 | 1.004 | 1.004 | 1.005 | 1.005 | 1.005 | 1.007 | 1.008 | 1.009 | 1.010 | 1.010 | 1.011 | 1.012 | 1.012 | 1.014 | 1.016 |
| | me | 1.007 | 1.007 | 1.007 | 1.007 | 1.008 | 1.008 | 1.008 | 1.009 | 1.007 | 1.007 | 1.009 | 1.007 | 1.007 | 1.004 | 1.007 | 1.006 | 1.009 | 1.008 | 1.008 | 1.009 | 1.011 | 1.013 |
| | mstr | 0.971 | 0.972 | 0.973 | 0.974 | 0.974 | 0.973 | 0.975 | 0.974 | 0.975 | 0.978 | 0.980 | 0.983 | 0.985 | 0.988 | 0.990 | 0.993 | 0.994 | 0.996 | 1.013 | 1.014 | 1.016 | 1.013 |
| | mgy | 0.991 | 0.995 | 0.996 | 0.996 | 0.997 | 0.996 | 0.996 | 0.994 | 0.993 | 0.993 | 0.993 | 0.994 | 0.994 | 0.994 | 0.993 | 0.994 | 0.994 | 0.994 | 0.996 | 0.996 | 0.994 | 0.993 |
| | my | 1.036 | 1.036 | 1.036 | 1.036 | 1.036 | 1.036 | 1.037 | 1.037 | 1.037 | 1.038 | 1.038 | 1.038 | 1.038 | 1.039 | 1.042 | 1.046 | 1.049 | 1.046 | 1.046 | 1.046 | 1.053 | 1.053 |
| **Primary Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.056 | 1.053 | 1.053 | 1.051 | 1.061 | 1.061 | 1.059 | 1.067 | 1.068 | 1.071 | 1.078 | 1.077 | 1.081 | 1.087 | 1.102 | 1.098 | 1.145 | 1.116 | 1.158 | 1.125 | 1.152 | 1.167 |
| | mc | 1.010 | 1.004 | 1.002 | 1.001 | 1.002 | 1.002 | 1.002 | 1.002 | 1.003 | 1.004 | 1.003 | 1.004 | 1.005 | 1.006 | 1.008 | 1.009 | 1.010 | 1.013 | 1.016 | 1.020 | 1.020 | 1.022 |
| | me | 1.011 | 1.011 | 1.011 | 1.010 | 1.010 | 1.009 | 1.010 | 1.012 | 1.013 | 1.012 | 1.014 | 1.013 | 1.012 | 1.012 | 1.012 | 1.013 | 1.012 | 1.013 | 1.011 | 1.012 | 1.012 | 1.013 |
| | mstr | 1.018 | 1.018 | 1.017 | 1.017 | 1.021 | 1.021 | 1.021 | 1.024 | 1.025 | 1.026 | 1.026 | 1.020 | 1.023 | 1.030 | 1.031 | 1.027 | 1.036 | 1.028 | 1.044 | 1.033 | 1.043 | 1.047 |
| | mgy | 0.983 | 0.987 | 0.987 | 0.987 | 0.991 | 0.990 | 0.985 | 0.986 | 0.985 | 0.984 | 0.987 | 0.989 | 0.987 | 0.990 | 0.997 | 1.003 | 1.015 | 1.007 | 1.012 | 1.003 | 1.014 | 1.015 |
| | my | 1.039 | 1.039 | 1.039 | 1.039 | 1.040 | 1.040 | 1.040 | 1.042 | 1.042 | 1.044 | 1.047 | 1.050 | 1.052 | 1.048 | 1.051 | 1.043 | 1.065 | 1.051 | 1.068 | 1.051 | 1.056 | 1.061 |
| **Secondary Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.047 | 1.053 | 1.060 | 1.062 | 1.070 | 1.075 | 1.082 | 1.090 | 1.095 | 1.109 | 1.121 | 1.124 | 1.151 | 1.157 | 1.156 | 1.171 | 1.182 | 1.184 | 1.188 | 1.195 | 1.206 | 1.214 |
| | mc | 1.010 | 1.011 | 1.011 | 1.011 | 1.013 | 1.016 | 1.018 | 1.020 | 1.021 | 1.022 | 1.024 | 1.024 | 1.027 | 1.027 | 1.028 | 1.029 | 1.028 | 1.029 | 1.030 | 1.028 | 1.032 | 1.028 |
| | me | 1.005 | 1.006 | 1.006 | 1.006 | 1.007 | 1.007 | 1.008 | 1.009 | 1.009 | 1.011 | 1.011 | 1.012 | 1.012 | 1.013 | 1.013 | 1.014 | 1.014 | 1.015 | 1.014 | 1.016 | 1.017 | 1.017 |
| | mstr | 1.007 | 1.007 | 1.010 | 1.010 | 1.010 | 1.011 | 1.012 | 1.015 | 1.016 | 1.020 | 1.021 | 1.028 | 1.035 | 1.035 | 1.037 | 1.043 | 1.047 | 1.044 | 1.046 | 1.052 | 1.053 | 1.057 |
| | mgy | 0.994 | 0.997 | 0.998 | 0.998 | 1.002 | 1.001 | 1.000 | 1.001 | 0.998 | 1.002 | 1.006 | 0.998 | 1.007 | 1.008 | 1.009 | 1.012 | 1.015 | 1.017 | 1.019 | 1.020 | 1.022 | 1.024 |
| | my | 1.031 | 1.032 | 1.033 | 1.035 | 1.036 | 1.039 | 1.042 | 1.044 | 1.048 | 1.051 | 1.054 | 1.057 | 1.062 | 1.066 | 1.061 | 1.064 | 1.068 | 1.065 | 1.065 | 1.065 | 1.068 | 1.072 |
| **Tertiary Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.066 | 1.065 | 1.061 | 1.059 | 1.059 | 1.057 | 1.059 | 1.056 | 1.063 | 1.061 | 1.059 | 1.058 | 1.077 | 1.077 | 1.073 | 1.088 | 1.090 | 1.093 | 1.095 | 1.094 | 1.102 | 1.104 |
| | mc | 1.005 | 1.006 | 1.005 | 1.006 | 1.007 | 1.005 | 1.007 | 1.007 | 1.008 | 1.011 | 1.013 | 1.013 | 1.015 | 1.017 | 1.018 | 1.023 | 1.024 | 1.024 | 1.023 | 1.019 | 1.021 | 1.021 |
| | me | 1.002 | 1.003 | 1.003 | 1.002 | 1.004 | 1.004 | 1.005 | 1.005 | 1.006 | 1.004 | 1.004 | 1.003 | 1.006 | 1.005 | 1.004 | 1.006 | 1.007 | 1.009 | 1.010 | 1.009 | 1.010 | 1.013 |
| | mstr | 1.002 | 1.002 | 1.002 | 1.001 | 1.001 | 1.001 | 1.002 | 1.004 | 1.005 | 1.002 | 1.003 | 1.001 | 1.011 | 1.009 | 1.008 | 1.009 | 1.008 | 1.007 | 1.009 | 1.014 | 1.013 | 1.012 |
| | mgy | 1.018 | 1.014 | 1.011 | 1.009 | 1.007 | 1.006 | 1.005 | 0.998 | 0.995 | 0.994 | 0.989 | 0.989 | 0.992 | 0.992 | 0.986 | 0.988 | 0.987 | 0.986 | 0.986 | 0.986 | 0.985 | 0.984 |
| | my | 1.034 | 1.034 | 1.035 | 1.035 | 1.037 | 1.039 | 1.041 | 1.040 | 1.048 | 1.049 | 1.050 | 1.051 | 1.051 | 1.052 | 1.055 | 1.060 | 1.063 | 1.068 | 1.067 | 1.067 | 1.071 | 1.073 |

*Table 2.7: Decomposition of the Aggregate U.S. Carbon Intensity by Industrial Sector, 1991-2012*

| Level | Factor | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Economy** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.087 | 1.097 | 1.105 | 1.120 | 1.126 | 1.136 | 1.134 | 1.144 | 1.149 | 1.147 | 1.145 | 1.152 | 1.139 | 1.167 | 1.117 | 1.117 | 1.064 | 1.047 | 0.968 | 0.981 | 0.974 | 0.998 |
| | mc | 1.030 | 1.032 | 1.032 | 1.038 | 1.041 | 1.045 | 1.047 | 1.047 | 1.051 | 1.051 | 1.053 | 1.057 | 1.054 | 1.074 | 1.056 | 1.060 | 1.044 | 1.029 | 0.979 | 0.995 | 0.986 | 0.995 |
| | me | 1.040 | 1.045 | 1.045 | 1.056 | 1.057 | 1.062 | 1.064 | 1.062 | 1.065 | 1.065 | 1.064 | 1.066 | 1.062 | 1.067 | 1.049 | 1.054 | 1.033 | 1.021 | 1.019 | 1.023 | 1.011 | 1.016 |
| | mstr | 1.019 | 1.017 | 1.022 | 1.021 | 1.023 | 1.024 | 1.025 | 1.029 | 1.027 | 1.024 | 1.021 | 1.023 | 1.015 | 1.023 | 1.017 | 1.016 | 0.994 | 1.004 | 0.976 | 0.990 | 0.984 | 1.003 |
| **Utility Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.036 | 1.035 | 1.041 | 1.039 | 1.039 | 1.046 | 1.045 | 1.055 | 1.055 | 1.053 | 1.052 | 1.055 | 1.055 | 1.052 | 1.037 | 1.026 | 1.017 | 0.989 | 0.983 | 0.967 | 1.001 | 1.004 |
| | mc | 1.010 | 1.011 | 1.012 | 1.013 | 1.014 | 1.016 | 1.018 | 1.019 | 1.020 | 1.021 | 1.022 | 1.023 | 1.024 | 1.025 | 1.014 | 1.009 | 1.006 | 0.981 | 0.980 | 0.974 | 1.002 | 1.011 |
| | me | 1.019 | 1.020 | 1.021 | 1.023 | 1.021 | 1.025 | 1.021 | 1.027 | 1.029 | 1.029 | 1.028 | 1.028 | 1.028 | 1.026 | 1.020 | 1.014 | 1.010 | 1.007 | 1.002 | 1.008 | 1.004 | 1.010 |
| | mstr | 1.006 | 1.003 | 1.007 | 1.003 | 1.003 | 1.005 | 1.006 | 1.008 | 1.005 | 1.003 | 1.001 | 1.003 | 1.002 | 1.001 | 1.003 | 1.004 | 1.001 | 1.001 | 1.001 | 1.000 | 1.003 | 1.003 |
| **Primary Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.017 | 1.019 | 1.020 | 1.022 | 1.023 | 1.023 | 1.025 | 1.025 | 1.026 | 1.026 | 1.026 | 1.034 | 1.004 | 1.031 | 1.006 | 1.030 | 1.001 | 1.032 | 0.983 | 1.025 | 0.981 | 1.028 |
| | mc | 1.005 | 1.005 | 1.004 | 1.006 | 1.005 | 1.006 | 1.007 | 1.008 | 1.008 | 1.009 | 1.009 | 1.015 | 0.997 | 1.015 | 0.998 | 1.015 | 0.995 | 1.017 | 0.982 | 1.013 | 0.982 | 1.014 |
| | me | 1.009 | 1.010 | 1.011 | 1.012 | 1.013 | 1.013 | 1.013 | 1.012 | 1.012 | 1.012 | 1.012 | 1.013 | 1.010 | 1.011 | 1.010 | 1.012 | 1.010 | 1.011 | 1.010 | 1.009 | 1.008 | 1.010 |
| | mstr | 1.004 | 1.004 | 1.004 | 1.004 | 1.005 | 1.004 | 1.004 | 1.005 | 1.005 | 1.005 | 1.005 | 1.006 | 0.996 | 1.005 | 0.998 | 1.002 | 0.996 | 1.004 | 0.991 | 1.004 | 0.991 | 1.003 |
| **Secondary Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.019 | 1.027 | 1.026 | 1.036 | 1.039 | 1.041 | 1.038 | 1.037 | 1.039 | 1.038 | 1.038 | 1.034 | 1.039 | 1.037 | 1.032 | 1.023 | 1.018 | 1.005 | 0.985 | 0.982 | 0.964 | 0.976 |
| | mc | 1.011 | 1.012 | 1.011 | 1.015 | 1.016 | 1.017 | 1.015 | 1.013 | 1.015 | 1.014 | 1.013 | 1.010 | 1.013 | 1.012 | 1.012 | 1.012 | 1.011 | 1.011 | 1.002 | 1.005 | 0.987 | 0.993 |
| | me | 1.001 | 1.008 | 1.007 | 1.010 | 1.011 | 1.011 | 1.011 | 1.011 | 1.012 | 1.013 | 1.012 | 1.013 | 1.013 | 1.011 | 1.008 | 1.002 | 1.000 | 0.987 | 1.007 | 1.014 | 1.009 | 1.012 |
| | mstr | 1.006 | 1.007 | 1.008 | 1.011 | 1.012 | 1.012 | 1.011 | 1.012 | 1.012 | 1.012 | 1.012 | 1.011 | 1.013 | 1.013 | 1.012 | 1.009 | 1.007 | 1.007 | 0.990 | 0.991 | 0.986 | 0.995 |
| **Tertiary Sector** | | | | | | | | | | | | | | | | | | | | | | | |
| | tot | 1.022 | 1.023 | 1.025 | 1.028 | 1.029 | 1.030 | 1.030 | 1.031 | 1.032 | 1.032 | 1.032 | 1.032 | 1.035 | 1.037 | 1.037 | 1.034 | 1.027 | 1.020 | 1.016 | 1.021 | 1.029 | 1.031 |
| | mc | 1.014 | 1.014 | 1.014 | 1.015 | 1.015 | 1.016 | 1.016 | 1.017 | 1.017 | 1.018 | 1.018 | 1.018 | 1.019 | 1.021 | 1.022 | 1.023 | 1.024 | 1.019 | 1.015 | 1.016 | 1.015 | 1.017 |
| | me | 1.006 | 1.006 | 1.007 | 1.010 | 1.011 | 1.011 | 1.010 | 1.010 | 1.010 | 1.010 | 1.011 | 1.010 | 1.012 | 1.013 | 1.011 | 1.009 | 1.012 | 1.009 | 1.008 | 1.009 | 1.010 | 1.011 |
| | mstr | 1.002 | 1.003 | 1.004 | 1.003 | 1.003 | 1.004 | 1.004 | 1.003 | 1.004 | 1.004 | 1.004 | 1.003 | 1.004 | 1.003 | 1.004 | 1.001 | 1.009 | 1.007 | 1.006 | 1.005 | 1.003 | 1.003 |

# CHAPTER 3: ESSAY 2 - Sharing-Based $CO_2$ Emission Allocation with a Perspective on a Multilateral Border Tax Adjustment-the U.S. Economy

## Abstract

Global production fragmentation significantly affects the allocation of emissions embodied in international trade. Thus, discrepancies between production-based emissions (PBE) and consumption-based emissions (CBE) allocations may impact mitigation efforts across economies given the current level of carbon transfers. As an alternative, a sharing-based emission (SE) allocation is an approach distinct from either the PBE or CBE allocation. The challenge facing the application of SE allocation is how to define a weighting procedure. In light of embodied emissions, Peters (2008) suggested that value-added should be used to define a weighting. However, a defined weighting procedure has yet to be addressed. The process of a SE allocation proposed in this essay complements a framework introduced by Peters (2008) with the application of multilateral border tax adjustments. Value added in embodied emissions is derived from effective carbon tariffs calculated based upon the environmentally-extended multi-regional input output (EE-MRIO) model and the use of value-added exports (VAX).

Due to uneven distributions between emission and global trade intensities across economies, a change in emission allocations from the current PBE approach to an alternative approach that considers both production and consumption can result in a significant emission responsibility burden for specific industries. Thus, an impact evaluation is important to explore mitigation efforts and define the consequences of alternative emission allocations. To identify allocations, the alternative approaches (a SE allocation and a consumption allocation with the application of a unilateral border tax adjustment: HCE) are empirically applied to the U.S. economy for the years 2005 and 2011.

At the level of the entire economy, the results show that CBE emissions exceeded the PBE emissions by 12% in 2005 and 29% in 2011. When the HCE was projected, emissions additionally declined from the CBE by 3% in 2005 and almost 2% in 2011. The SE showed an additional decline of 2% in 2005 and 4% in 2011. This analysis finds that the main reason for the slowness of the HCE decline was due in part to emissions of final import. Contributing to the great decline in SE was reductions in both exported and imported emissions. Particularly, imported emission declines was due solely to emissions attributable to intermediate imports.

The findings of industry levels reflect that ten industries (agriculture, paper, chemicals, rubber and plastics, basic metals, transport equipment, water transport service, post telecommunications, health services, and renting of machinery and equipment industries) were 40% discrepancies of CBE greater than PBE regarding three measures of emission burdens: an industrial role change, international trade change, and a change in import content. Cross-measure analyses indicate that six industries (chemicals, transport equipment, paper, rubber and plastics, basic metals, and water transport service industries) have confronted a major problem by putting these industries at a competitive disadvantage. As large portion of imports is in line to their products, the CBE allocation put considerable burdens for their import content changes and changes in international trade. An adoption of HCE allocation does not help solve this problem. This analysis explores that a HCE reduces emission burdens on international trade changes if there exist growth in final imports, at least faster than those of intermediate imports.

A SE, in turn, shows slight improvements in a competitive advantage of those industries. The SE allocation declines emission burdens on the change in industrial international trade if there exists an increase in composition of their intermediate imports. It also declines emission burdens on import content if a large portion of imports is highly relevant the products to deliver for exports. In this respect, it is likely that in light of global emissions as part of the fragmentation of international production, the SE allocation becomes more effective and even equitable than the HCE allocation. However, this analysis highlights that two industries (chemicals and water transport service industries) may lose attention to the application of SE emission responsibility because they would be challenged by the serious increase in competitive disadvantage.

## 3.1 Introduction

In recent decades, a control of carbon transfers due to the importance of international trade calls for an establishment of two perspectives of emission allocations: production-based (PBE), and consumption-based (CBE). PBE allocation assigns an economy to quantify emissions where products are produced and provides a basis for emission targets under its intended nationally determined contribution (INDC). For instance, the 2015 Paris Agreement, INDC is used to express what the post 2020 action an economy intends to take. In light of distortions in emissions embodied in international trade, CBE allocation is suggested as an alternative to PBE to mitigate significant risks of carbon transfers. The CBE allocation assigns an economy to take responsibility for emissions generated from its consumption regardless of where the consumed products are generated. It presents emissions taking place in imports, but not those in exports that are generally addressed in national voluntary reductions.

Global production fragmentation significantly affects the allocation of emissions embodied in international trade. Thus, differences between PBE and CBE allocations increasingly produce uneven policy actions for targeting emission reductions between exporting and importing economies. These differences may impact mitigation efforts across economies given the current level of carbon transfers. As an alternative, a sharing-based emissions (SE) allocation has recently arisen. This allocation distinct from either the PBE or CBE allocation assigns exporting and importing economies to be responsible for emissions based on benefits linked to their production and consumption (Ferng, 2003).

There are many existing studies which have provided frameworks for the SE allocation. These studies follow two lines of investigation: (1) sharing between economies associated with exports and imports; and (2) sharing between agents within an economy. Literature on the first line includes Peters (2008) and Chang (2013). Examples of the second line are covered by Rodrigues et al. (2006), Lenzen et al. (2007), and Cadarso et al. (2012). The challenge facing the application of the SE remains how to define a weighting procedure. In light of responsibility for emissions embodied in international trade, Peters (2008) suggested that value-added should be used to define a weighting framework because it involves emission responsibility in distribution of exporters and importers. Chang (2013) defined share responsibility in regard to the application of carbon costs between economies in order to compare results with conventional production and consumption responsibilities. However, no defined weighting procedure has been addressed so far in the literature with respect to the standpoint of value-added on emissions in exports and imports.

Therefore, the primary aim of this essay is to design a weighting procedure for establishing shares of the $CO_2$ emission allocation. An adoption of this procedure may result in emission responsibility greater than the current quantified national reduction targets under INDCs. Due to uneven distributions between emission and global trade intensities across economies, a change in emission allocations can produce a significant emissions responsibility burden for specific industries. Thus, an impact evaluation is critical to explore mitigation efforts and define the consequences of alternative emission allocations. To identify allocations, the application of four alternative allocations: production (PBE), consumption (CBE), consumption with the border adjustment application based on Chang (2013), and sharing (SE) are empirically applied to the entire U.S. economy for the years 2005 and 2011. In addition, emission allocations are broken down into 34 industries in order to evaluate the practical applications of alternative emission allocations. In this respect, this essay first examines industrial impacts on a shift towards the CBE allocation. Then, it investigates the consequences of the HCE and SE allocations. These impact calculations are assessed based on a benchmark of the PBE allocation, which has been recently utilized in the U.S. INDC.

The remainder of this essay is structured as follows. The second section reviews the relevant literature examining linkages between CBE allocation and SE allocation regarding an environmentally-extended multi-regional input-output model (EE-MRIO). This section also provides an in-depth discussion of the importance of sharing-based and relevant literature that brings about a procedure for defined weighting. The third section describes the EE-MRIO method and discuss linkages to a procedure for defined weighting. The fourth section discusses data. The fifth section presents the main findings of EE-MRIO analysis and industrial impact findings with respect to four emission allocations. The last section provides a summary of findings and policy strategies to deal with allocation problems.

## 3.2 Input-Output Analysis: from Consumption-Based to Sharing-Based Emission Allocations

Input-output framework has been widely used in the process of mapping and calculating $CO_2$ emissions embodied within economic activity (PBE) and through international trade (CBE). This framework has several advantages when compared with other frameworks. A computable general equilibrium (CGE) model appears useful for mapping emissions at global levels, but the quantitative analysis of this method is highly conditional upon what assumptions have been made in the way of key parameter values (e.g. elasticity, homogeneities of products contained) and model specifications (e.g. degrees of market competition) (Burfisher, 2011). In addition, CGE models involve complex interpretations when changing environmental impacts with high correlations of inter-industry linkages (Lee, 2014; Lee et al., 2011).

A process analysis of life cycle analysis, in turn, is a desirable method to map carbon footprint along global supply chains, but truncation errors is an important issue. This is due in part to system boundary problems (Tukker and Jansen, 2006; Lenzen, 2006; Liang and Zhang, 2013). There are many approaches proposed to deal with this issue. Examples include input-output life cycle analysis and hybrid life cycle analysis. However these novel approaches are intended for a product level analysis within a single set of consumption. In light of multi-regional input-output tables, a use of input-output method can provide more completeness to the analysis of different sets of consumption. High correlations of inter-industry linkages can also be examined (Peters et al., 2011). It is important that this method always avoid the issue of truncation errors (Lenzen and Treloar, 2002).

There is a realization that CBE allocation has been widely utilized to evaluate environmental impacts of international trade and study emission responsibilities into the post Kyoto (Ahmad and Wyckoff, 2003; Peters and Hertwich, 2008; Peter et al., 2011; Muradian et al., 2012; Sato, 203; Tukker and Dietzenbacher, 2013). With respect to the globalized economy, growth in international trade and changes in trade composition have brough about a transfer of emissions from developed economies (most importing-oriented economies) to developing (exporting-oriented economies) through relocation of carbon-intensive industries. This results in the issue of carbon transfer (i.e. carbon leakage[12]) when carbon production technologies across economies widely differ.

[12] Carbon leakage is the situation in which the proportion of emission increases in one economy is directly and indirectly due to changes in consumption patterns of other economies (Peters and Hertwich, 2008). Due to differences among emission intensities associated with imports and exports, one economy is able to transfer or absorb $CO_2$. Consequently, global emission reductions do not involve.

There are a number of studies where an input-output method was used to analyze CBE allocation of $CO_2$ emissions throughout major importing and exporting economies. However, these studies have conducted analyzes with vastly different mathematical forms (starting from the simple form of environmentally-extended bilateral-trade input-output models[13] EE-BTIOs to the more complicated form of environmentally-extended multi-regional input-output models[14] EE-MRIOs) and scales of studies (from a single economy[15] to multiple economies[16]). Wiedmann (2009) pointed out that the CBE allocation along with EE-MRIOs is an appropriate analytical tool for examining international policies on climate change because it can quantify the linkages between international supply chains of trade and emission flows occurring for imported products. The CBE allocation can also provide an understanding of emission responsibilities of importing economies. It is important when large disparities in carbon production technologies observed (Sato, 2013). The carbon technology differences can result in large errors of emission estimates, the so-called international feedback effects[17], and give rise to a misleading view of emission responsibility of importing economies. (Su and Ang, 2011).

Peters (2008) and Clarke (2010) indicated that the CBE allocation require more complex calculation of EE-MRIOs and may introduce uncertainty of emission analysis. In terms of policy implications, it can produce extreme emission responsibilities and has unconditional requirement for importing economies to make decisions on economic activities that are extended outside their geo-politic power (Peters and Hertwich, 2008). This issue is likely to affect incentives of importing economies and actions taken to reduce emissions by their trading partners (Clarke, 2010). Bastianoni et al. (2014) pointed out that a shift in emission allocations towards CBE implies weaker commitments to deal with emission reductions at global levels regarding no power outside their jurisdiction. Cadarso et al. (2010) added that when coming down to disaggregated industry levels, it is less reasonable to facilitate climate policies to consumers rather than producers. This reflects that consumers can never harness production process of emissions to reduce the impacts.

To deal with these issue on CBE allocation, a SE allocation shows a compromising way (Peters, 2008). The SE allocation lines on a choice of emissions behind the benefit principle. The benefit refers to

[13] See the U.S. examples: Weber and Matthews, 2007; Norman et al., 2007; Andrew et al., 2009; Chen and Chen, 2011; Edens et al., 2011; Aichele and Felbermayr, 2012; Tan et al., 2013; and Kanemoto et al., 2014)

[14] See the relevant U.S. examples: Ahmad and Wyckoff, 2003; Lenzen et al., 2004; Wiedmann et al., 2008; Peters and Hertwich, 2008; Zhou and Kojima, 2009; Nakano et al., 2009; Davis and Caldeira, 2010; Peters et al., 2011, Su and Ang, 2011; Wiebe et al., 2012

[15] In the U.S., Weber and Matthews, 2007, Ackerman et al., 2007, Norman et al., 2007

[16] See Nakano et al., 2009; Chen and Chen, 2011; Foren et al., 2012; Narayanan et al., 2012; Wiebe et al., 2012; Kanemoto et al., 2014; Timmer et al., 2015

[17] International feedback effects occur when changes in production in one economy that cause from changes in intermediate demand in another economy (Miller and Blair, 2009). Along this way, domestic and foreign inputs are traded with differing emission intensity levels between economies (Lenzen et al., 2004).

the fact that exporting economies associated with fuel combustion brings about income generation (Bastinanoni et al., 2004). Importing economies benefit from enhancements in their living standard through consuming quality imports (Ferng, 2003). Recently, there have been existing studies accessible to the SE allocation. Example includes Rodrigues et al. (2006), Lenzen et al. (2007), Peters (2008), Cadarso et al. (2012), and Chang (2013).

The primary design for sharing allocation places on a framework that allows emission responsibility within a single economy along with a single set of consumption. However, at that moment neither specification of responsibility proportions nor indicators of emission responsibility were demonstrated. Rodrigues et al. (2006) suggested an indicator for transaction of emission responsibilities between producers and consumers. Four properties were established to obtain the most acceptance of producers and consumers[18]. Further, Lenzen et al. (2007) demonstrated that value-added satisfied these four properties in regard to no double counting of emission responsibility. Their demonstration was limited to assigning emission responsibilities between producers and consumers within an economy. Peters (2008) first combined the system of emission responsibility by Lenzen et al. (2007) with the EE-MRIO and formulated equations of sharing emissions for interdependent industries across economies. He added that value-added is a good proxy for not only a part of benefits that are used to control over the production process of exports but also a part of incentives for importers to enter into the process of what to improve the profile of imported products. However, he has never clarified a procedure for allocating embodied emissions and not ever shown empirical work.

Cadarso et al. (2012) utilized EE-BRIO along with the system of emission responsibility by Lenzen et al. (2007) to analyze SE allocation for the impact of international trade on embodied emissions. Still, they did not clarified what the weighting procedure should be established. Chang (2013) designed the calculation for SE allocation with respect to carbon costs between economies. However, this standpoint deals with emission stimulated due to final source of traded products rather than embodied emissions in exports and imports. It is equivalent to estimating carbon to source ($CO_2$ emissions counted at the end of traded products consumed) versus virtual carbon ($CO_2$ emissions counted along the process of traded products) (Morris and mathur, 2015; Helm et al., 2012). In this respect, this weighting is able to share emission responsibility between exporters and importers on the assumption that elasticities of demand and supply for exports and imports is fixed and large enough for them to involve the production process of embodied emissions (Seuring and Müller, 2008). In addition, this weighting has possibility for emission

[18] The first property refers the responsibility of all producers and consumers is the sum of responsibility of each producer and consumer. The second property refers producers and consumers who benefits from environmental degradation is mostly responsible. The third property refers as long as economic activities of producers and consumers lead to environmental degradation, responsibility of them cannot decline. The last property refers the responsibility of all producers and consumers cannot change despite the interchangeable contribution of production and consumption behavior. See Rodrigues et al. (2006) for more details about how to fulfill those properties.

responsibility to be consistent if carbon contents and production technologies between economies are a bit differences. Davis and Caldeira (2010) pointed out that disparities of production technologies across international supply chains have become more critical. Sato (2013) added that such disparities take into account of large errors for embodied emissions with respect to multi-national feedback effects. In light of SE allocation, Lenzen et al. (2007) highlighted that dependence of emission allocation, which can occur when fixing weights for emission allocations between economies, can result in the problem of consistency in emission allocations. The major challenge maintains a weighting procedure that can establish shares of emissions to be consistent.

Despite extreme of CBE allocation, it has an advantage for trade adjustments. Such adjustments can provide a link between domestic consumption and global production to deal with carbon transfers (Su and Ang, 2013). There are many trade measures suggested to the issue of carbon transfers. Among of them, the most trade measure lately debated is a border adjustment. The border adjustment works for eliminating differential carbon contents through pricing and controlling emissions between economies (Helm et al., 2012). Peters and Hertwich (2008) emphasized that CBE allocation is a part of border adjustments because of using a process of trade to adjust the way of emissions released. In this respect, as SE allocations is a convex combination of CBE, border adjustments through networks of embodied emissions have become a basis for consistent weighting (Peters, 2008).

There are many different policies used to define border adjustments such as a tax policy[19] (e.g. border tax adjustments) and an allowance policy[20] (e.g. cross-border trade adjustments). However, no body of literature has far indicated what the best policy should definitely be adopting. In the context of General Agreement on Tariffs and Trade (GATT) 1994, border adjustments under emission tradable allowances provide a challenge for Article III of GATT 1994 and less likely to be acceptable in terms of technical barriers to trade[21] (TBT) and justifications of the chapeau of Article XX[22] (Yoshida, 2014). Based upon the historical experiences of the EU emissions trading system (EU ETS) and the regional greenhouse gas initiative (RGGI), tradable programs have the high possibility to create emission allowances greater than the actual emission target, the so-called hot air (Henriquez, 2013). Hot air is able to occur whenever emission allowances are set greater than the actual emission target given by a region within a year (Henriquez, 2013). Winchester et al. (2011) highlighted that this issue does not allow domestic and foreign

[19] See Cosbey (2008)

[20] See Henriquez (2013)

[21] Technical barriers to trade aims at ensuring that technical regulations, standards, assessment procedures do not create unnecessary obstacles to body of trade (WTO, 2015a).

[22] The chapeau of Article XX allows exception for policy measures necessary to protect human, animal or plant life or health. Such measures are made effective as long as they are in conjunction with restriction on domestic production or consumption (WTO, 2015b).

polluters to manage their abatement costs but encourages them to move towards additional profits. Consequently, the allowance policy does not guarantee that setting targets truly abate emissions at regional and global levels, even having the extension to an allowance reserve for emission trade (normally acts like an allowance ceiling) (Murray et al., 2012). Unlike trade allowance, border tax adjustments are more stringent when such adjustments reflect virtual social costs between economies or regions (Aldy and Pizer, 2015). In this way, border tax adjustments should design for imposing embodied (virtual) emissions in traded products rather than in final sources; named full border tax adjustments or multilaterally-coordinated border tax adjustments (Morris and Mathur, 2015). Cadarso et al. (2012) emphasized that with huge differences of carbon contents, border tax adjustments imposed on final sources of traded products, which refers to unilaterally-coordinated border tax adjustments, are more likely to be undermined by carbon transfer.

However, the application of border tax adjustments generally raises an issue of competitiveness-driven carbon transfer and produces unnecessary obstacles to trade. Fisher and Fox (2009) pointed out that if the border tax adjustment is formed in terms of a unilateral coordination, it is likely to induce a difficulty experienced by trade tensions. In turn, Monjon and Quirion (2011) found that a multilateral coordination can slightly eliminate trade distortion at the aggregate level. In this respect, they stated that in light of carbon transfers a multilaterally-coordinated border tax adjustment should become more effective than a unilaterally-coordinated one.

## 3.3 Production, Consumption, and Sharing Allocations: Methodology and Procedure

### 3.3.1 The Multi-Regional Input-Output (MRIO) Model

The MRIO model is recognized as a useful tool to trace the emission flows linked with the entire domestic and international supply chains based on the production of exports and imports. This model can be used to analyze and map emissions embodied from both domestic production (production-based perspective) and domestic consumption (consumption-based perspective). In this essay, an environmentally-extended seven region MRIO model is constructed for the U.S. economy based upon Peters and Hertwich (2008) and Peters (2008). To begin, this model is based upon an assumption that there are $r$ regions and the production of each region is classified into $n$ industries. The MRIO can be expressed in matrix form as follows:

$$X = AX + Y \tag{3.1}$$

where $X = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^r \end{bmatrix}$ is the aggregate output for all regions, in which each element $x^r$ represents the industrial aggregate output of the r^th region. $A = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1r} \\ A^{21} & A^{22} & \cdots & A^{2r} \\ \vdots & \vdots & \ddots & \vdots \\ A^{r1} & A^{r2} & \cdots & A^{rr} \end{bmatrix}$ is the aggregate cross-industry requirement matrix which includes both the domestic and imported input coefficient for each industry by region. For example, $A^{11}$ represents a matrix of intra-industry technological requirements within region 1 industries whereas $A^{21}$ represents a matrix of inter-industry technological requirements from region 2 to region 1. The aggregate inter-industry technological requirement of region 1 equals to the sum over column of A as $\sum_r A^{r1}$. $Y = \begin{bmatrix} y_f^{11} + y_x^{11} & y^{12} & \cdots & y^{1r} \\ y^{21} & y^{22} & \cdots & y^{2r} \\ \vdots & \vdots & \ddots & \vdots \\ y^{r1} & y^{r2} & \cdots & y^{rr} \end{bmatrix}$ is the aggregate final demand in which $y^{11}$ represents the final demand of region 1 and can decompose both final demand on domestic production[23] ($y_f^{11}$) and exports ($y_x^{11}$). $y^{21}$ represents the imported final demand flow from region 2 to region 1. The aggregate final demand flow to region 1 equals to the sum over column of A as $\sum_r y^{r1}$.

[23] This includes household and government consumption, and fixed and stock capital investment but it is independent from imports.

Equation (3.1) can be rewritten using the Leontief inverse matrix and expressed in matrix form as:

$$X = (I - A)^{-1} Y \tag{3.2}$$

where $I$ is the identity matrix

### 3.3.2 The Environmentally-Extended Multi-Regional Input-Output (EE-MRIO) Model

Equation (3.2) can be transformed with an environmental extension to examine $CO_2$ emissions. The emissions generated by producing output x to serve for final demand $y$ can be expressed as (Peters and Hertwich, 2008):

$$E = C(I - A)^{-1} Y \tag{3.3}$$

where $E = \begin{bmatrix} E^{11} & E^{12} & \cdots & E^{1r} \\ E^{21} & E^{22} & \cdots & E^{2r} \\ \vdots & \vdots & \ddots & \vdots \\ E^{r1} & E^{r2} & \cdots & E^{rr} \end{bmatrix}$ is the aggregate emissions associated with the production output from all regions. $E^{11}$ represents the emissions embodied in domestic production of region 1 whereas $E^{21}$ represents embodied emissions in the production of region 2 that satisfies demand in region 1. $C = \begin{bmatrix} c^1 & 0 & \cdots & 0 \\ 0 & c^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & c^r \end{bmatrix}$ is a matrix of the direct $CO_2$ emission intensity per dollar unit of produced output by industry of the r$^{th}$ region. Elements in matrix $c^r$ represent the direct emissions produced by each industry in the region r. For example, the element $(c_j^1)$ in matrix $c^1$ is the emissions directly produced by industry j in region 1. This element is obtained by multiplying the $CO_2$ conversion factor for fuel source $(e_j^1)$ by the direct fuel use by industry j per a dollar unit of industry j's production $(f_j^1)$. That is, $c_j^1 = e_j^1 f_j^1$.

In the simplest format, Equation (3.3) can be extended for r regions as shown by Wiebe et al. (2012):

$$\begin{bmatrix} E^{11} & E^{12} & \cdots & E^{1r} \\ E^{21} & E^{22} & \cdots & E^{2r} \\ \vdots & \vdots & \ddots & \vdots \\ E^{r1} & E^{r2} & \cdots & E^{rr} \end{bmatrix} = \begin{bmatrix} c^1 & 0 & \cdots & 0 \\ 0 & c^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & c^r \end{bmatrix} \cdot \begin{bmatrix} (I - A^{11}) & -A^{12} & \cdots & -A^{1r} \\ -A^{21} & (I - A^{22}) & \cdots & -A^{2r} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{r1} & -A^{r2} & \cdots & (I - A^{rr}) \end{bmatrix} \cdot \begin{bmatrix} y^{11} & y^{12} & \cdots & y^{1r} \\ y^{21} & y^{22} & \cdots & y^{2r} \\ \vdots & \vdots & \ddots & \vdots \\ y^{r1} & y^{r2} & \cdots & y^{rr} \end{bmatrix} \tag{3.4}$$

where elements $A^{r1}$ $(a_{ij}^{r1})$ can be computed from the bilateral trade data because generally these data provide dollar values of imported and exported products segregated by industrial sectors and end-use categories across regions.

When constructing the international supply-use table, each element of $A^{r1}$ is computed by the following procedure. Elements $a_{ij}^{r1}$ can be calculated as $a_{ij}^{r1} = m_j^{r1} a_{ij}^{im1}$ for all industries j in region r. $a_{ij}^{im1}$ represents the requirement of intermediate import j used by industry i in region 1 derived from the international supply-use data and the aggregate output of region 1. $m_j^{r1}$represents the share of import j from region r to region 1. It can be computed as $m_j^{r1} = \frac{M_j^{r1}}{\sum_{r\varepsilon R} M_j^r}$ where $M_j^{r1}$is the total value of imports j from region r to region 1. $\sum_{r\varepsilon R} M_j^r$ is the total value of import j from all regions R to region 1.

Similarly, elements $y^{r1}(y_{ij}^{r1})$ can be computed by using the same approach: $y_j^{r1} = m_j^{r1} y_j^{im1}$. In this sense, $y_j^{im1}$ represents the imported final demand flow j to region 1 extracted from the international supply-use data. However, it should be noted that $y_j^{r1}$is derived based on the underlying assumption that the imported final demands are in the same proportion as the imported intermediate demands with the similar set of trading partners. It should be noted that to clarify the inter-technological requirements and intermediate imports of region 1, $A^{r1}$ and $y^{r1}$can be rewritten as $A_m^{r1}$ and $y_{mf}^1$, respectively.

The EE-MRIO model allows an explicit breakdown of $CO_2$ emissions in order to analyze the environmental impact associated with embodied emissions in imports and exports (Serrano and Dietzenbacher, 2010). Likewise, this breakdown includes embodied emissions in region 1's exports to other regions r and vice versa embodied emissions from regions' r exports to region 1.

As an example of using region 1, the embodied emissions of this region's imports can be expressed as follows:

$$E_m{}^1 = \sum_{r\neq 1} c^r (I - A^r)^{-1} A_m{}^{r1} (I - A^1)^{-1} y_{mf}{}^1 + \sum_{r\neq 1} c^r (I - A^r)^{-1} A_m{}^{r1} (I - A^1)^{-1} y_x{}^1 + \sum_{r\neq 1} c^r (I - A^r)^{-1} y_m{}^{r1} \quad (3.5)$$

where the first term on the right hand side expresses the emissions released from r regions' production to serve for intermediate products consumed by region 1. The second term expresses the emissions from r regionals' production to serve products exported from region 1. The last term expresses from r regions' production to serve for final products consumed by region 1. It should be noted that for the sake of this example $A^{11}$, $A^{rr}$, $y_f^{11}$, and $y_x^{11}$ can be rewritten as $A^1$, $A^r$, $y_f^1$, and $y_x^1$ respectively.

The embodied emissions of region 1's exports to other regions r can be expressed as follows:

$$E_x{}^1 = c^1 (I - A^1)^{-1} y_x{}^1 + \sum_{r\neq 1} c^r (I - A^r)^{-1} A_m{}^{r1} (I - A^1)^{-1} y_x{}^1 \quad (3.6)$$

where the first term on the right hand side expresses the emissions released from region's 1 production to serve for products exported to other regions' r. The second term expresses the emissions of r regions' production to serve for intermediate products in region 1 that finally are coupled for exports.

### 3.3.3 Calculations of Production-Based and Consumption-Based Emissions

As the EE-MRIO model provides an analysis of environmental impacts of international trade, it is an appropriate analytical tool for assessing PBE and CBE allocations. The gap of these two allocations is defined by the geographical structure of international trade flows. This section describes how emissions are computed from each allocation.

From the above EE-MRIO model, the aggregate emissions attributable to production by industry in region 1 ($PBE^1$) can be written as:

$$PBE^1 = c^1(\mathrm{I} - \mathrm{A}^1)^{-1}(y_f{}^1 + y_x{}^1) \tag{3.7}$$

where $c^1$ is the diagonal matrix of direct emission intensity by industry in region 1. $y_f^1$ is the diagonal matrix of domestic final demand (household and government consumption, and fixed and stock capital investment). $y_x^1$ is the diagonal matrix of exports. From the EE-MRIO standpoint, it is possible to calculate emissions associated with exports from region 1 to the other r regions. $y_x^1$ can be decomposed into $y_x^{12}$, $y_x^{13}$, …, $y_x^{16}$ where r = 1,2,..,6.

With $\varepsilon^1$ being the matrix of emission multiplier by industry within region 1, $PBE^1$ can be rewritten as:

$$PBE^1 = \varepsilon^1(y_f{}^1 + y_x{}^1) \tag{3.8}$$

where $\varepsilon^1 = c^1(I - A^1)^{-1}$. According to Ferng (2003), Equation (3.8) can be read by either rows or columns. The sum of elements by each row considers the direct emissions associated with domestic production. It is equivalent to the emission allocations which were considered under the Kyoto Protocol or the current of INDC. Alternatively, the sum of elements by each column considers both the direct and indirect emissions associated with inputs used to produce products for domestic final demand. In this sense, it is important to note that the result of aggregate emissions is equal to either summation by rows or by columns, but the results of two sums will differ for each industry.

Conversely, a CBE allocation is normally expressed in three terms as noted by Peters and Hertwich (2008): (1) the conventional domestic emissions calculated with the exception of exports; (2) emissions associated with domestic products which are sold within region 1, and (3) emissions associated with products generated from r other regions that to serve as intermediate and final imports of region 1. In this way, the aggregate emissions attributable to consumption of region 1 ($CBE^1$) can be written in the following expression:

$$CBE^1 = PBE^1 + E_m{}^1 - E_x{}^1$$

$$CBE^1 = c^1(I - A^1)^{-1} y_f{}^1 + \sum_{r \neq 1} c^r (I - A^r)^{-1} A_m{}^{r1} (I - A^1)^{-1} y_{mf}{}^1 + \sum_{r \neq 1} c^r (I - A^r)^{-1} y_m{}^{r1}$$

$$CBE^1 = \varepsilon^1 y_f{}^1 + \sum_{r \neq 1} \varepsilon^r \left( A_m{}^{r1} (I - A^1)^{-1} \mathrm{y_{mf}}{}^1 + \mathrm{y_m}{}^{r1} \right) \qquad (3.9)$$

where $\varepsilon^r$ is the matrix of emission multipliers for regions r and denoted as $\varepsilon^r = c^r(I - A^r)^{-1}$. The second term on the right hand side represents the direct and indirect emissions associated with products imported from the other r regions.

According to Andrew et al. (2009), Equation (3.9) can be read in two different ways: by rows, or by columns. They illustrated that the sum of elements by row covers the direct emissions associated with domestic production plus emissions associated with imports. The sum of elements by column, on the other hand, covers both the direct and indirect emissions associated with domestic and import inputs used by an industry to produce products for domestic final demand.

### 3.3.4 Calculation and Weighting Procedure of Sharing-Based Emissions

The previous discussion shows that a PBE allocation includes emissions associated with domestic production. This is the mechanism used for controlling emissions under the Kyoto Protocol. However, international trade is growing and plays a more crucial in the growth of global emissions. Thus, a CBE allocation has some advantages for emission responsibilities. However, this allocation does generate doubts for importing economies who are expected to make decisions on economic activities along the supply chains that extend outside their standard geo-political power. A CBE allocation seems to not incentivize exporting economies to be responsible for emissions in the way that carbon transfers. Along this line, this issue can affect motivations of importing economies and degrees of mitigation efforts.

A SE allocation allows for both exporting and importing to be responsible for emissions based on the benefit that links between their production and consumption. In this respect, such an allocation may encourage exporting and importing economies to increase mitigation efforts for the process of traded products. A SE allocation represent the idea of weighting the PBE and CBE. Mathematically, it can simply be expressed in terms of a single region as (Peters, 2008):

$$SE = \phi PBE + (1-\phi)CBE \tag{3.10}$$

where $\phi$ represents the diagonal matrix of weighting between the production and consumption responsibilities. When $\phi = 1$, the result is equivalent to full emission responsibility for production. With $\phi = 0$, the result is equivalent to full emission responsibility for consumption. Therefore, SE emission responsibility involves a circumstance where $0 \leq \phi \leq 1$.

Using region 1 as an example, the SE responsibility between regions 1 and 2 can be rewritten as:

$$SE^1 = \phi^2 PBE^1 + (1-\phi^1)CBE^1 \tag{3.11}$$

where $\emptyset^2$ is part of emission responsibility associated with exports from region 1 to region 2. $\emptyset^1$ is part of emission responsibility associated with exports from region 2 to region 1. $(1-\emptyset^1)$ represents proportion of emission responsibility associated with imports purchased by region 1.

According to Cadarso et al. (2012), Equation (3.11) can be read in two different ways: by rows, or by columns. They illustrated that the sum of elements by row covers part of emissions associated with inputs required for domestic and export demand, plus part of emissions associated with intermediate import, plus part of emissions associated with final import. The sum of elements by columns considers parts of emissions associated with own input use by industry and inputs used by other industries to generate products for domestic demand, plus part of emissions associated with own input use by industry and inputs used by others to generate products for export demand, plus part of emissions associated with own intermediate import and intermediate import used by others to generate products for domestic demand, as well as part of emissions associated with final import.

Lenzen et al. (2007) pointed out that proportion of emission responsibility will not violate the property of additivity tested by Rodrigues et al. (2006) and result in double counting if either proportion is determined by the quotient of value added[24]. Further, Peters (2008) illustrated that the quotient of value added should be defined based on embodied emissions in imports and exports. The ongoing unresolved issue is how to define a weighting procedure in regard to value added on embodied emissions in imports and exports.

For region 1, Figure 3.1 demonstrates how to define a weighting procedure based upon value added of embodied emissions in imports and exports. The proposed procedure describes here starts with two basic assumptions. First, carbon prices will be passed to industries purchasing domestic and imported energy in

[24] This concept describes the same way at the multiple counting of trade if trade statistic does not estimate the source of value that is added in exported and imported products, more details please see OECD-WTO database on trade in value-added.

form of highest prices for carbon intensity of energy source in their production process. Second, production functions will not be adjusted by any input factor substitutions in response to highest or lowest input prices.

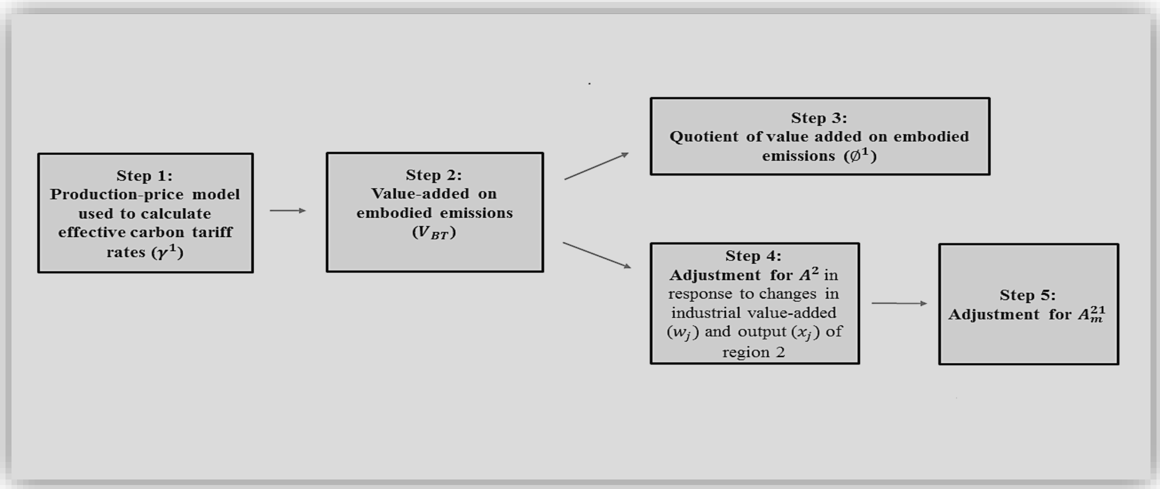


*Figure 3.1: Weighting Procedure for Region 1*

In order to obtain carbon prices of imports and exports with respect to their embodied emissions, production-price model is used in step 1 to calculate a matrix of region 2' price changes to reflect, so-called effective carbon tariff rate. This model is based largely on Metcalf (1999) and Miller and Blair (2009). However, the tax coefficient diagonal matrix here is calculated using the converted matrix of an indirect tax in the value added components of both domestic and import outputs (Atkinson et al., 2013). In this way, region 2' price changes in this model can represent prices of $CO_2$ embodied emissions rather than prices of $CO_2$ domestic production emissions. Despite prices of embodied $CO_2$, the carbon tariff needs to be mapped in form of value added on embodied emissions. Within step 2, effective carbon tariff rates are included in the computation of value added on embodied emissions. Analyses of trade in value added (TiVA)[25] and factorial distribution of value added are useful. The work by Johnson and Noguera (2012) suggests a measure of value content of exports known as value-added exports (VAX) in order to analyze TiVA embodied in final expenditure abroad. Further, Koopman et al. (2014) and Timmer et al. (2015) make a use of this concept in order to decompose value added in each factor. Using the region 1 as an example, the value added on embodied emissions associated with exports from region 2 to region 1 ($V_{BT}$) can be calculated in a matrix expression as:

[25] The flows of products within the global value chain are not intuitively reflected in measures of international trade. The joint project between OECD and WTO trade in value added (TiVA) firstly address this issue by considering value added on the production of goods and services that are consumed worldwide (OECD, 2015). Further, the work by Johnson and Noguera (2012) and Koopman et al. (2014) measures the value content of exports relied heavily on the concept of TiVA by using WIOTs.

$$V_{BT} = \gamma^1 (I - A^2)^{-1} y_x^{21} \tag{3.12}$$

where $\gamma^1$ is the diagonal matrix of effective carbon tariff rates calculated for region 2 (see step 1). $A^2$ is the matrix of intra-industry technological requirements within region 2 industries. $y_x^{21}$ is the vector of exports from region 2 to region 1. It is important to note that if multiple regions are considered, using the same procedure calculates the value added to embodied emissions due to regions r' exports to region 1.

Further, a weighting element of industry j can be represented by a quotient of value added on embodied emissions of industry j. Mathematically, the weighting elements of industry j in region 1 can be obtained in the following expression:

$$\phi_{j,1} = \frac{V_{BT,j,1}}{x_{m,j,1}} \tag{3.13}$$

where $\emptyset_{j,1}$ is the weighting element of industry j in region 1. $V_{BT,j,1}$ is the value added on embodied emissions for which region 1's industry j is responsible. $x_{m,j,1}$ is the value of industry j imports in region 1. It is important to note that this essay utilizes the mirror flow assumption of the world input-output database (WIOD). This assumption expresses that values of industry j imports purchased from region 2 are to be equal to values of industry j exports to region 1 (see section 4). In this sense, $x_{m,j}$ can be equivalent to the value of industry j exports from region 2.

However, to make weighting elements consistent across regions, adjustment for inter-technological coefficient matrix between regions 1 and 2 is important. Technically, when price changes occurring among international trade, both intra-technological coefficient matrices of regions 1 and 2 as well as their inter-technological matrix should be adjusted based upon value added on embodied emissions. In this way, these adjustments make interpretation of EE-MRIO more complicated and may not harness the property of additivity. I simplify this procedure by applying Armington assumption to address price effects of embodied emissions. This assumption states that no substitutions between domestic and import products occur within region 1 when carbon prices of embodied emissions impose differentiated across its trading partners. That means that intra-technological coefficient matrix of region 1 remained unchanged over the period studied. Inter-technological coefficient matrix between 2 regions can be modified in response to changes of value added in region 2.

Similarly, the weighting procedure regarding region 1's exports can be computed by using the same approach. In formulating the SE emission responsibility for region 1 trade with other regions r, Equation (3.11) can be re-expressed as:

$$SE^1 = \phi^r PBE^1 + (1-\phi^1)CBE^1$$

$$SE^1 = c^1(I-\ddot{A}^1)^{-1}{y_f}^1 + \sum_{r\neq 1}\phi^r c^1(I-\ddot{A}^1)^{-1}{y_x}^{1r} + \sum_{r\neq 1}(1-\phi^1)c^r(I-\ddot{A}^r)^{-1}\left[\left({\ddot{A}_m}^{r1}(I-A^1)^{-1}{y_{mf}}^1\right)+\left({y_m}^{r1}\right)\right] \qquad (3.14)$$

## 3.4 Data

The main source of data in the MRIO model is the world input-output database (WIOD) (www.wiod.org). It provides full transformation of national supply-use tables (SUTs), international supply-use tables (ISUTs), and world input-output table (WIOT). SUTs were the natural starting point to construct national input-output tables (IOTs). They were then linked across economies with bilateral international trade statistics to create the so-called ISUTs. Detailed ISUTs were subsequently used to construct the symmetric WIOT.

When compared to the methods used by other databases, the construction of WIOD has a distinguishing characteristic. Using SUTs to construct the WIOT could be easily combined with a high level of quality in bilateral international trade statistics. The combination of national and international flows of this format provides a powerful description of the transformation of global supply chain networks. It appears to be useful in the analysis of value added on $CO_2$ emissions partly related to trade in value added (TiVA) and the analysis of $CO_2$ allocations along global value chains (GVCs).

Institute of developing economies-Japan external trade organization (IDE-JETRO), the OECD input-output, and the GTAP database relied heavily on particular benchmark national input-output format rather than SUTs in order to construct multi-regional input-output tables. Consequently, their conventional tables cannot be used in comparisons over time when time series data from national account statistics (NAS) are available. From the NAS time series data on gross output, final expenditure categories (household and government consumption plus investment), total exports and imports, and value added by industry, bi-proportional updating method known as the SUT-RAS technique was applied to update SUTs. In this way, the updated SUTs would mostly match the important accounting identity engaged in gross domestic product (GDP) measurement[26]. Despite a limited time series consideration in this essay, the contribution of WIOD made the MRIO analysis up the most recently available data in 2011.

As the SUTs are in the product-industry format[27], which makes necessary the manual rebalancing of detailed products for each use category and reduces the extractability of WIOD method, the SUTs are transformed into the industry-industry type using additional assumptions concerning technology, the so-called fixed product-sales structure (Table 3.5 in Appendix 3-B). This sales structure refers to the proportions of the product output in which it is sold to the respective intermediate and final users (Timmer et al., 2012). This assumption helps to improve the precision of import share destination. In this way, a

[26] The sum of value added over the entire industries (the overall incomes) is equal to the sum of final use expenditure plus the net trade balance.

[27] The supply table indicates information on products that are produced by each domestic industry or imported and is generally available in product based. The use table indicates the use of either product by each of industry or its destinations (e.g. intermediate domestic use, domestic final demand, or exports) and available in industry-based.

breakdown of import shares for each use category by economy or industry of origin could be derived using a compromising assumption, the so-called import proportionality. Ratios between total imports and total use of imports are equal across industries but differ across use categories. It is important to note that this approach differs from the standard import proportionality which applies import shares for all uses irrespective of the category. Thus, when the WIOD is integrated with ISUTs into the WIOT, to ensure consistency between bilateral flows of exports and imports, bilateral exports were treated as mirror flows from bilateral imports. That implies that bilateral imports of economy A from economy B are ensured to be equal to bilateral exports from B to A. It is applicable to both aggregated and disaggregated levels. To study international production linkages, the mirror flows and the economy or industry of origin of imports seem to be substantially useful in the analysis of TiVA such that value added exports (VAX) are assumed to be equivalent to value added imports (VAM). This issue discuss through value added on $CO_2$ emissions and $CO_2$ allocations along global value chains.

The standard time series of the latest WIOT released in 2014 comprises 35 industries (including private household with employed persons) located in 40 economies plus the rest of the world (ROW). For the U.S. economy, the original WIOT are decomposed into the seven-region EE-MRIO model towards 34 industries for the years 2005 and 2011. The seven economies in this analysis consist of the U.S. and its major trading partners as follows: Canada, China, EU15, Japan, Mexico, and the rest of the world newly complied. The first five economies reflects over 75% of the U.S. exports and imports in 2011 expressed at current exchange rates (Table 3.1). As exports of the original ROW were defined as an additional trade reporter alongside the other 40 economies not originating from the set of WIOD economies, the new construction of the ROW ensures that exports summed over all economies of destination are equal to total exports given in the SUTs. As this result, according to mirror flows of bilateral exports and imports, the ROW's import shares have no longer recalculated using a RAS procedure to update the WIOT. MATLAB software is used for numerical computation of EE-MRIO analyses of this essay[28].

*Table 3.1: Trading Partners by Percentage of Trade Values, 2011*

| Rank | Economies | The Percentage of Trade Values |
|---|---|---|
| **1** | EU15[29] | 17.46% |
| **2** | Canada | 16.42% |
| **3** | China | 14.65% |
| **4** | Mexico | 13.25% |
| **5** | Japan | 7.67% |
| **6** | Germany | 7.53% |

[28] The complete codes in the form of EE-MRIO analyses will be available to download at Regional Research Institute, West Virginia University (rri.wvu.edu).

[29] Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Hungary, The Netherlands, Poland, Portugal, Spain, Slovakia, Sweden, and United Kingdom

In order to construct the seven-region MRIO model, intra- and inter-technological requirements of Canada, China, Japan, and Mexico came mainly from the original WIOT. Intra technological requirements of the EU15 and the ROW are calculated from the combination of individual technological requirements of 15 EU economy and other remaining economies respectively. To compile inter-technological requirements, mirror flows of bilateral exports and imports are consistently linked with each other as a bridge of SUTs and ISUTs of individual economies. In this way, inter-technological requirements of EU15 and the ROW are calculated from the import combination of individual members in EU15 economy and other remaining economies.

Total final demand and domestic final demand of each economy are directly taken from the columns in the WIOT. Domestic final demand contains household and government expenditure plus investment. Exports in the WIOT are commonly identified by the matrix of inter-industry correlations between economies. In order to investigate how domestic $CO_2$ emissions are induced through domestic segments of GVCs in an industry level, exports are redefined as the sum of columns across industries. Final imports are taken from ISUTs. ISUTs were normally product based but not industry based. Depending on the underlying assumptions of fixed-product sales structure and import proportionality, final imports are being harmonized in terms of industry classification based upon the structure of International Standard Industrial Classification of all Economic Activities (ISIC).

The WIOD is recognized as a consistent and harmonized multi-regional input-output tables used for trade and environmental analysis. As the core of WIOD environmental account contains separately primary fuel use, $CO_2$ emissions from fuel combustion of industrial processes are estimated using energy accounts and technology-related emission factors. Thirteen types of fuel combustion of industrial processes are employed: hard coal and derivatives (HCOAL), lignite and derivatives (BCOAL), coke, crude, diesel, gasoline, jet-fuel, light fuel oil (LFO), heavy fuel oil (HFO), naphtha, other petroleum products (e.g. ethane, liquefied petroleum gas, and lubricant), natural gas, and other derived gases (e.g. coke oven gas, gas). Emission factors for 34 industries in 7 economies were mainly collected from technical guidance report of UNFCC (2015). However, the conventional report was no longer enough to provide distinguishing fuel qualities and technologies used in each economy. The compilations of national emission inventories are used as a bridge to embed a relationship between industrial energy use and emissions. The list of national emission inventories used in this essay includes: Canada GHG Inventories (ECCC, 2013), Initiate National Communities on Climate Change in the People Republic of China (NCCP, 2013), National GHG Inventory of Japan (GIO, 2013), Instituto Nacional de Ecologia y Cambio Climático (SEMARNAT, 2013), Environmental Protection Agency GHG Inventories (USEPA, 2013), and $CO_2$ emission factors for Fuel used in European Union GHG Inventories (EUROPA, 2013). There is a lack of information specific for

ROW. The UNFCCC guidance for greenhouse gas inventories (UNFCCC, 2013) is used to represent emission factors for ROW.

Due to unavailable data on implemented border taxes for carbon with detailed specific information about 34 industries across seven economies, empirical outcomes of border taxes for carbon derived by Atkinson et al. (2009; 2013) were used to represent carbon effective tariff rates for specific 34 industries across seven economies. These authors conducted an empirical analysis of border taxes on the virtual carbon content of imports and calculated carbon effective rate per unit of output by industry for major developed and developing economies. Virtual carbon was taxed at $50 per ton of $CO_2$ in 2004 and updated to $56 in 2010. These taxes per ton were not picked up at random but reflected the estimates of social cost of carbon by U.S. federal government. The marginal social cost of carbon represents the damage cost of human health, economic productivity caused by increasing average surface temperatures and rising sea levels due to climate change. This type of cost also correlates with the magnitude of the national voluntary reduction targets required to summit as an INDC. However, the effective carbon tariff rates of Atkinson et al. (2009; 2013) were available for 19 sectors (Table 3.6 in the Appendix 3-B). In this essay, 34 industries were reclassified using the harmonized structure of ISIC (Table 3.7 in Appendix 3-B).

## 3.5 Empirical Results and Discussions

This section presents the main findings of EE-MRIO analysis with respect to PBE and CBE for the U.S. economy. The study period spans between 2005 and 2011. This analysis allows reading emission matrices by rows and by columns in order to evaluate impacts of U.S. industries when a change in emission allocations is considered. The differences of emission matrices either by rows or by columns reveals three important aspects suggested in this essay in terms of burdens on: (1)an industrial role change from a producer to an input consumer; (2) a change in international trade; and (3) a change in import contents of production. In doing so, the impact evaluation is important when the aim is to find out an alternative that will be able to deal with emission responsibility problems due to increases in international fragmentation of U.S. industrial production. Hence, this section first presents impact findings based on PBE allocation compared with the CBE allocation. Then, subsection 3.5.4 presents impact findings of the HCE and SE in regard to comparisons of differences between the PBE and CBE.

### 3.5.1 Production-Based Emission (PBE) Allocation

The PBE for the U.S. economy in 2011 was 5,266,315 kt of $CO_2$, which dropped by almost 8% below its 2005 levels (5,658,261 kt) As shown in Figure 3.2, a main reason for the drop was due to a decline in emissions associated with domestic demand, which accounted for a 13% decrease (from 4,853,930 to 4,354,864 kt). Based on the size of $CO_2$ emissions, the decline in emissions was dominated by utility (-16%) and refined petroleum industries (-17%) as a result of a transition to natural gas and other cleaner forms of energy (Figure 3.3). Other industries with substantial declines included transport equipment (-13%), construction (-23%), electrical equipment (-26%), and water transport service (-27%). These reductions were due to a very big slowdown in their direct production [30]

[30] Direct production describes a situation where an industry produces what it needs, independently the aid of the corresponding industry elsewhere or other related industries (Zhang et al., 2015).

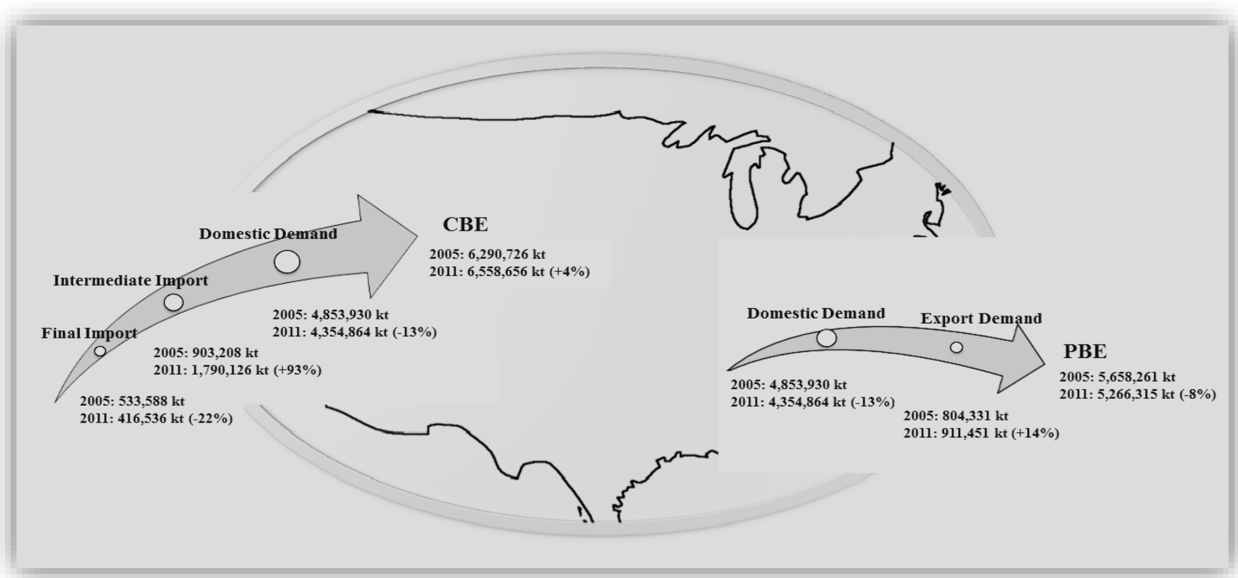


*Figure 3.2: U.S. Production-Based Emissions and Consumption-Based Emissions by End Use, 2005 and 2011*

Emissions associated with U.S. export demand in 2011 were 14% greater than its 2005 levels (from 804,331 kt to 911,451 kt), reflecting a recovery of the growth in U.S. exports after the great recession of 2008. As shown in Figure 3.3, large proportion of exported emissions was generated by mining (+18%), chemicals (+20%), non-metallic minerals (+25%), transport equipment (+19%), inland transport service (+26%), and air transport service (+23%).

Detailed distributions of exported emissions by industry and country are presented in Tables 3.8 and 3.9 of Appendix 3-C. They show that top three exported emissions are attributable to mining, chemicals, non-metallic minerals and these were mainly delivered to China, Mexico, plus ROW and partially delivered to EU15. Emissions attributable to transport equipment were primarily delivered to China and Mexico. Emissions attributable to air transport service industry were delivered to China, EU15, and ROW. Inland transport service industry were delivered to Canada and Mexico as a supporter of border trade activities. In this respect, U.S. emissions associated with exports to China, ROW, and Mexico grew by +23%, +24%, and +23% respectively from 2005 to 2011. For emissions attributable to domestic demand, health services and post telecommunications industries were also highlighted because their emissions grew quite fast between 2005 and 2011.

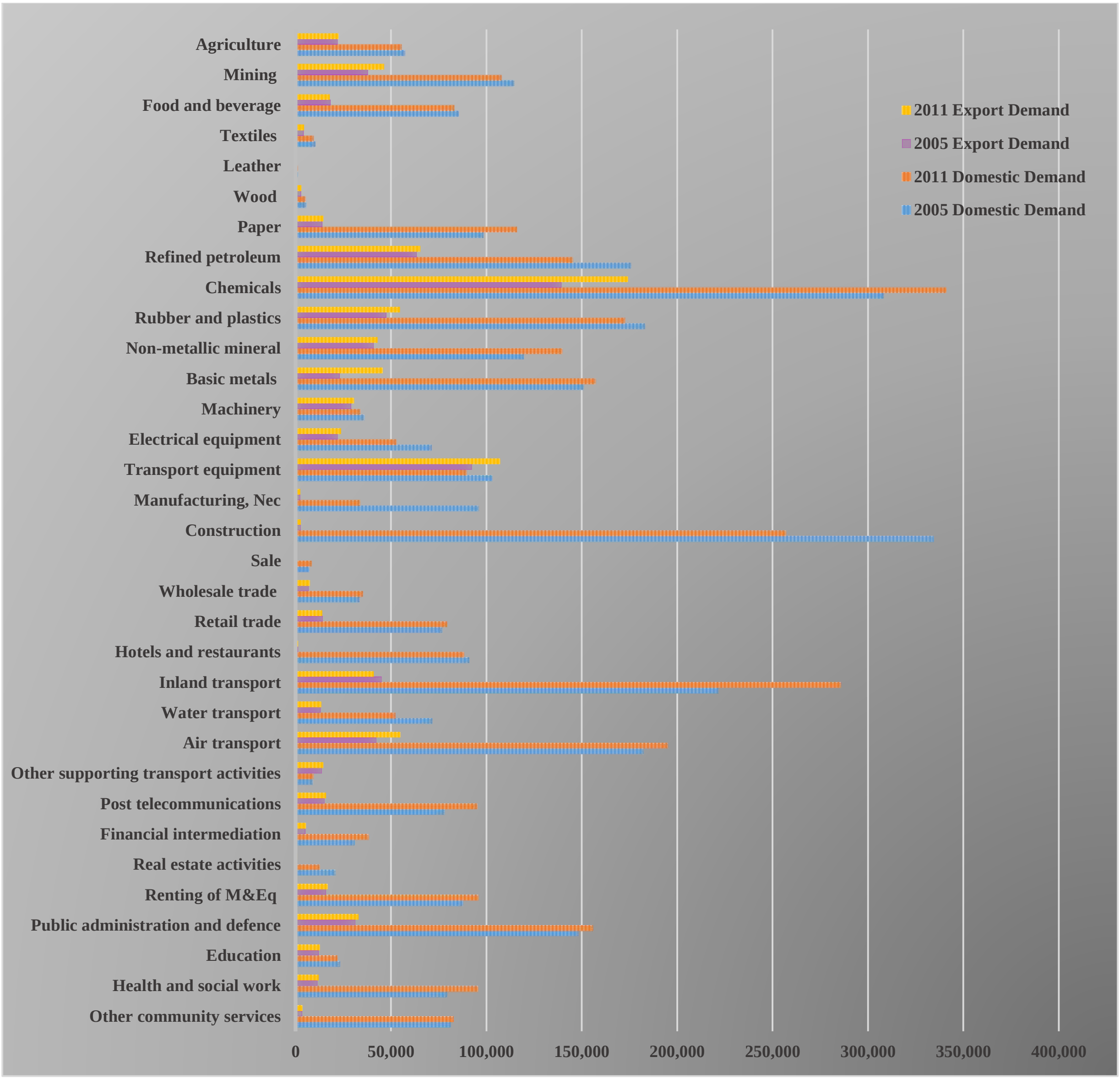


*Figure 3.3: A Breakdown of U.S. Production-Based Emissions by Industry, 2005 and 2011; kt of $CO_2$*

## 3.5.2 Consumption-Based Emission (CBE) Allocation

The total CBE for the U.S. economy was computed to be 6,558,656 kt of $CO_2$ in 2011, which increased by 4% above its 2005 levels (6,290,726 kt) (Figure 3.2). In 2011, the CBE exceeded the PBE by almost 29%, over twice as high as the 12% difference in 2005. Thus, the U.S. economy considerably induced emissions associated with imports from its trading partners and partially avoided producing emissions at home. Figure 3.2 shows that a large contribution of imported emissions was due to the substantial growth in intermediate imports, growing almost two-fold between 2005 and 2011.

Figure 3.3 shows that rapid growth in imported emissions was concentrated within nine industrial activities. These industries are paper (+57%), chemicals (+58%), rubber and plastics (+53%), non-metallic minerals (+35%), basic metals (+62%), water transport service (+35%), air transport service (+31%), post telecommunications (+41%), and renting of machinery and equipment (+37%). However, emissions associated with final imports consumed directly by U.S. consumers declined by roughly 22% over the study period. Main industries involved in the decline of such emissions include mining (-24%), textiles (-25%), non-metallic minerals (-36%), manufacturing (-44%), machinery (-25%), and construction (-26%).

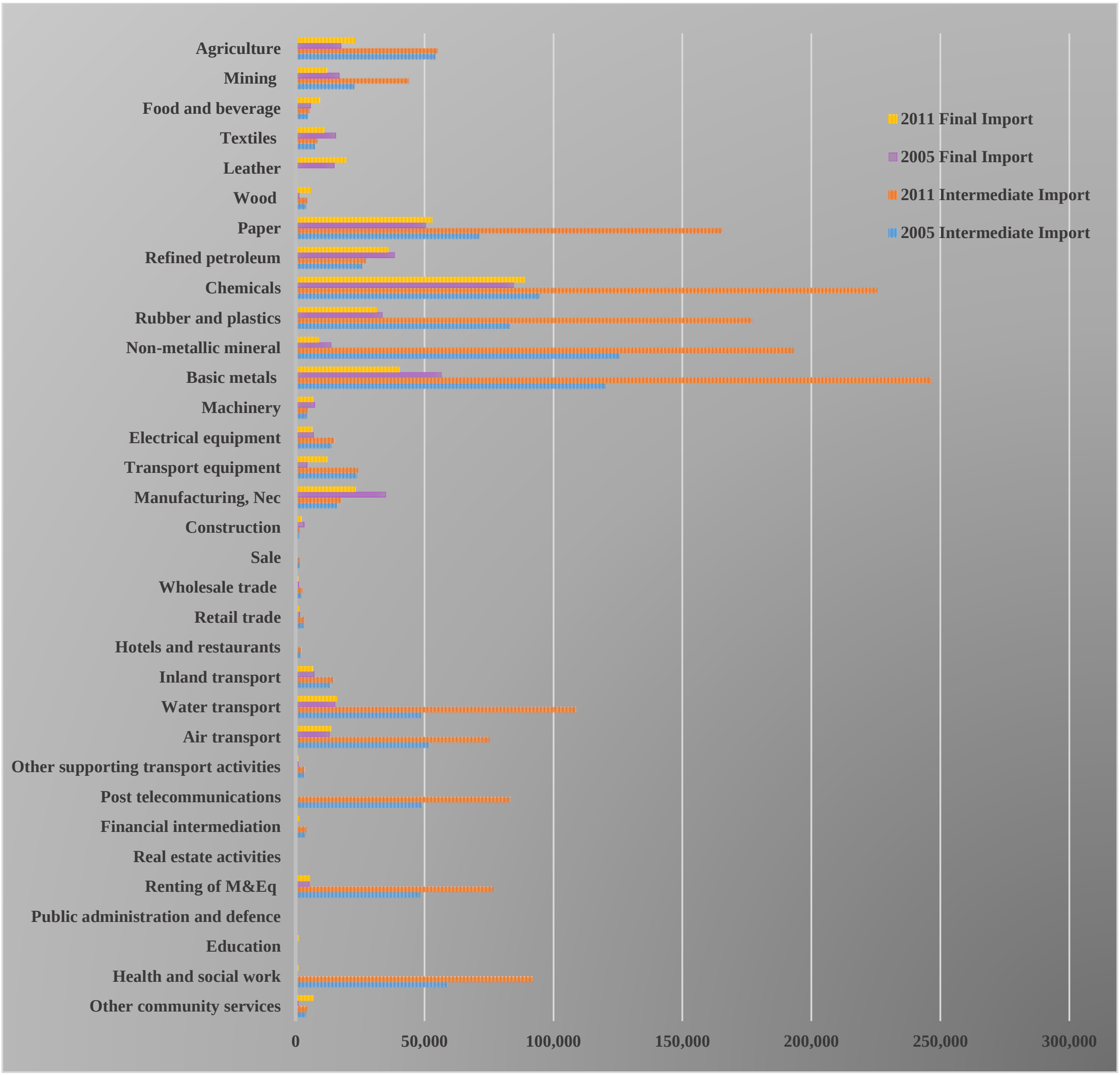


*Figure 3.4: A Breakdown of U.S. Imported Emissions by Industry, 2005 and 2011; kt of $CO_2$*

As shown on Tables 3.10 and 3.11 in Appendix 3-C, the chain of import distribution in response to country of origin indicates that embodied emissions associated with intermediate imports in 2011 were mainly driven by the supply growth from China (+162%), Mexico (+74%), and ROW (+145%). This observation includes that increased shares of over 100% growth from 2005 for Chinese exports in industries of paper, rubber and plastics, basic metals, and water transport service industries. Growth of imports from Mexico were mainly contributed by exports from the refined petroleum, chemicals, transport equipment, and inland transport service industries. The US-ROW trade resulted in increased U.S. imports throughout all industries with large increases in chemicals, basic metals, non-metallic minerals, water transport service, air transport service, agriculture, machinery, and rubber and plastics industries.

In contrast to emissions embodied in intermediate imports, emissions associated with final imports of refined petroleum, chemicals, and non-metallic minerals largely declined due to a dramatic slowdown of US-EU15 trade, which declined between 2005 and 2011. Emissions attributable to final imports of paper, refined petroleum, and chemicals were mostly due to a 60% shrinkage of US-Mexico trade. A slowdown in trade with Canada declined emissions over many industries, particularly agriculture, mining, and paper industries. It is important to note that despite the decrease in imported emissions with respect to trade with Mexico, imported emissions of US-Mexico trade experienced substantial growth due to a change in composition of intermediate import. The full presentation of emissions associated with final import broken down country of origin is given on Tables 3.12 and 3.13 in Appendix 3-C.

## 3.5.3 Impact Findings of the CBE Allocation

While big differences between U.S. emissions based on the PBE and CBE are observed, a change in emission allocations may be costly and likely to produce substantial burdens for some U.S. industries with regard to uneven distributions of their emission and global trade intensities. In this respect, PBE and CBE by rows and by columns at the detailed industry level must be examined. The differences by rows and by columns proposed in this essay reflect three important aspects of emission burdens on: (1) a change in industrial role from a producer to an input consumer (PBE by row versus PBE by column); (2) a change in industrial international trade (CBE by column versus PBE by column); (3) a change in industrial import content of production (CBE by row versus PBE by row). It is important to note that the second aspect of emission burdens relates to burdens of international trade on the total (direct and indirect) industrial emissions. The third aspect of emission burdens centers the discussion on the direct emissions associated with imports by industry. The amounts of emissions that each industry would be responsible regarding the PBE and CBE allocation are presented in Table 3.14 in Appendix 3-C.

As shown in the first and fourth columns ($PBE_{row}/PBE_{col}$) on Table 3.2, emission burdens on industrial role changes of ten industries were larger than 50% discrepancies in both 2005 and 2011. Other six industries were larger than 30%. Ten industries with more than 50% discrepancies include agriculture, mining, food, rubber and plastics, non-metallic minerals, basic metals, construction, other supporting transport services, post telecommunications, and public administration industries. Six industries with 30-50% discrepancies consist of machinery, manufacturing, inland transport service, water transport service, air transport service, plus renting of machinery and equipment industries. These large discrepancies can be clearly seen in two ways: positive and negative signs. A positive sign of the discrepancy refers to industries where emissions generate directly from production greater than those generate from the use of inputs. These industries need to regulate directly for the PBE allocation. In turn, a negative sign indicates industries where emissions mostly generate from the use of inputs. These industries take into account the emission regulation for the CBE allocation.

The reasons for the large discrepancies was due to industries highly related to pollutant inputs (most of them are service industries) and intermediate input industries (most of them are manufacturing industries). However, no all intermediate input industries had large discrepancies. Examples include refined petroleum, chemicals, and transport equipment industries. They showed less 10% discrepancies. It was because emissions associated with these industries were resulted from not only their production process but also a large part of pollutant inputs. The other remaining industries (18 industries) showed less than 30% discrepancies between 2005 and 2011. These findings reflect that they would not confront a serious problem of industrial role changes under the CBE allocation.

A shift to the CBE allocation may cause not only a big concern for emission burdens on industrial role changes, but also a large concern about emission burdens from changes in international trade by industry. The second and fifth columns ($CBE_{col}/PBE_{col}$) on Table 3.2 show that emission burdens on the change in international trade were greater than 50% within seven industries in both 2005 and 2011. Seven industries contain agriculture, rubber and plastics, non-metallic minerals, transport equipment, manufacturing, post and telecommunications, and renting of machinery and equipment industries. Discrepancies of these industries also increased significantly in 2011. Large discrepancies are all positive signs. A positive sign indicates industries where imported emissions are greater than those attributable to exports. Due to the benefit from less responsibility for emission burdens, these industries would remain in the PBE allocation. In turn, a negative sign interprets industries where imported emissions are smaller than exported emissions. In this view, they are likely to switch towards the CBE allocation. These industries are mining, wood, electrical equipment, and utility, construction, retailed trade, and education industries.

There are many reasons that explain large discrepancies of different industries. To describe how the CBE allocation exerts strong influences on industrial international trade, the distribution of emissions associated with exports and imports by industry provides such a close examination. The examination reveals that agriculture, chemicals and transport equipment had very strong influences due to not only rapid increases in emissions attributable to both intermediate and final imports but also an expansion of emissions attributable to exports. Paper, rubber and plastics, water transport service, post telecommunications, plus renting of machinery and equipment had large influences due to growth in emissions associated with intermediate imports. Non-metallic minerals extended a strong influence due to a slowdown of emissions associated with final imports. The strong influence of food and beverage were due to growth in emissions associated with intermediate import along with a slowdown of emissions associated with exports.

To examine the large differences in emission burdens due to industrial international trade, those industries also had big discrepancies between PBE by rows and CBE by rows. As shown in the third and sixth columns ($CBE_{row}/PBE_{row}$) on Table 3.2, agriculture, paper, chemicals, rubber and plastics, basic metals, transport equipment, water transport service, post telecommunications, health services, and renting of machinery and equipment industries had a 40% or greater difference between PBE by rows and CBE by rows. That means that a large proportion of emissions attributable to their domestic production was due to emissions associated with the import content of their production. These industries still benefit from the PBE allocation as a result of less emission burdens. In turn, a negative sign means that a large proportion of domestic content was used to deliver domestic products. Examples of industries include mining, wood, retailed trade, and education industries.

Comparing the three different aspects of emission burdens, a better understanding of an allocation problem can be seen. If emission burdens on industrial international trade changes (CBE by column versus PBE by column) is stronger than those on industrial role changes (PBE by row versus PBE by column), industries remain the PBE allocation due to less responsibility for emission burdens. Based on the large emission burden, these industries are agriculture, paper, chemicals, rubber and plastics, non-metallic minerals, transport equipment, and renting of machinery and equipment industries. In turn, if emission burdens on industrial international trade changes is smaller than those on industrial role changes, industries are likely to move towards the CBE allocation. Examples of industries include mining, food and beverages, basic metals, air transport service, and post telecommunication industries.

In addition, emission burdens on changes in industrial import content (CBE by row versus PBE by row) are greater than those of remaining two aspects. This situation refers to industries where their products depend on a large proportion of imports. In this respect, the CBE allocation could pose a major problem for a competitive disadvantage. They do not totally accept the CBE allocation. In regard to the large emission burdens, five industries are paper, chemical, rubber and plastic, transport equipment, and water transport service industries.

In this respect, this analysis points out that a decline in emission burdens on both industrial international trade and industrial import content are needed for incorporating industries to be responsible for imported emissions. Particularly, a decline in emission burdens on industrial import content should be larger than that on industrial international trade in order to solve a serious problem of the competitive disadvantage.

*Table 3.2: Discrepancies between CBE and PBE by Industry, 2005 and 2011; Numbers Are Percentage Change*

| Industry | Year 2005 | | | Year 2011 | | |
|---|---|---|---|---|---|---|
| | $PBE_{row}/PBE_{col}$ | $CBE_{col}/PBE_{col}$ | $CBE_{row}/PBE_{row}$ | $PBE_{row}/PBE_{col}$ | $CBE_{col}/PBE_{col}$ | $CBE_{row}/PBE_{row}$ |
| **Agriculture, hunting, forestry and fishing** | 57 | 63 | 41 | 66 | 72 | 46 |
| **Mining and quarrying** | 67 | -28 | -19 | 71 | -31 | -25 |
| **Food, beverages and tobacco** | -53 | 30 | 17 | -66 | 33 | 21 |
| **Textiles and textile products** | 14 | 14 | 14 | 19 | 20 | 13 |
| **Leather and footwear** | -17 | 14 | 12 | -15 | 19 | 11 |
| **Wood and products of wood and cork** | -14 | -17 | -28 | -18 | -22 | -15 |
| **Pulp, paper, printing and publishing** | 12 | 32 | 43 | 14 | 40 | 50 |
| **Coke, refined petroleum and nuclear fuel** | 6 | 4 | 5 | 3 | 8 | 8 |
| **Chemicals and chemical products** | 9 | 32 | 49 | 8 | 38 | 59 |
| **Rubber and plastics** | 54 | 68 | 70 | 56 | 72 | 73 |
| **Other non-metallic minerals** | 56 | 58 | 18 | 55 | 69 | 34 |
| **Basic metals and fabricated metal** | 55 | 47 | 50 | 51 | 51 | 55 |
| **Machinery** | -35 | 10 | 24 | -33 | 12 | 28 |
| **Electrical and optical equipment** | -11 | -11 | -6 | -25 | -17 | -4 |
| **Transport equipment** | 9 | 58 | 63 | 9 | 60 | 66 |
| **Manufacturing, nec** | -33 | 61 | 17 | -45 | 58 | 24 |
| **Electricity, gas and water supply** | 13 | -12 | -1 | 19 | -14 | -2 |
| **Construction** | 59 | -14 | 5 | 61 | -12 | 10 |
| **Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel** | -16 | 5 | 27 | -12 | 4 | 28 |
| **Wholesale trade and commission trade** | -25 | 17 | 9 | -27 | 8 | 4 |
| **Retail trade, except of motor vehicles and motorcycles; repair of household goods** | -13 | -29 | -10 | -18 | -33 | -32 |
| **Hotels and restaurants** | -22 | 12 | 8 | -27 | 13 | 5 |
| **Inland transport** | 41 | -4 | 1 | 32 | -9 | 8 |
| **Water transport** | -33 | 35 | 44 | -38 | 39 | 51 |
| **Air transport** | 35 | 28 | 14 | 36 | 34 | 34 |
| **Other supporting and auxiliary transport activities** | 55 | -2 | 16 | 52 | -7 | 30 |
| **Post and telecommunications** | -60 | 52 | 46 | -68 | 60 | 54 |
| **Financial intermediation** | -21 | 17 | 11 | -28 | 21 | 7 |
| **Real estate activities** | -19 | 13 | 12 | -22 | 23 | 25 |
| **Renting of machine and equipment** | -47 | 55 | 45 | -48 | 67 | 54 |
| **Public administration and defense** | -51 | 10 | 12 | -53 | 4 | 23 |
| **Education** | -16 | -17 | -12 | -22 | -23 | -8 |
| **Health and social work** | -28 | 28 | 27 | -36 | 30 | 28 |
| **Other community, social and personal services** | -36 | 21 | 26 | -39 | 26 | 24 |

### 3.5.4 Hypothetical Consumption Emission (HCE) and Sharing Emission (SE) Allocations

This subsection presents the impact findings with emission allocation changes from the PBE allocation to either the HCE or SE allocation. In order to get a clearer view of the HCE and SE impacts since the U.S. has a net positive emission trade balance, three aspects of emission burdens are evaluated in comparison with those of CBE. Two allocation approaches are different in terms of the way pricing embodied emissions. The HCE is subject to a unilateral border tax adjustment whereas the SE is subject to a multilateral border tax adjustment. The calculation procedure of the SE was described in section 3.3.4. The mathematical expressions for the HCE are presented in Appendix 3-A.

Figure 3.5 shows the amount of emissions by end use under the HCE and SE projections in 2005 and 2011. The numbers in parenthesis show the percentage change comparing exported emissions of either HCE or SE allocation with the PBE allocation, and imported emissions with the CBE allocation. The HCE projected a 3% reduction in 2005 and 2% in 2011. Emissions attributable to intermediate imports declined by 2% and 5%, respectively. Emissions attributable to final imports declined the most by 18% in 2005 and 22% in 2011. Despite the large decline in emissions from final imports, the HCE reduction was much smaller. The reason for the small decline was due in part to composition of emissions attributable to final imports grew less than those attributable to intermediate imports. However, some industries showed a large proportion of emissions attributable to final imports and were the main contributors to the HCE decline. Examples of these industries included agriculture, food and beverages, leather, wood, machinery, and transport equipment industries. Also, emissions attributable to export demand showed small declines for the years 2005 and 2011. It is likely that the HCE allocation would contribute a substantial reduction in emissions attributable to final imports.

The total SE emissions was projected to give a 2% reduction in 2005 emissions and 4% in 2011 relative to 2005 and 2011 emissions of the CBE. The reason for the larger rate of reduction in 2011 was due to not only emissions attributable to intermediate imports but also emissions attributable to export demand. Within the SE, emissions from intermediate imports declined by 11% in 2005 and 19% in 2011. The examples of industries with the large declines included paper, chemicals, rubber and plastics, transport equipment, and water transport industries. Emissions from export demand also declined by 7% in 2005 and a 10% decline in 2011. Mining, chemicals, and non-metallic minerals industries were the major contributors to this decline. Emissions attributable to domestic demand also declined in both 2005 and 2011 at about the same rate.

To get more detail view of projected emission reductions, it is important to further evaluate emission burdens of different industries with respect to three aspects of emission burdens. Differences of the HCE and SE emission burdens presented in Tables 3.3 and 3.4 are calculated based on the PBE benchmark. However, owing to the importance of international production fragmentation, emission burdens on international trade changes and changes in import content of production are examined. In this way, an impact evaluation of industrial emission burdens under the HCE and SE allocations should compare with the impact findings of the CBE allocation rather than the PBE because the PBE allocation always excludes the importance of emissions from imports.

However, the calculation of impact is based on a benchmark of the PBE allocation in order to make consistent analysis with the CBE allocation. In this respect, impact comparisons either the HCE or SE allocation with the CBE allocation are the main part of this section. The numbers of parentheses show the differences between two allocation approaches and the CBE allocation. The amounts of emissions that each industry would be responsible for under the HCE and SE allocations are presented in Tables 3.15 and 3.16 in Appendix 3-C.

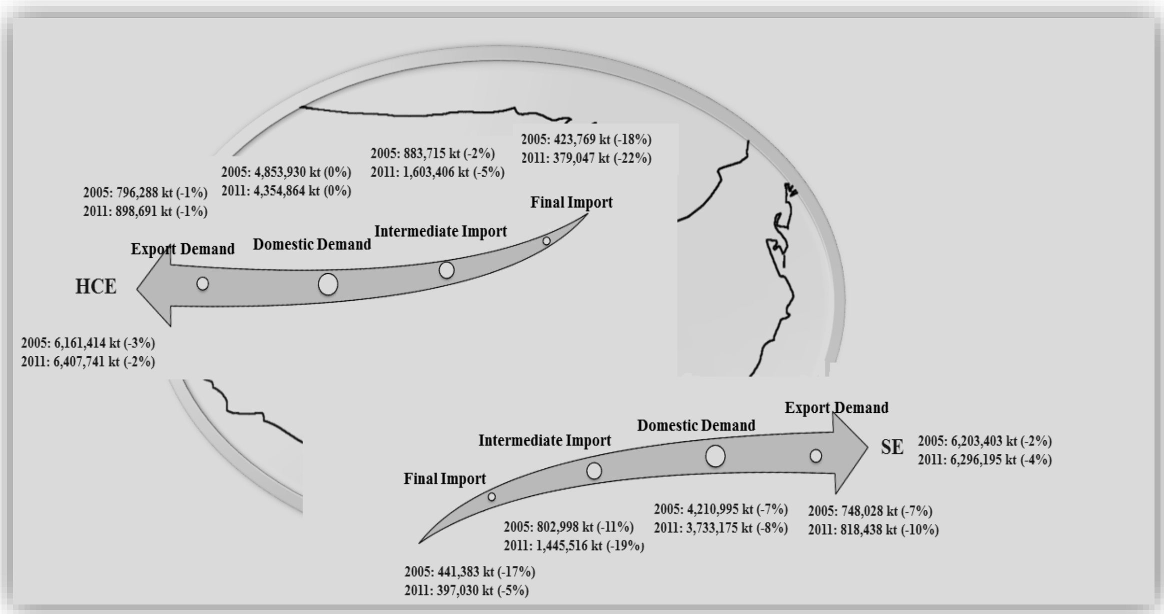


*Figure 3.5: U.S. Hypothetical Consumption Emissions (HCE) and Sharing-based Emissions (SE) by End Use, 2005 and 2011; kt of $CO_2$*

Notes: (i) The percentage changes in parentheses represent comparisons of the total emissions under the HCE and SE allocations with the total emissions under the CBE allocation;

(ii) The percentage changes in parentheses of exported emissions under the HCE and SE allocations were compared to exported emissions under the PBE allocation; and

(iii) The percentage changes in parentheses of imported emissions under the HCE and SE allocations were compared to imported emissions under the CBE allocation.

### 3.5.5 Impact Findings of the HCE Allocation

Table 3.3 shows emission burdens on three important measures under the HCE allocation. As shown in the first and fourth columns ($PBE_{row}/PBE_{col}$ ) on Table 3.3, emission burden on industrial role remained unchanged relative to the CBE allocation. This result was due to unchanged emissions attributable to domestic demand and infinitesimal changes in emissions attributable to export demand. In regard to a unilateral border tax standpoint, the little bit changes in exported emissions can be partially explained by low carbon intensities of U.S. industries relative to those of its trading partners to which U.S. exports were delivered[31].

As shown in the second and fifth columns ($HCE_{col}/PBE_{col}$ ) on Table 3.3, emission burdens of the HCE on industrial international trade declined by an average of 25% in 2005 compared with those of the CBE. Examples of industries with large declines include agriculture (-27%), food and beverages (-31%), paper (-30%), basic metals (-28%), transport equipment (-29%), and air transport (-29%). In 2011, HCE emission burdens on industrial international trade showed less percentages of the decline; which averaged 19% over the industries. The reason for the lower rate was due solely to the decrease in final imports of major carbon-intensive industries. Examples of industries with less negative percentages include refined petroleum, non-metallic minerals, basic metals, and manufacturing industries. In turn, some industries increasingly had more negative percentages in 2011 than in 2005, showing a greater emission burden from international trade. Examples include agriculture, food and beverages, leather, wood, machinery, and transport equipment industries. As shown in Figure 3.4, this finding is not surprising because these industries showed the continuous growth in emissions associated with final imports.

Comparing 2005 and 2011 percentages, those industries with small changes were ones with no visible growth in final imports relative to intermediate imports. These industries are electrical equipment, paper, and renting of machinery and equipment industries. This also refers to the case of industries of which the growth in emissions from their intermediate imports was greater than those from final imports. Chemicals, water transport service, air transport service, and health services industries were on track for this case.

In this respect, this analysis points out that the HCE allocation would allow industries to get lower emission burdens than the CBE allocation if there exists growth in emissions from final imports Six industries that show a decline in emission burdens when comparing the HCE and CBE, and also had discrepancies between $HCE_{col}$ and $PBE_{col}$ greater than 40% (numbers outside parentheses). These industries are agriculture (46%), rubber and plastics (49%), transport equipment (41%), post

[31] U.S. carbon intensity by industry will be later discussed in section 4.5.1 of Essay 3.

telecommunications (52%), and renting of machinery and equipment (42%). There are industries which are relatively dependent upon intermediate imports for production.

As shown in the third and sixth columns ($HCE_{row}/PBE_{row}$ ) on Table 3.3, the HCE did not show a great decline in emission burdens on industrial import content changes. Comparing with emission burdens of the CBE allocation, the HCE contributed more 15% of reduction within 10 industries in 2005. Examples of industries include agriculture (-20%), food and beverages (-16%), leather (-23%), non-metallic minerals (-23%), manufacturing (-16%), real estate (-23%), public administration (-23%), education (-23%), and other community services (-20%). However, these emission burden declines were a bit smaller in 2011. Particularly, five industries (paper, chemicals, rubber and plastics, transport equipment, and water transport service) had large discrepancies of emission burdens on import content changes greater than 40% under the HCE allocation. In regard to what the impact findings of the CBE tell us, this analysis points out that when linking between ($HCE_{col}/PBE_{col}$ ) and ($HCE_{row}/PBE_{row}$ ), those industries remained stronger emission burdens on industrial import content than those on industrial international trade.

These findings reflect that when taking international trade towards emission responsibilities of the U.S. economy, emission burdens under the HCE allocation declines relative to those under the CBE allocation. However, this allocation remains a serious problem of competitive disadvantages, in particular in five industries (paper, chemical, rubber and plastic, transport equipment, and water transport service). In this respect, the HCE allocation does not encourage industries to be responsible for imported emissions despite their products dependent on a large proportion of imports

*Table 3.3: Discrepancies between HCE and PBE by Industry, 2005 and 2011; All Numbers Are Percentage Change with Those in Parenthesis Comparing HCE and CBE*

| Industry | Year 2005 | | | Year 2011 | | |
|---|---|---|---|---|---|---|
| | $PBE_{row}/PBE_{col}$ | $HCE_{col}/PBE_{col}$ | $HCE_{row}/PBE_{row}$ | $PBE_{row}/PBE_{col}$ | $HCE_{col}/PBE_{col}$ | $HCE_{row}/PBE_{row}$ |
| **Agriculture, hunting, forestry and fishing** | 57 (0) | 46 (-27) | 33 (-20) | 66 (0) | 49 (-31) | 39 (-15) |
| **Mining and quarrying** | 67 (0) | -30 (-28) | -9 (-11) | 71 (0) | -33 (-19) | -11 (-8) |
| **Food, beverages and tobacco** | -53 (0) | 21 (-31) | 14 (-16) | -66 (0) | 22 (-32) | 18 (-14) |
| **Textiles and textile products** | 14 (0) | 12 (-14) | 12 (-11) | 19 (0) | 17 (-15) | 12 (-4) |
| **Leather and footwear** | -17 (0) | 12 (-16) | 9 (-23) | -15 (0) | 15 (-22) | 10 (-12) |
| **Wood and products of wood and cork** | -14 (0) | -20 (-16) | -31 (-10) | -18 (0) | -26 (-20) | -18 (-18) |
| **Pulp, paper, printing and publishing** | 12 (0) | 22 (-30) | 38 (-12) | 14 (0) | 28 (-30) | 47 (-5) |
| **Coke, refined petroleum and nuclear fuel** | 6 (0) | 3 (-18) | 5 (-3) | 3 (0) | 7 (-16) | 8 (-3) |
| **Chemicals and chemical products** | 9 (0) | 26 (-23) | 44 (-8) | 8 (0) | 29 (-23) | 57 (-4) |
| **Rubber and plastics** | 54 (0) | 49 (-29) | 66 (-7) | 56 (0) | 54 (-21) | 69 (-5) |
| **Other non-metallic minerals** | 56 (0) | 47 (-28) | 14 (-23) | 55 (0) | 51 (-19) | 31 (-8) |
| **Basic metals and fabricated metal** | 55 (0) | 32 (-31) | 44 (-12) | 51 (0) | 39 (-23) | 51 (-7) |
| **Machinery** | -35 (0) | 9 (-12) | 21 (-11) | -33 (0) | 10 (-20) | 24 (-15) |
| **Electrical and optical equipment** | -11 (0) | -12 (-15) | -6 (-1) | -25 (0) | -19 (-16) | -4 (-3) |
| **Transport equipment** | 9 (0) | 41 (-29) | 58 (-8) | 9 (0) | 41 (-31) | 64 (-4) |
| **Manufacturing, nec** | -33 (0) | 38 (-28) | 14 (-16) | -45 (0) | 49 (-19) | 20 (-18) |
| **Electricity, gas and water supply** | 13 (0) | -12 (-1) | -1 (-1) | 19 (0) | -14 (-3) | -2 (-3) |
| **Construction** | 59 (0) | -14 (-1) | 4 (-27) | 61 (0) | -12 (-3) | 10 (-3) |
| **Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel** | -16 (0) | 5 (-1) | 24 (-10) | -12 (0) | 4 (-3) | 25 (-10) |
| **Wholesale trade and commission trade** | -25 (0) | 15 (-12) | 9 (-1) | -27 (0) | 7 (-14) | 4 (-3) |
| **Retail trade, except of motor vehicles and motorcycles; repair of household goods** | -13 (0) | -14 (-19) | -11 (-12) | -18 (0) | -13 (-15) | -9 (-12) |
| **Hotels and restaurants** | -22 (0) | 10 (-18) | 8 (-1) | -27 (0) | 11 (-16) | 5 (-3) |
| **Inland transport** | 41 (0) | -4 (-1) | 1 (-1) | 32 (0) | -10 (-15) | 8 (-3) |
| **Water transport** | -33 (0) | 29 (-23) | 41 (-7) | -38 (0) | 33 (-22) | 48 (-5) |
| **Air transport** | 35 (0) | 20 (-29) | 13 (-10) | 36 (0) | 24 (-30) | 28 (-16) |
| **Other supporting and auxiliary transport activities** | 55 (0) | -2 (-1) | 15 (-8) | 52 (0) | -8 (-19) | 25 (-18) |
| **Post and telecommunications** | -60 (0) | 52 (0) | 43 (-7) | -68 (0) | 52 (-14) | 52 (-4) |
| **Financial intermediation** | -21 (0) | 14 (-16) | 11 (-1) | -28 (0) | 17 (-19) | 7 (-3) |
| **Real estate activities** | -19 (0) | 13 (-1) | 9 (-23) | -22 (0) | 22 (-5) | 21 (-16) |
| **Renting of machine and equipment** | -47 (0) | 42 (-29) | 43 (-5) | -48 (0) | 47 (-30) | 50 (-8) |
| **Public administration and defense** | -51 (0) | 10 (-1) | 9 (-23) | -53 (0) | 4 (-3) | 19 (-18) |
| **Education** | -16 (0) | -19 (-12) | -15 (-23) | -22 (0) | -24 (-18) | -8 (-3) |
| **Health and social work** | -28 (0) | 23 (-18) | 26 (-5) | -36 (0) | 24 (-20) | 25 (-11) |
| **Other community, social and personal services** | -36 (0) | 18 (-14) | 21 (-20) | -39 (0) | 22 (-16) | 18 (-23) |

### 3.5.6 Impact Findings of the SE Allocation

As shown in the first and fourth columns ($PBE_{row}/PBE_{col}$) on Table 3.4, the SE allocation shows a slight decline in emission burdens on a change in industrial role. This finding is not surprising because the SE allocation involve both emissions associated with domestic demand and emissions associated with export demand. Changes in PBE by columns are a part of exported emissions. Emission burdens of the SE allocation on industrial role changes showed more 5% decline within seventeen industries. However, seven of them showed consistent declines in 2011. Seven industries include chemicals (-9%), basic metals (-11%), transport equipment (-8%), water transport service (-9%), post and telecommunications (-11%), and renting of machinery and equipment (-10%). When deepening the analysis of different industry levels, the main reason for more negative percentage changes was due mostly to increasing export shares. This also refers to the case that increases in emissions attributable to export demand grew faster than decreases in emissions attributable to domestic demand. In this respect, this analysis points out that the SE allocation declines emission burdens on industrial role changes if there exists an increase in a composition of exported emissions.

The SE showed declines in emission burdens on changes in industrial international trade, but these declines were relatively small when compared with those of the HCE for the year 2005. In regard to what the impact finding of the HCE tell us, industries with a high proportion of final imports showed large reductions in these emission burdens. However, as shown in the fifth column ($SE_{col}/PBE_{col}$) on Table 3.4, negative percentages of the decline were larger within nine industries in 2011. These industries are chemicals (-48%), rubber and plastics (-42%), non-metallic minerals (-46%), basic metals (-42%), transport equipment (-41%), water transport service (-50%), post telecommunications (-42%), renting of machinery and equipment (-51%), and health services (-53%). The reason for the substantial declines was due in part to the increased composition of their industrial intermediate imports as clearly seen in Figure 3.4. This finding demonstrates that the major contribution of the SE reduction was due to declines in emissions from intermediate imports in 2011. In this respect, the SE allocation declines emission burdens on international trade changes if composition of emissions associated with intermediate import considerably increases.

As shown in the fourth column ($SE_{row}/PBE_{row}$) on Table 3.4, the SE also showed larger declines in emission burdens of some industries relative to the HCE in 2005. These industries are paper (-21%), chemicals (-29%), rubber and plastic (-30%), basic metals (-29%), machinery (-18%), transport equipment (-35%), manufacturing (-16%), water transport service (-28%), plus other supporting transport services (-29%). In 2011, four industries (chemicals, rubber and plastics, transport equipment, and water transport service) showed more negative percentages of the decline (numbers in parentheses of the sixth column).

For example, chemicals declined this emission burden from 29% to 38% whereas rubber and plastics declined from 30% to 37%. The reason for more percentages of declines was due to the proportion of industrial imports increasingly relating to the production process of products to deliver for export demand. It could be seen from the linkages between $PBE_{row}/PBE_{col}$ and $SE_{row}/PBE_{row}$. Due to large declines in emission burdens on both industrial role change and changes in import content, it has possibilities to encourage relevant industries that benefit from trade to involve the process of emission control occurring over networks of global supply chains. In addition, the SE allocation also declines emission burdens on both international trade changes and changes in import content of production. This implies that when taking international trade towards emission responsibilities of the U.S. economy, the SE allocation has high possibility to incorporate industries to be responsible for their imported emissions.

However, this analysis explores that strong discrepancies between SE by row versus PBE by row and SE by column versus PBE by column were clearly seen within two industries: chemicals and water transport service. In this respect, these industries may lose attention to the application of SE emission responsibilities since they are still challenged by a serious issue of a comparative disadvantage.

*Table 3.4: Discrepancies between SE and PBE, 2005 and 2011; All Numbers Are Percentage Changes with Those in Parenthesis Comparing SE and CBE*

| Industry | Year 2005 | | | Year 2011 | | |
|---|---|---|---|---|---|---|
| | $PBE_{row}/PBE_{col}$ | $SE_{col}/PBE_{col}$ | $SE_{row}/PBE_{row}$ | $PBE_{row}/PBE_{col}$ | $SE_{col}/PBE_{col}$ | $SE_{row}/PBE_{row}$ |
| **Agriculture, hunting, forestry and fishing** | 54 (-5) | 44 (-30) | 32 (-23) | 62 (-6) | 46 (-37) | 35 (-24) |
| **Mining and quarrying** | 63 (-6) | -23 (-19) | -9 (-14) | 66 (-6) | -27 (-26) | -11 (-5) |
| **Food, beverages and tobacco** | -51 (-4) | 19 (-36) | 14 (-16) | -63 (-4) | 19 (-40) | 17 (-19) |
| **Textiles and textile products** | 13 (-4) | 12 (-13) | 12 (-11) | 19 (-2) | 14 (-28) | 12 (-10) |
| **Leather and footwear** | -16 (-5) | 12 (-16) | 9 (-23) | -15 (-3) | 14 (-24) | 10 (-12) |
| **Wood and products of wood and cork** | -14 (-3) | -20 (-17) | -18 (-15) | -18 (-2) | -26 (-20) | -16 (-10) |
| **Pulp, paper, printing and publishing** | 11 (-7) | 23 (-27) | 20 (-21) | 13 (-7) | 26 (-35) | 19 (-22) |
| **Coke, refined petroleum and nuclear fuel** | 6 (0) | 3 (-19) | 5 (-3) | 3 (0) | 6 (-28) | 8 (-5) |
| **Chemicals and chemical products** | 8 (-7) | 20 (-30) | 34 (-29) | 7 (-9) | 17 (-48) | 37 (-38) |
| **Rubber and plastics** | 50 (-7) | 51 (-26) | 62 (-30) | 41 (-9) | 42 (-42) | 40 (-37) |
| **Other non-metallic minerals** | 54 (-3) | 44 (-24) | 15 (-15) | 49 (-8) | 37 (-46) | 30 (-12) |
| **Basic metals and fabricated metal** | 42 (-6) | 36 (-24) | 34 (-29) | 45 (-11) | 29 (-42) | 24 (-38) |
| **Machinery** | -34 (-4) | 9 (-13) | 15 (-18) | -32 (-4) | 9 (-22) | 13 (-19) |
| **Electrical and optical equipment** | -11 (0) | -13 (-19) | -6 (-3) | -25 (0) | -20 (-17) | -4 (-4) |
| **Transport equipment** | 8 (-6) | 44 (-24) | 41 (-35) | 8 (-8) | 37 (-41) | 35 (-39) |
| **Manufacturing, nec** | -32 (-4) | 46 (-24) | 14 (-16) | -44 (-2) | 39 (-33) | 21 (-11) |
| **Electricity, gas and water supply** | 13 (0) | -13 (-4) | -1 (-3) | 19 (0) | -15 (-6) | -2 (-11) |
| **Construction** | 59 (0) | -14 (-3) | 5 (-3) | 59 (-3) | -13 (-6) | 9 (-5) |
| **Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel** | -15 (-3) | 5 (-3) | 3 (-15) | -12 (-3) | 4 (-6) | 4 (-15) |
| **Wholesale trade and commission trade** | -24 (-3) | 15 (-13) | 8 (-15) | -27 (0) | 7 (-18) | 4 (-12) |
| **Retail trade, except of motor vehicles and motorcycles; repair of household goods** | -12 (-9) | -14 (-20) | -11 (-14) | -18 (-2) | -13 (-22) | -9 (-12) |
| **Hotels and restaurants** | -22 (0) | 10 (-19) | 8 (-3) | -27 (0) | 10 (-22) | 5 (-5) |
| **Inland transport** | 41 (-4) | -5 (-14) | 1 (-14) | 31 (-4) | -11 (-20) | 7 (-18) |
| **Water transport** | -31 (-7) | 24 (-31) | 29 (-28) | -35 (-9) | 20 (-50) | 31 (-39) |
| **Air transport** | 35 (0) | 20 (-27) | 11 (-19) | 36 (0) | 22 (-35) | 20 (-12) |
| **Other supporting and auxiliary transport activities** | 52 (-6) | -2 (-3) | 1 (-25) | 47 (-5) | -9 (-26) | 3 (-23) |
| **Post and telecommunications** | -57 (-5) | 38 (-27) | 36 (-27) | -61 (-11) | 35 (-42) | 31 (-24) |
| **Financial intermediation** | -21 (0) | 14 (-17) | 11 (-3) | -28 (0) | 17 (-20) | 7 (-5) |
| **Real estate activities** | -19 (-3) | 13 (-3) | 11 (-11) | -22 (-2) | 21 (-7) | 22 (-11) |
| **Renting of machine and equipment** | -44 (-5) | 41 (-26) | 35 (-29) | -42 (-10) | 33 (-51) | 31 (-24) |
| **Public administration and defense** | -48 (-5) | 9 (-10) | 9 (-23) | -52 (-2) | 3 (-18) | 20 (-12) |
| **Education** | -15 (-8) | -19 (-13) | -14 (-17) | -22 (0) | -25 (-24) | -9 (-15) |
| **Health and social work** | -26 (-6) | 18 (-36) | 11 (-19) | -34 (-6) | 14 (-53) | 12 (-23) |
| **Other community, social and personal services** | -34 (-6) | 18 (-14) | 14 (-18) | -38 (-4) | 22 (-17) | 20 (-18) |

## 3.6 Conclusions

Controlling carbon transfers may require a series of climate policies to be established. Correct identification of the consequences of emission allocations can lead to more effective policies. Global production fragmentation significantly affects the allocation of emissions embodied in international trade. Thus, differences between production-based emissions (PBE) and consumption-based emissions (CBE) allocations increasingly produce uneven policy actions and may increase a misleading view of mitigation efforts for the current carbon transfers. The SE allocation offers an alternative distinct from either the PBE or CBE allocation. However, the challenge facing the application of the SE remains how to define a weighting procedure. The primary objective of this essay is to design a weighting procedure for establishing shares of the emission allocation. The process of a SE allocation proposed in this essay complements a framework introduced by Peters (2008) with the application of multilateral border tax adjustments. Value added in embodied emissions is derived from effective carbon tariffs calculated based upon the EE-MRIO and the use of value-added exports (VAX) by Johnson and Noguera (2012). Further, a weighting element can be represented by a quotient of value added on emissions embodied in exports.

Due to uneven distributions between emissions and global trade intensities across economies, a change in emission allocations can produce significant emission responsibility burdens for specific industries. To identify emission allocations and examine mitigation effort levels, alternative approaches (HCE and SE allocations) are empirically applied to the U.S. economy for the years 2005 and 2011. The consequence of HCE and SE allocations are examined based upon conventional PBE and CBE allocations. The main findings of this essay are presented below.

At the level of the entire economy, CBE emissions exceed emissions of the PBE by 12% in 2005 and 29% in 2011. These findings empirically show large emission discrepancies between two allocations. Contributing to increased differences in emissions were growth in emissions attributable to intermediate imports and the slowdown in emissions attributable to domestic demand. Emissions attributable to intermediate import increased by almost two-fold between 2005 and 2011. Emissions attributable to domestic demand declined by roughly 13%. In this way, there is evidence that the U.S. economy induced emissions associated with intermediate imports at the same time partially avoided producing emissions at home. Taking emission responsibility for U.S. import demand becomes very important for dealing with the current carbon transfers.

The HCE emissions were projected to be lower than to the CBE emissions. In 2005, the HCE showed a 3% reduction. However, the HCE reduction was smaller in 2011; which remained 2%. The reason for the decline rate of reduction was due in part to changes in the composition of emissions attributable to final imports. This analysis finds that industries with a high composition of final imported emissions led to large reductions in emissions. Examples of these industries include agriculture, food and beverages, leather, wood, machinery, and transport equipment industries.

Conversely, the SE emissions declined by 2% in 2005 and almost 4% in 2011. A 4% reduction is equivalent to the percentage increase in the CBE emissions between 2005 and 2011. This implies that a SE allocation could take emissions embodied in U.S. international trade back to its 2005 level. Contributing to the larger rate of decline was due to not only emissions attributable to intermediate imports but also emissions attributable to export demand.

To get more detailed view of emission reductions, three aspects of industrial emission burdens are examined. These three aspects of industrial emission burdens include an industrial role change, a change in industrial international trade, and import content change of industries. The main findings of the CBE allocation reveal that ten industries showed greater than 40% of discrepancies among all three aspects in both 2005 and 2011. This means that the CBE allocation would put considerable emission burdens on these industries. These ten industries are agriculture, paper, chemicals, rubber and plastics, basic metals, transport equipment, water transport service, post telecommunications, health services, and renting of machinery and equipment industries.

Cross-aspect analyses of emission burdens indicate that if these burdens on changes in industrial import content are stronger than those of the other two burdens, then industries do not totally accept the CBE allocation because of the large emission responsibility burdens this allocation would entail. The products of these industries depend on a large proportion of imports. Implementing the CBE allocation causes a major problem by putting these industries at a competitive disadvantage. These industries are paper, chemicals, rubber and plastics, transport equipment, and water transport service industries. The acceptance issue on the CBE allocation includes the case that emission burdens on changes in industrial international trade are stronger than those on industrial role changes. In this respect, a decline in emission burdens on both industrial international trade and industrial import content are needed for incorporating industries to be responsible for their imported emissions.

In 2005, the HCE allocation declined emission burdens on international trade changes within ten industries in comparison with CBE allocation. However, the rates of decline were smaller for some industries in 2011. The reason for the declining rates was due solely to decreases in composition of emissions attributable to final imports. Examples of industries include non-metallic minerals and basic metals. Industries with higher rates are agriculture and transport equipment industries. As clearly seen in Figure 3.4, these findings are not surprising because the latter group of industries showed rapid growth in emissions attributable to final imports. The former group, in turn, showed growth in emissions attributable to final imports smaller than those attributable to intermediate imports.

In this respect, this analysis points out that the HCE allocation declines emission burdens on international trade if there exists growth in emissions from final imports, at least growth faster than those in intermediate imports. However, the HCE did not show a great decline in emission burdens on industrial import content changes except for agriculture and transport equipment industries. In this way, five industries (paper, chemicals, rubber and plastics, transport equipment, and water transport service industries) still confront with the issue of a competitive disadvantage due to strong emission burdens on import content.

A shift towards the SE allocation showed a great decline in industrial emission burdens among three measures relative to the CBE level. A great decline in emission burdens for industrial role changes occurred in industries associated with substantial increases in emissions attributable to export demand. Examples of these industries include agriculture, rubber and plastics, chemicals, basic metals, transport equipment, and water transport service industries. These industries except for agriculture industry showed a great decline in emission burdens from international trade changes too. This is relevant because those industries rapidly increased composition of emissions attributable to intermediate imports as shown in Figure 3.4. In this respect, this analysis points out that the SE allocation declines emission burdens on industrial international trade changes if there exists an increase in composition of emissions associated with intermediate imports.

The SE allocation showed a large decline in emission burdens on import content changes within four industries (chemicals, rubber and plastics, transport equipment, and water transport service). The reason for the large decline was due to their proportion of imports increasing relative to products exported. However, two industries (chemicals and water transport services) must be highlighted because discrepancies in emission burdens on their import content changes remained stronger than those in emission burdens on changes in their international trade. They may lose attention to the application of emission responsibilities.

Therefore, the importance of policy strategies recommended by this essay is that effectiveness and equitability should be regarded as complimentary tools for climate policies, in particular policies for dealing with carbon transfers as part of the fragmentation of international production of goods and services. This is relevant because the HCE and SE allocations can decline industrial emission burdens when taking international trade towards emission responsibilities of the U.S. economy (effectiveness standpoint). However, the SE allocation becomes more equitable in terms of declining both emission burdens on industrial role changes and changes in import content. The reason behind the decline in emission burdens on import content was due to the links between a proportion of industrial imports and products exported. Due to large declines in both emission burdens, the SE has high possibilities to encourage the commitment of importers that benefit from international trade to be involved the process of carbon transfer reductions. In context of global climate policies, more attention should be placed on mitigation efforts of industries with high carbon import content. Because emission burdens on import content are strong, they may lose attention to the application of emission responsibilities for carbon transfers in particular the importance of international production fragmentation. Based on the results of this essay, five industries (paper, chemicals, rubber and plastics, transport equipment, and water transport service) should be the focus of emission reduction policies at global levels.

In addition, it is critical that a balance between an appropriate emission allocation and a maintenance of international trade activities should be considered to establish long-term cooperative actions between inter-industries within and across economies. This may provide the direction for future work to investigate the nature of emissions of the different industries and their relationship that links between the distribution of industrial emissions and the structure of their export-import demands.

Even though this essay provides analyses of four allocation approaches and discusses advantages and disadvantages, it has several limitations to be characterized. First, the HCE modelled in this essay does not include additional government spending prevents within the U.S. economy from due to revenue from order taxes. Domestic final demand was not ever been adjusted. In this sense, calculations of emission responsibilities for thirty-four industries under the HCE allocation might not be absolutely precise. Second, tax rates used to calculate effective carbon tariff rates were for 2004 and 2010. The social cost of carbon used to estimate carbon taxes must be updated to the most recent year. This essay are used to be illustrative for the U.S. economy. If this weighting procedure is accepted, further study on identification of the emission allocation needs to be conducted and expanded to investigate impacts of other major economies.

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## Appendix 3-A

With the use of full MRIO, this essay considers the most possible determination of the carbon tariff rate with respect to comparable carbon intensities between importing and exporting economies, whereas previous studies normally chose carbon intensities of either importing or exporting economies in order to set carbon tariff rates (Clarke, 2010; Böhringer et al., 2011; Ghosh et al., 2012; Antimiani et al., 2013).

This essay makes a use of two assumptions in order to incorporate carbon tariffs into the underlying MRIO. First, carbon emission prices are set at \$50 per ton of CO2 in 2005 and \$56 in 2011 for a region of destination (i.e. a region that imports products)[32]. Second, tax revenue on carbon tariff rates do not stimulate the economy of destination through additional government spending. In this way, using region 1 as an example, when the border tax adjustment is considered, the monetary values of industry j outputs within region 2 are modified by carbon tariffs as:

$$\ddot{x}_j^{\,2} = x_j^{\,2} - \tau_j^{\,2} + \tau_j^{\,1} \tag{3.15}$$

where $\ddot{x}_j^2$ denotes the modified monetary value of industry j's outputs within region 2. $x_j^2$ is the original monetary value of industry j's outputs within region 2, which includes transportation of outputs between region 2 and region 1. $\tau_j^2$ is the carbon tariff associated with emission intensity of industry j in region 2. That is $\tau_j^2 = p_{co_2}^1 c_j^2 x_j^2$ where $p_{co_2}^1$ is equal to \$56. $\tau_j^1$ represents the carbon subsidy associated with emission intensity of industry j in region 1[33] such that $\tau_j^1 = p_{co_2}^1 c_j^1 x_j^1$. For this reason, $A^2$ is definitely recalculated. According to the mirror flow assumption, $A_m^{21}$ are redefined. Using the same procedure, $A^r$ and $A_m^{r1}$ (where r = 2, 3, and 4) must be recomputed and defined as $\bar{A}^r$ and $\bar{A}_m^{r1}$ so as to examine an effect of border adjustments on embodied trade emissions of the U.S. economy (region 1).

The expression of Equation (3.10) can be rewritten as:

$$HCE^1 = c^1(I-A^1)^{-1} y_f^{\,1} + \sum_{r\neq 1}(1-\phi^1)c^r(I-\bar{A}^r)^{-1}\left[\left(\bar{A}_m^{\,r1}(I-A^1)^{-1} y_{mf}^{\,1}\right)+\left(y_m^{\,r1}\right)\right] \tag{3.16}$$

[32] It is consistent with virtual carbon derived by Atkinson et al. (2013) in order to calculate carbon effective tariff rates. Later, these rates will take for multilaterally-coordinated border tax adjustments.

[33] In terms of the adjusted price of industry j, $\dot{p}_j^2 = p_j^2 + \tau i_j^2 - \tau i_j^1$ where $\dot{p}_j^2$ denotes the adjusted price of imports. $p_j^2$ is the original price of imports. $\tau i_j^2$ is the carbon tariff rate assigned to 1 unit of industry j's product imported from region 2. $\tau i_j^1$ is the carbon subsidy applied to 1 unit of industry j's product exported by region 1.

# Appendix 3-B

*Table 3.5: The Structure of the Symmetric WIOT, Industry by Industry*

| (Industry-by-Industry) | | Intermediate Demand | | | | | | | | | Final Demand | | | Output (Row Sum) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | R 1 | | | … | | | R41 | | | R 1 | … | R2 | |
| | | Ind 1 | … | Ind 34 | Ind 1 | … | Ind 34 | Ind 1 | … | Ind 34 | | | | |
| R 1 | Ind 1 | | | | | | | | | | | | | |
| | … | | | | | | | | | | | | | |
| | Ind 34 | | | | | | | | | | | | | |
| … | Ind 1 | | | | | | | | | | | | | |
| | … | | | | | | | | | | | | | |
| | Ind 34 | | | | | | | | | | | | | |
| R 41 | Ind 1 | | | | | | | | | | | | | |
| | … | | | | | | | | | | | | | |
| | Ind 34 | | | | | | | | | | | | | |
| Value added at basic prices | | | | | | | | | | | | | | |
| Output (Column Sum) | | | | | | | | | | | | | | |

Notes: (i) R represents a region in which starts from 1 to 41

(ii) Ind represents an industry in which starts from 1 to 34

(iii) Final demand can be further divided into five end-use categories as: final consumption expenditure by households, final consumption expenditure by non-profit organizations serving households, final consumption expenditure by government, gross fixed capital formation, and changes in inventories that were almost assumed to be 0.

*Table 3.6: The Effective Carbon Tariff Rates by Sector, 2005 and 2011, units are U.S. dollars per Thousand U.S. Dollars of Production.*

| Number | Sector | U.S. Carbon Effective Rates | | Canada Carbon Effective Rates | | China Carbon Effective Rates | | EU15 Carbon Effective Rates | | Japan Carbon Effective Rates | | Mexico Carbon Effective Rates | | ROW Carbon Effective Rates | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2005 | 2011 | 2005 | 2011 | 2005 | 2011 | 2005 | 2011 | 2005 | 2011 | 2005 | 2011 | 2005 | 2011 |
| 1 | Agriculture, forestry and fishing | 3 | 4 | 3 | 4 | 6 | 8 | 1 | 2 | 2 | 3 | 2 | 3 | 3 | 4 |
| 2 | Mining and quarrying (mineral products, natural gas and other mining) | 1 | 1 | 1 | 1 | 11 | 15 | 1 | 2 | 1 | 2 | 1 | 2 | 4 | 5 |
| 3 | Manufacture of food products | 3 | 4 | 4 | 6 | 18 | 25 | 2 | 3 | 0 | 0 | 0 | 0 | 4 | 7 |
| 4 | Manufacture of paper and paper products | 5 | 7 | 5 | 4 | 17 | 14 | 2 | 3 | 3 | 5 | 4 | 4 | 11 | 10 |
| 5 | Manufacture of coke and petroleum products (coal and refined oil) | 44 | 53 | 23 | 22 | 56 | 75 | 18 | 11 | 14 | 13 | 39 | 47 | 45 | 57 |
| 6 | Manufacture of chemicals and chemical products | 3 | 4 | 2 | 3 | 8 | 11 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 3 |
| 7 | Manufacture of rubber and plastics products | 1 | 1 | 1 | 1 | 5 | 7 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 3 |
| 8 | Manufacture of other non-metallic mineral products | 2 | 3 | 8 | 5 | 81 | 86 | 1 | 1 | 0 | 0 | 3 | 4 | 3 | 4 |
| 9 | Manufacture of basic metals (ferrous and non-ferrous metals) | 4 | 6 | 2 | 3 | 15 | 21 | 3 | 4 | 0 | 0 | 5 | 7 | 3 | 4 |
| 10 | Manufacture of machinery and equipment | 6 | 8 | 6 | 8 | 23 | 20 | 3 | 4 | 0 | 0 | 7 | 9 | 17 | 22 |
| 11 | Manufacture of transport equipment | 6 | 8 | 7 | 10 | 24 | 34 | 2 | 3 | 4 | 5 | 2 | 3 | 9 | 12 |
| 12 | Manufacture of textiles | 7 | 10 | 4 | 6 | 35 | 35 | 3 | 4 | 3 | 4 | 4 | 5 | 16 | 21 |
| 13 | Other manufacturing | 3 | 4 | 6 | 8 | 13 | 18 | 2 | 3 | 3 | 4 | 2 | 3 | 1 | 1 |
| 14 | Electricity, gas, and steam | 4 | 6 | 13 | 18 | 12 | 17 | 2 | 3 | 0 | 0 | 33 | 36 | 5 | 5 |
| 15 | Construction | 5 | 7 | 8 | 7 | 12 | 11 | 2 | 3 | 3 | 4 | 9 | 8 | 7 | 6 |
| 16 | Services | 4 | 6 | 5 | 7 | 13 | 18 | 1 | 1 | 1 | 1 | 2 | 2 | 6 | 5 |
| 17 | Accommodation and food processing services | 1 | 1 | 2 | 3 | 5 | 7 | 4 | 5 | 2 | 3 | 2 | 2 | 3 | 3 |
| 18 | Final services | 11 | 15 | 12 | 17 | 11 | 15 | 4 | 5 | 3 | 4 | 17 | 15 | 12 | 13 |
| 19 | Transport services | 2 | 3 | 1 | 1 | 8 | 11 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 3 |

Source: Atkinson et al. (2009; 2013)

*Table 3.7: The Industry Classification for Establishing Carbon Tariff Rates Based on Atkinson et al. (2009; 2013)*

| International Standard Industrial Classification of All Economic Activities (ISIC) | | | |
|---|---|---|---|
| 19 Sectors with Carbon Tariff | | 34 Industries from National and Inter-Country IO Tables | |
| Sector | | Industry | |
| 1 | Agriculture, forestry and fishing | 1 | Agriculture, forestry, and fishing |
| 2 | Mining and quarrying (mineral products, natural gas and other mining) | 2 | Mining and Quarrying |
| 3 | Manufacture of food products | 3 | Food, Beverages and Tobacco |
| 4 | Manufacture of paper and paper products | 4 | Pulp, Paper, Printing and Publishing |
| 5 | Manufacture of coke and petroleum products (coal and refined oil) | 5 | Coke, Refined Petroleum and Nuclear Fuel |
| 6 | Manufacture of chemicals and chemical products | 6 | Chemicals |
| 7 | Manufacture of rubber and plastics products | 7 | Rubber and Plastics |
| 8 | Manufacture of other non-metallic mineral products | 8 | Other Non-Metallic Minerals |
| 9 | Manufacture of basic metals (ferrous and non-ferrous metals) | 9 | Basic and Fabricated Metals |
| 10 | Manufacture of machinery and equipment | 10 | Machinery |
| | | 11 | Electrical and Optical Equipment |
| 11 | Manufacture of transport equipment | 12 | Transport Equipment |
| 12 | Manufacture of textiles | 13 | Textiles |
| 13 | Other manufacturing | 14 | Manufacturing, Nec; Recycling |
| | | 15 | Leather and Footwear |
| | | 16 | Wood and Cork |
| 14 | Electricity, gas, and steam | 17 | Electricity, Gas and Water Supply |
| 15 | Construction | 18 | Construction |
| 16 | Services | 19 | Sale, Maintenance and Repair of Motor Vehicles and Motorcycles |
| | | 20 | Wholesale Trade and Commission Trade, |
| | | 21 | Retail Trade |
| 17 | Accommodation and food processing services | 22 | Hotels and Restaurants |
| 18 | Final services | 23 | Post and Telecommunications |
| | | 24 | Financial Intermediation |
| | | 25 | Real Estate Activities |
| | | 26 | Renting of Machinery and Equipment |
| | | 27 | Public Administration and Defence |
| | | 28 | Education |
| | | 29 | Health and Social Work |
| | | 30 | Other Community, Social and Personal Services |
| 19 | Transport services | 31 | Inland Transport |
| | | 32 | Water Transport |
| | | 33 | Air Transport |
| | | 34 | Other Supporting and Auxiliary Transport |

Source: ISIC (2012)

# Appendix 3-C

*Table 3.8: A Breakdown of U.S. Production-Based Emissions (PBE) by Industry, 2005; kt of $CO_2$*

| Industry | Breakdown of U.S. PBE in kt of $CO_2$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | Domestic Demand | Export Demand | | | | | |
| | | Canada | China | EU15 | Japan | Mexico | ROW |
| Agriculture, hunting, forestry and fishing | 57,364 | 3,553 | 1,839 | 1,034 | 1,728 | 5,921 | 6,669 |
| Mining and quarrying | 114,411 | 3,967 | 8,802 | 6,357 | 1,930 | 4,977 | 16,247 |
| Food, beverages and tobacco | 85,617 | 5,513 | 449 | 446 | 2,710 | 4,189 | 7,349 |
| Textiles and textile products | 10,255 | 1,430 | 302 | 413 | 696 | 2,383 | 2,684 |
| Leather and footwear | 1,163 | 34 | 6 | 9 | 17 | 60 | 64 |
| Wood and products of wood and cork | 5,499 | 461 | 567 | 416 | 224 | 769 | 866 |
| Pulp, paper, printing and publishing | 113,361 | 2,925 | 1,193 | 2,734 | 1,453 | 4,874 | 5,490 |
| Coke, refined petroleum and nuclear fuel | 175,586 | 11,818 | 666 | 9,586 | 5,749 | 20,120 | 22,184 |
| Chemicals and chemical products | 357,933 | 26,252 | 12,864 | 22,106 | 12,770 | 32,933 | 49,278 |
| Rubber and plastics | 183,034 | 3,848 | 578 | 1,068 | 1,911 | 16,388 | 16,622 |
| Other non-metallic minerals | 149,461 | 1,687 | 2,131 | 2,630 | 821 | 15,617 | 16,927 |
| Basic metals and fabricated metal | 150,883 | 7,130 | 5,576 | 4,438 | 3,578 | 11,884 | 13,384 |
| Machinery | 36,038 | 5,351 | 1,695 | 2,266 | 2,603 | 9,110 | 10,044 |
| Electrical and optical equipment | 71,232 | 3,921 | 2,043 | 2,060 | 1,907 | 6,535 | 7,360 |
| Transport equipment | 103,064 | 16,494 | 14,804 | 3,305 | 7,896 | 27,637 | 30,960 |
| Manufacturing, nec | 95,895 | 1,501 | 218 | 399 | 730 | 2,501 | 2,817 |
| Electricity, gas and water supply | 1,448,871 | 34,709 | 19,835 | 19,031 | 17,239 | 57,848 | 45,152 |
| Construction | 334,210 | 2,365 | 0 | 0 | 1,150 | 1,942 | 2,440 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 8,118 | 2 | 0 | 0 | 1 | 3 | 125 |
| Wholesale trade and commission trade | 33,373 | 8,959 | 0 | 0 | 1,358 | 5,253 | 6,817 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 76,900 | 2,169 | 2,964 | 2,035 | 2,023 | 4,948 | 6,825 |
| Hotels and restaurants | 90,920 | 39 | 81 | 8 | 19 | 66 | 73 |
| Inland transport | 271,518 | 3,206 | 1,763 | 10,904 | 1,747 | 5,906 | 6,743 |
| Water transport | 71,682 | 2,684 | 12 | 1,774 | 1,305 | 4,473 | 5,038 |
| Air transport | 182,415 | 6,319 | 4,282 | 9,568 | 3,009 | 10,532 | 11,861 |
| Other supporting and auxiliary transport activities | 9,085 | 594 | 207 | 6,136 | 289 | 990 | 1,115 |
| Post and telecommunications | 78,071 | 3,215 | 1,114 | 1,808 | 1,105 | 3,366 | 3,403 |
| Financial intermediation | 40,936 | 1,425 | 83 | 4,245 | 693 | 2,374 | 2,674 |
| Real estate activities | 11,886 | 114 | 0 | 81 | 2 | 116 | 127 |
| Renting of machine and equipment | 101,582 | 1,386 | 1,252 | 8,370 | 674 | 2,310 | 2,602 |
| Public administration and defense | 148,060 | 4,347 | 2,710 | 1,517 | 1,169 | 6,592 | 13,652 |
| Education | 23,203 | 2,176 | 114 | 124 | 137 | 3,129 | 5,142 |
| Health and social work | 81,280 | 2,114 | 1 | 118 | 117 | 2,524 | 6,427 |
| Other community, social and personal services | 81,159 | 327 | 602 | 1,367 | 159 | 545 | 613 |
| Aggregate emissions by component | 4,853,930 | 74,269 | 72,202 | 260,378 | 46,068 | 73,000 | 278,416 |
| | | 804,331 | | | | | |
| U.S. Production Emissions (PBE) | 5,658,261 | | | | | | |

*Table 3.9: A Breakdown of U.S. Production-Based Emissions (PBE) by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of U.S. PBE in kt of $CO_2$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | Domestic Demand | Export Demand | | | | | |
| | | Canada | China | EU15 | Japan | Mexico | ROW |
| Agriculture, hunting, forestry and fishing | 55,693 | 3,820 | 1,936 | 1,088 | 1,819 | 6,367 | 14,467 |
| Mining and quarrying | 107,935 | 4,266 | 12,574 | 7,479 | 2,031 | 7,110 | 17,922 |
| Food, beverages and tobacco | 83,123 | 4,928 | 473 | 469 | 2,823 | 4,881 | 15,977 |
| Textiles and textile products | 9,584 | 1,538 | 318 | 435 | 732 | 2,563 | 2,856 |
| Leather and footwear | 1,118 | 37 | 6 | 9 | 18 | 61 | 68 |
| Wood and products of wood and cork | 5,237 | 496 | 597 | 438 | 236 | 827 | 922 |
| Pulp, paper, printing and publishing | 105,945 | 3,145 | 1,256 | 2,878 | 1,498 | 5,241 | 18,136 |
| Coke, refined petroleum and nuclear fuel | 145,112 | 12,708 | 701 | 10,091 | 6,051 | 21,179 | 23,600 |
| Chemicals and chemical products | 340,889 | 28,228 | 19,805 | 26,007 | 13,442 | 47,047 | 52,423 |
| Rubber and plastics | 172,673 | 4,137 | 608 | 1,124 | 1,970 | 16,895 | 17,683 |
| Other non-metallic minerals | 139,683 | 1,814 | 3,044 | 3,094 | 864 | 8,024 | 16,135 |
| Basic metals and fabricated metal | 157,170 | 7,667 | 5,869 | 4,672 | 3,651 | 12,778 | 14,239 |
| Machinery | 33,998 | 5,754 | 1,784 | 2,385 | 2,740 | 9,590 | 10,686 |
| Electrical and optical equipment | 52,764 | 4,216 | 2,151 | 2,168 | 2,008 | 7,027 | 7,830 |
| Transport equipment | 89,621 | 14,735 | 21,148 | 4,722 | 8,445 | 21,559 | 26,937 |
| Manufacturing, nec | 33,638 | 614 | 229 | 420 | 769 | 690 | 997 |
| Electricity, gas and water supply | 1,217,538 | 27,321 | 23,335 | 22,389 | 17,772 | 32,202 | 69,310 |
| Construction | 257,085 | 543 | 0 | 220 | 211 | 239 | 25,203 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 8,369 | 2 | 0 | 0 | 1 | 3 | 134 |
| Wholesale trade and commission trade | 35,129 | 2,634 | 0 | 1,804 | 4,587 | 3,056 | 5,891 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 79,279 | 1,482 | 3,120 | 800 | 135 | 2,471 | 23,514 |
| Hotels and restaurants | 88,272 | 42 | 85 | 8 | 20 | 1,269 | 26,658 |
| Inland transport | 285,809 | 5,862 | 1,856 | 11,478 | 1,839 | 9,437 | 18,173 |
| Water transport | 52,323 | 2,886 | 13 | 1,867 | 1,374 | 4,810 | 16,754 |
| Air transport | 190,015 | 6,795 | 6,117 | 13,668 | 3,236 | 11,324 | 12,618 |
| Other supporting and auxiliary transport activities | 9,464 | 639 | 218 | 6,459 | 304 | 1,064 | 1,186 |
| Post and telecommunications | 95,208 | 2,231 | 1,120 | 1,903 | 1,110 | 3,385 | 6,429 |
| Financial intermediation | 38,258 | 1,532 | 87 | 468 | 729 | 1,553 | 2,845 |
| Real estate activities | 12,644 | 4 | 0 | 43 | 2 | 7 | 7 |
| Renting of machine and equipment | 95,833 | 1,490 | 1,318 | 8,810 | 710 | 2,484 | 2,768 |
| Public administration and defense | 155,852 | 5,374 | 2,853 | 1,544 | 1,178 | 7,623 | 14,652 |
| Education | 21,890 | 1,181 | 2,576 | 1,125 | 939 | 2,136 | 5,151 |
| Health and social work | 95,624 | 1,515 | 1 | 19 | 7 | 3,524 | 28,564 |
| Other community, social and personal services | 82,816 | 351 | 634 | 1,439 | 167 | 586 | 652 |
| Aggregate emissions by component | 4,354,864 | 59,232 | 98,838 | 287,010 | 37,001 | 84,108 | 345,263 |
| | | 911,451 | | | | | |
| U.S. Production Emissions (PBE) | 5,266,315 | | | | | | |

*Table 3.10: A Breakdown of Emissions from U.S. Intermediate Import by Industry, 2005; kt of $CO_2$*

| Industry | Breakdown of the Emissions from U.S. Intermediate Import | | | | | |
|---|---|---|---|---|---|---|
| | Canada | China | EU15 | Japan | Mexico | ROW |
| Agriculture, hunting, forestry and fishing | 11,398 | 17,891 | 1,898 | 137 | 5,591 | 9,924 |
| Mining and quarrying | 12,565 | 3,708 | 2,493 | 174 | 4,113 | 2,508 |
| Food, beverages and tobacco | 4,203 | 1,573 | 510 | 2,326 | 2,469 | 6,038 |
| Textiles and textile products | 197 | 2,501 | 774 | 70 | 3,203 | 1,958 |
| Leather and footwear | 7 | 121 | 69 | 447 | 20 | 1,006 |
| Wood and products of wood and cork | 1,135 | 1,236 | 414 | 676 | 88 | 240 |
| Pulp, paper, printing and publishing | 4,898 | 20,171 | 15,099 | 318 | 421 | 23,543 |
| Coke, refined petroleum and nuclear fuel | 3,313 | 7,409 | 2,397 | 2,695 | 3,550 | 6,973 |
| Chemicals and chemical products | 11,711 | 74,349 | 32,515 | 4,019 | 11,707 | 39,468 |
| Rubber and plastics | 409 | 26,307 | 16,816 | 130 | 1,313 | 30,567 |
| Other non-metallic minerals | 107 | 48,196 | 19,030 | 25 | 4,372 | 33,101 |
| Basic metals and fabricated metal | 6,557 | 41,039 | 26,616 | 6,185 | 2,077 | 33,798 |
| Machinery | 1,271 | 1,242 | 382 | 2,157 | 1,100 | 2,907 |
| Electrical and optical equipment | 450 | 707 | 441 | 457 | 216 | 7,107 |
| Transport equipment | 1,081 | 1,082 | 333 | 4,775 | 15,298 | 4,282 |
| Manufacturing, nec | 1,182 | 1,366 | 1,403 | 100 | 1,527 | 2,966 |
| Electricity, gas and water supply | 2,182 | 27,785 | 4,968 | 4,424 | 6,638 | 11,785 |
| Construction | 396 | 394 | 121 | 531 | 416 | 561 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 382 | 162 | 49 | 581 | 166 | 225 |
| Wholesale trade and commission trade | 502 | 706 | 217 | 859 | 317 | 793 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 437 | 339 | 277 | 132 | 776 | 1,544 |
| Hotels and restaurants | 545 | 196 | 183 | 233 | 802 | 784 |
| Inland transport | 1,531 | 259 | 404 | 395 | 1,586 | 5,059 |
| Water transport | 669 | 16,591 | 7,070 | 764 | 167 | 17,515 |
| Air transport | 5,671 | 7,570 | 2,779 | 12,842 | 1,869 | 25,039 |
| Other supporting and auxiliary transport activities | 219 | 791 | 290 | 139 | 392 | 4,145 |
| Post and telecommunications | 1,413 | 18,450 | 10,012 | 3,408 | 1,464 | 10,632 |
| Financial intermediation | 1,510 | 917 | 390 | 2,690 | 1,666 | 1,618 |
| Real estate activities | 85 | 127 | 54 | 35 | 120 | 206 |
| Renting of machine and equipment | 1,931 | 20,605 | 9,373 | 1,282 | 5,443 | 16,602 |
| Public administration and defense | 128 | 139 | 59 | 9 | 86 | 166 |
| Education | 35 | 3 | 44 | 3 | 87 | 162 |
| Health and social work | 11,130 | 21,065 | 7,482 | 1,682 | 7,380 | 28,011 |
| Other community, social and personal services | 1,828 | 952 | 405 | 118 | 868 | 1,137 |
| Aggregate emissions by component | 130,268 | 208,022 | 133,582 | 61,237 | 111,293 | 258,805 |
| Aggregate Emissions from Intermediate Import | 903,208 | | | | | |

*Table 3.11: A Breakdown of Emissions from U.S. Intermediate Import by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of Emissions from U.S. Intermediate Import | | | | | |
|---|---|---|---|---|---|---|
| | **Canada** | **China** | **EU15** | **Japan** | **Mexico** | **ROW** |
| Agriculture, hunting, forestry and fishing | 11,513 | 21,048 | 2,157 | 148 | 6,077 | 18,043 |
| Mining and quarrying | 12,692 | 4,120 | 2,833 | 189 | 4,471 | 3,135 |
| Food, beverages and tobacco | 4,246 | 1,788 | 579 | 2,528 | 2,683 | 7,547 |
| Textiles and textile products | 199 | 2,719 | 880 | 76 | 3,482 | 2,447 |
| Leather and footwear | 7 | 142 | 78 | 486 | 22 | 1,258 |
| Wood and products of wood and cork | 1,146 | 1,454 | 471 | 735 | 96 | 300 |
| Pulp, paper, printing and publishing | 4,948 | 63,033 | 17,158 | 346 | 458 | 29,429 |
| Coke, refined petroleum and nuclear fuel | 3,347 | 8,716 | 2,820 | 2,929 | 6,017 | 8,716 |
| Chemicals and chemical products | 11,829 | 99,132 | 25,602 | 4,368 | 13,154 | 49,335 |
| Rubber and plastics | 413 | 82,209 | 22,126 | 141 | 1,563 | 38,208 |
| Other non-metallic minerals | 108 | 66,939 | 25,039 | 27 | 5,205 | 41,377 |
| Basic metals and fabricated metal | 6,623 | 128,248 | 35,021 | 6,722 | 2,472 | 42,248 |
| Machinery | 1,283 | 1,553 | 502 | 2,345 | 1,310 | 5,285 |
| Electrical and optical equipment | 455 | 884 | 580 | 497 | 258 | 8,884 |
| Transport equipment | 1,162 | 1,353 | 438 | 5,190 | 25,928 | 5,353 |
| Manufacturing, nec | 1,219 | 1,707 | 1,846 | 109 | 1,660 | 3,707 |
| Electricity, gas and water supply | 2,227 | 34,731 | 6,537 | 4,809 | 7,215 | 14,731 |
| Construction | 404 | 492 | 159 | 577 | 452 | 702 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 390 | 202 | 65 | 632 | 180 | 281 |
| Wholesale trade and commission trade | 512 | 882 | 285 | 933 | 344 | 992 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 446 | 424 | 364 | 144 | 843 | 1,930 |
| Hotels and restaurants | 556 | 245 | 241 | 253 | 872 | 980 |
| Inland transport | 1,563 | 324 | 531 | 429 | 2,688 | 6,324 |
| Water transport | 682 | 51,846 | 9,303 | 830 | 182 | 31,846 |
| Air transport | 5,787 | 11,299 | 3,656 | 13,958 | 2,031 | 31,299 |
| Other supporting and auxiliary transport activities | 223 | 1,181 | 382 | 151 | 426 | 5,181 |
| Post and telecommunications | 1,442 | 27,538 | 13,174 | 3,705 | 1,591 | 13,289 |
| Financial intermediation | 1,541 | 1,369 | 443 | 2,924 | 1,811 | 2,023 |
| Real estate activities | 86 | 189 | 61 | 38 | 131 | 258 |
| Renting of machine and equipment | 1,971 | 30,753 | 10,773 | 1,393 | 5,916 | 20,753 |
| Public administration and defense | 131 | 208 | 67 | 9 | 94 | 208 |
| Education | 36 | 5 | 50 | 3 | 94 | 202 |
| Health and social work | 11,358 | 31,440 | 8,407 | 1,829 | 8,022 | 35,014 |
| Other community, social and personal services | 1,865 | 1,421 | 460 | 128 | 944 | 1,421 |
| Aggregate emissions by component | 140,773 | 553,815 | 195,352 | 65,679 | 193,220 | 641,286 |
| Aggregate Emissions from Intermediate Import | 1,790,126 | | | | | |

*Table 3.12: A Breakdown of Emissions from U.S. Final Import by Industry, 2005; kt of $CO_2$*

| Industry | Breakdown of Emissions from U.S. Final Import | | | | | |
|---|---|---|---|---|---|---|
| | Canada | China | EU15 | Japan | Mexico | ROW |
| Agriculture, hunting, forestry and fishing | 5,968 | 3,021 | 408 | 144 | 2,127 | 6,075 |
| Mining and quarrying | 6,580 | 500 | 930 | 183 | 2,066 | 1,056 |
| Food, beverages and tobacco | 2,158 | 1,604 | 2,053 | 269 | 939 | 3,214 |
| Textiles and textile products | 103 | 1,170 | 94 | 74 | 1,219 | 824 |
| Leather and footwear | 3 | 4,245 | 37 | 1,196 | 2,518 | 4,396 |
| Wood and products of wood and cork | 594 | 43 | 56 | 711 | 34 | 91 |
| Pulp, paper, printing and publishing | 13,365 | 12,024 | 579 | 335 | 17,586 | 8,917 |
| Coke, refined petroleum and nuclear fuel | 1,735 | 1,251 | 12,187 | 5,740 | 15,435 | 2,641 |
| Chemicals and chemical products | 16,932 | 13,732 | 20,699 | 4,228 | 5,631 | 32,724 |
| Rubber and plastics | 1,294 | 11,724 | 169 | 137 | 2,085 | 11,577 |
| Other non-metallic minerals | 56 | 2,818 | 4,431 | 26 | 895 | 5,467 |
| Basic metals and fabricated metal | 3,434 | 6,063 | 3,174 | 6,507 | 1,004 | 12,801 |
| Machinery | 665 | 2,194 | 510 | 4,206 | 532 | 4,631 |
| Electrical and optical equipment | 236 | 1,275 | 202 | 481 | 511 | 2,692 |
| Transport equipment | 516 | 1,049 | 1,435 | 1,394 | 1,537 | 3,642 |
| Manufacturing, nec | 632 | 819 | 3,312 | 106 | 2,298 | 1,729 |
| Electricity, gas and water supply | 5,474 | 17,714 | 2,509 | 4,655 | 17,429 | 14,563 |
| Construction | 210 | 244 | 317 | 558 | 3,740 | 516 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 25 | 113 | 25 | 67 | 23 | 75 |
| Wholesale trade and commission trade | 1,821 | 2,869 | 1,578 | 903 | 1,171 | 604 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 210 | 180 | 179 | 18 | 320 | 585 |
| Hotels and restaurants | 56 | 21 | 99 | 124 | 105 | 327 |
| Inland transport | 836 | 84 | 54 | 52 | 1,191 | 1,714 |
| Water transport | 354 | 4,571 | 455 | 804 | 64 | 9,649 |
| Air transport | 2,000 | 4,492 | 2,138 | 512 | 711 | 4,484 |
| Other supporting and auxiliary transport activities | 116 | 105 | 230 | 146 | 429 | 888 |
| Post and telecommunications | 99 | 35 | 666 | 77 | 57 | 88 |
| Financial intermediation | 99 | 16 | 67 | 11 | 134 | 179 |
| Real estate activities | 70 | 16 | 109 | 13 | 131 | 139 |
| Renting of machine and equipment | 1,022 | 1,578 | 333 | 348 | 871 | 2,288 |
| Public administration and defense | 10 | 64 | 7 | 5 | 13 | 63 |
| Education | 8 | 2 | 6 | 15 | 43 | 31 |
| Health and social work | 56 | 22 | 31 | 0 | 10 | 75 |
| Other community, social and personal services | 103 | 76 | 126 | 124 | 205 | 633 |
| Aggregate emissions by component | 67,739 | 95,616 | 66,149 | 48,989 | 108,931 | 146,163 |
| Aggregate Emissions from Final Import | 533,588 | | | | | |

*Table 3.13: A Breakdown of Emissions from U.S. Final Import by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of Emissions from U.S. Final Import | | | | | |
|---|---|---|---|---|---|---|
| | Canada | China | EU15 | Japan | Mexico | ROW |
| Agriculture, hunting, forestry and fishing | 5,526 | 4,873 | 343 | 119 | 1,702 | 7,614 |
| Mining and quarrying | 6,092 | 641 | 782 | 151 | 1,252 | 1,045 |
| Food, beverages and tobacco | 1,998 | 2,056 | 1,725 | 223 | 751 | 3,182 |
| Textiles and textile products | 95 | 1,500 | 79 | 61 | 975 | 816 |
| Leather and footwear | 3 | 5,443 | 32 | 988 | 1,526 | 4,353 |
| Wood and products of wood and cork | 550 | 55 | 47 | 588 | 27 | 90 |
| Pulp, paper, printing and publishing | 12,375 | 15,415 | 487 | 277 | 12,128 | 8,829 |
| Coke, refined petroleum and nuclear fuel | 1,606 | 1,604 | 10,241 | 4,744 | 10,645 | 2,615 |
| Chemicals and chemical products | 15,678 | 17,606 | 17,394 | 3,495 | 3,883 | 32,400 |
| Rubber and plastics | 1,198 | 15,030 | 143 | 113 | 1,438 | 11,463 |
| Other non-metallic minerals | 52 | 3,613 | 3,211 | 22 | 617 | 5,413 |
| Basic metals and fabricated metal | 3,179 | 7,774 | 2,690 | 5,378 | 692 | 12,674 |
| Machinery | 616 | 2,812 | 432 | 3,476 | 367 | 4,585 |
| Electrical and optical equipment | 218 | 1,635 | 172 | 398 | 352 | 2,665 |
| Transport equipment | 478 | 1,345 | 1,205 | 1,152 | 1,060 | 3,606 |
| Manufacturing, nec | 585 | 1,050 | 2,400 | 87 | 1,585 | 1,712 |
| Electricity, gas and water supply | 5,069 | 22,711 | 2,127 | 3,847 | 12,020 | 14,419 |
| Construction | 194 | 313 | 269 | 461 | 267 | 511 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 23 | 145 | 21 | 55 | 18 | 74 |
| Wholesale trade and commission trade | 1,686 | 3,678 | 1,337 | 747 | 936 | 598 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 194 | 231 | 152 | 15 | 256 | 579 |
| Hotels and restaurants | 52 | 27 | 84 | 102 | 84 | 324 |
| Inland transport | 774 | 108 | 46 | 43 | 953 | 1,697 |
| Water transport | 327 | 5,860 | 385 | 664 | 51 | 9,554 |
| Air transport | 2,778 | 5,759 | 6,897 | 11,167 | 569 | 9,390 |
| Other supporting and auxiliary transport activities | 107 | 2,057 | 195 | 121 | 343 | 3,354 |
| Post and telecommunications | 92 | 45 | 565 | 64 | 46 | 87 |
| Financial intermediation | 92 | 20 | 56 | 9 | 107 | 177 |
| Real estate activities | 65 | 20 | 93 | 11 | 105 | 137 |
| Renting of machine and equipment | 946 | 3,819 | 1,130 | 1,114 | 1,657 | 6,226 |
| Public administration and defense | 9 | 82 | 6 | 4 | 10 | 62 |
| Education | 7 | 2 | 5 | 13 | 34 | 31 |
| Health and social work | 52 | 29 | 26 | 0 | 8 | 74 |
| Other community, social and personal services | 95 | 97 | 107 | 102 | 164 | 626 |
| Aggregate emissions by component | 54,733 | 112,696 | 28,896 | 42,560 | 43,822 | 133,829 |
| Aggregate Emissions from Final Import | 416,536 | | | | | |

*Table 3.14: U.S. Consumption-Based Emissions (CBE) and Production-Based Emissions (PBE) by Rows and by Columns, 2005 and 2011; kt of $CO_2$*

| Industry | 2005 | | | | 2011 | | | |
|---|---|---|---|---|---|---|---|---|
| | $PBE_{row}$ | $PBE_{col}$ | $CBE_{row}$ | $CBE_{col}$ | $PBE_{row}$ | $PBE_{col}$ | $CBE_{row}$ | $CBE_{col}$ |
| Agriculture, hunting, forestry and fishing | 103,565 | 65,965 | 146,027 | 107,523 | 101,981 | 61,434 | 148,892 | 105,667 |
| Mining and quarrying | 141,140 | 84,515 | 129,849 | 75,218 | 156,076 | 91,272 | 140,468 | 77,581 |
| Food, beverages and tobacco | 127,761 | 171,831 | 149,480 | 223,380 | 134,497 | 255,578 | 162,741 | 339,919 |
| Textiles and textile products | 39,664 | 34,793 | 45,217 | 39,664 | 17,653 | 14,834 | 19,947 | 17,801 |
| Leather and footwear | 1,667 | 2,008 | 1,867 | 2,289 | 1,323 | 1,557 | 1,469 | 1,853 |
| Wood and products of wood and cork | 12,206 | 14,193 | 8,788 | 11,780 | 10,750 | 13,110 | 9,138 | 10,226 |
| Pulp, paper, printing and publishing | 107,707 | 96,167 | 154,021 | 126,941 | 92,111 | 80,799 | 138,167 | 113,119 |
| Coke, refined petroleum and nuclear fuel | 385,215 | 363,411 | 404,476 | 377,947 | 291,078 | 282,600 | 314,365 | 305,209 |
| Chemicals and chemical products | 417,383 | 382,920 | 621,900 | 490,138 | 625,709 | 579,360 | 994,878 | 764,756 |
| Rubber and plastics | 15,108 | 9,810 | 24,173 | 16,481 | 40,310 | 27,609 | 69,736 | 47,488 |
| Other non-metallic minerals | 50,083 | 32,105 | 59,098 | 50,725 | 72,875 | 50,259 | 97,653 | 84,937 |
| Basic metals and fabricated metal | 189,490 | 130,682 | 284,234 | 192,103 | 46,271 | 32,817 | 71,721 | 49,553 |
| Machinery | 38,655 | 59,469 | 47,932 | 65,416 | 35,670 | 53,239 | 45,658 | 59,627 |
| Electrical and optical equipment | 83,300 | 93,595 | 78,302 | 83,300 | 40,179 | 53,573 | 38,572 | 44,465 |
| Transport equipment | 224,853 | 206,288 | 366,511 | 325,934 | 201,638 | 184,989 | 334,720 | 295,983 |
| Manufacturing, nec | 9,109 | 13,596 | 10,658 | 21,890 | 6,204 | 11,280 | 7,693 | 17,823 |
| Electricity, gas and water supply | 1,991,521 | 1,762,408 | 1,971,605 | 1,550,919 | 1,582,998 | 1,230,251 | 1,551,338 | 1,058,016 |
| Construction | 472,087 | 296,910 | 495,691 | 255,342 | 282,061 | 175,193 | 310,268 | 154,170 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 12,401 | 14,764 | 15,750 | 15,502 | 13,923 | 15,822 | 17,822 | 16,455 |
| Wholesale trade and commission trade | 51,596 | 68,795 | 56,240 | 80,490 | 41,877 | 57,366 | 43,552 | 61,955 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 59,085 | 67,914 | 53,176 | 59,764 | 127,309 | 75,255 | 117,125 | 66,977 |
| Hotels and restaurants | 92,082 | 118,054 | 99,449 | 132,221 | 85,322 | 66,880 | 89,588 | 75,574 |
| Inland transport | 181,912 | 129,015 | 183,731 | 123,855 | 207,447 | 137,157 | 224,042 | 124,812 |
| Water transport | 135,998 | 202,983 | 195,838 | 274,026 | 49,544 | 79,910 | 74,812 | 111,075 |
| Air transport | 70,931 | 52,541 | 80,861 | 67,253 | 182,392 | 134,112 | 244,406 | 179,710 |
| Other supporting and auxiliary transport activities | 19,517 | 12,592 | 22,640 | 12,340 | 25,734 | 17,747 | 33,454 | 16,505 |
| Post and telecommunications | 88,746 | 221,865 | 129,569 | 337,235 | 139,388 | 385,587 | 214,657 | 616,939 |
| Financial intermediation | 63,567 | 80,465 | 70,560 | 94,144 | 42,600 | 59,166 | 45,582 | 71,591 |
| Real estate activities | 21,491 | 26,532 | 24,070 | 29,981 | 12,692 | 16,272 | 15,865 | 20,014 |
| Renting of machine and equipment | 63,208 | 119,260 | 91,651 | 184,852 | 68,235 | 131,222 | 105,082 | 219,141 |
| Public administration and defense | 196,453 | 400,924 | 220,027 | 441,016 | 245,202 | 451,706 | 301,598 | 469,774 |
| Education | 22,920 | 27,286 | 20,170 | 22,647 | 35,444 | 45,441 | 32,609 | 36,353 |
| Health and social work | 55,639 | 77,276 | 70,661 | 98,914 | 124,380 | 194,343 | 159,206 | 252,646 |
| Other community, social and personal services | 132,771 | 207,455 | 167,292 | 251,021 | 115,036 | 188,584 | 142,645 | 237,616 |

*Table 3.15: U.S. Hypothetical Consumption Emissions (HCE) and Production-Based Emissions (PBE) by Rows and by Columns, 2005 and 2011; kt of $CO_2$*

| Industry | 2005 | | | | 2011 | | | |
|---|---|---|---|---|---|---|---|---|
| | $PBE_{row}$ | $PBE_{col}$ | $HCE_{row}$ | $HCE_{col}$ | $PBE_{row}$ | $PBE_{col}$ | $HCE_{row}$ | $HCE_{col}$ |
| Agriculture, hunting, forestry and fishing | 103,565 | 65,965 | 137,365 | 96,220 | 101,981 | 61,434 | 141,874 | 91,831 |
| Mining and quarrying | 141,140 | 84,515 | 128,620 | 73,954 | 156,076 | 91,272 | 139,195 | 75,906 |
| Food, beverages and tobacco | 127,761 | 171,831 | 145,935 | 207,256 | 134,497 | 255,578 | 158,900 | 312,391 |
| Textiles and textile products | 39,664 | 34,793 | 44,612 | 39,001 | 17,653 | 14,834 | 19,854 | 17,357 |
| Leather and footwear | 1,667 | 2,008 | 1,820 | 2,243 | 1,323 | 1,557 | 1,451 | 1,788 |
| Wood and products of wood and cork | 12,206 | 14,193 | 8,463 | 11,386 | 10,750 | 13,110 | 8,853 | 9,637 |
| Pulp, paper, printing and publishing | 107,707 | 96,167 | 148,353 | 117,733 | 92,111 | 80,799 | 135,662 | 103,449 |
| Coke, refined petroleum and nuclear fuel | 385,215 | 363,411 | 403,952 | 375,377 | 291,078 | 282,600 | 313,731 | 299,367 |
| Chemicals and chemical products | 417,383 | 382,920 | 582,960 | 462,433 | 625,709 | 579,360 | 954,712 | 724,414 |
| Rubber and plastics | 15,108 | 9,810 | 23,556 | 14,576 | 40,310 | 27,609 | 68,135 | 42,622 |
| Other non-metallic minerals | 50,083 | 32,105 | 57,014 | 44,648 | 72,875 | 50,259 | 95,631 | 75,977 |
| Basic metals and fabricated metal | 189,490 | 130,682 | 272,638 | 172,891 | 46,271 | 32,817 | 69,644 | 45,684 |
| Machinery | 38,655 | 59,469 | 46,923 | 64,688 | 35,670 | 53,239 | 44,163 | 58,324 |
| Electrical and optical equipment | 83,300 | 93,595 | 78,370 | 80,359 | 40,179 | 53,573 | 38,616 | 41,740 |
| Transport equipment | 224,853 | 206,288 | 358,805 | 291,763 | 201,638 | 184,989 | 323,860 | 261,264 |
| Manufacturing, nec | 9,109 | 13,596 | 10,405 | 19,183 | 6,204 | 11,280 | 7,430 | 16,310 |
| Electricity, gas and water supply | 1,991,521 | 1,762,408 | 1,971,335 | 1,548,042 | 1,582,998 | 1,230,251 | 1,550,477 | 1,053,331 |
| Construction | 472,087 | 296,910 | 489,270 | 254,777 | 282,061 | 175,193 | 309,500 | 153,598 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 12,401 | 14,764 | 15,431 | 15,492 | 13,923 | 15,822 | 17,450 | 16,437 |
| Wholesale trade and commission trade | 51,596 | 68,795 | 56,177 | 79,058 | 41,877 | 57,366 | 43,507 | 61,331 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 59,085 | 67,914 | 52,453 | 58,212 | 127,309 | 75,255 | 115,878 | 65,739 |
| Hotels and restaurants | 92,082 | 118,054 | 99,349 | 129,716 | 85,322 | 66,880 | 89,472 | 74,155 |
| Inland transport | 181,912 | 129,015 | 183,706 | 123,785 | 207,447 | 137,157 | 223,591 | 122,966 |
| Water transport | 135,998 | 202,983 | 191,768 | 250,838 | 49,544 | 79,910 | 73,437 | 102,174 |
| Air transport | 70,931 | 52,541 | 79,916 | 63,051 | 182,392 | 134,112 | 234,285 | 166,067 |
| Other supporting and auxiliary transport activities | 19,517 | 12,592 | 22,385 | 12,343 | 25,734 | 17,747 | 32,089 | 16,269 |
| Post and telecommunications | 88,746 | 221,865 | 126,793 | 337,235 | 139,388 | 385,587 | 211,586 | 585,476 |
| Financial intermediation | 63,567 | 80,465 | 70,465 | 91,912 | 42,600 | 59,166 | 45,501 | 69,226 |
| Real estate activities | 21,491 | 26,532 | 23,473 | 29,934 | 12,692 | 16,272 | 15,347 | 19,810 |
| Renting of machine and equipment | 63,208 | 119,260 | 90,104 | 166,119 | 68,235 | 131,222 | 102,076 | 192,835 |
| Public administration and defense | 196,453 | 400,924 | 214,576 | 440,471 | 245,202 | 451,706 | 291,627 | 469,283 |
| Education | 22,920 | 27,286 | 19,534 | 22,079 | 35,444 | 45,441 | 32,532 | 34,746 |
| Health and social work | 55,639 | 77,276 | 69,844 | 95,088 | 124,380 | 194,343 | 155,417 | 240,753 |
| Other community, social and personal services | 132,771 | 207,455 | 160,250 | 245,096 | 115,036 | 188,584 | 136,262 | 229,614 |

*Table 3.16: U.S. Sharing-Based Emission (SE) and Production-Based Emissions (PBE) by Rows and by Columns, 2005 and 2011; kt of $CO_2$*

| Industry | 2005 | | | | 2011 | | | |
|---|---|---|---|---|---|---|---|---|
| | $PBE_{row}$ | $PBE_{col}$ | $SE_{row}$ | $SE_{col}$ | $PBE_{row}$ | $PBE_{col}$ | $SE_{row}$ | $SE_{col}$ |
| Agriculture, hunting, forestry and fishing | 98,387 | 65,965 | 129,400 | 94,869 | 95,862 | 61,434 | 127,841 | 89,425 |
| Mining and quarrying | 132,671 | 84,515 | 120,614 | 73,492 | 146,711 | 91,272 | 131,242 | 75,822 |
| Food, beverages and tobacco | 122,650 | 171,831 | 140,098 | 204,977 | 129,117 | 255,578 | 151,069 | 298,110 |
| Textiles and textile products | 38,077 | 34,793 | 42,828 | 39,038 | 17,300 | 14,834 | 19,334 | 16,984 |
| Leather and footwear | 1,583 | 2,008 | 1,729 | 2,245 | 1,284 | 1,557 | 1,408 | 1,782 |
| Wood and products of wood and cork | 11,840 | 14,193 | 8,029 | 11,367 | 10,535 | 13,110 | 8,805 | 9,643 |
| Pulp, paper, printing and publishing | 100,168 | 96,167 | 135,039 | 118,591 | 85,664 | 80,799 | 119,175 | 101,845 |
| Coke, refined petroleum and nuclear fuel | 385,215 | 363,411 | 403,952 | 375,248 | 291,078 | 282,600 | 313,098 | 298,982 |
| Chemicals and chemical products | 388,166 | 382,920 | 518,872 | 457,985 | 575,653 | 579,360 | 785,955 | 676,255 |
| Rubber and plastics | 14,050 | 9,810 | 19,958 | 14,767 | 36,682 | 27,609 | 53,627 | 39,094 |
| Other non-metallic minerals | 48,581 | 32,105 | 56,017 | 46,205 | 67,045 | 50,259 | 87,051 | 69,020 |
| Basic metals and fabricated metal | 178,120 | 130,682 | 239,322 | 177,193 | 41,182 | 32,817 | 55,206 | 42,486 |
| Machinery | 37,109 | 59,469 | 44,440 | 64,652 | 34,243 | 53,239 | 42,006 | 58,220 |
| Electrical and optical equipment | 83,300 | 93,595 | 78,166 | 81,389 | 40,179 | 53,573 | 38,572 | 42,960 |
| Transport equipment | 211,362 | 206,288 | 297,436 | 296,889 | 185,507 | 184,989 | 259,654 | 253,188 |
| Manufacturing, nec | 8,745 | 13,596 | 9,989 | 19,877 | 6,080 | 11,280 | 7,380 | 15,660 |
| Electricity, gas and water supply | 1,991,521 | 1,762,408 | 1,971,064 | 1,541,859 | 1,582,998 | 1,230,251 | 1,549,616 | 1,048,529 |
| Construction | 472,087 | 296,910 | 495,049 | 254,155 | 273,600 | 175,193 | 299,471 | 153,012 |
| Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel | 12,029 | 14,764 | 14,791 | 15,523 | 13,505 | 15,822 | 16,721 | 16,420 |
| Wholesale trade and commission trade | 50,048 | 68,795 | 53,879 | 78,987 | 41,877 | 57,366 | 43,347 | 61,113 |
| Retail trade, except of motor vehicles and motorcycles; repair of household goods | 53,767 | 67,914 | 47,659 | 58,135 | 124,763 | 75,255 | 113,561 | 65,154 |
| Hotels and restaurants | 92,082 | 118,054 | 99,248 | 129,591 | 85,322 | 66,880 | 89,356 | 73,659 |
| Inland transport | 181,912 | 129,015 | 183,484 | 123,118 | 199,149 | 137,157 | 212,264 | 122,319 |
| Water transport | 126,478 | 202,983 | 164,721 | 251,707 | 45,581 | 79,910 | 59,659 | 95,626 |
| Air transport | 70,931 | 52,541 | 78,970 | 63,261 | 182,392 | 134,112 | 236,815 | 163,804 |
| Other supporting and auxiliary transport activities | 18,346 | 12,592 | 20,683 | 12,333 | 24,447 | 17,747 | 30,085 | 16,186 |
| Post and telecommunications | 84,309 | 221,865 | 114,652 | 305,933 | 124,055 | 385,587 | 174,646 | 519,244 |
| Financial intermediation | 63,567 | 80,465 | 70,370 | 91,800 | 42,600 | 59,166 | 45,420 | 69,082 |
| Real estate activities | 20,846 | 26,532 | 23,075 | 30,079 | 12,438 | 16,272 | 15,209 | 19,739 |
| Renting of machine and equipment | 60,047 | 119,260 | 81,189 | 167,992 | 61,412 | 131,222 | 86,456 | 173,943 |
| Public administration and defense | 186,630 | 400,924 | 203,848 | 437,008 | 240,298 | 451,706 | 288,801 | 466,457 |
| Education | 21,086 | 27,286 | 18,040 | 22,051 | 35,444 | 45,441 | 32,184 | 34,184 |
| Health and social work | 52,301 | 77,276 | 63,541 | 91,189 | 116,917 | 194,343 | 142,085 | 221,604 |
| Other community, social and personal services | 124,805 | 207,455 | 151,517 | 244,800 | 110,435 | 188,584 | 132,253 | 229,514 |

# CHAPTER 4: ESSAY 3 - The Decomposition of Key Industries in Embodied $CO_2$ Emissions within the U.S., China, and EU15 Economies


## Abstract

In light of carbon transfers as part of the fragmentation of international production, a different allocation of mitigation efforts is needed across industries and economies throughout the world. However, an important challenge towards industrial responsibility is the identification of the consequences from different policy measures appropriate for industries with differences in emission levels and type of linkages. It is critical to investigate the nature of emissions from different industries and their relationships with one another in regard to trade structures and embodied emissions across economies. In this essay, I first construct a four-region EE-MRIO model in order to evaluate the significance of international trade in response to embodied emissions of the U.S., China, and EU15 economies for the year 2011. I further extend production-demand elasticity to identify roles of the different industries and emission relationships between industries. These role is used to classify industries into four categories: a key industry (category 1); a relevant industry with own demand (category 2); a relevant industry with the demand from others (category 3), and non-relevant industry (category 4).

The results show that the U.S. and EU15 are net importers of $CO_2$ emissions whereas China is net exporter. Despite net importer and exporter, the proportion of emissions from intermediate imports linked to exports in the U.S. and China economies were 31% and 24% respectively. This implies that the fragmentation of international production gave rise to the significant effect on structures of carbon transfers. Responsibility of these embodied emissions is no longer limited by fragmented climate actions, but should be designed to account for the complex of carbon transfer structures.

The results of U.S. key industries point out that there is a gap of industrial policy designs between voluntary national emission reductions and emission reductions necessary for dealing with the complex of carbon transfers. For example, industrial coverage in reference to the U.S. INDC should not have limited to category 1, but should involve category 3 industries. Most of key industries in imported emissions had low own total effects relative to those of key industries in exported emissions. Along this line, industrial policy measures to specific key industry may not effective enough for curbing U.S. imported emissions. Cross-industrial measures appear more appropriate. These industries are paper, chemical, non-metallic mineral, and basic metal industries.

The results of key industries of China reveal that category 1 industries in exported emissions would be the most important on when evaluating China's exported emission reductions because of large magnitude of their total and distributive effects. Category 1 industries are less important due to small their distributive effect on imported emissions. Other parts are taken by category 3 industries. Due to high own distributive effects, industrial measures are likely to be an alternative policy strategy for industries within categories 1 and 3 to deal with carbon transfers. However, a gap of industrial coverage is not an important issue in China because category 3 industries are in category 1 for exported emissions.

Key industries of EU15 exported emissions are more distributed compared with the findings of the U.S. and China. Among them, this analysis points out that food and beverage, chemical, and basic metal industries should be taken for EU15 exported emission reductions. In this view, food and beverage industry is dropped from the list of EU emission trading systems (ETS). However, the results of key industries in EU15 imported emissions could not precisely affirm as a result of multiple sets of industrial classification found.

The outcomes of this study are used to evaluate the practical applications of climate policies. Due to the importance of carbon transfers, this essay considers three policy alternatives: an emission standard of utility industry (P1); a unilateral border tax adjustment (P2); and a multilateral border tax adjustment (P3). The results indicate that when compared with the findings of P1 and P2 policies, a P3 policy will contribute greater emission reductions, but have a limited effect on trade activity losses.

## 4.1 Introduction

Global energy-related carbon dioxide ($CO_2$) was on track to level off or even slightly decline in 2015. However, growth in an average global concentration of $CO_2$ in the atmosphere has remained an important challenge for the future of climate change (PBL, 2015). Continuing a downward trend in global emissions requires effective policies to control carbon transfers and long-term cooperative actions among nations. It is likely that long term actions call for an establishment of responsibilities to be shared between economies rather than to be differentiated based upon their own voluntary reductions as clearly seen from the results of the last chapter. In light of carbon transfers occurring as part of the fragmentation of international production, different mitigation efforts are needed across industries and economies throughout the world. However, an important challenge towards industry level responsibility is that industries with differences in emission levels and type of linkages may need different policy measures to effectively reduce emissions. It is important to investigate the nature of emissions within the different industries and their relationships between industries. A distinction of industrial policies also needs to be clear before thinking of policy designs for their emission reductions.

Each industry not only contributes emissions directly by producing its products, but also in an indirect way by consuming intermediate inputs supplied by other domestic and foreign industries. Ignoring these connections (industrial interdependencies) can underestimate the amounts of emissions from their activities. To investigate industrial interdependencies, an environmentally-extended multi-regional input-output (EE-MRIO) has emerged as the worthwhile alternative in environmental analysis. It has been used to examine international trade among trading partners regarding emissions linked with products imported to or exported from (Wiedmann, 2009). It allows consideration of emission allocations in regard to geographical separations between upstream producers and ultimate downstream consumers (Peters and Hertwich, 2008). It gives rise to a clear distinction of a production-based emission (PBE) allocation and a consumption-based emission (CBE) allocations (Peters, 2008). The traditional way of determining emissions embodied in international trade is to analyze the roles played by different industries of a single or multiple economies associated with their PBEs and CBEs (Davis and Caldeira, 2010; Peters et al., 2011; Foren et al., 2012; Muradian et al., 2012; Sato, 2013; Tukker and Dietzenbacher, 2013; Xu and Dietzenbacher, 2014).

However, existing literature has paid scarce attention to the roles of different industries and the nature of emissions responses within their import-export structures and emission distributions. These roles become crucial because differences in emissions nature deserve differences in policy measures. In this respect, there is a need to extend a technique along with the EE-MRIO that broadens the scope of emissions attributed to individual industries.

An analysis of key industries extends the EE-MRIO to establish industrial responsibility in response to the nature of emissions by industry. It allows examining how industries are inter-related to affect levels of emissions. Explanations of industrial interrelationships depend upon the structure of economic activity through demand-driven or supply-driven multipliers (Sonis et al., 2000; Lenzen, 2003). Departing from a single set of economic structure, an identification of key industries in embodied emissions needs either demand-driven or supply-driven multipliers with a hierarchy of backward and forward linkages. As the fragmentation of international trade plays an important role in the modern international trade, a determination of key industries associated with demand-driven needs to be made. This is essential because a demand-driven perspective is suggested for examining a hierarchy of backward and forward linkages in response to the same set or different sets of consumption structures (Rueda-Cantuche and Amores, 2010). Nevertheless, Dietzenbacher (2005) demonstrated that conventional weighting multipliers (given a linear relationship between output and demand) can overestimate linkages of industries. To avoid biased estimates, a technique of a disaggregated calculation of production-demand elasticity has gained increasing attention, as reflected in studies by Alcántara and Padilla (2006); Carvalho and Perobelli (2009); Jodar (2009); Imori and Guihoto (2010); Piaggio et al. (2012); Carvalho et al. (2013); Othman and Jafari (2015). However not all these existing studies provide the same mathematical formula of weighting multipliers or use similar scales of analyses for key industries.

Therefore, in light of carbon transfers due to the fragmentation of international production, this essay aims to identify key industries in $CO_2$ emission generation which are stimulated due to industrial import and export demands in the year 2011. A four-region MRIO model is constructed in order to: (1) evaluate the significance of international trade in response to embodied emissions of the U.S., China, and EU15 economies; (2) examine contributions of industrial import and export structures that mostly affect the embodied emissions; and (3) extend production-demand elasticity to the embodied emissions in order to identify roles of different industries and their interrelationships with one another regarding trade structures and structures of carbon transfers. Industrial roles are classified into four categories: a key industry, a relevant industry with own demand; a relevant industry with demand from others; and non-relevant industry.

A knowledge of key industries allows us to understand the nature of emissions played by the different industries and emission relationships between industries for recommending what policy measures will be implemented to reduce their emissions. The outcomes of this essay can be assessed to evaluate the practical applications of climate policies. In the respect of carbon transfers, three policy alternatives will be considered: (1) an emission standard of utility industry; (2) a unilateral border tax adjustment; and (3) a multilateral border tax adjustment.

The remainder of this essay is structured as follows. The second section reviews the relevant literature providing the importance of key industries analysis in corporation to the input-output framework. This section also presents some evidence from the literature on EE-MRIOs that addresses the current issue in carbon transfers. The third section describes the EE-MRIO model and its connection to the concept of production-demand elasticity. The fourth section describes the data used to construct the EE-MRIO model. The fifth section presents and discusses the results of the empirical work for the U.S., China, and EU15 economies. The sixth section describes three policy alternatives and evaluates their practical applications based upon the outcomes of this essay. Finally, the last section concludes with a summary of main findings.

## 4.2 EE-MRIO and Key Industry Analyses: Approaches and Extensions

Enhanced economic integration due to international trade contributes to embodied emissions along international production chains (Peters et al., 2011). To manage transport costs, industries have a desire to perform their production process close to one another, but gain lower production costs through complex chains of production (Sato, 2013). In this sense, the environmental profile of international trade tends to transfer and absorb embodied emissions due in part to the disparities of industrial carbon production technologies[34] as well as the imbalance of national environmental regulations (Lenzen, 2011; Peters and Hertwich, 2008). An environmentally-extended multi-regional input-output (EE-MRIO) analysis has become an optional tool to investigate embodied emissions in international trade that take into account the complex linkages of inter-industries across global supply chains. This type of analysis is also used to investigate the geographical separation between final consumers and the pollutant generated from the production process of products consumed; the so-called consumption-based emission (CBE) allocation (Wiedmann, 2009). However, with increased availability of multi-national input-output database[35], empirical works on this comprehensive analysis have been recently constructed (Tukker and Dietzenbacher, 2013).

A number of multi-regional input-output (MRIO) studies using consumption-based accounting have been recently presented after the 2008 international input-output conferences in Istanbul. Most of them are based on the GTAP and WIOT databases. Wiedmann et al. (2008) first used the UK-MRIO model in GTAP 6 database covering the year 2001 to consider emissions embodied in the unidirectional trade towards the UK but not yet presented a full MRIO that considers embodied emissions in trade to final consumption of the nation. Peters (2008) distinguishes two accountings (PBE and CBE accountings) for considering CBE inventory of the nation. His study does not consider the components of bilateral trade flows into the intermediate and final consumption. It is important for determining the total emissions

[34] Emission transfer is the situation in which the proportion of emission increases in one economy is directly and indirectly due to changes in consumption patterns of other economies (Peters and Hertwich, 2008). Due to differences among carbon intensities associated with imports and exports, one economy is able to transfer or absorb $CO_2$. Consequently, global emission reductions do not involve.

[35] Currently, there are four international input-output databases available to construct multi-regional input output models (Tukker and Dietzenbacher, 2013). No all models have the same mathematical form. Global trade analysis project (GTAP) covers 57 industrial sectors for 129 economies with dual base years of 2004 (GTAP 7) and 2007 (GTAP 8); lately updated year of 2011 (GTAP 9) with the exception of full environmental updated data (i.e. national greenhouse gas emissions). Actually, it does not aim to construct input output models but can convert into multi-regional input output using GTAP trade data (Peters et al, 2011). World input output table (WIOT) comprise 35 industrial sectors for 27 European economies and 13 others plus the rest of the world (Timmer et al., 2012). This database made the first for creating the extensive time series of international supply-use tables and international input-output tables for the period of 1995 to 2011 (Timmer et al., 2013). The advantage of this database is that it is available for both current and previous prices (Tukker and Dietzenbacher, 2013). As this result, it contributes to world input output tables. Asian international input output (AIIO) consists of 76 industrial sectors for limited 9 Asian economies plus the United States with the reference years 1995, 2000, and 2005. It carried out an in-depth cross economy survey to harmonize international input-output tables; however, this database is expected to launch out by 2016 (Tukker and Dietzenbacher, 2013). Lastly, OECD input-output (OECDIO) database has some background that is relevance to WIOT database in terms of harmonized bilateral trade statistic, but comprises 48 industrial sectors for 28 OECD economies plus 9 others (Yamano and Ahmad, 2006). It is fully available for the discrete years 1995, 2000, and 2005. With the joint project between OECDIO and WIOT, both European Commission research projects have continuously modified bilateral trade data in value-added to construct their international input-output tables (Degain et al., 2013)

generated by a certain product that require imports to produce exports. Nevertheless, this study contributes to research by Peters and Hertwich (2008) by redefining carbon transfers (i.e. carbon leakages) that take into account the entire emissions generated in the production of traded products.

Carbon transfers named by carbon leakages can be defined as the increase in global emissions in the way that an economy is responsible for only embodied emissions generated within its territory but ignores other emissions from its consumption (Peters and Hertwich, 2008). Nakono et al. (2009) used the EE-MRIO model in WIOT database to recalculate the consumption-based $CO_2$ emissions. They found that CBEs of the overall 41 OECD economies were roughly more 16% higher than their emissions calculated by Peters (2008) whereas more than half of the emissions took place in non-OECD economies were attributed to the consumption of OECD economies in the late 2000s. Their results suggest that the increase in the global trade intensity leads to the enormous impact on the embodied emissions. Finally, several studies have employed different EE-MRIO models such as Giljum et al. (2009); and Wiebe et al. (2012) with the application of the global resource accounting model (GRAM); Peters et al. (2011) and Narayanan et al. (2012) with the application of GTAP-MRIO model; as well as Davis and Caldeira (2010), and Foren et al. (2012), plus Timmer et al. (2015) with the application of WIOT-MRIO model.

The results of these previous studies have not revealed what the main factors have driven changes in embodied emissions in trade. There are many efforts to construct structural decomposition analysis (SDA) for analyzing embodied emissions in trade in regard to world coverage (Wood, 2008; Yamakawa and Peters, 2011; and Xu and Dietzenbacher, 2014). The advanced SDAs have extended the original SDA method for tracing the path for specific factors. Wood (2008) combines components of SDA with structural path analysis (SPA) to estimate the path of greenhouse gas emission from trade substitution within three economic regions (OECD-EU, Non-OECD EU, and the rest of the world). Yamakawa and Peters (2011) extended the original method of Wood (2008) for the entire OECD economies. With this method, it is possible to identify the main international supply paths of emissions that could be the most benefit from trade substitution. This method appears to be powerful if knowing what the main factors driving changes in embodied emissions incorporate final products back to an economy and generate emissions. Xu and Dietzenbacher (2014) applied the SDA within the EE-MRIO framework to analyze the major factors for the growth in embodied emissions attributable to imports of 40 WIOT economies between 1995 and 2007. They found that the key reason for the growth was due to the change in trade structures between intermediate and final imports[36]. However, those findings have not gone so far how emission nature of interindustry dependencies shape trade structures in order to influence the growth in imported emissions.

[36] Their results are in line with the findings of essay 1. This is relevant that the key contributing factors to increase emissions embodied in US import demand are changes in the final import scale and the structure of imports as clearly seen after 2003.

This is relevant that some industries produce relatively minor influence on trade substitution of emissions but can encourage others to affect substantially both trade activities and emissions. When thinking about international policies on climate change, it is important to get a clear distinction between them. Without a consideration of their emission nature, such policies can undermine their efforts and affect substantially trade activities as a whole.

The analysis of key industries takes into account the weight of industries that are associated with above average environmental effects on embodied emissions in trade. The identification of key industries can be addressed from the change in structural interdependence and economic standpoint (Carvalho et al., 2013). The concept of key industries was first developed by Hirschman (1958) and the mathematical interpretation of key industries further elaborated by Oosterhaven and Stelder (2002).

Hirschman (1958) postulated that industries can affect the whole economy through either backward linkages (induced by upstream supply of inputs) or forward linkages (induced by downstream use of outputs[37]) as long as they predominantly proceed above average linkages in the form of economic development and structural changes. Sonis et al. (2000) noticed that on the hierarchies of backward and forward linkages, matrices of economic multiplier product should be regarded as complementing each other; the so-called a minimum information approach. In the mathematical expression, Oosterhaven and Stelder (2002) elaborated that multiplier effects of a unit change in final demand can be used to determine the hierarchies of backward and forward linkages. Given the linear nature, the increase in the level of gross output requires to hold a unit change in final demand. In this sense, an industry that takes a small part of inputs from other industries will likely have relevant multipliers. Dietzenbacher (2005) pointed out that the total effect of industries can yield double counting and overestimate the potential of industrial linkages. To avoid biased estimates, there are several proposals lately introduced. Examples of methodology that enables the identification of key industries include Dietzenbacher (2005), Díaz et al. (2006), Alcántara and Padilla (2006), Reuda-Cantuche and Amores (2010), and Piaggio et al. (2012).

Dietzenbacher (2005) suggests the formation of net multiplier to weigh the importance of industries. The net multiplier is the ratio of the multiplier vector[38] calculated from all industries in response to the final demand of the corresponding industry to the multiplier vector calculated from the corresponding industry in response to the final demand of all industries. Given this weight technique, when the exogenous outputs increase, corresponding industries will vary a change in final demand based upon the hierarchies of their backward and forward linkages. In this respect, a meaningful economic interpretation for the

[37] As this result, the most industrial rapid growth is not necessary to become key industries but may mostly tie to them (Sonis and Hewings, 2000)

[38] Multiplier vectors can be output multipliers, value-added multipliers, energy use multipliers, and emission multipliers.

importance of the industry can be yielded. To a great extent of this interpretation, Alcántara and Padilla (2006) developed a methodology of production-demand elasticity in order to determine the key industries that are important in the design of energy and environmental policies to combat the greenhouse gas emissions[39]. Carvalho et al. (2013) extended the presentation of elasticity concept to analyze key industries in response to the changes in final imports and embodied $CO_2$ emissions.

Work on key industries is often formulated in the correlation between the linkages of economic development and unbalanced growth[40] (Clements and Rossi, 1991; Sonis et al., 1995; Oosterhaven, 1996; Dietzenbacher, 1997). Given increasingly pressing climate change issues, the key industries analysis has recently applied to examining economic structures in terms of the consumption of energy and the environmental impacts of greenhouse gas emissions, mostly $CO_2$. The examples include Carvalho and Perobelli (2009), Imori and Guihoto (2010), Piaggio et al. (2012), and Carvalho et al. (2013).

[39] See supply-side perspective in Alcántara and Padilla (2003)

[40] A good review of this issue can be seen in Lenzen (2003).

## 4.3 Emission Allocations and Key Industries: Methodology and Procedure

An environmentally-extended MRIO (EE-MRIO) model should proceed the analysis of environmental profiles of international trade. It is an analytical tool for assessing regional production-based emissions (PBE) and consumption-based emissions (CBE). The gap of these two perspectives is defined by the geographical structure of international trade flows. This section describes how emissions are computed for each allocation. Then, it discusses the method for identification of key industries in embodied $CO_2$ emissions stimulated due to export and import flows.

### 4.3.1 Calculations of PBE and CBE Allocations

A transformed EE-MRIO model with $CO_2$ emissions can express the aggregate emissions associated with domestic production by industry within region 1 ($PBE^1$) as:

$$PBE^1 = c^1(I - A^1)^{-1} y_d{}^1 = c^1(I - A^1)^{-1}(y_f{}^1 + y_x{}^1) \quad (4.1)$$

where $c^1$ is the diagonal matrix of direct emission intensity by industry within region 1. Example includes that the diagonal element in the matrix $c^1(c_j^1)$ is the emission directly produced by industry j in region 1. It is obtained by multiplying the $CO_2$ conversion factor for fuel source ($e_j^1$) by the direct fuel use by industry j per a dollar unit of industry j's production ($f_j^1$). That is, $c_j^1 = e_j^1 f_j^1$. $I$ is the identity matrix. $A^1$ is the matrix of intra-industry technological requirements within region 1 industries. $y_d^1$ is the diagonal matrix of total final demand captured by domestic final consumption plus investment ($y_f^1$) and export demand ($y_x^1$). From the EE-MRIO standpoint, it is possible to calculate emissions associated with exports from region 1 to other regions' r. $y_x^1$ can be decomposed into $y_x^{12}$, $y_x^{13}$, and $y_x^{14}$ where r = 1,2,..,4. Let $\varepsilon^1$ be the matrix of emission multiplier by industry within region 1, a reduced form of $PBE^1$ can be expressed as: $PBE^1 = \varepsilon^1(y_f^1 + y_x^1)$, where $\varepsilon^1 = c^1(I - A^1)^{-1}$.

CBE allocations generally include total emissions attributable to domestic products distributed within region 1 and total emissions attributable to products generated by other regions' r industries in order to meet the need of intermediate and final imports within region 1 (Peters and Hertwich, 2008). Generally, this type of emission allocation is independent from exports. However, this essay modifies the second part of CBE through inclusion of emissions involved in re-exports occurring along the process of intermediate import. In another words, the new $y_{mf}^1$ is comprised of two components: domestic demand ($y_f^1$) and export demand ($y_x^1$) rather than domestic demand like in the calculation of previous chapter.

In this respect, total (direct and indirect) emissions attributable to products imported from other regions' r can be calculated as:

$$E_m{}^1 = \sum_{r \neq 1} c^r (I - A^r)^{-1} A_m{}^{r1} (I - A^1)^{-1} (y_f{}^1 + y_x{}^1) + \sum_{r \neq 1} c^r (I - A^r)^{-1} y_m{}^{r1} \qquad (4.2)$$

where $c^r$are the diagonal matrices of direct emission intensity by industry in other regions' r. $A^r$ are the matrices of intra-industry technological requirements in other regions' r. $A_m^{r1}$ are the matrices of inter-industry technological requirements from other regions' r to region 1. $y_m^{r1}$ are the diagonal matrices of imported final demand flow from other regions' r to region 1. To calculate $A_m^{r1}$ and $y_m^{r1}$, it is necessary to know the multilateral trade data that provides allocations of dollar values of imported and exported products split up by industry and end-use categories so that multi-national supply-use tables[41] will need to be constructed. Let $\varepsilon^r$ be the matrices of emission multipliers by industry in other regions' r so that, a reduced form of $E_m^1$ can be expressed as: $E_m^1 = \sum_{r \neq 1} \varepsilon^r (A_m^{r1} (I - A^1)^{-1}\, y_{mf}^1 + y_m^{r1})$ where $\varepsilon^r = c^r (I - A^r)^{-1}$ and $y_{mf}^1 = y_f^1 + y_x^1$.

The aggregate emissions associated with consumption of domestic products by industry of region 1 and imported products from other regions' r to region 1 ($CBE^1$) can be calculated as:

$$CBE^1 = PBE^1 + E_m{}^1 - E_x{}^1 \qquad (4.3)$$

$$CBE^1 = \varepsilon^1 y_f{}^1 + \sum_{r \neq 1} \varepsilon^r (A_m{}^{r1} (I - A^1)^{-1} y_{mf}{}^1 + y_m{}^{r1}) \qquad (4.4)$$

[41] Elements $a_{m_{ij}}^{r1}$can be calculated as $a_{m_{ij}}^{r1} = m_j^{r1} a_{ij}^{im1}$ for all industry j in region r. $a_{ij}^{im1}$ represents the requirement of intermediate import j used by industry i in region 1 derived from the international supply-use data and the aggregate output of region 1. $m_j^{r1}$ represents the share of import j from region r to region 1. It can be computed as $m_j^{r1} = \frac{M_j^{r1}}{\sum_{r \epsilon R} M_j^r}$ where $M_j^{r1}$ is the total value of import j from region r to region 1. $\sum_{r \epsilon R} M_j^r$ is the total value of import j from all regions r to region 1.

Similarly, elements $y_m^{r1}$ ($y_{m_{ij}}^{r1}$) can be computed by using the same approach as $y_{m_j}^{r1} = m_j^{r1} y_j^{r1}$. In this case, $y_j^{im1}$represents the imported final demand flow j to region 1 extracted from the international supply-use data. However, it should be noted that $y_{m_j}^{r1}$is derived based on the underlying assumption that the imported final demands are in the same proportion as the imported intermediate demands with the similar set of trading partners.

### 4.3.2 Key Industry Analysis: Embodied Emissions

This subsection presents the elasticity concept and the method for identification of key industries in embodied $CO_2$ emissions stimulated due to export and import demands. The methodology utilized here was proposed by Alcántara and Padilla (2006) [42] and further elaborated by Piaggio et al. (2012) and Carvolho et al. (2013).

To calculate the elasticity of embodied $CO_2$ emissions with respect to export demand. I first construct a matrix of inter-industrial emissions in regard to the total final demand ($y_d^1$) for the region 1 economy. Suppose the inter-industrial emissions as a whole (domestic production emissions) depends on the total final demand, the change in $PBE^1$can be expressed as:

$$\Delta PBE^1 = c^1(I - A^1)^{-1} y_d{}^1 \alpha \tag{4.5}$$

where $\alpha$ is the scalar of the proportional change in total final demand of region 1.

Let $s_y^1$ be a diagonal matrix that represents the share of industrial total final demands with respect to their respective production, then:

$$s_y{}^1 = (x^1)^{-1} y_d{}^1$$

$$\text{or} \quad y_d{}^1 = s_y{}^1 x^1 \tag{4.6}$$

where $x^1$ is the diagonal matrix of region 1's industrial effective outputs

Substituting Equation (4.6) into Equation (4.5), $\Delta PBE^1$ can be rewritten as:

$$\Delta PBE^1 = c^1(I - A^1)^{-1} s_y{}^1 x^1 \alpha \tag{4.7}$$

In elasticity form, dividing by $PBE^1$ in both sides generates:

$$(PBE^1)^{-1} \Delta PBE^1 = (PBE^1)^{-1} c^1 (I - A^1)^{-1} s_y{}^1 x^1 \alpha \tag{4.8}$$

where the left hand side of Equation (4.8) expresses the total change in domestic emissions relative to a change in total final demand of region 1. That is the elasticity of (aggregate) domestic emissions with respect to total final demand of region 1. However, given the linear solution and a unit change in final demand, Equation (4.8) does not give any additional information to identify key industries. This term needs to be broken down to the matrix that provides an industrial disaggregation of the elasticity. Thus, let d be a diagonal matrix of the distribution of domestic emissions among industries of the region 1 economy, such

[42] Extended from Alcántara and Padilla (2003)

that $\sum_i d_i = 1$. For this reason, I can rewrite $c^1$ in terms of the diagonal matrix of the industrial distribution coefficients as $c^1 = PBE^1 d^1 (x^1)^{-1}$Substituting into Equation (4.8) generates:

$$(PBE^1)^{-1} \Delta PBE^1 = d^1 (x^1)^{-1} (I - A^1)^{-1} s_y{}^1 x^1 \alpha \quad (4.9)$$

According to Miller and Blair (2009), if two matrices P and Q are relevant in $P = KQK^{-1}$, they can be expressed by $P \approx Q$. In this way, $(x^1)^{-1}(I - A^1)^{-1} x^1 = (I - D^1)^{-1}$. It is noteworthy that the matrix D is just the matrix of distribution coefficients of an underlying input-output table[43].

By substituting, equation (4.9) can be rewritten as:

$$\xi_y{}^1 = d^1 (I - D^1)^{-1} s_y{}^1 \quad (4.10)$$

where $\xi_y^1$ represents the proportional variation of industrial domestic emissions in response to a proportional change in total final demand. For more accurate information, $\xi_{y_{ij}}^1$ represents the characteristic element of the matrix $\xi_y^1$ that expresses the percentage change in emissions of industry i in relation to a percentage change of final demand in industry j. Expressions of the elasticity include that the sum of industry j column expresses the percentage change in emissions of the entire region 1's economy in response to a 1 % of change in final demand of industry j. The sum of industry i row, in turn, expresses the percentage change in emissions of industry i in response to a 1 % of change in the final demand experienced by the industries as a whole in region 1.

Alcántara and Padilla (2006) introduced a mathematical proof that the sum by columns has a correspondence with the hierarchy of backward linkages and the sum by rows has a correspondence with the hierarchy of forward linkages introduced by Sonis et al. (2000). In this respect, they stated that the sum by columns of the elasticity matrix can indicate the emission effect of the entire region 1's economy such that the total effect of emissions is $\sum_{i=1}^{n} \xi_{y_{ij}}^1$where i=1,2,…,n. The sum by rows can indicate the emission effect of the corresponding industry i such that the distributive effect of emissions is $\sum_{j=1}^{n} \xi_{y_{ij}}^1$where j=1,2,…n. In this way, the productive structure and the structure of demand in Equation (4.8) can influence computation of the elasticity as key elements of the effect of demand on domestic emissions of an industry. Alcantara and Padilla (2006) further used this indication to set out a classification of industries with respect

[43] As a consequence of the relationship of $P = KQK^{-1}$, the characteristic element of matrix D cannot remain constant, but the element of matrix A is constant. A crucial problem is known as the joint stability problem (Chen and Rose, 1986). Dietzenbacher (1989) notions that the element of both matrices can remain stable as far as the relative change in total outputs is still the same across industries as a whole. Lenzen et al. (2007) and Lenzen (2003) consider that this relation cannot be interpreted as an injection of inputs but can only indicate how inputs depend on further processing. Thus, this relation can be used as the descriptive tool for backward and forward linkages, but not for the impact work.

to the behavior of their emissions by means of the median values[44] of the total effect ($\xi_T^1$) and the distributive effect ($\xi_D^1$). The classification of industries is presented on Table 4.1.

*Table 4.1: The Classification of Industries*

| | $\sum_i \xi_{y_{ij}}^1 > \xi_T^1$ | $\sum_i \xi_{y_{ij}}^1 < \xi_T^1$ |
|---|---|---|
| $\sum_j \xi_{y_{ij}}^1 > \xi_D^1$ | Key industries (1) | Relevant industries in terms of the demand from others (3) |
| $\sum_j \xi_{y_{ij}}^1 < \xi_D^1$ | Relevant industries in terms of own demand (2) | Non-relevant industries (4) |

Key industries in category 1 represent both the total and distributive effects greater than the median values of the economy as a whole. This is relevant because their emissions can be induced by an increase in final demand from other industries. In the meantime, the emissions of other industries can be pushed by own demand of these corresponding industries. In this way, industries in this category are crucial for climate change policies. Relevant industries in category 3 represent the distributive effect greater than the median values of the economy. This is relevant because their emissions are determined by an increase in final demand from other industries. In addition, due to the total effect less than the distributive effect, category 3 industries have the potential to share reductions in final demand greater than reductions in emissions. In this sense, when thinking about policies on climate change, it is important to get a clear distinction of this category of industries. Climate change policies can affect the magnitude of their production.

Relevant industries in category 2 represent the total effect greater than the median of the economy. This means their emissions are determined by an increase in their own demand, but not largely contributed by final demand from other industries. In this case, it is likely that climate change policies will directly affect their demand but not have a significant effect on final demand of others. Category 4 includes industries that are relatively low in both total effect and their share in the emission distribution. In this case, category 4 industries will be less relevant when implementing climate change policies.

Carvolho et al. (2013) showed that production-demand elasticity derived from net multipliers can be decomposed into each category of demand. It is important to note that this approach differs from the minimum information by Sonis et al. (2000) and complementary approach by Rasmussen (1956)[45]. In this respect, total final demand of the region 1 economy ($y_d^1$) can be broken down into domestic final demand ($y_f^1$) and export demand ($y_x^1$). The underlying method can be applied for reproducing the elasticity matrices of industrial $CO_2$ emissions in response to $y_f^1$ and $y_x^1$ as:

[44] Alcántara and Padilla (2006) and (2003) would choose the median values rather than the mean values because the distribution of emissions is not always symmetrical. For avoiding classification biases due to outliers, the median values are more decent for a measure of central tendency.
[45] These approaches basically apply for measuring backward and forward linkages through weight structure for total demand of a single economy.

$$\xi_{yf}{}^{1} = d^{1}(I - D^{1})^{-1} s_{yf}{}^{1} \tag{4.11}$$

$$\xi_{yx}{}^{1} = d^{1}(I - D^{1})^{-1} s_{yx}{}^{1} \tag{4.12}$$

where $\xi_{yf}^{1}$ represents the proportional variation of industrial domestic emissions of region 1 in response to a proportional change in domestic final demand. $\xi_{yx}^{1}$ represents the proportional variation of industrial domestic emissions of region 1 in response to a proportional change in export demand. $s_{yf}^{1}$ is the share of industrial domestic final demands with respect to their respective intra-production. $s_{yx}^{1}$ is the share of industrial exports with respect to their respective intra-production. From the EE-MRIO standpoint, exports ($y_{x}^{1}$) can be decomposed into $y_{x}^{12}$, $y_{x}^{13}$, and $y_{x}^{14}$ where there are four economic regions of trade. It is relevant to break down $\xi_{yx}^{1}$ as $\xi_{yx}^{1} = \sum_{r\neq 1} \xi_{yx}^{1r}$ where r = 2,3, and 4, respectively.

The EE-MRIO model allows for creation of import matrices by using the recipe of inter-industry production factor inputs between regions[46]. The elasticity of emissions attributable to import demand through the hierarchy of backward and forward linkages can be computed by applying the same approach. However, two additional assumptions are needed: import proportionality and mirror flow[47]. In this sense, this calculation of elasticity has been unique for WIOD database. It is relevant because the magnitude of inter-industry deliveries (imports) depends on the boundary chosen for the transactions between different establishments of the inter-industry relationship (Weber, 1998). If all parts of the inter-industry connections produce identical inputs (intermediate imports) or outputs (final imports), inter-industry deliveries can be explained by multipliers of the elements in the inter-industry technological requirement matrix (Lenzen, 2003). In this way, the productive structure and the structure of (total) imports can potentially influence a computation of the elasticity of embodied emissions in response to import demand. The sum over rows and columns of such an elasticity matrix is employed to set out the classification of industries due to the correspondence with the hierarchies of backward and forward linkages (Carvalho et al., 2013). However, embodied emissions in import demand can be channeled by the productive structure of intermediate imports and the structure of final imports. This essay will provide the computations of the elasticity matrices of industrial embodied $CO_2$ emissions within region 1 in response to both intermediate and final imports as:

$$\xi_{my_f}{}^{1} = \sum_{r\neq 1} d^{r}(I - D^{r})^{-1} D_{m}{}^{r1}(I - D^{1})^{-1} s_{myf}{}^{1} \tag{4.13}$$

$$\xi_{ym}{}^{1} = d^{r}(I - D^{r})^{-1} s_{ym}{}^{1} \tag{4.14}$$

[46] This procedure can be employed by full MRIO tables but not by partial forms of MRIOs with the underlying assumption of domestic technology.
[47] See section 4.4

where $\xi^1_{myf}$ represents the proportional variation of industrial embodied emissions in response to a proportional change in intermediate import required by region 1. $\xi^1_{ym}$ represents the proportional variation of industrial embodied emissions in response to a proportion change in final import required by region 1. $d^r$ is the diagonal matrix of the emission distributions among the productive industries of relevant regions r when r ≠ 1. For example, $d^2$ is the diagonal matrix of the region 2 emissions distributed among the region 2 productive industries. $D^r$ represents the matrix of distribution coefficients of input-output tables of relevant regions r. $D^{r1}_m$ is the matrix of distribution coefficients of an multi-national input-output table that represents imports from other regions' r allocated to economic activities of region 1's industries. According Armington assumption[48], it is important that as the multipliers of $A^{r1}_m$ are dependent of the elements in the $A^r$ and $A^1$ , at least in the underlying assumption of WIOD dataset, the use of $D^{r1}_m$ in this purpose is indicated along with the corresponding $D^r$ and $D^1$ results (Lenzen et al., 2007). $s^1_{myf}$ is the share of industrial domestic final demands of region 1 with respect to their respective interrelated-production[49]. Interrelated-production refers to the total production of relevant regions r. $s^1_{ym}$ is the share of industrial imports of region 1 with respect to their respective interrelated-production[50].

From use of the full EE-MRIO in this essay, final imports ($s^1_{ym}$) can be decomposed into $s^{21}_{ym}$, $s^{31}_{ym}$, and $s^{41}_{ym}$ for 4 economic regions. Meanwhile, $\xi^1_{ym}$ can be broken a possibility to break down as $\xi^1_{ym} = \sum_{r\neq 1} \xi^{r1}_{ym}$ where r = 2, 3, and 4 respectively. As long as full multi-regional input-output tables are available, the above expressions are widely worthwhile identifying key industries in response to how their export and import structures function in terms of a change in demand by each end use category. Specifically, they take account of the classification of industries with respect to embodied emissions stimulated due to export and import demands of other regions' r economies.

[48] See section 3.3.4

[49] The full mathematical formation is available in Lenzen (2003) and Lenzen et al. (2007).

[50] The elaboration is available in Carvalho et al. (2013).

## 4.4 Data

The main source of data in the MRIO model is the world input-output database (WIOD) (www.wiod.org). It provides full transformation of national supply-use tables (SUTs), international supply-use tables (ISUTs), and world input-output tables (WIOT). SUTs are the natural starting point to construct national input-output tables (IOTs). They were then linked across economies with bilateral international trade statistics to create the so-called ISUTs. Detailed ISUTs are used to construct the symmetric WIOT (Dietzenbacher et al., 2013).

The standard time series of the latest WIOT released in 2014 comprises of 35 industries located in 40 economies plus the rest of the world (ROW) (Timmer et al., 2015). In conjunction with available value added data from $CO_2$ emissions, the original WIOT is decomposed into four economic regions towards 34 industries for the year 2011 in order to construct the EE-MRIO model outlined in section 4.3. The four economic regions consist of the U.S., China, EU15, and a new compiled the rest of the world (ROW). It should be noted that the current ROW differs from the ROW stated in Chapter 3 due to the distinguishing region coverage. The coverage of these three regions (excluding the new ROW) reflects 74% of world GDP in 2011 (expressed at current exchange rates). As exports of the original ROW are defined as an additional trade reporter alongside the other forty economies, not originating from the set of WIOD regions, the new construction of the ROW ensures that exports summed over all regions of destination are equal to total exports given in the SUTs (Temurshoev and Timmer, 2011). As this result, mirror flows of the new ROW's import shares are not necessarily recalculated using a SUT-RAS procedure.

In order to construct a four-region EE-MRIO model, intra- and inter-technological requirements of the U.S. and China come mainly from the original WIOT. Intra technological requirements of the EU15 and the ROW are calculated from the combination of individual technological requirements of 15 EU economies and other remaining regions respectively. To compile inter-technological requirements, mirror flows of bilateral exports and imports are consistently linked to each other as a bridge of SUTs and ISUTs of individual economies[51]. In this way, inter-technological requirements of EU15 and the ROW are

[51] As SUTs which was the product-industry format[51] could generate manual rebalancing of detailed products for each use category and reduced the extractability of WIOD method, SUTs would be transformed into the industry-industry type using additional assumptions concerning technology, the so-called fixed product-sales structure. This sales structure refers to the proportions of the product output in which it is sold to the respective intermediate and final users (Timmer et al., 2012). This assumption helps to improve the precision of import share destination. In this way, a breakdown of import shares for each use category by economy and industry of origin could be derived using a compromising assumption, the so-called import proportionality. Ratios between total imports and total use of imports are equal across industries but differ across use categories. It should be noticed that this approach differs from the standard import proportionality which applies import shares for all uses irrespective of the category. Thus, when WIOD integrates ISUTs into the WIOT, to ensure consistency between bilateral flows of exports and imports, bilateral exports were treated as mirror flows from bilateral imports. That implies that bilateral imports of economy A from economy B are ensured to be equal to bilateral exports from B to A. It is applicable to both aggregated and disaggregated levels.

calculated from the import combination of individual 15 EU economies and other remaining regions. MATLAB software is used for numerical computation of EE-MRIO analyses of this essay[52].

Moreover, to study international production linkages, the mirror flows and the economy-industry of imports are substantially useful in the analysis of trade in value added (TiVA) such that value added exports (VAX) are assumed to be equivalent to value added imports (VAM) (Johnson and Noguera, 2012; Koopman et al., 2014). This issue will be discussed through section 4.6 in terms of value added in $CO_2$ emissions and emission allocations along global supply chains

Total final demand and domestic final demand of each economic region were directly taken from the columns in the WIOT. Domestic final demand contains household and government expenditure plus investment. Exports in the WIOT are commonly identified by the matrix of inter-industry correlations between regions. In order to investigate how domestic $CO_2$ emissions are induced through domestic segments of global supply chains at an industry level, exports are redefined as the sum of columns across industries. Final imports are taken from ISUTs. ISUTs are normally product based, not industry based. Depending on the underlying assumptions of fixed-product sales structure[53] and import proportionality[54], final imports are harmonized in terms of industry classification based upon the structure of International Standard Industrial Classification of all Economic Activities (ISIC).

The WIOD recognizes as consistent and harmonized multi-regional input-output tables used for trade and environmental analysis. As the core of WIOD environmental account contains separately primary fuel use, $CO_2$ emissions from fuel combustion of industrial processes are estimated using energy accounts and technology-related emission factors (Timmer et al., 2013). Thirteen types of fuel combustion of industrial processes are employed: hard coal and derivatives (HCOAL), lignite and derivatives (BCOAL), coke, crude, diesel, gasoline, jet-fuel, light fuel oil (LFO), heavy fuel oil (HFO), naphtha, other petroleum products (e.g. ethane, liquefied petroleum gas, and lubricant), natural gas, and other derived gases (e.g. coke oven gas, gas). Emission factors for 34 industries in the four economic regions were mainly collected from technical guidance report of United Nations Framework Convention on Climate Change (UNFCCC, 2015). However, this conventional report was no longer enough to provide distinguishing fuel qualities and technologies used in each economic region. The compilations of national emission inventories are used as a bridge to embed a relationship between industrial energy use and its emissions. The list of national

[52] The complete codes in the form of EE-MRIO analyses will be available to download at Regional Research Institute, West Virginia University (rri.wvu.edu).

[53] This sales structure refers to the proportions of the product output in which it is sold to the respective intermediate and final users (Timmer et al., 2012)

[54] Ratios between total imports and total use of imports are equal across industries but differ across use categories (Dietzenbacher et al., 2013). It should be noticed that this approach differs from the standard import proportionality which applies import shares for all uses irrespective of the category. Thus, when WIOD integrates ISUTs into the WIOT, to ensure consistency between bilateral flows of exports and imports

emission inventories used in this essay includes Environmental Protection Agency GHG Inventories (USEAP, 2013), Initiate National Communities on Climate Change in the People Republic of China (NCCP, 2013), and $CO_2$ emission factors for Fuel used in European Union GHG Inventories (EUROPA, 2013). There is a lack of information specific for ROW. The UNFCCC guidance for greenhouse gas inventories is used to represent emission factors for ROW (UNFCCC, 2013).

## 4.5 Empirical Results and Discussions

This section presents the main findings of EE-MRIO analysis with respect to PBE and CBE allocations. This analysis can be used to extend the elasticity concept to identify key industries in response to the nature of emission industrial interdependencies. These elasticity largely depend on the linkages between the structures of export-import demands and emission distributions for an economy. Hence, this section first presents the main findings of PBE and CBE with respect to the U.S., China (CHN), and European Union 15 (EU15) economies. Then, subsequent subsections present the results of key industries in embodied $CO_2$ emissions stimulated due to the significance of export and import flows for each of these economies.

### 4.5.1 Production-Based Emissions (PBE) Allocation

In 2011, the top three world economies produced around 54% of the global $CO_2$ emissions, the approximation of 16,858,661 kilotons (kt) $CO_2$. The U.S. economy accounted for 16% of the world emissions whereas the China economy produced almost 30%. The EU15 economy contributed 8%. Figure 4.1 shows the contributions of PBEs in the U.S., CHN, and EU15 economies. A total of 5,255,865 kt $CO_2$ occurred on the U.S. domestic production. 85% of which (4,354,864 kt) was due to the production of domestic demand and the 15% (901,001 kt) was due to the production of export demand. In China, 8,597,216 kt of $CO_2$ were generated by its domestic production in 2011. 66% of the emissions (6,219,407 kt) was engaged in the production of domestic demand and the 34% (2,377,809 kt) was associated with export demand. Total production of EU15 occurred on its territory was contributed to 2,985,580 kt of $CO_2$, 73% of which (2,382,031 kt) was the emissions due to domestic demand and the 27% (603,549 kt) was emissions due to export demand.

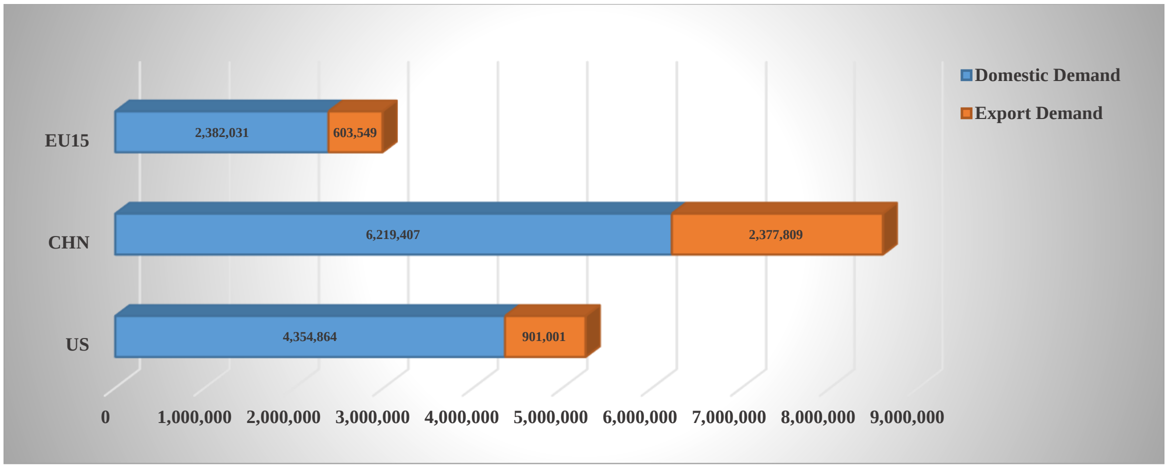


*Figure 4.1: Production-Based Emissions by End Use in the U.S., China, and EU15 Economies, 2011; kt of $CO_2$*

When the PBEs by industry are analyzed, emissions from industries with high carbon intensities are allocated substantial emissions when supplying domestic and export demands. Figure 4.2 presents the U.S. industry contributions of emissions linked with carbon intensities and showing the production due to domestic and export demands. A full presentation of these data are given in Tables 4.7-4.9 in Appendix 4-A. In 2011, carbon intensities of 12 industries (utility, refined petroleum, chemicals, rubber and plastics, non-metallic minerals, basic metals, machinery, transport equipment, inland transport service, water transport service, air transport service, and other supporting transport services industries) are far higher than other industries. Emissions associated with these industries accounted for 57% of emissions attributable to domestic demand (2,482,272 kt), 33% of which was due to the emissions from a utility industry. These emissions contributed 70% of emissions from exports (630,700 kt). In this respect, a control of emissions in those industries may pave a way for the U.S. to a low-carbon transition.

However, this analysis points out that despite low carbon intensities, some industries are important contributors of the U.S. domestic emissions. Examples include construction, food and beverages, hotels and restaurants, public administration, and health services industries. In 2011, emissions linked to these economic activities accounted for 32% of emissions on U.S. production (1,681,877 kt). In this way, carbon intensities by industry alone have no longer been a productive indicator to measure industrial responsibilities for emissions. This may be relevant because differences between direct and indirect emissions generated across their entire productive systems.

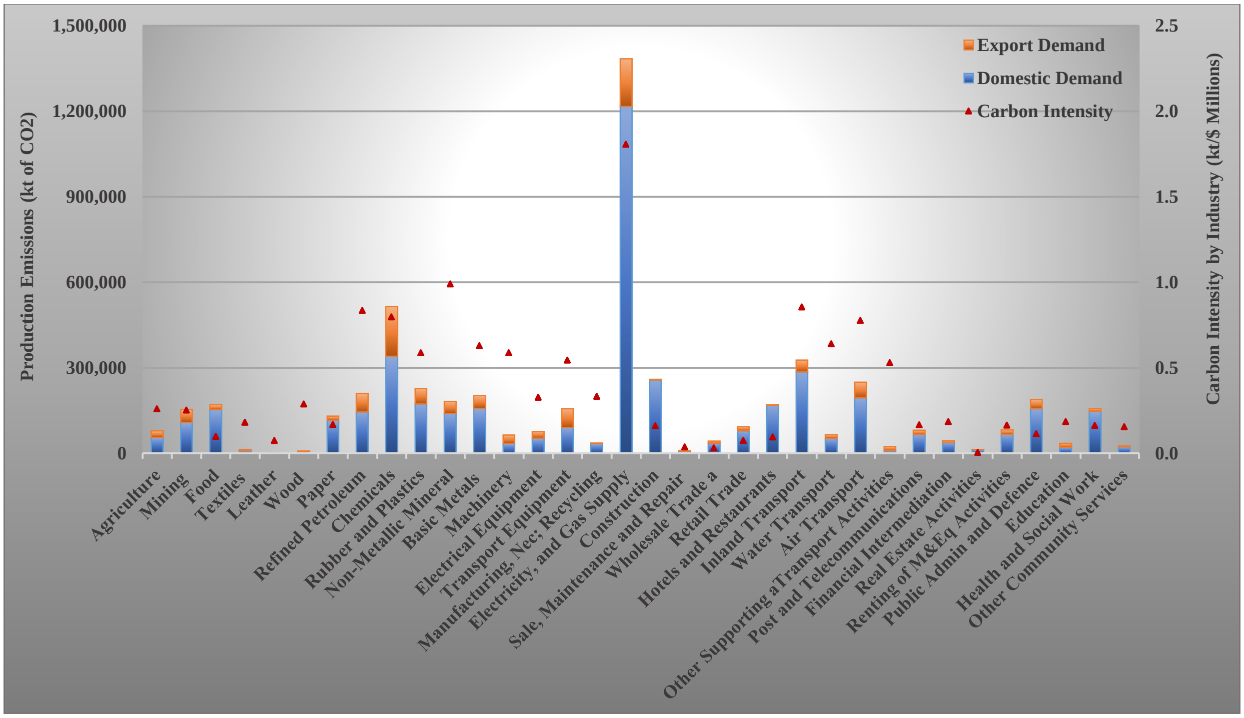


*Figure 4.2: A Breakdown of Production-Based Emissions by Industry in the U.S. Economy, 2011*

As shown in Figure 4.3, carbon intensities of Chinese industries are far greater than those of U.S. industries, 17 of which are higher than 1.00 kt/$ million. In 2011, China domestic emissions are substantial for 10 industries: utility; food and beverages; textiles; refined petroleum; chemicals; basic metals; machinery; electrical equipment; transport equipment; and inland transport service industries. These emissions accounted for 64% of emissions attributable to domestic demand (3,980,420 kt). However, this analysis points out that emissions generated by 9 out of 10 industries, with the exception of inland transport service industry, are highly relevant to a proportion of exports, accounting for 81% of emissions generated by those industries and approximately 72% of emissions attributable to China exports.

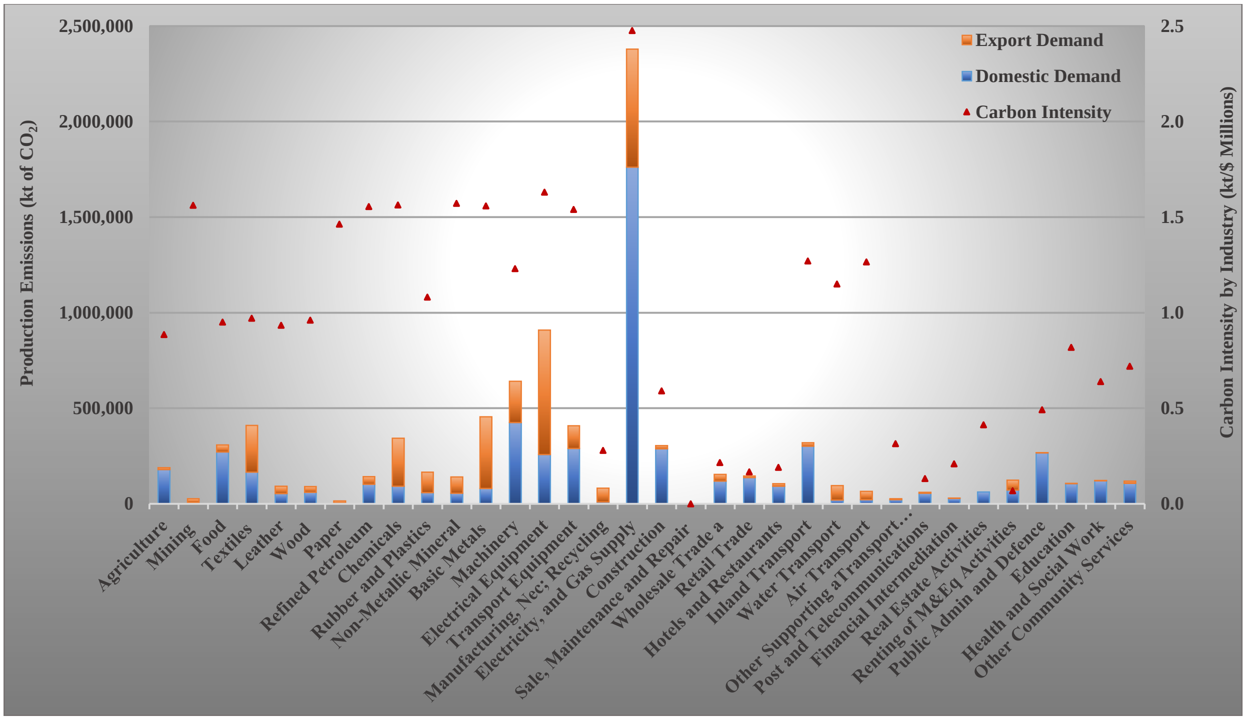


*Figure 4.3: A Breakdown of Production-Based Emissions by Industry in China Economy, 2011*

Carbon intensities of EU15 are relatively low compared with those of U.S. and China (Figure 4.4). with only the utility industry being above 1.0 kt/$ million. Nevertheless, carbon intensities clearly make distinctive contributions to industrial emissions attributable to both domestic and export demands within economic region. Industries with high carbon intensities are responsible for a large part of total emissions produced. Examples include utility, refined petroleum, chemicals, basic metals, machinery, transport equipment, construction, inland transport service, water transport service, and air transport service industries. In 2011, these emissions accounted for 54% of emissions attributable to domestic demand (1,453,039 kt), of which only 21% was due to emissions associated with utility industry. This finding is not surprising as electricity in EU15 is largely generated from non-fossil energy sources[55]. However, it reflects that emissions associated with the above industries except utility industry were responsible for almost 72% of emissions attributable to export demand (432,662 kt).

Moreover, since EU15 has become a service-oriented economy, emissions from some service industries (wholesale, retail trade, hotels and restaurants, public administration, and health services) must be highlighted. Despite less direct emissions due to low carbon intensities, their emissions have large effects

[55] Among the non-fossil energy, the large share of electricity generation was from nuclear power plants (28%), hydropower plants (18%), wind turbines (8%), and solar power (3%) which was recorded in 2011.

on emissions associated with domestic demand, which accounted for 39% of EU15 production emissions (1,164,376 kt).

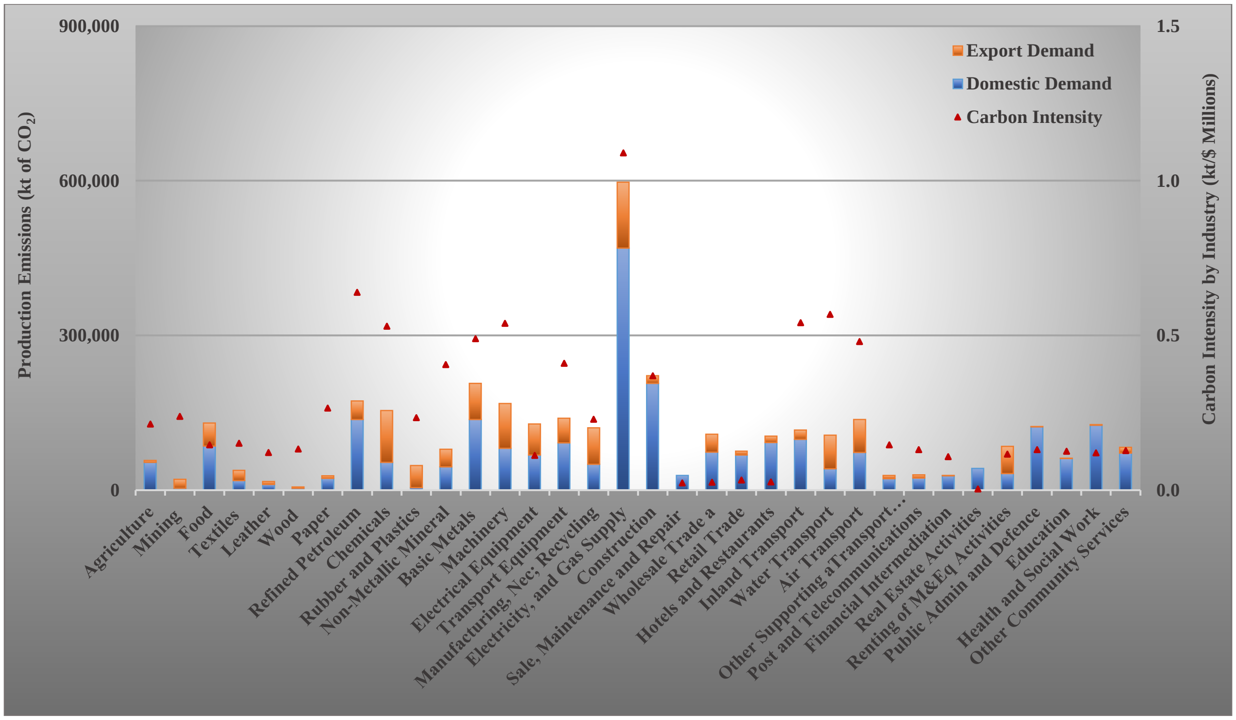


*Figure 4.4: A Breakdown of Production-Based Emissions by Industry in EU15 Economy, 2011*

## 4.5.2 Consumption-Based Emissions (CBE) Allocation

Consumption emissions include, both direct and indirect emissions that are produced outside a border in order to provide goods and services consumed inside a border (Figure 4.5). In 2011, the U.S. economy was responsible for 6,528,137 kt of $CO_2$ emissions. $CO_2$ emissions stimulated due to China consumption were 7,422,804 kt while the EU15 consumption contributed to 3,621,893 kt. The differences between PBE and CBE refer to a net trade balance of emissions. Along this line, the U.S. and EU15 are net importers of emissions. China is a net exporter. By way of comparison, the trade balance of U.S. emissions is +28% of its production emissions while the EU15 trade emission balance are +25%. China emissions based on net exports are approximately -19% less than its production emissions. In this respect, this evidence reflects that $CO_2$ emissions stimulated due to trade flows of three economies have a significant consideration for international policies on climate change.

Figure 4.5 also shows the contributions of emissions stimulated due to imports into the U.S., China, and EU15 economies. In the case of U.S., emissions embodied in import demands were approximately 51% of its production emissions from Figure 4.1 (2,173,272 kt), 82 % of which (1,775,927 kt) was used to supply intermediate inputs to domestic industries and the 18% (397,345 kt) was due to final products solely directly to U.S. consumers. Emissions embodied in EU import demands also were relatively high, approximately 53% of its production emissions. Around 52% of such emissions (654,001 kt) were due to the supply of intermediate imports and 47% of emissions (585,861 kt) were due to final imports. Finally for China, emissions embodied in import demand accounted for only 20% of its production emissions, 74% of which (894,655 kt) was due to the supply of intermediate imports and the 26% (308,742 kt) was associated with final imports. In this respect, the main contribution of U.S. and China imported emissions was due to intermediate imports whereas the key contribution of EU15 imported emissions was associated with both intermediate and final imports almost equally.

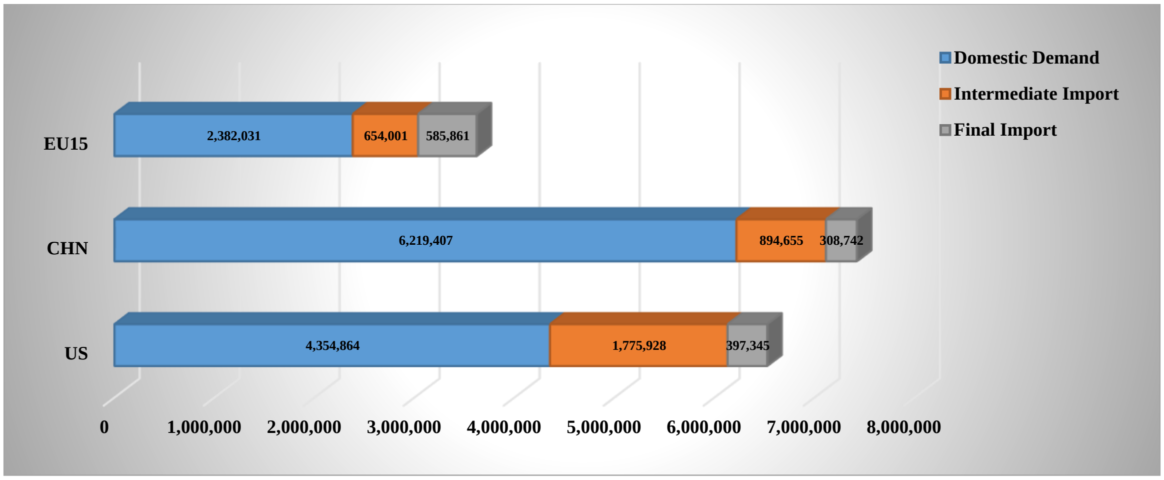


*Figure 4.5: Consumption-Based Emissions by End Use in the U.S., China, and EU15 Economies, 2011; kt of $CO_2$*

A close examination of the import structure and emissions stimulated due to import demand potentially establishes insights into the significant contributors and their contributions to the global emissions associated with trading across three economies plus the rest of the world (ROW). Figures 4.6-4.8 present breakdowns of imported emissions by industry in the U.S., China, and EU15 economies. It is important to note that a breakdown by country of origin is not shown in these figures. A full presentation of these data are given in Tables 4.10-4.12 of Appendix 4-A.

Emissions due to imports from the ROW contributed 54% of the total emissions associated with U.S. import demand (1,168,167 kt). China and EU15 accounted for 35% (757,145 kt) and 11% (237,959 kt) respectively. As shown in Figure 4.5, 82% of overall embodied emissions (1,775,928 kt) were due to the supply of intermediate inputs to U.S. industries. Paper, chemical, rubber and plastics, non-metallic minerals, basic metals, and utility industries were the main contributors to the emissions. This finding is not surprising because such industries have been characterized by high carbon intensive industries. However, it is important that with respect to the PBE of the U.S. economy, not all of them are included as crucial contributors. Consequently, industrial coverage may become a central issue of discussions on climate policy strategies.

Moreover, this analysis also reveals that the amount of imported emissions relies on not only carbon intensities of industries that produce imports but also values of imports that differ economy by economy. For example, chemicals from the ROW accounted for 45% of the total chemical imports to U.S. while those from China accounted for 25%. However, emissions associated with chemical imports from China and ROW amounted correspondingly to around 41% of the total emissions with respect to chemical imports to the U.S. economy. This is relevant because carbon intensity of the ROW chemicals was lower than that of the China chemical. This evidence can be clearly seen in the case of basic metals and non-metallic minerals.

Examples of other industries contributions of imported emissions include water transport service, agriculture, post telecommunications, renting of business activities, and health services industries. Despite low carbon intensities except for water transport service industry, emissions associated with their imports accounted for 32% of the total imported emissions (695,447 kt). The value of industrial imports by economy is an important consideration for industrial responsibility shares.

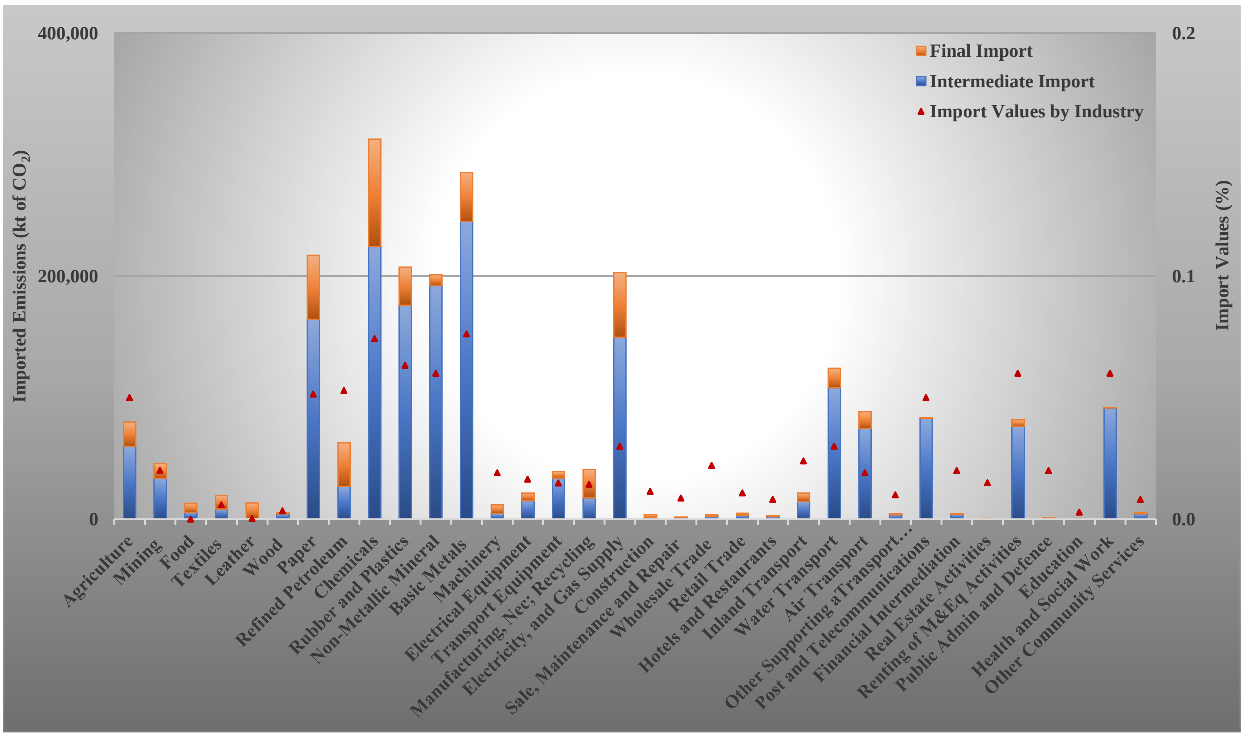


*Figure 4.6: A Breakdown of U.S. Imported Emissions by Industry, 2011*

The examination of import distribution chains with respect to country of origin is needed for allocating emission responsibility by industry. However, the importance of those chains with respect to the structure of imports may become an important feature taken to create fairer responsibilities. Normally, CBE is independent of emissions attributable to export demand. In order to thoroughly look to the importance of import structures, EE-MRIO analysis allows a decomposition of emissions attributable to import demand into embodied emissions associated with the supply of intermediate import for domestic industries to produce re-exports to foreign consumers. To decompose the emissions due to re-exports, I employed the technique of Zhao et a. (2014) to calculate embodied emissions attributable to re-exports[56]. This analysis

[56] Embodied emissions attributable to re-exports of region 1 ($E^1_{yx}$) can be expressed as:

$$E^1_{yx} = \sum_{r \neq 1} \varepsilon^1 (y^1_x - y^{r1}_{mf}) + \sum_{r} \varepsilon^r (y^{r1}_{mf})$$

where $\varepsilon^1$ represents the matrix of emission multiplier by industry within region 1. $\varepsilon^r$ represents the matrix of emission multiplier by industry in other regions r. $y^1_x$ is the value of exports by industry in region 1. $y^{r1}_{mf}$ is the value of intermediate import by industry contained in the production explores that a proportion of intermediate imports in the U.S. economy contributed emissions embodied in its exports by 31% in 2011 (281,000 kt). This shows a clear evidence that a proportion of imports is reprocessed by domestic industries to supply foreign demand.

Emissions due to imports from ROW accounted for 75% of the total emissions associated with China import demand (902,548 kt). EU15 and U.S. accounted for 15% (180,510 kt) and 10% (120,340 kt) respectively. As shown in Figure 4.7, a large proportion of emissions was attributed to intermediate imports. In 2011, these imports accounted for 74% of the total emissions from China imports to China (894,655 kt). Mining, paper, refined petroleum, chemicals, rubber and plastics, and non-metallic minerals, water transport service, and air transport service industries were the main contributors for driving the embodied emissions. When decomposing the proportion of intermediate imports that were utilized to produce contained exports, this analysis reveals that the production process of re-exports contributed 24% of the emissions embodied in exports (571,000 kt).

Other industries significant for the embodied emissions include agriculture, leather, wood, renting of business activities, education, plus health services. However, contributions of these industries were due to the supply of intermediate imports for producing products to meet domestic demand. Emissions associated with such industries contributed 48% of the total embodied emissions (577,630 kt)

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process of exports of region 1. It is important to note that $y_{mf}^{r1}$ in the above equation has no longer been satisfied by import proportionality assumption generally used by WIOD. In this respect, using the same data set, $y_{mf}^{r1}$ can be recalculated as:

$$y_{mf}^{r1} = (\sum_{r \neq 1} \frac{M_{mf}^{1r}}{X^1})(y_x^1)$$

where $M_{mf}^{1r}$ denotes the total value of intermediate import by industry consumed by region 1. $X^1$ is the total output by industry in region 1.

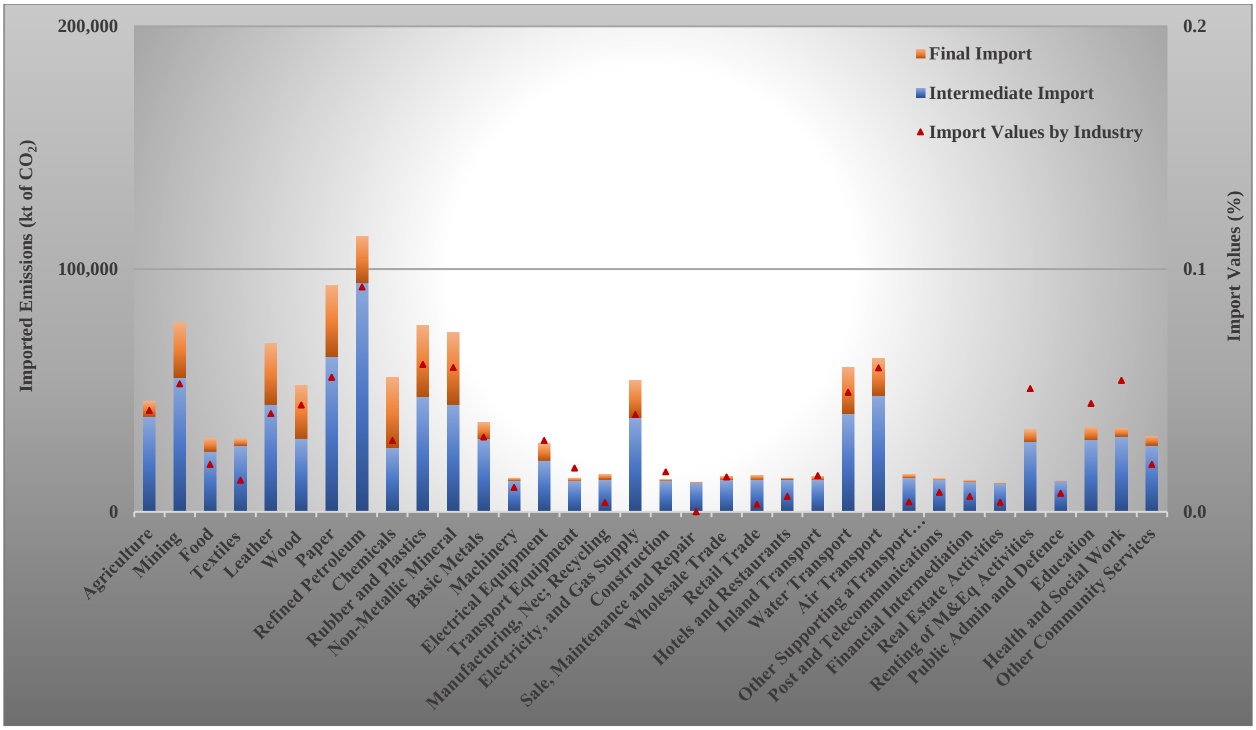



*Figure 4.7: A Breakdown of China Imported Emissions by Industry, 2011*

The amount of $CO_2$ emissions embodied in the EU15 import demand was largely generated by the supply of intermediate imports for producing products to meet domestic demand as well as by final imports sold directly to consumers (see Figure 4.8). In 2011, intermediate imports accounted for 53% of the total embodied emissions (654,001 kt), 29% of which was due to re-exports. The final imports contributed 47% of the total embodied emissions (585,861 kt). The domestic industries mainly were agriculture, mining, food and beverage, paper, rubber and plastics, non-metallic minerals, electrical equipment, and manufacturing industries. The production processes from these industries contributed 69% of the total embodied emissions (855,504 kt). Regarding the geographical separations of emissions, the most embodied emissions was from the ROW, accounting for 53% (657,127 kt). 27% of emissions (334,762 kt) were due to imports from China and 20% (247,972 kt) were due to imports from the U.S.

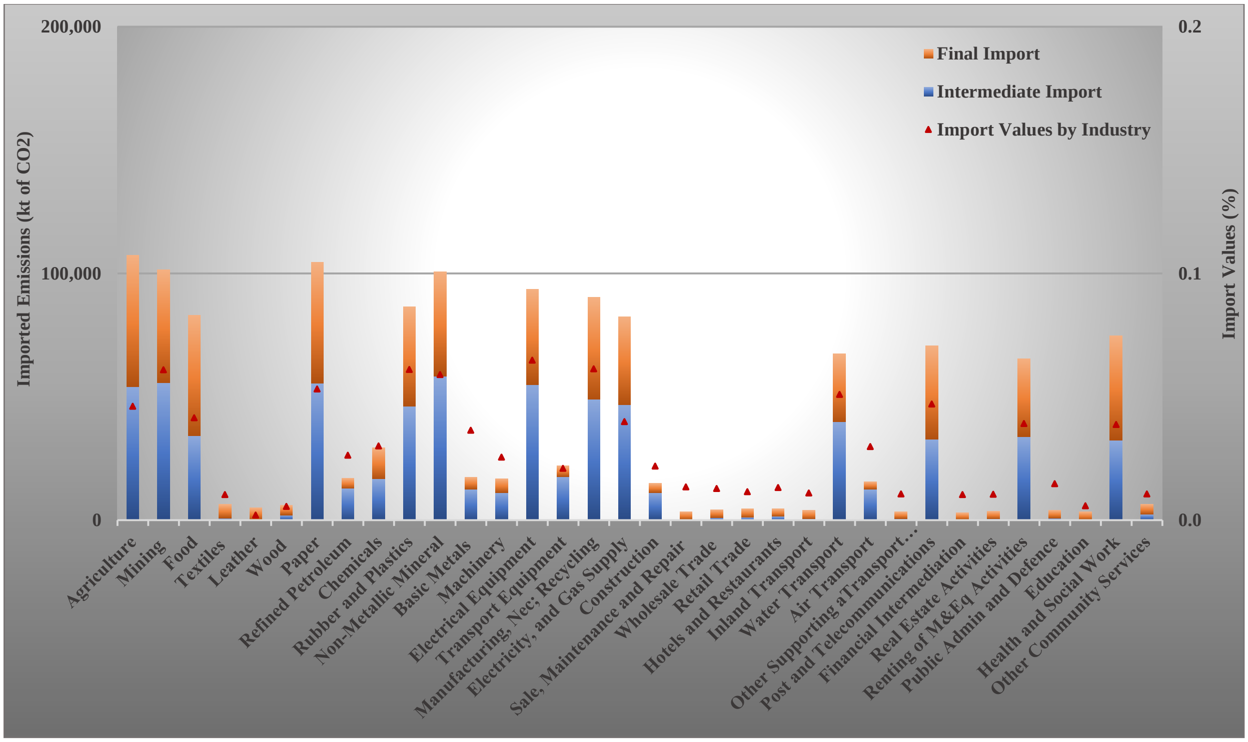



*Figure 4.8: A Breakdown of EU15 Imported Emissions by Industry, 2011*

### 4.5.3 Key Industries in Embodied $CO_2$ Emissions

This subsection industries associated with embodied emissions in international trade. The key industries analysis takes into account how the nature of emissions stemming from inter-industry dependencies shapes an emission distribution associate with the structure of their export and import demands. As shown in Table 4.1, an industry can be identified into four categories: (1) a key industry, (2) a relevant industry in terms of own demand, (3) a relevant industry in terms of the demand from others, and (4) non-relevant industry. In this way, the analysis of key industries in embodied $CO_2$ can help characterize long-term responsibilities of industrial interdependencies based on emissions associated with the importance of their export and import structures. Moreover, this analysis is going to become important for industrial coverage to construct a general view of international policies on climate change. In order to provide a clear identification of industrial responsibilities, this subsection presents the main findings in the sense of geographical separations of embodied emissions.

Overall, Equations 4.11 and 4.12 were used to compute the variation of $CO_2$ emissions by industry in response to changes in their domestic and export demands. This analysis indicates an identical set of industrial classifications between $CO_2$ emissions stimulated due to two types of demands, but shows different scales of the elasticity which experience the differential rates of emission changes. This finding is not surprising because elasticities are calculated from a unique output set and identical carbon technology. In this respect, policy measures proposed for emissions associated with export demand can partially adopt to production emissions stimulated due to the entire economy.

Equations 4.13 and 4.14 are used to compute the variation of $CO_2$ emissions in response to changes in both intermediate and final import demand of industries. As WIOD recognizes mirror flows of bilateral exports and imports to the WIOTs[57], key industries in embodied emissions with respect to final import from an economy should reflect a similar classification of industries with respect to embodied emissions in exports from the corresponding economy. Thus, key industries analyses in imported emissions would center on the importance of intermediate import. The full presentations of elasticities decomposed into each end use by three economies are presented in Tables 4.14-4.16 in Appendix 4-A.

To classify industries based on Table 4.1, comparisons were made between the median values of the total effect and the distributive effect illustrated in the last column of Tables 4.2 and 4.3. As shown in Figures 4.9-4.11, industries in category 1 (the upper left) are considered as the key industries. Industries in category 2 (the lower left) are considered as the relevant industries in terms of own demand. Industries in category 3 (the upper right) are considered as the relevant industries in terms of the demand from the other industries. Lastly, industries in category 4 (the lower right) are considered as non-relevant industries that are no longer affected by own demand and the demand from the others. Figures 4.9-4.11 present sub-headings A and B in order to indicate the industrial classification of exported and imported emissions.

## The United States

### 1. Exported Emissions

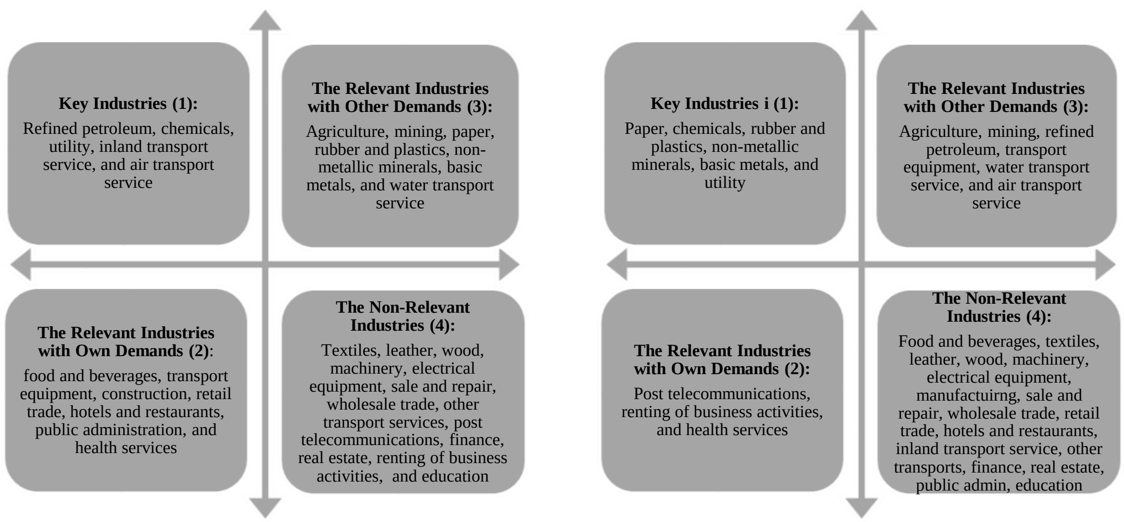
As shown in Figure 4.9-A, key industries in emissions attributable to export demand (category 1) are composed of refined petroleum, chemicals, utility, inland transport service, and air transport service industries. In 2011, their total effect accounted for 44% of the U.S. exports[58]. Their effect on the distribution of exported emissions represented 56%. This means that 56% of exported emissions were generated by these key industries. It is not surprising that these industries would be the most importance on when evaluating U.S. exported emissions.

As distributive effect is greater than total effect, these key industries are relevant for exported emissions due to strong forward linkages. This means that variation in the demand for their products by other industries has stronger effects on exported emissions than variation in the demand for their inputs. As

[57] See Section 4
[58] This number is estimated by the sum of total effects through five key industries.

shown in Table 4.2, distributive effect of refined petroleum was 29% greater than its total effect. Chemicals had 25% of difference between distributive effect and total effect. Utility industry showed 29% of difference while inland transport service showed 20% of difference. Air transport service showed 18% of difference. Due to big differences, it is likely that industrial policy measures would be implemented to deal with emissions from consumption of their outputs.

However, before implementing industrial policy measures, this analysis points out that it is important to decompose the own component. The own component represents the percentage of industrial total in regard to distributive effects. Almost all key industries showed a high own distributive effect at close to or over 50%. This implies that industrial policy measures for consumption of their outputs should be applied for these industries because a large proportion of export activity losses places in their own. Only the inland transport service industry should take a careful consideration of the large proportion of export activity losses posed to other industries supplying inland services. In this respect, an industrial policy measure for consumption of their outputs would not be a good policy design for inland transport service industry. Policy measures relate to sustain output consumption will be more appropriate.




*(A) Exported Emissions* *(B) Imported Emissions*

*Figure 4.9: Classification of U.S. Industries in Response to Exported and Imported Emissions*

The relevant industries in terms of own demand (category 2) in the U.S. are food and beverages, transport equipment, construction, retail trade, hotels and restaurants, public administration, plus health service industries. In 2011, their total effect represented 36% of the total U.S. exported emissions while their effect on the distribution of exported emissions accounted for only 12%. Due to high total effect, this finding reflects that these industries are relevant for exported emissions due to their backward linkages. This means that variation in the demand for inputs supplied to other industries has a larger effect on exported emissions than variation in the demand for their products by other industries. Industrial policy measures applied to category 2 industries to reduce emissions may be an effective policy for encouraging other industries to mitigate emissions for supplying its inputs. Taking into account own component of those industries, some industries showed low own total effects. Examples of industries with low own total effects include food and beverages (21%), retail trade (23%), hotels and restaurants (17%), and health services (22%). In this way, industrial policy measures may not be enough for such industries to encourage other industries to curb emissions for supplying their inputs. A Policy measure on demand management which is relevant to demanding the quality of input use will be an alternative.

The relevant industries in terms of the demand from other industries (category 3) are agriculture, mining, paper, rubber and plastics, non-metallic minerals, basic metals, and water transport service industries. Their total effect represented only 15% of exported emissions in 2011. However, their effect on the distribution of exported emissions accounted for 30%. This reflects that 30% of the exported emissions were distributed to these industries. Due to high distributive effect, these industries are relevant exported emissions due to forward linkages. Increases in demand for their products play an important role in U.S. exported emissions. Taking their own component into consideration, forward linkages of some industries (paper and non-metallic mineral industries) were largely driven by other industries supplying inputs to the paper and non-metallic minerals industries due to low own distributive effects.

Conversely, high own distributive effects and forward linkages of other category 3 industries were mainly driven by their own demand. Along this line, category 3 industries except for paper and non-metallic mineral industries should implement industrial policy measures to reduce emissions based on consumption of their outputs to curb the U.S. exported emissions.

The remaining industries are grouped in non-relevant industries. In 2011, the magnitude of total and distributive effects for each of them was low and contributed only a limited influence on the U.S. exported emissions. For this reason, they would be less relevant to design policy measures for the U.S. exported emission reductions.

## 2. Imported Emissions

Key industries for imported emissions are widely distributed among the 34 industries. It is important to note that as clearly seen in section 4.5.2, around 76% of emissions associated with the U.S. imports were due to the supply of intermediate imports for domestic industries in 2011. 89% of these emissions were generated by China and the ROW. In this sense, the key industries for imported emissions by this end use mainly occur within these two economic regions.

Key industries in emissions associated with U.S. imports (category 1) are composed of paper, chemicals, rubber and plastics, non-metallic minerals, basic metals, and utility industries (Figure 4.9-B). Some of them were classified as the relevant industries in terms of category 3 in regard to U.S. exported emissions. In this respect, the connection of key industries points out that the contribution of emissions associated with U.S. imports was due in part to a shift in carbon-intensive products to U.S. trading partners (Figure 4.2). Total effect of these key industries represented 65% of the entire U.S. imports in 2011. Their effect on the distribution of imported emissions accounted for 67%. This means that 67% of U.S. imported were distributed to key industries.

At an industry level, paper, chemicals, basic metals, and utility industries showed total effects greater than distributive effects (Table 4.3). In turn, rubber and plastics plus non-metallic minerals industries showed total effects less than distributive effects. However, due to slight differences (less 10%) between the magnitude of total and distributive effects, it is unclear that the above industries should be identified as key through either backward or forward linkages. If a key industry is relevant due to either its backward or forward linkage, industrial policy measures for curbing its imported emissions are going to be different. The importance of own component through total and distributive effects may help make this uncertainty clear. Important criteria for identifying linkages is that if a difference between total and distributive effects is greater than that between own component of two effects, an industry will be identified as key through an effect that has a higher number. If not, an industry will be identified as key through larger own component.

This analysis finds that almost all key industries are identified as key based on the criteria of a high number of two effects. Only rubber and plastics has to be identified based on a larger own component. As shown in Table 4.3, rubber and plastics showed 5% difference in two effects, but a 20% difference in own component. For this reason, paper, chemicals, rubber and plastics, basic metals, and utility industries are relevant for imported emissions due to strong backward linkages. Variation in their intermediate imports have more effect on imported emissions than variation in the demand for their products. In turn, non-metallic minerals industry is relevant imported emissions due to strong forward linkage.

By way of comparisons with own component of industrial exported emissions, chemicals industry showed own component of 34% in regard to imported emissions versus 41% in regard to exported emissions. Rubber and plastics industry showed own component of 35% in regard to imported emissions versus 54% in regard to exported emissions. In this respect, due to carbon transfers in light of the fragmentation of international production, industries with low own component of either total or distributive effect complicates emission reductions by means of encouraging industry actions. Industrial policy measures may not be effective for curbing U.S. import emissions. In turn, it is likely that cross-industrial policy measures go more appropriate.

The relevant industries in terms of own demand (category 2) are post telecommunications, renting of machinery and equipment, and health services industries. Only the health services industry was included in the industrial classification of exported emissions. Their total effect represented 19% of the whole U.S. imports in 2011. Their effect on the distribution of imported emissions accounted for less 6%. However, due to low own total effects (below 30%), changes in their intermediate imports would constitute a large effect on the emissions of other industries. By comparison with exported emissions, category 2 industries showed less importance for imported emissions as a result of small total effect.

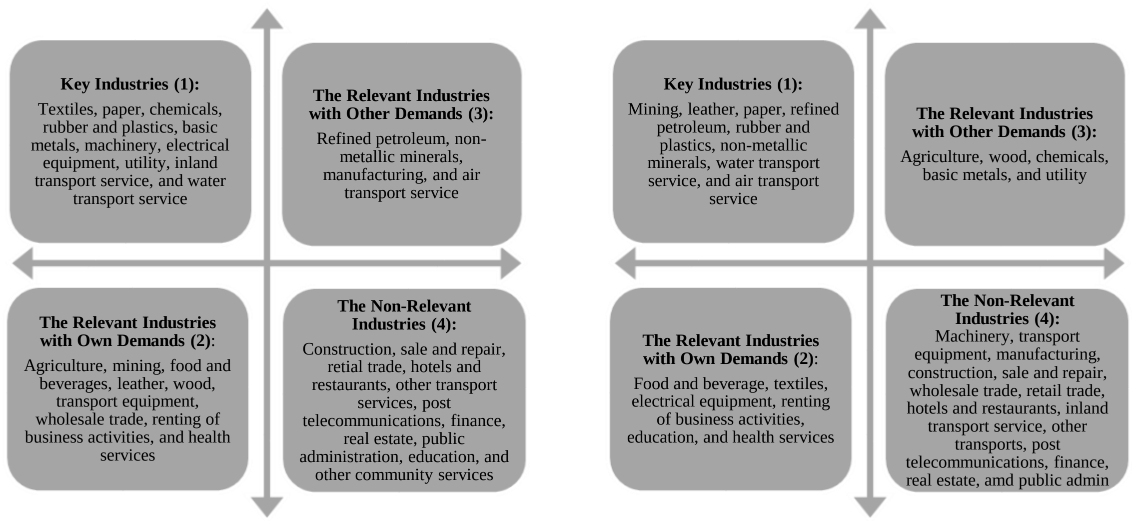
The relevant industries in terms of the demand from others (category 3) are agriculture, mining, refined petroleum, transport equipment, water transport service, and air transport service industries. Their total effect represented almost 7% of imported emissions while the share in imported emissions accounted for 26%. Agriculture, transport equipment, and air transport service industries showed nearly 50% of own component. This reflects that variations in their own contributes to emissions associated with U.S. imports. Comparing with exported emissions, category 3 industries play a small role in U.S. imported emissions.

## China

### 1. Exported Emissions

Key industries in China exported emissions are more distributed among industries than those in the U.S. However, the magnitude of total and distributive effects of some key industries is relatively high. As shown in Figure 4.10-A, key industries (category 1) are composed of textiles, paper, chemicals, rubber and plastics, basic metals, machinery, electrical equipment, utility, inland transport service, and air transport service industries. Their total effect represented 63% of the China exports in 2011. Their effect on the distribution of exported emissions accounted for 79%. This large impact stems from basic metals, machinery, electrical equipment, utility, and water transport service industries playing a relevant role in distributive effects. Variation in the demand for their products through other industries have a larger effect on exported emissions than on variation in the demand for their inputs. Because the magnitude of distributive effects and own components of those industries was high in 2011, industrial policy measures may become important to reduce exported emissions associated with these industries. However, due to low own distributive effect, implementation of industrial policy measures for basic metals industry would highly influence economic activities of other industries. It is likely that this type of policy measures can lead to a bottleneck of export activities along global supply chains of basic metals industry.

As shown in Table 4.2, textiles, paper, chemicals, rubber and plastics, plus inland transport service industries have total effects greater than distributive effects. This means that variation in the demand for their inputs are the main reason leading to increases in their emissions. This analysis points out that only the textiles industry showed low own total effect (26%). Industrial policy measures may not be effective for the textiles industry owing to the potential to share reductions in demand greater than reductions in its emissions.




(A) Exported Emissions (B) Imported Emissions

*Figure 4.10: Classification of China Industries in Response to Exported and Imported Emissions*

The relevant industries in terms of own demand (category 2) are agriculture, mining, food and beverages, leather, wood, transport equipment, wholesale trade, renting of machinery and equipment, plus health services industries. Their total effect accounted for 19% while their share in exported emissions represented almost 7%. With respect to small total effect, category 2 industries are less importance for China exported emissions.

The relevant industries in terms of the demand from others (category 3) are refined petroleum, non-metallic minerals, manufacturing, plus air transport service industries. Their total effect accounted for 8% while their effect on the distribution of exported emissions represented 10%. This analysis indicates a small role of category 3 industries in China exported emissions because of very low distributive effects. In regard to the magnitude of both total and distributive effects, key industries play an outstanding role in China exported emissions.

## 2. Imported Emissions

Eight industries are considered as key in emissions associated with China imports. They are composed of mining, leather, paper, refined petroleum, rubber and plastics, non-metallic minerals, water transport service, and air transport service industries (Figure 4.10-B). Their total effect represented 50% of the entire imports while their share in imported emissions accounted for 45%.

Mining, paper, refined petroleum, rubber and plastics, and non-metallic minerals industries showed total effects greater than distributive effects. They are relevant imported emissions due to strong backward linkages. Only the paper and rubber and plastics industries have relatively low own component; 34% and 37% respectively. Conversely, water transport service and air transport service industries showed total effects smaller than distributive effects. These two industries are relevant imported emissions due to strong forward linkages. However, owing to low own components (less 30%), the demand created by other industries is the major contribution.

The relevant industries in terms of own demand (category 2) are food and beverages, textiles, electrical equipment, renting of machine and equipment, education, and health services industries. Total effect of category 2 industries in regard to imported emissions was larger relative to that in regard to exported emissions. Their total effect represented 29%. Their effect on the distribution of imported emissions accounted for 10%. Textiles and electrical equipment industries displayed high own total effects of 63% and 77% of their aggregate total. This implies that changes in the demand for intermediate imports of textiles and electrical equipment contribute imported emissions of other industries by 37% and 23% respectively. In turn, renting of machinery and equipment plus education showed own components of 37% and 32%. This implies that changes in the demand for intermediate imports of these industries contribute imported emissions of other industries by more than 60%.

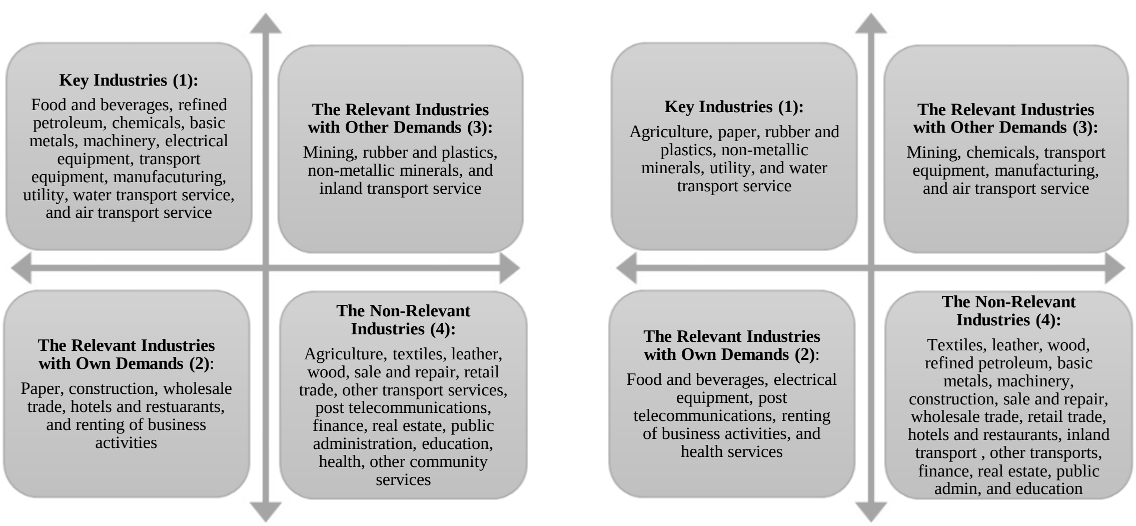
The relevant industries in terms of the demand from others (category 3) are agriculture, wood, chemicals, basic metals, and utility industries. Their total effect represented 13% while their share in imported emissions accounted for 41%. This magnitude of distributive effect regarding imported emissions is also relatively high compared with that regarding exported emissions. In this respect, policy measures for dealing with carbon transfers of China economy should not pay limited attention to key industries (category 1). Category 3 industries play an outstanding role in China imported emissions. Wood, chemicals, and utility industries had own distributive effects of greater 50% while agriculture and basic metals industries showed own distributive effects of 32% and 41%. However, comparing results of above industries with the findings of exported emissions is a dedicate issue due to identical sets of industrial classification.

## European Union 15

### 1. Exported Emissions

Comparing with the findings of the U.S. and China, key industries of EU15 are more distributed. However, the magnitude of total and distributive effects by industry is relatively small. This reflects more advanced carbon production technologies within this economy. Key industries (category 1) are composed of food and beverages, refined petroleum, chemicals, basic metals, machinery, electrical equipment, transport equipment, manufacturing, utility, water transport service, and air transport service industries (see Figure 4.11-A). Their total effect accounted for 47% of the entire EU15 exports. Their effect on the distribution of exported emissions represented 62%. It is not surprising that these key industries would be more crucial when evaluating EU15 exported emissions relative to key industries of the U.S.

Unlike the U.S. and China where utility industry has very high specific weight, utility industry for EU15 accounted for less 30% of the exported emissions calculated within category 1. According to section 4.5.1, EU15's utility industry is largely generated from non-fossil energy sources. However, this analysis points out that food and beverage, chemical, and basic metal industries should be taken for EU15's exported emissions. Their emissions accounted for almost 43% of the emissions calculated within this category. In addition, these industries are relevant exported emissions due to strong backward linkages. This implies that variation in the demand for inputs supplying to these industries is the main reason for the increased exported emissions within these industries. Chemical industry is the most highlight because of the largest magnitude of two effects combined.




*(A) Export Emissions* *(B) Import Emissions*

*Figure 4.11: Classification of EU15 Industries in Response to Exported and Imported Emissions*

The relevant industries in terms of own demand (category 2) are paper, construction, wholesale trade, hotels and restaurants, and renting of machinery and equipment industries. Their total effect accounted for 32% while their share in exported emissions represented 10%. Despite backward linkages, these industries showed low own total effects (less 35%). In this way, industrial policy measures are not on track for curbing emissions associated with these industries.

The relevant industries in terms of the demand from others (category 3) are mining, rubber and plastics, non-metallic minerals, and inland transport service industries. Their total effect accounted for 14% of the entire exported emissions while their share in exported emissions represented 20%. This reflects that category 3 industries would be less relevant to design policy measures for the EU15 exported emission reductions.

## 2. Imported Emissions

Key industries in emissions associated with intermediate import of EU15 economy are composed of industries which was due to a shift in the production to its trading partners. These industries consist of agriculture, paper, rubber and plastics, non-metallic minerals, utility, and water transport service industries. As clearly seen in section 4.5.2, they have relatively high emission intensities within EU15 economy, but the value of their (domestic) outputs have minor distributive effects on its production emissions. However, this finding must be interpreted carefully. It is relevant because around 47% of emissions associated with EU15 imports were due to final import directly supplied to domestic consumers. Owing to the assumption of WIOD, the key industries in emissions associated with final import are consistent with the key industries in emissions associated with exports from its trading partners. However, this essay explores the multiple sets of industrial classification in terms of both changes in intermediate and final imports. As shown in Figure 4.11-B, key industries mainly occurs on the ROW. It represented 53% of emissions associated with EU15 imports in 2011. Thus, the results of key industries in imported emissions of EU15 could not precisely affirm. Comprehensive analysis of key industries has been called for the upcoming research. The EU28 may become a need for analyzing key industries in imported emissions.

*Table 4.2: Industrial Distributive and Total Effects of Exported Emissions, 2011, Percentage Contribution of Exported Emissions in Response to Demand; (Own Component Percentage in Parenthesis)*

| Industry | US | | CHN | | EU15 | |
|---|---|---|---|---|---|---|
| | Distributive Effect | Total Effect | Distributive Effect | Total Effect | Distributive Effect | Total Effect |
| **Agriculture, hunting, forestry and fishing** | 0.047 (29) | 0.021 (36) | 0.013 (41) | 0.036 (45) | 0.009 (35) | 0.010 (37) |
| **Mining and quarrying** | 0.054 (26) | 0.022 (23) | 0.011 (36) | 0.034 (46) | 0.055 (25) | 0.016 (22) |
| **Food, beverages and tobacco** | 0.015 (19) | 0.046 (21) | 0.012 (21) | 0.023 (36) | 0.048 (31) | 0.069 (32) |
| **Textiles and textile products** | 0.002 (46) | 0.006 (42) | 0.051 (36) | 0.057 (26) | 0.010 (32) | 0.013 (46) |
| **Leather and footwear** | 0.003 (41) | 0.004 (52) | 0.010 (30) | 0.026 (38) | 0.009 (41) | 0.004 (39) |
| **Wood and products of wood and cork** | 0.001 (45) | 0.004 (36) | 0.012 (31) | 0.022 (31) | 0.010 (45) | 0.012 (41) |
| **Pulp, paper, printing and publishing** | 0.045 (25) | 0.021 (32) | 0.053 (26) | 0.058 (68) | 0.018 (31) | 0.052 (24) |
| **Coke, refined petroleum and nuclear fuel** | 0.094 (48) | 0.066 (24) | 0.057 (29) | 0.020 (39) | 0.038 (21) | 0.041 (62) |
| **Chemicals and chemical products** | 0.115 (45) | 0.093 (41) | 0.061 (30) | 0.058 (64) | 0.058 (22) | 0.071 (30) |
| **Rubber and plastics** | 0.049 (54) | 0.022 (31) | 0.047 (56) | 0.056 (67) | 0.052 (22) | 0.014 (24) |
| **Other non-metallic minerals** | 0.052 (24) | 0.023 (29) | 0.045 (27) | 0.019 (31) | 0.059 (27) | 0.015 (29) |
| **Basic metals and fabricated metal** | 0.042 (58) | 0.024 (31) | 0.055 (31) | 0.043 (55) | 0.048 (56) | 0.077 (27) |
| **Machinery** | 0.002 (32) | 0.006 (47) | 0.055 (57) | 0.042 (47) | 0.048 (30) | 0.035 (22) |
| **Electrical and optical equipment** | 0.001 (34) | 0.006 (35) | 0.051 (65) | 0.037 (25) | 0.049 (32) | 0.035 (34) |
| **Transport equipment** | 0.016 (45) | 0.046 (63) | 0.013 (34) | 0.034 (47) | 0.032 (25) | 0.034 (62) |
| **Manufacturing, nec** | 0.002 (57) | 0.005 (61) | 0.043 (72) | 0.018 (32) | 0.049 (53) | 0.035 (47) |
| **Electricity, gas and water supply** | 0.142 (47) | 0.115 (75) | 0.162 (59) | 0.084 (83) | 0.075 (48) | 0.059 (64) |
| **Construction** | 0.019 (35) | 0.056 (65) | 0.004 (61) | 0.014 (63) | 0.019 (25) | 0.060 (36) |
| **Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel** | 0.002 (32) | 0.004 (45) | 0.000 (0) | 0.000 (0) | 0.011 (27) | 0.005 (36) |
| **Wholesale trade and commission trade** | 0.002 (19) | 0.006 (32) | 0.011 (25) | 0.022 (36) | 0.018 (24) | 0.051 (25) |
| **Retail trade, except of motor vehicles and motorcycles; repair of household goods** | 0.015 (38) | 0.042 (23) | 0.003 (52) | 0.009 (45) | 0.010 (26) | 0.013 (32) |
| **Hotels and restaurants** | 0.014 (25) | 0.044 (17) | 0.004 (67) | 0.013 (54) | 0.017 (26) | 0.054 (26) |
| **Inland transport** | 0.107 (36) | 0.088 (67) | 0.068 (52) | 0.077 (67) | 0.076 (21) | 0.012 (25) |
| **Water transport** | 0.057 (49) | 0.023 (31) | 0.057 (61) | 0.039 (54) | 0.051 (53) | 0.042 (41) |
| **Air transport** | 0.093 (65) | 0.079 (43) | 0.055 (66) | 0.019 (52) | 0.052 (58) | 0.047 (42) |
| **Other supporting and auxiliary transport activities** | 0.003 (47) | 0.006 (34) | 0.003 (53) | 0.016 (49) | 0.000 (0) | 0.000 (0) |
| **Post and telecommunications** | 0.002 (26) | 0.008 (31) | 0.005 (47) | 0.016 (35) | 0.002 (27) | 0.016 (26) |
| **Financial intermediation** | 0.001 (29) | 0.003 (22) | 0.004 (45) | 0.013 (34) | 0.010 (28) | 0.004 (25) |
| **Real estate activities** | 0.001 (37) | 0.003 (26) | 0.002 (49) | 0.008 (42) | 0.002 (27) | 0.001 (32) |
| **Renting of machine and equipment** | 0.002 (24) | 0.003 (32) | 0.012 (27) | 0.027 (34) | 0.018 (24) | 0.064 (33) |
| **Public administration and defense** | 0.012 (37) | 0.043 (56) | 0.003 (66) | 0.009 (54) | 0.010 (32) | 0.010 (35) |
| **Education** | 0.002 (31) | 0.005 (33) | 0.004 (52) | 0.014 (41) | 0.008 (26) | 0.012 (23) |
| **Health and social work** | 0.018 (29) | 0.050 (22) | 0.012 (32) | 0.030 (34) | 0.013 (27) | 0.006 (25) |
| **Other community, social and personal services** | 0.002 (41) | 0.004 (35) | 0.003 (51) | 0.007 (47) | 0.005 (34) | 0.012 (36) |
| **Median Values** | 0.021 | 0.028 | 0.017 | 0.025 | 0.020 | 0.019 |

Notes: (i) Distributive impact of industry i emissions is calculated from the sum by rows such that $\sum_{j=1}^{n} \xi_{y_{ij}}^{1}$ where j=1,2,…n. In this way, it can be used to explain the percentage increase in the distribution of industry i's emissions with respect to export demand.

(ii) Total emission impact of industry i's total demand is calculated from the sum by columns such that $\sum_{i=1}^{n} \xi_{y_{ij}}^{1}$ where i=1,2,…,n. It can be interpreted as the percentage increase in the exported emissions as a whole with respect to export demand of industry i.

*Table 4.3: Industrial Distributive and Total Effects of Imported Emissions, 2011, Percentage Contribution of Imported Emissions in Response to Demand; (Own Component Percentage in Parenthesis)*

| Industry | US | | CHN | | EU15 | |
|---|---|---|---|---|---|---|
| | Distributive Effect | Total Effect | Distributive Effect | Total Effect | Distributive Effect | Total Effect |
| **Agriculture, hunting, forestry and fishing** | 0.062 (62) | 0.024 (26) | 0.068 (32) | 0.019 (43) | 0.072 (33) | 0.051 (28) |
| **Mining and quarrying** | 0.065 (30) | 0.025 (28) | 0.050 (35) | 0.062 (58) | 0.067 (42) | 0.021 (27) |
| **Food, beverages and tobacco** | 0.001 (32) | 0.005 (37) | 0.020 (32) | 0.059 (30) | 0.019 (31) | 0.062 (34) |
| **Textiles and textile products** | 0.002 (54) | 0.006 (61) | 0.014 (25) | 0.050 (63) | 0.012 (45) | 0.011 (48) |
| **Leather and footwear** | 0.001 (41) | 0.002 (45) | 0.054 (27) | 0.043 (43) | 0.013 (47) | 0.006 (43) |
| **Wood and products of wood and cork** | 0.002 (46) | 0.003 (49) | 0.056 (73) | 0.021 (35) | 0.012 (52) | 0.004 (46) |
| **Pulp, paper, printing and publishing** | 0.072 (26) | 0.082 (20) | 0.052 (28) | 0.058 (34) | 0.067 (29) | 0.052 (21) |
| **Coke, refined petroleum and nuclear fuel** | 0.065 (30) | 0.024 (42) | 0.048 (27) | 0.064 (62) | 0.015 (45) | 0.012 (41) |
| **Chemicals and chemical products** | 0.097 (27) | 0.105 (34) | 0.075 (62) | 0.020 (28) | 0.069 (28) | 0.018 (30) |
| **Rubber and plastics** | 0.084 (35) | 0.079 (55) | 0.045 (36) | 0.059 (37) | 0.075 (35) | 0.055 (49) |
| **Other non-metallic minerals** | 0.083 (26) | 0.077 (21) | 0.054 (26) | 0.066 (67) | 0.068 (32) | 0.047 (45) |
| **Basic metals and fabricated metal** | 0.087 (21) | 0.092 (24) | 0.067 (41) | 0.022 (26) | 0.013 (44) | 0.010 (47) |
| **Machinery** | 0.001 (42) | 0.004 (47) | 0.009 (42) | 0.005 (48) | 0.012 (42) | 0.005 (49) |
| **Electrical and optical equipment** | 0.001 (52) | 0.005 (45) | 0.019 (26) | 0.061 (77) | 0.021 (34) | 0.061 (31) |
| **Transport equipment** | 0.064 (58) | 0.024 (29) | 0.010 (57) | 0.013 (64) | 0.059 (36) | 0.014 (27) |
| **Manufacturing, nec** | 0.003 (35) | 0.008 (39) | 0.012 (45) | 0.010 (47) | 0.057 (35) | 0.020 (38) |
| **Electricity, gas and water supply** | 0.128 (76) | 0.132 (83) | 0.126 (64) | 0.020 (83) | 0.066 (53) | 0.084 (76) |
| **Construction** | 0.002 (55) | 0.005 (61) | 0.006 (53) | 0.009 (58) | 0.002 (49) | 0.003 (52) |
| **Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel** | 0.002 (42) | 0.004 (48) | 0.008 (41) | 0.009 (52) | 0.010 (45) | 0.012 (47) |
| **Wholesale trade and commission trade** | 0.002 (40) | 0.003 (46) | 0.006 (46) | 0.010 (55) | 0.012 (42) | 0.012 (46) |
| **Retail trade, except of motor vehicles and motorcycles; repair of household goods** | 0.002 (43) | 0.005 (51) | 0.004 (35) | 0.010 (39) | 0.010 (40) | 0.009 (46) |
| **Hotels and restaurants** | 0.001 (37) | 0.001 (45) | 0.005 (42) | 0.002 (45) | 0.010 (38) | 0.005 (41) |
| **Inland transport** | 0.001 (51) | 0.005 (43) | 0.013 (78) | 0.009 (64) | 0.014 (62) | 0.006 (53) |
| **Water transport** | 0.063 (35) | 0.021 (37) | 0.062 (26) | 0.052 (43) | 0.072 (49) | 0.052 (43) |
| **Air transport** | 0.067 (67) | 0.020 (33) | 0.067 (28) | 0.055 (47) | 0.071 (36) | 0.020 (39) |
| **Other supporting and auxiliary transport activities** | 0.011 (39) | 0.008 (42) | 0.008 (52) | 0.005 (64) | 0.011 (44) | 0.006 (46) |
| **Post and telecommunications** | 0.015 (21) | 0.086 (26) | 0.004 (35) | 0.004 (33) | 0.021 (25) | 0.078 (27) |
| **Financial intermediation** | 0.005 (51) | 0.005 (58) | 0.003 (42) | 0.002 (46) | 0.010 (52) | 0.003 (55) |
| **Real estate activities** | 0.005 (54) | 0.008 (63) | 0.002 (57) | 0.002 (63) | 0.012 (54) | 0.002 (58) |
| **Renting of machine and equipment** | 0.018 (27) | 0.079 (24) | 0.020 (27) | 0.062 (37) | 0.020 (23) | 0.063 (26) |
| **Public administration and defense** | 0.008 (47) | 0.008 (54) | 0.006 (48) | 0.010 (54) | 0.001 (46) | 0.003 (52) |
| **Education** | 0.006 (35) | 0.008 (42) | 0.017 (33) | 0.055 (32) | 0.012 (31) | 0.008 (35) |
| **Health and social work** | 0.017 (22) | 0.084 (27) | 0.018 (28) | 0.060 (35) | 0.019 (27) | 0.065 (29) |
| **Other community, social and personal services** | 0.010 (37) | 0.004 (46) | 0.008 (42) | 0.006 (43) | 0.012 (45) | 0.004 (36) |
| **Median Values** | 0.021 | 0.027 | 0.021 | 0.025 | 0.023 | 0.026 |

Notes: (i) Distributive impact of industry's i emissions is calculated from the sum by rows such that $\sum_{j=1}^{n} \xi_{y_{ij}}^{1}$ where j=1,2,…n. In this way, it can be used to explain the percentage increase in the distribution of industry i's emissions with respect to import demand.

(ii) Total emission impact of industry i's total demand is calculated from the sum by columns such that $\sum_{i=1}^{n} \xi_{y_{ij}}^{1}$ where i=1,2,…,n. It can be interpreted as the percentage increase in the exported emissions as a whole with respect to import demand of industry i.

## 4.6 Policy Alternatives

This section discusses policy alternatives that aim to deal with carbon transfers stimulated due to international trade flows between the U.S. and Chinese economies, which would fill the gap of trade emission balances to reduce the problems of carbon leakages. Such policy alternatives are also used to verify what key industries tell us and understand advantages, disadvantages, and limitations for guiding climate change and trade-driven economic policies. Three policy alternatives are considered: an emission standard of utility industry (P1), a unilaterally-coordinated border tax adjustment (P2), and a multilaterally-coordinated border tax adjustment (P3). It should be noted that EU15 was not included due to unclear outcomes of key industries[59]. The discussion below describes the justification and reasoning for consideration of each of these policy alternatives.

Emission standards of electricity generation in the U.S. are based upon the 2015 Clean Power Plan (CPP). This plan requires the electricity generation industry to reduce $CO_2$ emissions by an estimated 32% below 2005 levels by 2030 (EPA, 2015a). By setting this goal for $CO_2$ emissions, the Environmental Protection Agency (EPA) plans to primarily meet formal emission reduction targets submitted as an Intended Nationally Determined Contribution (INDC) (EPA, 2015b). The INDC is a bridge to express what post 2020 actions participating economies intend to take towards the evaluation of Paris agreement (WRI, 2015). For example, the U.S. plans to curtail its territorial $CO_2$ emissions by 26-28% below 2005 levels in 2025 (INDC, 2015a). China plans to strengthen renewable shares of utility industry by 25% before 2030 and let its territorial $CO_2$ emissions peak in 2030[60] (INDC, 2015b). EU15 plans to reduce its territorial greenhouse gas emissions by 40% in 2030 due to the increases in renewable shares of the economy (INDC, 2015c). Overall, the average of emission reduction target communicated in INDCs is 22% (Levin and Fransen, 2015). Thus, this essay sets emission standards of utility industry within four economies based upon emission reduction targets of their INDCs. By these settings, the emission intensity matrices ($c^r$) of three economies plus the ROW must be recalculated.

There are various policy options to address the issue of carbon leakages. Among of them, a number of studies have proposed the use of unilaterally-coordinated border tax adjustments (Cosbey, 2008; Winchester et al., 2011; Murray et al., 2012; Henriquez, 2013; Yoshida, 2014; Aldy and Pizer, 2015). The border tax adjustments have several advantages such as small price volatility, compatibility with General

[59] Share of emissions associated with final import nearly equals to that of emissions associated with intermediate import. However, the strong assumption of WIOD database does not allow investigating internal multiplier effects between intermediate and final imports. In this respect, multiple sets of industrial classification in terms of both changes in intermediate and final imports are observed in this essay.

[60] Moreover, China puts forward reducing per capita $CO_2$ emissions by 60 to 65% bellows 2005 levels by 2030. This part of expression is out of the scope of this essay.

Agreements on Tariffs and Trade (GATT), and limited of trade disruption of emission price changes compared with quotas[61]. However, the effects of this policy on embodied trade emissions rely on a unit cost of carbon (i.e. the carbon tariff rate) that is set in accordance with the embodied $CO_2$ emission intensities (Fisher and Fox, 2009; Dong et al., 2015). With the use of EE-MRIO, this essay considers possible determination of the carbon tariff rate with respect to comparable carbon intensities between importing and exporting economies, whereas previous studies normally chose carbon intensities of either importing or exporting economies in order to set carbon tariff rates (Clarke, 2010; Böhringer et al., 2011; Ghosh et al., 2012; Antimiani et al., 2013).

Additionally, this essay makes a use of two assumptions in order to incorporate carbon tariffs into the underlying MRIO. First, carbon emission prices are set at \$56 per ton of $CO_2$ in a region of destination (i.e. a region that imports products)[62]. Second, tax revenue on carbon tariff rates do not stimulate the economy of destination through additional government spending. In this way, in context of MRIO for region 1, when the border tax adjustment is considered, the monetary values of industry j outputs within region 2 are modified by carbon tariffs as:

$$\ddot{x}_j^{\,2} = x_j^{\,2} - \tau_j^{\,2} + \tau_j^{\,1} \tag{4.15}$$

where $\ddot{x}_j^2$ denotes the modified monetary value of industry j's outputs within region 2. $x_j^2$ is the original monetary value of industry j's outputs within region 2, which includes transportation of outputs between region 2 and region 1. $\tau_j^2$ is the carbon tariff associated with emission intensity of industry j in region 2. That is $\tau_j^2 = p_{co_2}^1 c_j^2 x_j^2$ where $p_{co_2}^1$ is equal to \$56. $\tau_j^1$ represents the carbon subsidy associated with emission intensity of industry j in region 1[63] such that $\tau_j^1 = p_{co_2}^1 c_j^1 x_j^1$. For this reason, $A^2$ is definitely recalculated. According to the mirror flow assumption, $A_m^{21}$ are redefined. Using the same procedure, $A^r$ and $A_m^{r1}$ (where r = 2, 3, and 4) must be recomputed and defined as $\bar{A}^r$ and $\bar{A}_m^{r1}$ so as to examine an effect of border adjustments on embodied trade emissions of the U.S. economy (region 1). The expression is:

$$\bar{E}_m^{\,1} = \sum_{r \neq 1} (1-\phi^1) c^r (I - \bar{A}^r)^{-1} \left[ \left( \bar{A}_m^{\,r1} (I - A^1)^{-1} y_{mf}^{\,1} \right) + y_m^{\,r1} \right] \tag{4.16}$$

[61] See the literature review of essay 2 in details.

[62] It is consistent with virtual carbon derived by Atkinson et al. (2013) in order to calculate carbon effective tariff rates. Later, these rates will take for multilaterally-coordinated border tax adjustments.

[63] In terms of the adjusted price of industry j, $\dot{p}_j^2 = p_j^2 + \tau i_j^2 - \tau i_j^1$ where $\dot{p}_j^2$ denotes the adjusted price of imports. $p_j^2$ is the original price of imports. $\tau i_j^2$ is the carbon tariff rate assigned to 1 unit of industry j's product imported from region 2. $\tau i_j^1$ is the carbon subsidy applied to 1 unit of industry j's product exported by region 1.

It should be noted that when the border tax adjustment is considered $A^1$ and $y_f^1$ are not affected in regard to the importance of above assumptions. Hence, embodied emissions from export demand of region 1 are assumed to be constant.

Unilaterally-coordinated border tax adjustments seem to be particularly useful in the management of carbon leakages. However, as clearly seen in section 4.5, some products are reprocessed before they are consumed by ultimate consumers. The flow of emissions may be undermined under stimulations due to a complexity of international trade flows when unilaterally-coordinated border tax adjustments are considered. Moreover, the effects of the conventional adjustment are highly depend upon industrial carbon intensities rather than the relationship between economic activities of interindustry dependencies through which emissions occur across networks of global supply chains. Therefore, there may be a need to extend a multilaterally-coordinated border tax adjustment which entails distributing emissions between exporting and importing economies, not merely importing economies in particular[64].

Within this alternative, carbon tariffs are redefined as carbon effective tariffs in which the rate denotes the quotient of value added to the net monetary values of outputs (Lenzen et al., 2007; Peters, 2008). In order to calculate carbon effective tariffs derived across global supply chains, analyses of trade in value added (TiVA)[65] and factorial distribution of value added are useful. The work by Johnson and Noguera (2012) suggests a measure of value content of exports known as value-added exports (VAX) in order to analyze TiVA embodied in final expenditure abroad. Further, Koopman et al. (2014) and Timmer et al. (2015) make a use of this concept in order to decompose value added in production. Thus, using the U.S. economy (region 1) as an example, this essay utilizes VAX technique to calculate carbon effective tariff of region r in response to strong assumptions of WIOTs; the mirror flows of bilateral exports and imports[66]. Specifically, let $\emptyset$ be a diagonal matrix of carbon effective tariff rates. The value added on embodied emissions due to exports from region 2 to region 1 ($V_{BT}$) can be calculated in a matrix expression as:

$$V_{BT} = \gamma^1 (I - A^2)^{-1} y_x^{21} \tag{4.17}$$

where $\gamma^1$ is the diagonal matrix of carbon effective tariff rates calculated in region 2. $A^2$ is the matrix of intra-industry technological requirements within region 2 industries. $y_x^{21}$ is the vector of exports from region 2 to region 1. Use of the same procedure calculates the value added on embodied emissions due to

[64] More details about multilaterally-coordinated border tax adjustments present in the literature review of essay 2.

[65] The flows of products within the global value chain are not intuitively reflected in measures of international trade. The joint project between OECD and WTO trade in value added (TiVA) firstly address this issue by considering value added in the production of goods and services that are consumed worldwide (OECD, 2015). Further, the work by Johnson and Noguera (2012) and Koopman et al. (2014) measures the value content of exports relied heavily on the concept of TiVA by using WIOTs.

[66] See data discussion in details.

exports from other regions r to region 1 as well as regions r' imports from region 1. The calculations of $V_{BT}$ are then used to modify $A^1$ and $A^r$ expressed in part of Equations (4.1) and (4.4) through changes in values of industrial outputs in order to be consistent analysis. Modified $A^1$ is defined as $\ddot{A}^1$ when sharing emissions from exports from region 1 to others regions. Modified $A^r$ are defined as $\ddot{A}^r$ when sharing emissions from imports from other regions r to region 1. According to the mirror flow assumption, $A_m^{r1}$ has to be modified and denoted as $\ddot{A}_m^{r1}$. However, both exporting and importing regions are involved in allocations of emissions arising across networks of global supply chains so that emission responsibilities should be weighed based upon embodied emissions in imports and exports (Peters, 2008).

In this respect, a weighting element of industry j can be represented by a quotient of value added on embodied emissions of industry j such that $\emptyset_j = \frac{V_{BT,j}}{x_{m,j}}$ where $V_{BT,j}$ is the value added on embodied emissions for which industry j is responsible. $x_{m,j}$ is the value of industry j imports in region 1.

The expressions for the sharing emissions from exports and imports for region 1 are as:

$$\ddot{E}_x^{\,1} = \sum_{r \neq 1} \phi^r \left( c^1 (I - \ddot{A}^1)^{-1} y_x^{\,1r} \right) \tag{4.18}$$

$$\ddot{E}_m^{\,1} = (1 - \phi^1) \sum_{r \neq 1} c^r (I - \ddot{A}^r)^{-1} \left[ \left( \ddot{A}_m^{\,r1} (I - A^1)^{-1} y_{mf}^{\,1} \right) + \left( y_m^{\,r1} \right) \right] \tag{4.19}$$

where $\emptyset^1$ is a part of the emission responsibility associated with exports from other regions r to region 1. $(1 - \emptyset^1)$ represents a remaining proportion of the responsibility associated with imports purchased from region 2. It should be noted that $V_{BT}$ will be calculated for each region that exports to region 1. In this sense, $\emptyset^1$ can differ according to trade with each trading partner. $\emptyset^r$ is a part of the responsibility associated with exports from region 1 to other regions r.

Due to unavailable data on effective tariff rates, empirical outcomes derived by Atkinson et al. (2013) were used to represent carbon effective tariff rates for specific 34 industries in four economic regions. These authors conducted an empirical analysis of carbon taxes on the virtual carbon content of exports and calculated carbon effective tariff rate per unit of output by industry for major developed and developing economies. A virtual carbon tax of $56 was computed for 2011. This tax reflected the estimate of the social cost of carbon by U.S. federal government. The marginal social cost of carbon represents the damage cost of human health, economic productivity caused by increasing average surface temperatures and rising sea levels due to climate change. This type of cost also correlates with the magnitude of the national voluntary reduction targets required to summit as INDCs. However, the effective carbon tariff rates of Atkinson et al. (2013) were available for 19 sectors. There is a need to reclassify the 34 industries using the harmonized structure of ISIC. This has already presented in Table 3.7 of Appendix B in Chapter 3.

This subsection presents the projected emission reductions for the U.S. and China economies under three policy alternatives. The emission reductions are based on a benchmark that takes into reference volumes for embodied emissions in export and import demands during the year 2011. The emission volumes and percentages of emission reductions expressed for the entire economy are presented in Table 4.2. A breakdown of such emission reductions in response to four industrial categories are presented in Table 4.3. The main findings of projected reductions for each policy alternative are first presented. Then, the detailed findings associated with the importance of four industrial categories are discussed.

### 4.6.1 An Emission Standard of Utility Industry (P1)

#### 1. Exported Emissions

As shown in Table 4.4, a P1 policy accounts for a projected 13% reduction of exported emissions in the U.S. economy (119,295 kt). The largest reduction occurs within the key industries of category 1 (Table 4.5). They contribute 41% of the projected reduction, which is equivalent to 10% reduction given within this category. Utility industry accounts for 65% of the reduction while chemicals and air transport service combined represent 28%.

This analysis also explores that a control of emissions within utility industry can contribute the emission reductions of relevant industries due to backward linkage. Its backward linkage contributes 19% of the total projected reduction of exported emissions, which is equivalent to 14% reduction in category 1. Examples of the relevant industries include mining (14%), and non-metallic minerals (17%) (Table 4.17 in Appendix 4-A). This results stems from emissions in these industries are mostly contributed by the demand for their products so that, a control of utility industry is able to generate emission reductions of mining and non-metallic minerals by 14% and 17%. These industries are primarily classified in category 3.

However, this analysis highlights that emission controls can strongly affect the emission reductions of other industries due to forward linkages. The forward linkages contributes 35% of the projected reduction (31% reduction given in this category). Examples of the other industries include food and beverages (25%), transport equipment (12%), construction (16%), retails trade (29%), hotels and restaurants (24%), and health services (26%). These findings are not surprising because utility industry is classified for its importance of forward linkages and its own component of distributive component is low (section 4.5.3). A large part of projected reductions must occur industries which highly demand its products. Consequently, due to the demand for utility products strongly pushed by the economic activities of forward linkage industries, an adoption of P1 policy can have considerable effects on their production.

This evidence can be clearly seen in the China economy. P1 projects its exported emissions reduction of 8% (188,596 kt). The main contribution of this reduction is due to utility industry in category 1. Category 1 industries contribute 72 % or equivalently an 8% reduction given within this category. The utility industry accounts for almost 79% of this reduction while textiles, paper, chemicals, and rubber and plastics industries represent 18%. Another part of this reduction takes place with relevant industries due to backward and forward linkages. Backward linkages contribute merely 7% of the projected reduction (8% reduction in category 3) whereas forward linkages contribute 21% (12% reduction in category 2). Examples of backward linkages include refined petroleum (9%), non-metallic minerals (13%), and manufacturing (11%). Industries with forward linkages are food and beverage (11%), leather (9%), transport equipment (15%), wholesale trade (12%), renting of machine and equipment (9%), and health services (12%) (Table 4.18 in Appendix 4-A). However, as the own effect of China's utility industry is relatively high when compared with the U.S. utility industry, an adoption of P1 policy contributes a smaller effect on the economic activities of relevant industries through their emission reductions.

### 2. Imported Emissions

Regarding projected emission reductions associated with the U.S. imports, a P1 policy accounts for only a 5% decline (108,663 kt). Even though the utility industry is classified as a key industry, it does not project much reduction due to the importance of its backward linkages. As shown in Table 4.5, industries within the first category are the main contributors. They contribute 48% of the projected reduction or equivalently 4% reduction given within this category. Utility industry accounts for 65% of the reduction while chemicals and non-metallic minerals industries represent roughly the other 35%.

A part of the projected reduction occurs in industries of category 3 which is relevant due to backward linkages. They contribute 39% of the projected reduction or equivalently 8% reduction given in this category. Examples include mining with a decline of 10% and refined petroleum industry with a decline of almost 7% (Table 4.17 in Appendix 4-A). Forward linkages contribute a few emission reductions (10% of the projected reduction). In this respect, an adoption of a P1 policy will not be enough for convincing relevant industries to reduce their imported emissions. This is relevant because utility industry relates imported emissions due to the importance of backward linkage.

When comparing the U.S. economy with the China economy, projected imported reductions in China are slightly higher. However, despite utility industry of China being relevant due to forward linkages (category 3), a control of its emissions will have a minor effect on the reductions of other relevant industries.

This is due to a high own component within utility industry. In this way, category 3 industries contribute 47% of the projected reduction (16% reduction within its category) while category 1 industries contribute to 40% (5% reduction within its category). Basic metals and chemicals are the main drivers of the projected reductions with estimates of 16% and 10% reductions respectively (Table 4.18 in Appendix 4-A). Other industry reductions include paper (8%), rubber and plastics (9%), and non-metallic minerals (9%). In this respect, there is a clear indication that an adoption of P1 policy will not be effective for encouraging other relevant industries to deal with their emissions stimulated due to China imports.

*Table 4.4: Projections of Exported and Imported Emissions in the U.S. and China Economies, 2011; kt of $CO_2$*

| Policy Alternatives | The Component of Emissions | U.S. (kt of $CO_2$) | CHN (kt of $CO_2$) |
|---|---|---|---|
| **Benchmark** | Exported emissions | 901,001 | 2,377,809 |
| | Imported emissions | 2,173,272 | 1,203,397 |
| **The emission standard of utility industry (P1)** | Exported emissions | 781,706<br>(-13%) | 2,189,213<br>(-8%) |
| | Imported emissions | 2,064,609<br>(-5%) | 1,131,193<br>(-6%) |
| **The unilaterally-coordinated border tax adjustment (P2)** | Exported emissions | 901,001<br>(0%) | 2,377,809<br>(0%) |
| | Imported emissions | 1,999,411<br>(-8%) | 1,095,091<br>(-9%) |
| **The multilaterally-coordinated border tax adjustment (P3)** | Exported emissions | 789,277<br>(-12%) | 2,225,078<br>(-6%) |
| | Imported emissions | 1,849,140<br>(-15%) | 1,060,721<br>(-12%) |

Note: Parentheses are used to enclose the percentage of reductions based on the benchmarks

## 4.6.2 A Unilateral Border Tax Adjustment (P2)

### 1. Exported Emissions

In this essay, revenue from a carbon tariff is assumed not to stimulate the economy of destination by the contribution of government transfers. This assumption leads to no projections of emissions due to re-exports. Hence, emissions stimulated due to exports of the U.S. and China are the same as benchmark case.

Under a P2 policy, a 8% reduction in emissions embodied in imports is experienced by the U.S. economy (173,861 kt). Large contributions occur within industries which have a large difference in carbon intensities between trading partners. Examples of carbon intensive industries for the U.S. include chemicals, utility, paper, rubber and plastics, non-metallic minerals, mining and refined petroleum industries. The first five of these industries are key industries in category 1 and the remaining industries are grouped by category 3. However, this analysis finds that the contribution of category 3 industries is larger than that of category 1 industries. Category 3 industries contribute 55% of the reduction (21% reduction within category 3) while category 1 industries contribute 35% (5% reduction within category 1).

These findings can be explained by the pattern of industrial backward and forward linkages as well as the significance of industrial own effect. Chemical and utility industries are relevant to imported emissions due to their backward linkages. This means that their emission reductions are contributed by a change in their intermediate imports. As their own effects are relatively low, their emission reductions are able to largely affect emission reductions of relevant industries. This implies that the relevant industries most likely appear in category 3 according to the amount of industrial projected reductions. Paper, rubber and plastics, and non-metallic minerals are relevant to imported emissions through forward linkages. Their emissions are induced by the demand for their products. Because their own effects are low, a large part of their projected reductions is able to affect the reductions of other industries due to a change in the demand through them. These other industries are most likely to be in category 3.

Despite mining and refined petroleum being classified in category 3, they show high own components. A large part of their emission reductions occurs in this category. Based upon these findings, this analysis points out that an adoption of P2 policy will contribute to the projected reductions not only in defined industries but also industries relevant to backward and forward linkages. These findings affirm that because they are identical for a key through industrial interdependencies, industrial policy measures may not be effective for the application of key industries. This may be considered unfair because an important part of the reduction is out of their controls. In this respect, this policy is more likely to have a limited effect on emission reductions, but a strong effect on import activity losses as a whole.

A P2 policy is projected to reduce emissions from China imports by 9% (108,306 kt). Examples of carbon intensive industries include refined petroleum, rubber and plastics, non-metallic minerals, water transport service, agriculture, chemicals, utility, and basic metals industries. Almost all of them are in category 1. For this reason, category 1 is the main contributor to imported emission reductions, followed by categories 3 and 4. The reason for the substantial reduction in category 3 is because water transport service, agriculture, chemicals, utility, and basic metals industries are relevant to imported emissions due to their forward linkages. That means that their emissions are contributed by the demand of other industries. Their emission reductions is able to affect the reductions of relevant industries which most likely appear in categories 2 and 4 (26% of the projected reduction). Due to high own components of chemicals and utility industries in terms of their backward linkages, their reductions can partially affect the reductions of other industries in category 3 (14% of the projected reduction). In this way, there is a clear review that an adoption of P2 policy will affect not only the projected reductions of defined industries but also the reductions of industries relevant to backward and forward linkages.

Empirical results of this policy also highlights that the importance of border tax adjustments is not determined by industrial carbon intensities alone in accordance with the projection of industrial emission reductions. If so, emission associated with intermediate and final imports by industry should be reducing with the same amount. However, in the U.S., projected reductions attributable to industrial final imports exceed those attributable to industrial intermediate import by almost 17% on average. China shows a smaller gap at 15.5% (Tables 4.19 and 4.29 in Appendix 4-A). Along this line, these differences may cost future reductions with respect to the practice of this policy. This essay assumes that projected reductions depend not only on industrial carbon intensities between trading partners but also are due to carbon technologies between them. This is relevant that a transfer of carbon technologies may become more important feature for increasing their emission reductions. Such technology transfer programs could well be financed by a revenue on carbon tariff.

### 4.6.3 A Multilateral Border Tax Adjustment (P3)

#### 1. Exported Emissions

Under this policy, the U.S. economy experiences a projected 12% reduction in emissions attributable to its exports (111,725 kt). Largest part of this reduction is attributed to industries in category 1. They contribute 80% of the projected reduction or equivalently to 12% reduction given within this category (see Table 4.3). Chemicals, utility, and air transport service industries account for almost 82% of the reduction. As their emissions are due to their forward linkages, their emission reductions can be affected the reductions of relevant industries through the demand for their products. Due to high own components, large part of the reductions occurs in category 1 industries. The rest of the reductions leaves for category 2 (12% of the projected reduction). Examples of the relevant industries include food and beverages (14%), retail trade (8%), and hotels and restaurants (11%) (Table 4.21 in Appendix 4-A). This analysis also explores that a slight decline in the emissions of category 3 industries is due to a ripple effect as a result of the demand of chemicals, air transport service, food and beverages, and hotels and restaurants industries in accordance with the importance of industrial interdependencies. Examples of industries include agriculture, paper, and non-metallic minerals industries. However, due to low own components, a large amount of the reductions distributes mostly to category 1 industries. The rest of the reductions remains category 3 industries. In this respect, comparing with the result of a P1 policy is slightly different in a project reduction but significantly different in an effect on the U.S. export activities. This analysis indicates that an adoption of a P3 policy will contribute a great reduction in terms of exported emissions, and have a limited effect on export activity losses. It is very likely because a major projected reduction occurs in category 1 industries.

With a P3 policy, a projected 6% reduction in exported emission is witnessed in China economy (152,731 kt). As shown in Table 4.3, category 1 industries contribute 83% of the projected reductions (7% reduction in category 1). Mining, paper, refined petroleum, rubber and plastics, and non-metallic minerals industries are the main contributors. As their emissions are relevant due to forward linkages, their reductions can be affected by reductions of relevant industries through the demand for their products. The relevant industries include agriculture (4%), food and beverages (6%), transport equipment (7%), renting of machinery and equipment (10%), plus health services (5%) (Table 4.22 in Appendix 4-A). Due to low own components of food and beverages, wholesale, and renting of machinery and equipment, the large part of the reductions is in category one.

Conversely, a ripple effect as a result of the demand of mining plus rubber and plastics is the most contribution to reductions of refined petroleum and non-metallic minerals. Due to low own components of refined petroleum and non-metallic minerals industries, great part of reductions distributes to category 1. This analysis points out that an adoption of P3 policy will establish a reduction nearly as much as a P1 policy does. However, comparing the effect on export activity losses is a dedicate issue because the values of China exports are largely distributed among industries. In this respect, a P3 policy may arrive at a compromise policy for China exported emissions.

### 2. Imported Emissions

A P3 policy is projected to reduce emissions from the U.S. imports by 15% (324,133 kt). It is undoubted that largest reduction is due to industries in category 1. They contribute 82% of the projected reduction or equivalently to a 22% reduction in this category. Major contributors to reduce imported emissions place to chemicals (16%), non-metallic minerals (21%), utility (9%), paper (13%), rubber and plastics (18%), and basic metals (17%) (Table 4.21 in Appendix 4-A). However, the reasons behind the projected reduction are identical in accordance with the amounts of emission reductions. The emission reduction of chemicals industry is affected due to the reductions of paper, non-metallic minerals, health services, and rubber and plastics industries through their intermediate import. The reduction of non-metallic minerals industry is affected due to the reduction of chemicals, rubber and plastics, post telecommunications, and health services. The reduction of utility industry is affected due to reductions of chemicals, rubber and plastics, non-metallic minerals, post telecommunications, and health services industries. Along this line, this analysis points out that emission reductions distribute to categories 1 and 2. Due to their low components (< 30%), large part of the reductions is in category 1. In turn, paper, rubber and plastics, and basic metals industries are projected to reduce emissions due to a ripple effect of relevant industries in category 3. In this respect, because a main reduction is in category 1, an adoption of a P3 policy will establish great reduction in the U.S. imports. When compared with the results of P1 and P2 policies, a P3 policy marginally gains in the light of tradeoff between emission reductions and U.S. import losses. This is in part because emission reductions under a P3 policy would rely on an importance of industrial interdependencies rather than a consideration of industrial carbon intensities. Cross policy measures may be a better alternative for emission reductions associated with the U.S. imports, in the way that the importance of international fragmentation of production has been increasingly arising.

A P3 policy plays a crucial role in emission reductions attributable to China imports. A 12% reduction is projected (142,676 kt). Category 1 industries accounts for almost 17% of the total reductions. Mining, refined petroleum, rubber and plastics, and non-metallic minerals industries are the major contributors. The emission reductions of mining and refine petroleum industries are due to the reductions of paper, leather, water transport service, air transport service industries. The reduction of rubber and plastics industries is due to the reductions of textiles, electrical equipment, and renting of machine and equipment industries while the reduction of non-metallic minerals industry is due to the reductions of paper, renting of machine and equipment, health services and rubber and plastics industries. It is not surprising that large part of emission reductions distribute to the first 2 categories. However, this analysis also explores that a ripple effect of relevant industries in category 3 are highly relevant to the reductions of rubber and plastics, non-metallic minerals, and health services industries. The relevant industries involve chemicals and utility industries. Total emission reductions of category 3 industries are moderately low when comparing with that of the P2 case (from 16% to 5% of the projected reduction). In this respect, it is a clear indication that a P3 policy gains in light of tradeoff between emission reductions and China import losses

*Table 4.5: A Breakdown of Exported and Imported Emissions by Industrial Classification, 2011; kt of $CO_2$*

| Policy Alternatives | The Classification of Industries | U.S. (kt of $CO_2$) | | CHN (kt of $CO_2$) | |
|---|---|---|---|---|---|
| | | **Exported Emissions** | **Imported Emissions** | **Exported Emissions** | **Imported Emissions** |
| **Benchmark** | Key Industries (1) | 488,963 | 1,202,456 | 1,825,649 | 627,392 |
| | Relevant industries in terms of own demand (2) | 131,601 | 329,908 | 346,073 | 192,107 |
| | Relevant industries in terms of the demand from others (3) | 203,400 | 444,957 | 155,663 | 206,532 |
| | Non-relevant industries (4) | 77,037 | 195,951 | 50,424 | 177,366 |
| **The emission standard of utility industry (P1)** | Key Industries (1) | 440,067 (-10%) | 1,150,750 (-4%) | 1,690,551 (-8%) | 598,532 (-5%) |
| | Relevant industries in terms of own demand (2) | 90,437 (-31%) | 319,021 (-3%) | 307,046 (-12%) | 185,575 (-3%) |
| | Relevant industries in terms of the demand from others (3) | 175,707 (-14%) | 402,805 (-8%) | 143,210 (-8%) | 173,976 (-16%) |
| | Non-relevant industries (4) | 75,495 (-2%) | 192,033 (-2%) | 48,406 (-3%) | 173,109 (-2%) |
| **The unilaterally-coordinated border tax adjustment (P2)** | Key Industries (1) | 488,963 (0%) | 1,141,131 (-5%) | 1,825,649 (0%) | 568,417 (-9%) |
| | Relevant industries in terms of own demand (2) | 131,601 (0%) | 315,998 (-4%) | 346,073 (0%) | 163,542 (-15%) |
| | Relevant industries in terms of the demand from others (3) | 203,400 (0%) | 349,736 (-21%) | 155,663 (0%) | 189,461 (-8%) |
| | Non-relevant industries (4) | 77,037 (0%) | 192,546 (-2%) | 50,424 (0%) | 173,671 (-2%) |
| **The multilaterally-coordinated border tax adjustment (P3)** | Key Industries (1) | 398,994 (-12%) | 935,511 (-22%) | 1,697,854 (-7%) | 515,089 (-12%) |
| | Relevant industries in terms of own demand (2) | 118,302 (-10%) | 298,897 (-8%) | 328,383 (-5%) | 174,433 (-8%) |
| | Relevant industries in terms of the demand from others (3) | 196,484 (-3%) | 425,379 (-4%) | 149,436 (-3%) | 199,166 (-4%) |
| | Non-relevant industries (4) | 75,496 (-2%) | 189,353 (-3%) | 49,405 (-2%) | 172,033 (-2%) |

## 4.7 Conclusions

Using WIOD to construct four-region EE-MRIO model reflects the significance of international trade in response to embodied $CO_2$ emissions through PBE and CBE allocations of the U.S., China, and EU15 economies. The results of U.S. economy show that CBE emissions was 28% higher than emissions of the PBE in 2011. The emissions stimulated due to import demand are higher proportion than those stimulated due to export demand. EU15 economy was in line with trade emission balance of +25% but showed a different driver behind the trade emission balance. The U.S. surplus emissions were solely due to trade in intermediate imports while the EU15 surplus emissions were due to trade in both intermediate and final imports. For China economy, CBE was 19% less than PBE in 2011. China is a net exporter of $CO_2$. However, despite net exporter, the contribution of China imported emissions was due largely to trade in intermediate imports.

This analysis found that a proportion of intermediate imports stimulated by the U.S. and China economies contributed 31% and 24% of exported emissions for the U.S. and China, respectively in 2011. This implies that the fragmentation of international production not only induced an increased volume of international trade, but also gave rise to the significant effect on the structure of carbon transfers. In this respect, responsibility of emissions stimulated due to export and import demands should no longer be limited by fragmented climate actions, but designed to account for the complex of carbon transfer structures.

Different mitigation efforts are needed across industries and economies throughout the world. An important challenge towards industrial responsibility is that industries with differences in emission levels and type of linkages require different policy measures to reduce emissions. This essay utilizes a production-demand elasticity in order to identify roles of different industries and relationships between export-import structures and embodied emissions. These roles are used to classify industries into one of four categories: key industries (category 1); relevant industries with own demand (category 2); relevant industries with the demand from others (category 3); and non-relevant industries (category 4). The main findings of this essay are presented below.

Key industries for U.S. exported emissions are refined petroleum, chemicals, utility, inland transport service, and air transport service industries. As distributive effects are greater than total effects, these industries are relevant for exported emissions due to strong forward linkages. Variation in the demand for their products by other industries has stronger effects on exported emissions than variation in the demand for their inputs. In order to reduce $CO_2$ emissions, industrial policy measures would need to be implemented to deal with emissions from consumption of their outputs. However, this analysis indicates that it is important to decompose an own component for determining linkage effects in order to design appropriate policy measures. Only the inland transport service industry showed a low own distributive effect. Thus, an industrial policy measure for consumption of output in the inland transport industry would not be a good policy measure because a large proportion of export activities losses posed by other industries supplying inland transport services.

Key industries in U.S. imported emissions are paper, chemicals, rubber and plastics, non-metallic minerals, basic metals, and utility industries. Unlike exported emissions, key industries in imported emissions are relevant imported emissions due to both backward and forward linkages because the magnitude of distributive and total effect are not much different. Own components of both effects are useful to identify key through either backward or forward linkages. This analysis indicates that paper, chemicals, rubber and plastics, basic metals, and utility industries are relevant imported emissions due to strong backward linkages. Only the non-metallic mineral industry is relevant imported emissions due to strong forward linkage. The Policy measure for rubber and plastics, and utility industries is an enhancement for input efficiency due to high own total effects. The policy measures for paper, chemical, and basic metal industries is demand management due to low own total effect. Input efficiency focuses on the volume of input factors that are purchased from suppliers while demand management centers on the lowering the carbon emissions of producing inputs. Policy measures for non-metallic mineral industry relate sustain level of output consumption due to the low own distributive effect.

However, as a point of comparison with own component of industrial exported emissions, almost key industries in imported emissions showed relatively low own components. Due to carbon transfers in light of the fragmentation of international production, industries with low own total effects complicates emission reductions by means of encouraging industry actions. In this respect, policy measures to specific key industry are not effective enough for curbing U.S. imported emissions. Cross-industrial measures, in turn, appear more appropriate.

Cross-over key industry analysis also reveals that a number of industries in category 1 for U.S. imported emissions that are in category 3 for the export case. Industrial coverage may become an important issue of climate policy strategies for the U.S. This implies that there is a gap of industrial policy design between voluntary national emission reductions (e.g. INDC) and emission reductions necessary for dealing with the complex of U.S. carbon transfers. This implies that industrial coverage of climate policies in reference to the U.S. INDC has no longer limited to category 1, but should involve category 3 industries.

The results of China show that key industries would be the most importance on when evaluating China exported emission reductions because the magnitude of their total and distributive effects got very high, accounting for 63% and 79% respectively. The large impact stems from basic metals, machinery, electrical equipment, utility, and water transport service industries playing a role in distributive effects. In turn, textiles, paper, chemicals, rubber and plastics, and inland transport service industries are the large role in total effects. This implies that the former industries are relevant exported emissions due to strong forward linkages while the latter industries are relevant due to strong backward linkages. This analysis also deepens that almost key industries except for basic metal and textile industries showed high own total and distributive effects. Industrial policy measures may become important to reduce China exported emissions. In turn, due to low own component, industrial policy measures can lead to a bottleneck of China export activities along global supply chains of basic metal and textile industries.

Unlike exported emissions, key industries in China imported emissions show less importance because their distributive effect was small (45%). Water transport service and air transport service industries are the large contributors to this distributive effect. Other large proportions of China imported emissions are taken by category 3 industries with distributive effect of 41%. Category 3 industries include agriculture, wood, chemicals, basic metals, and utility industries. Due to high own distributive effects, industrial policy measures implementing to these industries are likely to be an alternative for dealing with China imported emissions. However, a gap of industrial coverage is not an important issue in China because category 3 industries are already in category 1 for exported emissions.

Key industries of EU15 exported emissions are more distributed compared with the findings of the U.S. and China, but the magnitude of total and distributive effects of category 1 industries is relatively small. This implies that advanced carbon production technologies were significantly developed within this economy. Example of the advanced technology include utility industry. Share in EU15 exported emissions accounted for less 30% calculated within category 1 while share in U.S. exported emissions accounted for greater 45%. However, this analysis points out that food and beverage, chemical, and basic metal industries should be taken for EU15 exported emission reductions because share in exported emissions accounted for almost 43%. These industries are relevant exported emissions due to strong backward linkages.

In this view, food and beverage industry is dropped from the list of EU emission trading system (ETS). This analysis also highlights that chemical industry is the most importance for EU15 exported emissions because of the largest magnitude of total and distributive effects combined. Based upon the results of key industries in exported and imported emissions across three economies, a number of policy measures are concluded in Table 4.6.

*Table 4.6: Linkage Effects and Recommended Policy Measures*

| Linkage Effect | Own Component | Recommended Policy Measure |
|---|---|---|
| **Backward linkage** | **Low** | -Demand management for carbon emissions of inputs<br>-Carbon technological improvement to reduce emissions per unit of production value |
| | **High** | -Industrial measures to reduce emissions from input producing industries |
| **Forward linkage** | **Low** | -Emission reduction policies that span across-multiple industries<br>-Move towards sustainable levels of consumption |
| | **High** | -Industrial measure applied to industries with high forward linkages to reduce emissions from these industries |

The outcomes of key industries are used to evaluate the practical applications of climate policies. Due to the importance of carbon transfers, this essay considers three policy alternatives: an emission standard of utility industry (P1); a unilateral border tax adjustment (P2); and a multilateral border tax adjustment (P3). The results indicate that a P1 policy accounts for a projected 13% reduction in the U.S. exported emissions (119,295 kt). The projected reduction is largely due to forward linkages as a result of demand for utility products. This analysis points out that an adoption of P1 policy will contribute to a remarkable reduction in exported emissions, but has a considerable effect on economic activities of forward linkage industries at the same time (e.g. food and beverages, transport equipment, construction, retails trade, hotels and restaurants). When a P1 policy is adopted by China economy, an 8% reduction in emissions is projected (188,596 kt). Due to high own component of China utility industry, a P1 policy will contribute a smaller effect on economic activities of forward linkage industries compared to the U.S. However, a P1 policy does not project much reductions in imported emissions to the U.S. and China economies. This may be explained by the importance of strong backward linkages. It is very likely that an adoption of P1 policy will not be effective enough for convincing relevant industries to reduce their imported emissions for supplying utility’s intermediate import.

Under a P2 policy, an 8% reduction in imported emissions (173,861 kt) is experienced by the U.S. while 9% reduction (108,306 kt) is experienced by China. The large contributions were anticipated within industries which have large differences in carbon intensities between domestic and exporting emissions. Examples in the U.S. include chemicals, utility, paper, rubber and plastics, and non-metallic minerals industries. Examples of China are refined petroleum, rubber and plastics, and agriculture industries. However, this analysis points out that a P2 policy will contribute projected reductions not only to defined industries but also relevant industries to backward and forward linkages. A large proportion of reductions occurs in the latter group. In this way, it is likely that a P2 policy will have a limited effect on emission reductions, but a strong effect on import activity losses. This analysis also points out that an effectiveness of a P2 policy should not have depended only on industrial carbon intensities alone, but should also pay more attention to carbon technologies between them across economies.

A P3 policy projects a 12% reduction in emissions from U.S. exports (111,725 kt). A large proportion of this reduction is attributed to key industries. It is very likely that a P3 policy will contribute a great reduction in exported emissions, but have a limited effect on export activity losses. For China economy, a projected 6% reduction in exported emissions is estimted (152,731 kt). A large contribution is due to category 1 industries. This analysis indicates that a P3 policy will reduce emissions nearly as much as a P1 policy does. However, comparing the effect on export activity losses is a dedicate issue because the values of China exports are largely distributed among industries. In this respect, a P3 policy may arrive at a compromise policy for China exported emissions.

With a P3 policy, the U.S. experiences a projected 15% reduction in imported emissions (324,133 kt) while China has a projected 12% reduction (142,676 kt). Large proportion of reductions in imported emissions within both economies occur in category 1 industries. When compared with the results of P1 and P2 policies, a P3 policy will contribute greater emission reductions, but have a more limited effect on trade activity losses. This is relevant because emission reductions under this policy would rely on industrial interdependencies rather than a consideration of industrial carbon intensities. In this respect, it is likely that cross industrial policy measures would be a better alternative for emission reductions associated with import demand given that international production fragmentation has been increasingly occurring. The outcomes of three policy alternatives in response to the effect of international trade activities on the projection of embodied emission reductions are concluded in Table 4.7.

*Table 4.7: The Main Findings of Three Policy Alternatives*

| **Policy Alternative** | **Findings** |
|---|---|
| **P1** | -This policy will contribute a remarkable reduction in exported emissions, but have a strong impact on trade activity losses occurring in industries that highly demand for electricity<br>-This policy will have a limited impact on reductions in imported emissions |
| **P2** | -This policy will have a limited effect on emission reductions, but a strong impact on import activity losses because projected reductions are contributed by not only high carbon intensity industries but also industries in categories 2 and 3 due to backward and forward linkages. However, a large proportion of reductions occurs in category 3 industries. |
| **P3** | -This policy will contribute to a large emission reduction, but have a limited impact on trade activity losses because backward and forward linkage effects are within category 1 industries. |

Even though this essay provides analyses of key industries and employs their outcomes to evaluate the applications of climate policies, it has several limitations to be characterized. First, future studies are warranted to analyze identification of key industries from more levels of detailed industries. The relative strength of them may provide more in-depth policy measures. Second, tax rates used to calculate carbon effective tariff rates were for 2010. To get more precise empirical results for 2011, the social cost of carbon used to estimate carbon taxes must be updated. Finally, the findings of this essay will be complemented if future studies of the determination of key industries in exported and imported emissions are associated with supply-driven multipliers.

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# Appendix 4-A

*Table 4.8: A Breakdown of U.S. Production-Based Emissions (PBE[1]) by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of PBE[1] | | | |
|---|---|---|---|---|
| | Domestic Demand ($y_f^1$) | Export Demand ($y_x^1$) | | |
| | | CHN ($y_x^{12}$) | EU 15 ($y_x^{13}$) | ROW ($y_x^{14}$) |
| 1.Agriculture, hunting, forestry and fishing | 55,693 | 1,936 | 1,088 | 26,473 |
| 2.Mining and quarrying | 107,935 | 12,574 | 7,479 | 31,015 |
| 3.Food, beverages and tobacco | 83,123 | 473 | 469 | 28,609 |
| 4.Textiles | 9,584 | 318 | 435 | 7,611 |
| 5.Leather and footwear | 1,118 | 6 | 9 | 182 |
| 6.Wood and cork | 5,237 | 597 | 438 | 2,456 |
| 7.Pulp, paper, printing and publishing | 105,945 | 1,256 | 2,878 | 28,020 |
| 8.Coke, refined petroleum and nuclear fuel | 145,112 | 701 | 10,091 | 62,902 |
| 9.Chemicals | 340,889 | 19,805 | 26,007 | 139,729 |
| 10.Rubber and plastics | 172,673 | 608 | 1,124 | 40,279 |
| 11.Other non-metallic mineral | 139,683 | 3,044 | 3,094 | 26,837 |
| 12.Basic and fabricated metals | 157,170 | 5,869 | 4,672 | 37,951 |
| 13.Machinery | 33,998 | 1,784 | 2,385 | 8,544 |
| 14.Electrical and optical equipment | 52,764 | 2,151 | 2,168 | 8,348 |
| 15.Transport equipment | 89,621 | 21,148 | 4,722 | 70,959 |
| 16.Manufacturing, nec; recycling | 33,638 | 229 | 420 | 3,039 |
| 17.Electricity, gas and water supply | 1,217,538 | 23,335 | 22,389 | 145,139 |
| 18.Construction | 257,085 | 0 | 220 | 26,195 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 8,369 | 0 | 0 | 138 |
| 20.Wholesale trade and commission trade, | 35,129 | 0 | 1,804 | 9,604 |
| 21.Retail trade | 79,279 | 3,120 | 800 | 27,954 |
| 22.Hotels and restaurants | 88,272 | 85 | 8 | 26,777 |
| 23.Inland transport | 285,809 | 1,856 | 11,478 | 34,958 |
| 24.Water transport | 52,323 | 13 | 1,867 | 25,713 |
| 25.Air transport | 190,015 | 6,117 | 13,668 | 33,633 |
| 26.Other supporting and auxiliary transport | 9,464 | 218 | 6,459 | 3,161 |
| 27.Post and telecommunications | 95,208 | 1,120 | 1,903 | 6,512 |
| 28.Financial intermediation | 38,258 | 87 | 468 | 6,592 |
| 29.Real estate activities | 12,644 | 0 | 43 | 20 |
| 30.Renting of machinery and equipment | 95,833 | 1,318 | 8,810 | 3,689 |
| 31.Public administration and defense | 155,852 | 2,853 | 1,544 | 28,538 |
| 32.Education | 21,890 | 2,576 | 1,125 | 4,098 |
| 33.Health and social work | 95,624 | 1,214 | 1,900 | 29,637 |
| 34.Other community, social and personal services | 82,816 | 634 | 1,439 | 1,739 |
| Aggregated emissions by component | 4,354,864 | 88,838 | 287,010 | 525,153 |
| | | 901,001 | | |
| U.S. production emissions (PBE[1]) | 5,255,865 | | | |

Notes: (i) Superscript represents economies staring from the U.S. = 1, China = 2, EU15 = 3, and the rest of the world (ROW) = 4 respectively

(ii) Subscript refers to the components of final demand (y) such as domestic demand ($y_f$) and export demand ($y_x$)

*Table 4.9: A Breakdown of China Production-Based Emissions (PBE[2]) by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of PBE[2] | | | |
|---|---|---|---|---|
| | Domestic Demand ($y_f^2$) | Export Demand ($y_x^2$) | | |
| | | USA ($y_x^{21}$) | EU 15 ($y_x^{23}$) | ROW ($y_x^{24}$) |
| 1.Agriculture, hunting, forestry and fishing | 162,727 | 1,756 | 1,044 | 42,650 |
| 2.Mining and quarrying | 6,714 | 1,566 | 1,415 | 35,158 |
| 3.Food, beverages and tobacco | 246,371 | 344 | 461 | 35,890 |
| 4.Textiles | 150,162 | 16,118 | 13,123 | 75,391 |
| 5.Leather and footwear | 48,426 | 3,749 | 748 | 34,226 |
| 6.Wood and cork | 54,093 | 2,036 | 2,015 | 27,317 |
| 7.Pulp, paper, printing and publishing | 1,843 | 8,144 | 1,256 | 35,268 |
| 8.Coke, refined petroleum and nuclear fuel | 93,332 | 2,592 | 2,846 | 33,984 |
| 9.Chemicals | 83,599 | 29,745 | 29,975 | 191,331 |
| 10.Rubber and plastics | 53,378 | 11,688 | 13,599 | 82,101 |
| 11.Other non-metallic mineral | 49,542 | 11,597 | 10,331 | 64,158 |
| 12.Basic and fabricated metals | 73,599 | 39,660 | 52,968 | 282,450 |
| 13.Machinery | 386,779 | 14,471 | 15,649 | 186,220 |
| 14.Electrical and optical equipment | 234,165 | 84,760 | 84,296 | 181,974 |
| 15.Transport equipment | 263,725 | 10,788 | 11,099 | 97,129 |
| 16.Manufacturing, nec; recycling | 9,653 | 1,215 | 894 | 68,825 |
| 17.Electricity, gas and water supply | 1,900,955 | 101,249 | 45,715 | 470,854 |
| 18.Construction | 262,349 | 0 | 4,885 | 10,474 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 0 | 0 | 0 |
| 20.Wholesale trade and commission trade, | 107,700 | 0 | 7,846 | 26,795 |
| 21.Retail trade | 124,471 | 311 | 42 | 7,443 |
| 22.Hotels and restaurants | 84,153 | 0 | 2,851 | 9,622 |
| 23.Inland transport | 273,869 | 671 | 6,026 | 26,843 |
| 24.Water transport | 17,500 | 0 | 11,166 | 64,151 |
| 25.Air transport | 19,154 | 12,994 | 7,626 | 24,687 |
| 26.Other supporting and auxiliary transport | 19,207 | 0 | 3,959 | 2,182 |
| 27.Post and telecommunications | 49,816 | 0 | 2,600 | 3,493 |
| 28.Financial intermediation | 26,159 | 82 | 87 | 388 |
| 29.Real estate activities | 55,918 | 0 | 0 | 0 |
| 30.Renting of machinery and equipment | 65,161 | 30,586 | 8,822 | 13,318 |
| 31.Public administration and defense | 241,736 | 0 | 3 | 584 |
| 32.Education | 96,532 | 1 | 7 | 396 |
| 33.Health and social work | 109,950 | 410 | 5,084 | 36,080 |
| 34.Other community, social and personal services | 97,630 | 85 | 6,502 | 4,582 |
| Aggregated emissions by component | | 328,357 | 342,980 | 1,706,472 |
| | 6,219,407 | 2,377,809 | | |
| China production emissions (PBE[2]) | 8,597,216 | | | |

Notes: (i) Superscript represents economies staring from the U.S. = 1, China = 2, EU15 = 3, and the rest of the world (ROW) = 4 respectively

(ii) Subscript refers to the components of final demand (y) such as domestic demand ($y_f$) and export demand ($y_x$)

*Table 4.10: A Breakdown of EU15 Production-Based Emissions (PBE$^3$) by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of PBE$^3$ | | | |
|---|---|---|---|---|
| | Domestic Demand ($y_f^3$) | Export Demand ($y_x^3$) | | |
| | | USA ($y_x^{31}$) | CHN ($y_x^{32}$) | ROW ($y_x^{34}$) |
| 1.Agriculture, hunting, forestry and fishing | 53,669 | 599 | 615 | 3,829 |
| 2.Mining and quarrying | 3,532 | 1,842 | 333 | 15,724 |
| 3.Food, beverages and tobacco | 85,279 | 319 | 20,201 | 23,692 |
| 4.Textiles | 18,370 | 214 | 8,267 | 10,803 |
| 5.Leather and footwear | 11,360 | 130 | 2,113 | 2,345 |
| 6.Wood and cork | 3,953 | 149 | 63 | 2,239 |
| 7.Pulp, paper, printing and publishing | 23,094 | 1,065 | 462 | 3,888 |
| 8.Coke, refined petroleum and nuclear fuel | 136,838 | 11,635 | 2,590 | 15,713 |
| 9.Chemicals | 53,944 | 20,847 | 17,035 | 69,232 |
| 10.Rubber and plastics | 5,045 | 549 | 10,428 | 27,367 |
| 11.Other non-metallic mineral | 45,105 | 2,877 | 3,664 | 27,995 |
| 12.Basic and fabricated metals | 137,030 | 15,948 | 13,307 | 47,649 |
| 13.Machinery | 81,402 | 15,776 | 23,147 | 39,994 |
| 14.Electrical and optical equipment | 68,154 | 11,358 | 12,397 | 36,128 |
| 15.Transport equipment | 92,010 | 11,837 | 11,162 | 21,815 |
| 16.Manufacturing, nec; recycling | 49,951 | 10,222 | 14,64 | 52,042 |
| 17.Electricity, gas and water supply | 469,149 | 7,114 | 32,076 | 87,868 |
| 18.Construction | 206,842 | 1,093 | 1,307 | 12,555 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 28,590 | 0 | 0 | 0 |
| 20.Wholesale trade and commission trade, | 74,099 | 5,159 | 10,132 | 15,790 |
| 21.Retail trade | 67,995 | 1,051 | 1,047 | 5,901 |
| 22.Hotels and restaurants | 92,207 | 2,109 | 3,270 | 6,250 |
| 23.Inland transport | 98,315 | 1,078 | 1,147 | 15,378 |
| 24.Water transport | 41,350 | 11,065 | 15,143 | 40,331 |
| 25.Air transport | 72,982 | 7,020 | 4,799 | 41,734 |
| 26.Other supporting and auxiliary transport | 22,341 | 34 | 161 | 5,507 |
| 27.Post and telecommunications | 23,637 | 1,528 | 1,414 | 3,451 |
| 28.Financial intermediation | 28,193 | 63 | 43 | 401 |
| 29.Real estate activities | 42,350 | 0 | 0 | 0 |
| 30.Renting of machinery and equipment | 32,477 | 15,155 | 17,720 | 27,002 |
| 31.Public administration and defense | 122,980 | 85 | 45 | 361 |
| 32.Education | 61,533 | 47 | 70 | 225 |
| 33.Health and social work | 126,155 | 1,417 | 1,206 | 3,254 |
| 34.Other community, social and personal services | 71,990 | 186 | 205 | 739 |
| Aggregated emissions by component | 2,382,031 | 96,784 | 52,355 | 454,410 |
| | | 603,549 | | |
| EU15 production emissions (PBE$^3$) | 2,985,580 | | | |

Notes: (i) Superscript represents economies staring from the U.S. = 1, China = 2, EU15 = 3, and the rest of the world (ROW) = 4 respectively

(ii) Subscript refers to the components of final demand (y) such as domestic demand ($y_f$) and export demand ($y_x$)

*Table 4.11: A Breakdown of U.S. Consumption-Based Emissions ($CBE^1$) by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of $CBE^1$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | Domestic Demand ($y_f^1$) | Intermediate Import ($y_{mf}^{r1}$) | | | Final Import ($y_m^{r1}$) | | |
| | | CHN ($y_{mf}^{21}$) | EU15 ($y_{mf}^{31}$) | ROW ($y_{mf}^{41}$) | CHN ($y_m^{21}$) | EU15 ($y_m^{31}$) | ROW ($y_m^{41}$) |
| 1.Agriculture, hunting, forestry and fishing | 55,693 | 21,048 | 2,157 | 35,782 | 4,873 | 343 | 14,961 |
| 2.Mining and quarrying | 107,935 | 4,120 | 2,833 | 20,488 | 641 | 782 | 8,540 |
| 3.Food, beverages and tobacco | 83,123 | 1,788 | 579 | 17,004 | 2,056 | 1,725 | 6,154 |
| 4.Textiles | 9,584 | 2,719 | 880 | 6,204 | 1,500 | 79 | 1,947 |
| 5.Leather and footwear | 1,118 | 142 | 78 | 1,772 | 5,443 | 32 | 6,870 |
| 6.Wood and cork | 5,237 | 1,454 | 471 | 2,277 | 55 | 47 | 1,255 |
| 7.Pulp, paper, printing and publishing | 105,945 | 63,033 | 17,158 | 35,180 | 15,415 | 487 | 33,608 |
| 8.Coke, refined petroleum and nuclear fuel | 145,112 | 8,716 | 2,820 | 21,009 | 1,604 | 10,241 | 19,610 |
| 9.Chemicals | 340,889 | 99,132 | 25,602 | 78,686 | 17,606 | 17,394 | 55,456 |
| 10.Rubber and plastics | 172,673 | 82,209 | 22,126 | 40,326 | 15,030 | 143 | 14,212 |
| 11.Other non-metallic mineral | 139,683 | 66,939 | 25,039 | 46,716 | 3,613 | 3,211 | 6,104 |
| 12.Basic and fabricated metals | 157,170 | 128,248 | 35,021 | 58,066 | 7,774 | 2,690 | 21,924 |
| 13.Machinery | 33,998 | 1,553 | 502 | 10,223 | 2,812 | 432 | 9,044 |
| 14.Electrical and optical equipment | 52,764 | 884 | 580 | 10,093 | 1,635 | 172 | 3,633 |
| 15.Transport equipment | 89,621 | 1,353 | 438 | 37,633 | 1,345 | 1,205 | 6,295 |
| 16.Manufacturing, nec; recycling | 33,638 | 1,707 | 1,846 | 6,695 | 1,050 | 2,400 | 3,969 |
| 17.Electricity, gas and water supply | 1,217,538 | 34,731 | 6,537 | 28,981 | 22,711 | 2,127 | 35,355 |
| 18.Construction | 257,085 | 492 | 159 | 2,135 | 313 | 269 | 1,433 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 8,369 | 202 | 65 | 1,482 | 145 | 21 | 171 |
| 20.Wholesale trade and commission trade, | 35,129 | 882 | 285 | 2,782 | 3,678 | 1,337 | 3,967 |
| 21.Retail trade | 79,279 | 424 | 364 | 3,363 | 231 | 152 | 1,044 |
| 22.Hotels and restaurants | 88,272 | 245 | 241 | 2,660 | 27 | 84 | 563 |
| 23.Inland transport | 285,809 | 324 | 531 | 11,003 | 108 | 46 | 3,467 |
| 24.Water transport | 52,323 | 51,846 | 9,303 | 33,540 | 5,860 | 385 | 10,597 |
| 25.Air transport | 190,015 | 11,299 | 3,656 | 53,076 | 5,759 | 6,897 | 23,903 |
| 26.Other supporting and auxiliary transport | 9,464 | 1,181 | 382 | 5,981 | 2,057 | 195 | 3,926 |
| 27.Post and telecommunications | 95,208 | 27,538 | 13,174 | 20,027 | 45 | 565 | 288 |
| 28.Financial intermediation | 38,258 | 1,369 | 443 | 8,299 | 20 | 56 | 385 |
| 29.Real estate activities | 12,644 | 189 | 61 | 513 | 20 | 93 | 317 |
| 30.Renting of machinery and equipment | 95,833 | 30,753 | 10,773 | 30,033 | 3,819 | 1,130 | 9,943 |
| 31.Public administration and defense | 155,852 | 208 | 67 | 442 | 82 | 6 | 86 |
| 32.Education | 21,890 | 5 | 50 | 336 | 2 | 5 | 85 |
| 33.Health and social work | 95,624 | 31,440 | 8,407 | 56,222 | 29 | 26 | 134 |
| 34.Other community, social and personal services | 82,816 | 1,421 | 460 | 4,358 | 97 | 107 | 988 |
| Aggregated emissions by component | | 553,815 | 195,352 | 1,026,760 | 112,696 | 28,896 | 255,753 |
| | 4,354,864 | 1,775,927 | | | 397,345 | | |
| U.S. consumption emissions ($CBE^1$) | 6,528,136 | | | | | | |

Notes: (i) Superscript represents economies staring from the U.S. = 1, China = 2, EU15 = 3, and the rest of the world (ROW) = 4 respectively

(ii) Subscript refers to the use category of imports such as imports for intermediate use ($y_{mf}^r$) and imports for final use ($y_m^r$)

*Table 4.12: A Breakdown of China Consumption-Based Emissions ($CBE^2$) by Industry, 2011; kt of $CO_2$*

| Industry | Breakdown of $CBE^2$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | Domestic Demand ($y_f^2$) | Intermediate Import ($y_{mf}^{r2}$) | | | Final Import ($y_m^{r2}$) | | |
| | | USA ($y_{mf}^{12}$) | EU15 ($y_{mf}^{32}$) | ROW ($y_{mf}^{42}$) | USA ($y_m^{12}$) | EU15 ($y_m^{32}$) | ROW ($y_m^{42}$) |
| 1.Agriculture, hunting, forestry and fishing | 162,727 | 3,538 | 2,752 | 33,020 | 876 | 938 | 4,442 |
| 2.Mining and quarrying | 6,714 | 4,970 | 3,865 | 46,382 | 3,210 | 3,439 | 16,278 |
| 3.Food, beverages and tobacco | 246,371 | 2,245 | 1,746 | 20,949 | 742 | 795 | 3,765 |
| 4.Textiles | 150,162 | 2,442 | 1,899 | 22,793 | 423 | 453 | 2,144 |
| 5.Leather and footwear | 48,426 | 3,974 | 3,091 | 37,089 | 3,513 | 3,764 | 17,815 |
| 6.Wood and cork | 54,093 | 3,162 | 2,459 | 29,514 | 3,088 | 3,308 | 15,659 |
| 7.Pulp, paper, printing and publishing | 1,843 | 5,749 | 4,472 | 53,661 | 4,095 | 4,387 | 20,765 |
| 8.Coke, refined petroleum and nuclear fuel | 93,332 | 8,478 | 6,594 | 79,131 | 2,715 | 2,909 | 13,767 |
| 9.Chemicals | 83,599 | 2,361 | 1,836 | 22,034 | 4,112 | 4,406 | 20,853 |
| 10.Rubber and plastics | 53,378 | 4,255 | 3,309 | 39,713 | 4,110 | 4,404 | 20,845 |
| 11.Other non-metallic mineral | 49,542 | 3,969 | 3,087 | 37,043 | 4,169 | 4,466 | 21,141 |
| 12.Basic and fabricated metals | 73,599 | 2,703 | 2,102 | 25,230 | 936 | 1,003 | 4,749 |
| 13.Machinery | 386,779 | 1,154 | 898 | 10,775 | 165 | 176 | 835 |
| 14.Electrical and optical equipment | 234,165 | 1,902 | 1,479 | 17,753 | 995 | 1,066 | 5,045 |
| 15.Transport equipment | 263,725 | 1,144 | 890 | 10,676 | 179 | 192 | 910 |
| 16.Manufacturing, nec; recycling | 9,653 | 1,207 | 939 | 11,264 | 279 | 299 | 1,414 |
| 17.Electricity, gas and water supply | 1,900,955 | 4,371 | 5,559 | 23,637 | 1,673 | 1,534 | 11,867 |
| 18.Construction | 262,349 | 1,156 | 899 | 10,787 | 84 | 90 | 427 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 1,073 | 835 | 10,019 | 38 | 41 | 194 |
| 20.Wholesale trade and commission trade, | 107,700 | 1,182 | 919 | 11,031 | 205 | 220 | 1,042 |
| 21.Retail trade | 124,471 | 1,196 | 930 | 11,162 | 234 | 251 | 1,187 |
| 22.Hotels and restaurants | 84,153 | 1,205 | 937 | 11,245 | 78 | 84 | 397 |
| 23.Inland transport | 273,869 | 1,180 | 918 | 11,016 | 202 | 217 | 1,027 |
| 24.Water transport | 17,500 | 3,630 | 2,823 | 33,879 | 2,685 | 2,877 | 13,617 |
| 25.Air transport | 19,154 | 4,315 | 3,356 | 40,271 | 2,144 | 2,297 | 10,874 |
| 26.Other supporting and auxiliary transport | 19,207 | 1,263 | 982 | 11,787 | 191 | 205 | 971 |
| 27.Post and telecommunications | 49,816 | 1,176 | 915 | 10,980 | 84 | 90 | 427 |
| 28.Financial intermediation | 26,159 | 1,104 | 859 | 10,306 | 104 | 111 | 525 |
| 29.Real estate activities | 55,918 | 1,059 | 823 | 9,880 | 18 | 19 | 89 |
| 30.Renting of machinery and equipment | 65,161 | 2,581 | 2,008 | 24,093 | 732 | 785 | 3,714 |
| 31.Public administration and defense | 241,736 | 1,135 | 883 | 10,597 | 43 | 46 | 218 |
| 32.Education | 96,532 | 2,653 | 2,063 | 24,761 | 779 | 835 | 3,951 |
| 33.Health and social work | 109,950 | 2,786 | 2,167 | 26,004 | 498 | 534 | 2,527 |
| 34.Other community, social and personal services | 97,630 | 2,471 | 1,922 | 6,919 | 545 | 584 | 2,764 |
| Aggregated emissions by component | | 65,659 | 84,419 | 744,577 | 42,272 | 45,291 | 221,179 |
| | 6,219,407 | | 894,655 | | | 308,742 | |
| China consumption emissions ($CBE^2$) | | | | 7,422,804 | | | |

Notes: (i) Superscript represents economies staring from the U.S. = 1, China = 2, EU15 = 3, and the rest of the world (ROW) = 4 respectively
(ii) Subscript refers to the use category of imports such as imports for intermediate use ($y_{mf}^r$) and imports for final use ($y_m^r$)

*Table 4.13: A Breakdown of EU15 Consumption-Based Emissions ($CBE^3$) by Industry, 2011; kt of $CO_2$*

| **Industry** | **Breakdown of $CBE^3$** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Domestic Demand ($y_f^3$)** | **Intermediate Import ($y_{mf}^{r3}$)** | | | **Final Import ($y_m^{r3}$)** | | |
| | | **USA ($y_{mf}^{13}$)** | **CHN ($y_{mf}^{23}$)** | **ROW ($y_{mf}^{43}$)** | **USA ($y_m^{13}$)** | **CHN ($y_m^{23}$)** | **ROW ($y_m^{43}$)** |
| 1.Agriculture, hunting, forestry and fishing | 53,669 | 5,956 | 13,535 | 34,650 | 4,794 | 15,447 | 33,024 |
| 2.Mining and quarrying | 3,532 | 6,118 | 13,905 | 35,596 | 4,119 | 13,271 | 28,373 |
| 3.Food, beverages and tobacco | 85,279 | 3,755 | 8,534 | 21,846 | 4,416 | 14,230 | 30,422 |
| 4.Textiles | 18,370 | 95 | 216 | 553 | 492 | 1,584 | 3,387 |
| 5.Leather and footwear | 11,360 | 15 | 35 | 88 | 445 | 1,434 | 3,065 |
| 6.Wood and cork | 3,953 | 227 | 517 | 1,323 | 353 | 1,136 | 2,429 |
| 7.Pulp, paper, printing and publishing | 23,094 | 6,114 | 13,896 | 35,572 | 4,411 | 14,212 | 30,384 |
| 8.Coke, refined petroleum and nuclear fuel | 136,838 | 1,414 | 3,214 | 8,227 | 379 | 1,223 | 2,614 |
| 9.Chemicals | 53,944 | 1,846 | 4,196 | 10,742 | 1,130 | 3,640 | 7,781 |
| 10.Rubber and plastics | 5,045 | 5,080 | 11,545 | 29,555 | 3,627 | 11,686 | 24,983 |
| 11.Other non-metallic mineral | 45,105 | 6,424 | 14,601 | 37,378 | 3,801 | 12,248 | 26,185 |
| 12.Basic and fabricated metals | 137,030 | 1,392 | 3,164 | 8,100 | 429 | 1,383 | 2,957 |
| 13.Machinery | 81,402 | 1,236 | 2,809 | 7,190 | 510 | 1,642 | 3,511 |
| 14.Electrical and optical equipment | 68,154 | 6,031 | 13,707 | 35,091 | 3,479 | 11,209 | 23,965 |
| 15.Transport equipment | 92,010 | 1,949 | 4,430 | 11,341 | 386 | 1,245 | 2,661 |
| 16.Manufacturing, nec; recycling | 49,951 | 5,401 | 12,274 | 31,421 | 3,708 | 11,948 | 25,545 |
| 17.Electricity, gas and water supply | 469,149 | 2,116 | 14,512 | 23,284 | 1,340 | 11,907 | 12,352 |
| 18.Construction | 206,842 | 1,234 | 2,806 | 7,182 | 338 | 1,090 | 2,330 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 28,590 | 35 | 80 | 204 | 291 | 939 | 2,007 |
| 20.Wholesale trade and commission trade, | 74,099 | 113 | 256 | 656 | 296 | 953 | 2,037 |
| 21.Retail trade | 67,995 | 138 | 314 | 804 | 314 | 1,010 | 2,160 |
| 22.Hotels and restaurants | 92,207 | 176 | 401 | 1,025 | 262 | 846 | 1,808 |
| 23.Inland transport | 98,315 | 67 | 151 | 387 | 314 | 1,012 | 2,163 |
| 24.Water transport | 41,350 | 4,384 | 9,964 | 25,508 | 2,483 | 8,001 | 17,105 |
| 25.Air transport | 72,982 | 1,380 | 3,137 | 8,031 | 269 | 867 | 1,854 |
| 26.Other supporting and auxiliary transport | 22,341 | 72 | 164 | 420 | 247 | 797 | 1,703 |
| 27.Post and telecommunications | 23,637 | 3,612 | 8,208 | 21,013 | 3,406 | 10,976 | 23,465 |
| 28.Financial intermediation | 28,193 | 33 | 75 | 193 | 248 | 800 | 1,709 |
| 29.Real estate activities | 42,350 | 56 | 127 | 326 | 288 | 929 | 1,987 |
| 30.Renting of machinery and equipment | 32,477 | 3,731 | 8,479 | 21,706 | 2,839 | 9,148 | 19,558 |
| 31.Public administration and defense | 122,980 | 84 | 191 | 488 | 296 | 954 | 2,040 |
| 32.Education | 61,533 | 22 | 50 | 127 | 287 | 925 | 1,977 |
| 33.Health and social work | 126,155 | 3,571 | 8,116 | 20,778 | 3,808 | 12,272 | 26,236 |
| 34.Other community, social and personal services | 71,990 | 264 | 601 | 1,538 | 373 | 1,201 | 2,567 |
| Aggregated emissions by component | 2,382,031 | 72,026 | 163,695 | 418,280 | 52,838 | 170,254 | 362,769 |
| | | 654,001 | | | 585,861 | | |
| EU15 consumption emissions ($CBE^3$) | 3,621,893 | | | | | | |

Notes: (i) Superscript represents economies staring from the U.S. = 1, China = 2, EU15 = 3, and the rest of the world (ROW) = 4 respectively

(ii) Subscript refers to the use category of imports such as imports for intermediate use ($y_{mf}^r$) and imports for final use ($y_m^r$)

*Table 4.14: Industrial Distributive and Total Effects of Exported Emissions in the U.S., China, and EU15 Economies, 2011; Percent*

| Industry | USA | | CHN | | EU15 | |
|---|---|---|---|---|---|---|
| | Distributive Effect | Total Effect | Distributive Effect | Total Effect | Distributive Effect | Total Effect |
| 1.Agriculture, hunting, forestry and fishing | 0.047 | 0.021 | 0.013 | 0.036 | 0.009 | 0.010 |
| 2.Mining and quarrying | 0.054 | 0.022 | 0.011 | 0.034 | 0.055 | 0.016 |
| 3.Food, beverages and tobacco | 0.015 | 0.046 | 0.012 | 0.023 | 0.048 | 0.069 |
| 4.Textiles | 0.002 | 0.006 | 0.051 | 0.057 | 0.010 | 0.013 |
| 5.Leather and footwear | 0.003 | 0.004 | 0.010 | 0.026 | 0.009 | 0.004 |
| 6.Wood and cork | 0.001 | 0.004 | 0.012 | 0.022 | 0.010 | 0.012 |
| 7.Pulp, paper, printing and publishing | 0.045 | 0.021 | 0.053 | 0.058 | 0.018 | 0.052 |
| 8.Coke, refined petroleum and nuclear fuel | 0.094 | 0.066 | 0.057 | 0.020 | 0.038 | 0.041 |
| 9.Chemicals | 0.115 | 0.093 | 0.061 | 0.058 | 0.058 | 0.071 |
| 10.Rubber and plastics | 0.049 | 0.022 | 0.047 | 0.056 | 0.052 | 0.014 |
| 11.Other non-metallic mineral | 0.052 | 0.023 | 0.045 | 0.019 | 0.059 | 0.015 |
| 12.Basic and fabricated metals | 0.042 | 0.024 | 0.055 | 0.043 | 0.048 | 0.077 |
| 13.Machinery | 0.002 | 0.006 | 0.055 | 0.042 | 0.048 | 0.035 |
| 14.Electrical and optical equipment | 0.001 | 0.006 | 0.051 | 0.037 | 0.049 | 0.035 |
| 15.Transport equipment | 0.016 | 0.046 | 0.013 | 0.034 | 0.032 | 0.034 |
| 16.Manufacturing, nec; recycling | 0.002 | 0.005 | 0.043 | 0.018 | 0.049 | 0.035 |
| 17.Electricity, gas and water supply | 0.142 | 0.115 | 0.162 | 0.084 | 0.085 | 0.059 |
| 18.Construction | 0.019 | 0.056 | 0.004 | 0.014 | 0.019 | 0.060 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0.002 | 0.004 | 0.000 | 0.000 | 0.011 | 0.005 |
| 20.Wholesale trade and commission trade, | 0.002 | 0.006 | 0.011 | 0.022 | 0.018 | 0.051 |
| 21.Retail trade | 0.015 | 0.042 | 0.003 | 0.009 | 0.010 | 0.013 |
| 22.Hotels and restaurants | 0.014 | 0.044 | 0.004 | 0.013 | 0.017 | 0.054 |
| 23.Inland transport | 0.107 | 0.088 | 0.068 | 0.077 | 0.076 | 0.012 |
| 24.Water transport | 0.057 | 0.023 | 0.057 | 0.039 | 0.051 | 0.042 |
| 25.Air transport | 0.093 | 0.079 | 0.055 | 0.019 | 0.052 | 0.047 |
| 26.Other supporting and auxiliary transport | 0.003 | 0.006 | 0.003 | 0.016 | 0.000 | 0.000 |
| 27.Post and telecommunications | 0.002 | 0.008 | 0.005 | 0.016 | 0.002 | 0.016 |
| 28.Financial intermediation | 0.001 | 0.003 | 0.004 | 0.013 | 0.010 | 0.004 |
| 29.Real estate activities | 0.001 | 0.003 | 0.002 | 0.008 | 0.002 | 0.001 |
| 30.Renting of machinery and equipment | 0.002 | 0.003 | 0.012 | 0.027 | 0.018 | 0.064 |
| 31.Public administration and defense | 0.012 | 0.043 | 0.003 | 0.009 | 0.010 | 0.010 |
| 32.Education | 0.002 | 0.005 | 0.004 | 0.014 | 0.008 | 0.012 |
| 33.Health and social work | 0.018 | 0.050 | 0.012 | 0.030 | 0.013 | 0.006 |
| 34.Other community, social and personal services | 0.002 | 0.004 | 0.003 | 0.007 | 0.005 | 0.012 |
| Median | 0.021 | 0.028 | 0.017 | 0.025 | 0.020 | 0.019 |

Notes: (i) Distributive impact of industry's i emissions is calculated from the sum by rows such that $\sum_{j=1}^{n} \xi_{y_{ij}}^{1}$ where j=1,2,…n. In this way, it can be used to explain elasticities in response to domestic and export demands in the same manner.

(ii) Total emission impact of industry i's total demand is calculated from the sum by columns such that $\sum_{i=1}^{n} \xi_{y_{ij}}^{1}$ where i=1,2,…,n. It can be applied to elasticities of DE in response to domestic and export demands in the same manner.

*Table 4.15: Distributive and Total Effects of Emissions by Industry in Response to U.S. Intermediate and Final Imports, 2011; Percent*

| Industry | Intermediate Import | | | | | | Final Import | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CHN | | EU15 | | ROW | | CHN | | EU15 | | ROW | |
| | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef |
| 1.Agriculture, hunting, forestry and fishing | 0.020 | 0.008 | 0.013 | 0.005 | 0.030 | 0.012 | 0.003 | 0.009 | 0.002 | 0.002 | 0.006 | 0.017 |
| 2.Mining and quarrying | 0.021 | 0.008 | 0.014 | 0.005 | 0.031 | 0.012 | 0.003 | 0.009 | 0.011 | 0.003 | 0.005 | 0.016 |
| 3.Food, beverages and tobacco | 0.000 | 0.002 | 0.000 | 0.001 | 0.000 | 0.002 | 0.003 | 0.006 | 0.010 | 0.014 | 0.006 | 0.011 |
| 4.Textiles | 0.001 | 0.002 | 0.000 | 0.001 | 0.001 | 0.003 | 0.013 | 0.014 | 0.002 | 0.003 | 0.024 | 0.027 |
| 5.Leather and footwear | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.003 | 0.007 | 0.002 | 0.001 | 0.005 | 0.012 |
| 6.Wood and cork | 0.001 | 0.001 | 0.000 | 0.001 | 0.001 | 0.001 | 0.003 | 0.006 | 0.002 | 0.002 | 0.006 | 0.011 |
| 7.Pulp, paper, printing and publishing | 0.028 | 0.017 | 0.018 | 0.011 | 0.042 | 0.025 | 0.013 | 0.015 | 0.004 | 0.010 | 0.025 | 0.028 |
| 8.Coke, refined petroleum and nuclear fuel | 0.021 | 0.008 | 0.014 | 0.005 | 0.031 | 0.012 | 0.014 | 0.005 | 0.008 | 0.008 | 0.027 | 0.010 |
| 9.Chemicals | 0.021 | 0.035 | 0.014 | 0.023 | 0.032 | 0.052 | 0.015 | 0.015 | 0.012 | 0.014 | 0.029 | 0.028 |
| 10.Rubber and plastics | 0.031 | 0.017 | 0.020 | 0.011 | 0.046 | 0.026 | 0.012 | 0.014 | 0.010 | 0.003 | 0.023 | 0.027 |
| 11.Other non-metallic mineral | 0.028 | 0.020 | 0.018 | 0.013 | 0.042 | 0.030 | 0.011 | 0.005 | 0.012 | 0.003 | 0.022 | 0.009 |
| 12.Basic and fabricated metals | 0.017 | 0.029 | 0.011 | 0.019 | 0.025 | 0.044 | 0.014 | 0.011 | 0.010 | 0.015 | 0.026 | 0.021 |
| 13.Machinery | 0.000 | 0.001 | 0.000 | 0.001 | 0.001 | 0.002 | 0.014 | 0.011 | 0.010 | 0.007 | 0.026 | 0.020 |
| 14.Electrical and optical equipment | 0.000 | 0.002 | 0.000 | 0.001 | 0.000 | 0.002 | 0.013 | 0.009 | 0.010 | 0.007 | 0.024 | 0.018 |
| 15.Transport equipment | 0.020 | 0.008 | 0.013 | 0.005 | 0.031 | 0.012 | 0.003 | 0.009 | 0.006 | 0.007 | 0.006 | 0.016 |
| 16.Manufacturing, nec; recycling | 0.001 | 0.003 | 0.001 | 0.002 | 0.001 | 0.004 | 0.011 | 0.005 | 0.010 | 0.007 | 0.021 | 0.009 |
| 17.Electricity, gas and water supply | 0.031 | 0.045 | 0.021 | 0.030 | 0.047 | 0.068 | 0.041 | 0.021 | 0.017 | 0.012 | 0.078 | 0.040 |
| 18.Construction | 0.001 | 0.001 | 0.000 | 0.001 | 0.001 | 0.002 | 0.001 | 0.004 | 0.004 | 0.012 | 0.002 | 0.007 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0.001 | 0.001 | 0.000 | 0.001 | 0.001 | 0.002 | 0.000 | 0.000 | 0.002 | 0.001 | 0.000 | 0.000 |
| 20.Wholesale trade and commission trade, | 0.001 | 0.001 | 0.000 | 0.001 | 0.001 | 0.001 | 0.003 | 0.006 | 0.004 | 0.010 | 0.005 | 0.011 |
| 21.Retail trade | 0.001 | 0.001 | 0.000 | 0.001 | 0.001 | 0.002 | 0.001 | 0.002 | 0.002 | 0.003 | 0.001 | 0.004 |
| 22.Hotels and restaurants | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.003 | 0.003 | 0.011 | 0.002 | 0.006 |
| 23.Inland transport | 0.000 | 0.002 | 0.000 | 0.001 | 0.000 | 0.002 | 0.017 | 0.019 | 0.015 | 0.002 | 0.033 | 0.037 |
| 24.Water transport | 0.020 | 0.007 | 0.013 | 0.004 | 0.030 | 0.010 | 0.014 | 0.010 | 0.010 | 0.008 | 0.027 | 0.019 |
| 25.Air transport | 0.021 | 0.006 | 0.014 | 0.004 | 0.032 | 0.010 | 0.014 | 0.005 | 0.010 | 0.009 | 0.026 | 0.009 |
| 26.Other supporting and auxiliary transport | 0.004 | 0.003 | 0.002 | 0.002 | 0.005 | 0.004 | 0.001 | 0.004 | 0.000 | 0.000 | 0.001 | 0.008 |
| 27.Post and telecommunications | 0.007 | 0.028 | 0.004 | 0.018 | 0.010 | 0.041 | 0.001 | 0.004 | 0.000 | 0.003 | 0.002 | 0.008 |
| 28.Financial intermediation | 0.001 | 0.002 | 0.001 | 0.001 | 0.002 | 0.002 | 0.001 | 0.003 | 0.002 | 0.001 | 0.002 | 0.006 |
| 29.Real estate activities | 0.002 | 0.003 | 0.001 | 0.002 | 0.002 | 0.004 | 0.001 | 0.002 | 0.000 | 0.000 | 0.001 | 0.004 |
| 30.Renting of machinery and equipment | 0.007 | 0.025 | 0.004 | 0.017 | 0.010 | 0.038 | 0.003 | 0.007 | 0.004 | 0.013 | 0.006 | 0.013 |
| 31.Public administration and defense | 0.003 | 0.003 | 0.002 | 0.002 | 0.004 | 0.004 | 0.001 | 0.002 | 0.002 | 0.002 | 0.001 | 0.004 |
| 32.Education | 0.002 | 0.003 | 0.001 | 0.002 | 0.003 | 0.004 | 0.001 | 0.004 | 0.002 | 0.002 | 0.002 | 0.007 |
| 33.Health and social work | 0.006 | 0.027 | 0.004 | 0.018 | 0.009 | 0.040 | 0.003 | 0.008 | 0.003 | 0.001 | 0.006 | 0.014 |
| 34.Other community, social and personal services | 0.003 | 0.001 | 0.002 | 0.001 | 0.005 | 0.002 | 0.001 | 0.002 | 0.001 | 0.002 | 0.001 | 0.003 |
| Median | 0.007 | 0.009 | 0.004 | 0.006 | 0.010 | 0.013 | 0.008 | 0.009 | 0.002 | 0.003 | 0.012 | 0.014 |

Notes: (i) Distributive impact of industry's i emissions is calculated from the sum by rows such that $\sum_{j=1}^{n} \xi_{y_{ij}}^{1}$ where j=1,2,…n.

(ii) Total emission impact of industry i's total demand is calculated from the sum by columns such that $\sum_{i=1}^{n} \xi_{y_{ij}}^{1}$ where i=1,2,…,n.

*Table 4.16: Distributive and Total Effects of Emissions by Industry in Response to China Intermediate and Final Imports, 2011*

| Industry | Intermediate Import | | | | | | Final Import | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | USA | | EU15 | | ROW | | USA | | EU15 | | ROW | |
| | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef |
| 1.Agriculture, hunting, forestry and fishing | 0.014 | 0.004 | 0.017 | 0.005 | 0.036 | 0.010 | 0.016 | 0.007 | 0.002 | 0.003 | 0.024 | 0.011 |
| 2.Mining and quarrying | 0.011 | 0.013 | 0.013 | 0.016 | 0.027 | 0.033 | 0.019 | 0.008 | 0.015 | 0.004 | 0.028 | 0.011 |
| 3.Food, beverages and tobacco | 0.004 | 0.013 | 0.005 | 0.015 | 0.011 | 0.031 | 0.005 | 0.016 | 0.013 | 0.019 | 0.008 | 0.024 |
| 4.Textiles | 0.003 | 0.011 | 0.004 | 0.013 | 0.007 | 0.027 | 0.001 | 0.002 | 0.003 | 0.004 | 0.001 | 0.003 |
| 5.Leather and footwear | 0.012 | 0.009 | 0.014 | 0.011 | 0.029 | 0.023 | 0.001 | 0.001 | 0.002 | 0.001 | 0.001 | 0.002 |
| 6.Wood and cork | 0.012 | 0.004 | 0.014 | 0.005 | 0.030 | 0.011 | 0.000 | 0.001 | 0.003 | 0.003 | 0.001 | 0.002 |
| 7.Pulp, paper, printing and publishing | 0.011 | 0.012 | 0.013 | 0.015 | 0.028 | 0.031 | 0.016 | 0.007 | 0.005 | 0.014 | 0.023 | 0.011 |
| 8.Coke, refined petroleum and nuclear fuel | 0.010 | 0.014 | 0.012 | 0.016 | 0.026 | 0.034 | 0.033 | 0.023 | 0.010 | 0.011 | 0.049 | 0.034 |
| 9.Chemicals | 0.016 | 0.004 | 0.019 | 0.005 | 0.040 | 0.011 | 0.040 | 0.033 | 0.016 | 0.019 | 0.060 | 0.048 |
| 10.Rubber and plastics | 0.010 | 0.013 | 0.011 | 0.015 | 0.024 | 0.031 | 0.017 | 0.008 | 0.014 | 0.004 | 0.025 | 0.011 |
| 11.Other non-metallic mineral | 0.012 | 0.014 | 0.014 | 0.017 | 0.029 | 0.035 | 0.018 | 0.009 | 0.016 | 0.004 | 0.027 | 0.014 |
| 12.Basic and fabricated metals | 0.014 | 0.005 | 0.017 | 0.006 | 0.036 | 0.012 | 0.015 | 0.008 | 0.013 | 0.021 | 0.022 | 0.012 |
| 13.Machinery | 0.002 | 0.001 | 0.002 | 0.001 | 0.005 | 0.003 | 0.001 | 0.002 | 0.013 | 0.009 | 0.001 | 0.003 |
| 14.Electrical and optical equipment | 0.004 | 0.013 | 0.005 | 0.016 | 0.010 | 0.032 | 0.000 | 0.002 | 0.013 | 0.009 | 0.001 | 0.003 |
| 15.Transport equipment | 0.002 | 0.003 | 0.003 | 0.003 | 0.005 | 0.007 | 0.006 | 0.016 | 0.009 | 0.009 | 0.008 | 0.024 |
| 16.Manufacturing, nec; recycling | 0.003 | 0.002 | 0.003 | 0.003 | 0.006 | 0.005 | 0.001 | 0.002 | 0.013 | 0.009 | 0.001 | 0.003 |
| 17.Electricity, gas and water supply | 0.027 | 0.004 | 0.032 | 0.005 | 0.067 | 0.011 | 0.050 | 0.040 | 0.023 | 0.016 | 0.074 | 0.060 |
| 18.Construction | 0.001 | 0.002 | 0.002 | 0.002 | 0.003 | 0.005 | 0.007 | 0.020 | 0.005 | 0.016 | 0.010 | 0.029 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0.002 | 0.002 | 0.002 | 0.002 | 0.004 | 0.005 | 0.001 | 0.001 | 0.003 | 0.001 | 0.001 | 0.002 |
| 20.Wholesale trade and commission trade, | 0.001 | 0.002 | 0.002 | 0.003 | 0.003 | 0.005 | 0.001 | 0.002 | 0.005 | 0.014 | 0.001 | 0.003 |
| 21.Retail trade | 0.001 | 0.002 | 0.001 | 0.003 | 0.002 | 0.005 | 0.005 | 0.015 | 0.003 | 0.004 | 0.008 | 0.022 |
| 22.Hotels and restaurants | 0.001 | 0.000 | 0.001 | 0.000 | 0.003 | 0.001 | 0.005 | 0.015 | 0.005 | 0.015 | 0.007 | 0.023 |
| 23.Inland transport | 0.003 | 0.002 | 0.003 | 0.002 | 0.007 | 0.005 | 0.037 | 0.031 | 0.021 | 0.003 | 0.056 | 0.046 |
| 24.Water transport | 0.013 | 0.011 | 0.016 | 0.013 | 0.033 | 0.028 | 0.020 | 0.008 | 0.014 | 0.011 | 0.030 | 0.012 |
| 25.Air transport | 0.014 | 0.012 | 0.017 | 0.014 | 0.036 | 0.029 | 0.033 | 0.028 | 0.014 | 0.013 | 0.048 | 0.041 |
| 26.Other supporting and auxiliary transport | 0.002 | 0.001 | 0.002 | 0.001 | 0.004 | 0.003 | 0.001 | 0.002 | 0.000 | 0.000 | 0.001 | 0.003 |
| 27.Post and telecommunications | 0.001 | 0.001 | 0.001 | 0.001 | 0.002 | 0.002 | 0.001 | 0.003 | 0.001 | 0.004 | 0.001 | 0.004 |
| 28.Financial intermediation | 0.001 | 0.000 | 0.001 | 0.001 | 0.002 | 0.001 | 0.000 | 0.001 | 0.003 | 0.001 | 0.001 | 0.002 |
| 29.Real estate activities | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.000 | 0.001 | 0.000 | 0.000 | 0.001 | 0.001 |
| 30.Renting of machinery and equipment | 0.004 | 0.013 | 0.005 | 0.016 | 0.011 | 0.033 | 0.001 | 0.001 | 0.005 | 0.017 | 0.001 | 0.002 |
| 31.Public administration and defense | 0.001 | 0.002 | 0.002 | 0.003 | 0.003 | 0.005 | 0.004 | 0.015 | 0.003 | 0.003 | 0.006 | 0.022 |
| 32.Education | 0.004 | 0.012 | 0.004 | 0.014 | 0.009 | 0.029 | 0.001 | 0.002 | 0.002 | 0.003 | 0.001 | 0.003 |
| 33.Health and social work | 0.004 | 0.013 | 0.005 | 0.015 | 0.010 | 0.032 | 0.006 | 0.018 | 0.004 | 0.002 | 0.009 | 0.026 |
| 34.Other community, social and personal services | 0.002 | 0.001 | 0.002 | 0.002 | 0.004 | 0.003 | 0.001 | 0.002 | 0.001 | 0.003 | 0.001 | 0.002 |
| Median | 0.004 | 0.005 | 0.005 | 0.006 | 0.011 | 0.013 | 0.002 | 0.006 | 0.002 | 0.004 | 0.012 | 0.028 |

Notes: (i) Distributive impact of industry's i emissions is calculated from the sum by rows such that $\sum_{j=1}^{n} \xi_{y_{ij}}^{1}$ where j=1,2,…n.

(ii) Total emission impact of industry i's total demand is calculated from the sum by columns such that $\sum_{i=1}^{n} \xi_{y_{ij}}^{1}$ where i=1,2,…,n.

*Table 4.17: Distributive and Total Effects of Emissions by Industry in Response to EU15 Intermediate and Final Imports, 2011; Percent*

| Industry | Intermediate Import | | | | | | Final Import | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | USA | | CHN | | ROW | | USA | | CHN | | ROW | |
| | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef | Distributive Ef | Total Ef |
| 1.Agriculture, hunting, forestry and fishing | 0.016 | 0.003 | 0.009 | 0.014 | 0.043 | 0.031 | 0.005 | 0.002 | 0.002 | 0.000 | 0.021 | 0.009 |
| 2.Mining and quarrying | 0.010 | 0.001 | 0.015 | 0.023 | 0.040 | 0.013 | 0.006 | 0.002 | 0.000 | 0.002 | 0.024 | 0.010 |
| 3.Food, beverages and tobacco | 0.002 | 0.003 | 0.012 | 0.004 | 0.011 | 0.049 | 0.002 | 0.005 | 0.003 | 0.003 | 0.007 | 0.021 |
| 4.Textiles | 0.002 | 0.003 | 0.001 | 0.003 | 0.007 | 0.007 | 0.000 | 0.001 | 0.002 | 0.003 | 0.001 | 0.003 |
| 5.Leather and footwear | 0.001 | 0.003 | 0.001 | 0.003 | 0.008 | 0.004 | 0.000 | 0.000 | 0.001 | 0.002 | 0.001 | 0.002 |
| 6.Wood and cork | 0.001 | 0.002 | 0.002 | 0.004 | 0.007 | 0.002 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.002 |
| 7.Pulp, paper, printing and publishing | 0.026 | 0.011 | 0.012 | 0.011 | 0.046 | 0.031 | 0.005 | 0.002 | 0.002 | 0.000 | 0.020 | 0.009 |
| 8.Coke, refined petroleum and nuclear fuel | 0.000 | 0.011 | 0.003 | 0.012 | 0.009 | 0.007 | 0.010 | 0.007 | 0.000 | 0.002 | 0.042 | 0.030 |
| 9.Chemicals | 0.007 | 0.009 | 0.002 | 0.008 | 0.041 | 0.011 | 0.013 | 0.010 | 0.003 | 0.003 | 0.052 | 0.042 |
| 10.Rubber and plastics | 0.013 | 0.008 | 0.014 | 0.010 | 0.045 | 0.033 | 0.005 | 0.002 | 0.001 | 0.001 | 0.022 | 0.010 |
| 11.Other non-metallic mineral | 0.014 | 0.007 | 0.024 | 0.012 | 0.041 | 0.029 | 0.006 | 0.003 | 0.001 | 0.001 | 0.023 | 0.012 |
| 12.Basic and fabricated metals | 0.007 | 0.010 | 0.003 | 0.014 | 0.008 | 0.006 | 0.005 | 0.003 | 0.003 | 0.003 | 0.019 | 0.011 |
| 13.Machinery | 0.002 | 0.003 | 0.002 | 0.018 | 0.007 | 0.003 | 0.000 | 0.001 | 0.005 | 0.004 | 0.001 | 0.003 |
| 14.Electrical and optical equipment | 0.002 | 0.003 | 0.010 | 0.014 | 0.013 | 0.049 | 0.000 | 0.001 | 0.003 | 0.004 | 0.000 | 0.003 |
| 15.Transport equipment | 0.003 | 0.028 | 0.002 | 0.024 | 0.035 | 0.008 | 0.002 | 0.005 | 0.004 | 0.004 | 0.007 | 0.021 |
| 16.Manufacturing, nec; recycling | 0.002 | 0.002 | 0.012 | 0.015 | 0.034 | 0.012 | 0.000 | 0.001 | 0.003 | 0.003 | 0.001 | 0.002 |
| 17.Electricity, gas and water supply | 0.003 | 0.001 | 0.002 | 0.001 | 0.034 | 0.051 | 0.016 | 0.013 | 0.012 | 0.016 | 0.064 | 0.052 |
| 18.Construction | 0.002 | 0.003 | 0.006 | 0.017 | 0.001 | 0.002 | 0.002 | 0.006 | 0.002 | 0.000 | 0.009 | 0.025 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0.001 | 0.003 | 0.001 | 0.002 | 0.006 | 0.007 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.002 |
| 20.Wholesale trade and commission trade, | 0.002 | 0.003 | 0.003 | 0.001 | 0.007 | 0.007 | 0.000 | 0.001 | 0.002 | 0.000 | 0.001 | 0.003 |
| 21.Retail trade | 0.001 | 0.003 | 0.003 | 0.000 | 0.006 | 0.005 | 0.002 | 0.005 | 0.002 | 0.000 | 0.007 | 0.019 |
| 22.Hotels and restaurants | 0.002 | 0.003 | 0.001 | 0.004 | 0.006 | 0.003 | 0.002 | 0.005 | 0.000 | 0.000 | 0.006 | 0.020 |
| 23.Inland transport | 0.001 | 0.025 | 0.001 | 0.001 | 0.008 | 0.004 | 0.012 | 0.010 | 0.003 | 0.003 | 0.048 | 0.040 |
| 24.Water transport | 0.007 | 0.014 | 0.012 | 0.024 | 0.043 | 0.031 | 0.006 | 0.003 | 0.001 | 0.002 | 0.026 | 0.010 |
| 25.Air transport | 0.001 | 0.013 | 0.001 | 0.027 | 0.043 | 0.012 | 0.010 | 0.009 | 0.000 | 0.002 | 0.042 | 0.036 |
| 26.Other supporting and auxiliary transport | 0.000 | 0.013 | 0.001 | 0.004 | 0.007 | 0.004 | 0.000 | 0.001 | 0.000 | 0.000 | 0.001 | 0.003 |
| 27.Post and telecommunications | 0.013 | 0.001 | 0.020 | 0.005 | 0.013 | 0.047 | 0.000 | 0.001 | 0.000 | 0.000 | 0.001 | 0.004 |
| 28.Financial intermediation | 0.001 | 0.003 | 0.001 | 0.002 | 0.006 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.002 |
| 29.Real estate activities | 0.001 | 0.002 | 0.001 | 0.003 | 0.007 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 |
| 30.Renting of machinery and equipment | 0.010 | 0.002 | 0.022 | 0.003 | 0.012 | 0.050 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 |
| 31.Public administration and defense | 0.001 | 0.003 | 0.002 | 0.002 | 0.000 | 0.002 | 0.001 | 0.005 | 0.003 | 0.000 | 0.005 | 0.019 |
| 32.Education | 0.001 | 0.003 | 0.003 | 0.003 | 0.007 | 0.005 | 0.000 | 0.001 | 0.001 | 0.001 | 0.001 | 0.002 |
| 33.Health and social work | 0.009 | 0.000 | 0.020 | 0.003 | 0.011 | 0.051 | 0.002 | 0.006 | 0.001 | 0.001 | 0.008 | 0.023 |
| 34.Other community, social and personal services | 0.001 | 0.004 | 0.003 | 0.003 | 0.007 | 0.002 | 0.000 | 0.000 | 0.001 | 0.002 | 0.001 | 0.002 |
| Median | 0.003 | 0.004 | 0.005 | 0.006 | 0.015 | 0.016 | 0.001 | 0.002 | 0.002 | 0.004 | 0.010 | 0.009 |

Notes: (i) Distributive impact of industry's i emissions is calculated from the sum by rows such that $\sum_{j=1}^{n} \xi_{y_{ij}}^{1}$ where j=1,2,…n.

(ii) Total emission impact of industry i's total demand is calculated from the sum by columns such that $\sum_{i=1}^{n} \xi_{y_{ij}}^{1}$ where i=1,2,…,n.

*Table 4.18: Projections of U.S. Exported and Imported Emissions Associated with P1, 2011; kt of $CO_2$*

| Industry | Breakdown of U.S. Exported Emissions | | | Breakdown of U.S. Imported Emissions | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Intermediate Import | | | Final Import | | |
| | CHN | EU 15 | ROW | CHN | EU15 | ROW | CHN | EU15 | ROW |
| 1.Agriculture, hunting, forestry and fishing | 1,704 | 964 | 23,201 | 19,990 | 2,054 | 33,875 | 4,628 | 327 | 14,164 |
| 2.Mining and quarrying | 10,814 | 6,484 | 26,543 | 3,696 | 2,556 | 18,251 | 575 | 705 | 7,608 |
| 3.Food, beverages and tobacco | 355 | 358 | 21,242 | 1,749 | 567 | 16,609 | 2,011 | 1,689 | 6,011 |
| 4.Textiles | 299 | 410 | 7,141 | 2,652 | 859 | 6,042 | 1,463 | 77 | 1,896 |
| 5.Leather and footwear | 6 | 9 | 174 | 138 | 76 | 1,725 | 5,308 | 31 | 6,690 |
| 6.Wood and cork | 573 | 421 | 2,355 | 1,422 | 461 | 2,224 | 54 | 46 | 1,226 |
| 7.Pulp, paper, printing and publishing | 1,130 | 2,605 | 25,134 | 62,098 | 16,916 | 34,627 | 15,186 | 480 | 33,080 |
| 8.Coke, refined petroleum and nuclear fuel | 666 | 9,612 | 59,663 | 8,088 | 2,627 | 19,403 | 1,488 | 9,540 | 18,111 |
| 9.Chemicals | 16,636 | 22,054 | 116,701 | 81,774 | 21,343 | 64,082 | 14,523 | 14,500 | 45,163 |
| 10.Rubber and plastics | 529 | 985 | 34,886 | 80,177 | 21,606 | 39,270 | 14,659 | 140 | 13,839 |
| 11.Other non-metallic mineral | 2,527 | 2,594 | 22,138 | 55,218 | 20,874 | 38,045 | 2,981 | 2,677 | 4,971 |
| 12.Basic and fabricated metals | 5,165 | 4,139 | 33,260 | 125,078 | 34,199 | 56,545 | 7,581 | 2,627 | 21,349 |
| 13.Machinery | 1,659 | 2,226 | 7,928 | 1,522 | 493 | 10,009 | 2,757 | 424 | 8,855 |
| 14.Electrical and optical equipment | 2,022 | 2,044 | 7,832 | 871 | 572 | 9,935 | 1,610 | 169 | 3,576 |
| 15.Transport equipment | 18,610 | 4,184 | 62,188 | 1,291 | 419 | 35,817 | 1,284 | 1,153 | 5,992 |
| 16.Manufacturing, nec; recycling | 211 | 388 | 2,788 | 1,682 | 1,820 | 6,590 | 1,035 | 2,366 | 3,907 |
| 17.Electricity, gas and water supply | 17,268 | 16,859 | 100,988 | 25,430 | 4,874 | 20,754 | 16,629 | 1,586 | 25,319 |
| 18.Construction | 0 | 187 | 21,878 | 480 | 155 | 2,079 | 305 | 263 | 1,395 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 0 | 131 | 199 | 64 | 1,459 | 143 | 21 | 168 |
| 20.Wholesale trade and commission trade, | 0 | 1,307 | 6,735 | 865 | 280 | 2,724 | 3,606 | 1,312 | 3,883 |
| 21.Retail trade | 2,746 | 709 | 24,499 | 418 | 359 | 3,310 | 228 | 149 | 1,028 |
| 22.Hotels and restaurants | 65 | 6 | 20,158 | 239 | 235 | 2,591 | 26 | 82 | 548 |
| 23.Inland transport | 1,726 | 10,715 | 32,438 | 318 | 521 | 10,773 | 105 | 45 | 3,394 |
| 24.Water transport | 12 | 1,743 | 23,859 | 49,475 | 8,899 | 31,915 | 5,592 | 369 | 10,083 |
| 25.Air transport | 5,016 | 11,331 | 27,397 | 10,726 | 3,480 | 50,225 | 5,467 | 6,565 | 22,619 |
| 26.Other supporting and auxiliary transport | 207 | 6,152 | 2,998 | 1,163 | 377 | 5,887 | 2,027 | 192 | 3,864 |
| 27.Post and telecommunications | 1,030 | 1,758 | 5,975 | 26,290 | 12,607 | 19,065 | 43 | 540 | 274 |
| 28.Financial intermediation | 80 | 432 | 6,049 | 1,342 | 435 | 8,125 | 20 | 55 | 377 |
| 29.Real estate activities | 0 | 39 | 18 | 186 | 60 | 505 | 20 | 91 | 312 |
| 30.Renting of machinery and equipment | 1,213 | 8,140 | 3,385 | 29,347 | 10,305 | 28,577 | 3,644 | 1,081 | 9,461 |
| 31.Public administration and defense | 2,625 | 1,427 | 26,187 | 204 | 66 | 433 | 81 | 6 | 84 |
| 32.Education | 2,370 | 1,040 | 3,760 | 5 | 50 | 332 | 2 | 5 | 84 |
| 33.Health and social work | 898 | 1,431 | 21,701 | 30,158 | 8,081 | 53,791 | 27 | 25 | 128 |
| 34.Other community, social and personal services | 590 | 1,343 | 1,614 | 1,407 | 456 | 4,312 | 97 | 106 | 978 |
| Aggregated emissions by component | 74,624 | 255,806 | 451,276 | 531,663 | 185,584 | 976,131 | 108,188 | 27,451 | 235,591 |
| | 781,706 | | | 1,693,379 | | | 371.230 | | |

*Table 4.19: Projections of China Exported and Imported Emissions Associated with P1, 2011; kt of $CO_2$*

| Industry | Breakdown of China Exported Emissions | | | Breakdown of China Imported Emissions | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Intermediate Import | | | Final Import | | |
| | USA | EU 15 | ROW | USA | EU15 | ROW | USA | EU15 | ROW |
| 1.Agriculture, hunting, forestry and fishing | 1,616 | 966 | 38,965 | 3,516 | 2,736 | 32,796 | 870 | 932 | 4,410 |
| 2.Mining and quarrying | 1,456 | 1,323 | 32,500 | 4,924 | 3,831 | 45,909 | 3,177 | 3,406 | 16,104 |
| 3.Food, beverages and tobacco | 306 | 414 | 31,626 | 2,217 | 1,726 | 20,664 | 732 | 785 | 3,711 |
| 4.Textiles | 13,539 | 11,170 | 62,363 | 2,375 | 1,850 | 22,103 | 410 | 440 | 2,076 |
| 5.Leather and footwear | 3,412 | 685 | 30,899 | 3,925 | 3,055 | 36,585 | 3,465 | 3,716 | 17,561 |
| 6.Wood and cork | 1,873 | 1,865 | 24,957 | 3,142 | 2,445 | 29,313 | 3,067 | 3,287 | 15,547 |
| 7.Pulp, paper, printing and publishing | 6,841 | 1,069 | 29,174 | 5,394 | 4,210 | 50,013 | 3,817 | 4,105 | 19,283 |
| 8.Coke, refined petroleum and nuclear fuel | 2,359 | 2,608 | 30,681 | 8,373 | 6,517 | 78,055 | 2,678 | 2,872 | 13,570 |
| 9.Chemicals | 24,986 | 25,515 | 158,269 | 2,166 | 1,693 | 20,037 | 3,739 | 4,028 | 18,868 |
| 10.Rubber and plastics | 9,818 | 11,575 | 67,914 | 3,992 | 3,115 | 37,013 | 3,831 | 4,121 | 19,357 |
| 11.Other non-metallic mineral | 10,089 | 9,082 | 55,150 | 3,683 | 2,876 | 34,105 | 3,838 | 4,131 | 19,380 |
| 12.Basic and fabricated metals | 37,677 | 50,505 | 267,198 | 2,369 | 1,856 | 21,800 | 809 | 874 | 4,071 |
| 13.Machinery | 13,892 | 15,067 | 178,175 | 1,143 | 890 | 10,665 | 163 | 174 | 826 |
| 14.Electrical and optical equipment | 82,217 | 81,944 | 176,078 | 1,851 | 1,442 | 17,233 | 966 | 1,036 | 4,890 |
| 15.Transport equipment | 9,170 | 9,551 | 81,394 | 1,130 | 880 | 10,531 | 177 | 190 | 897 |
| 16.Manufacturing, nec; recycling | 1,081 | 803 | 60,649 | 1,200 | 934 | 11,187 | 277 | 297 | 1,404 |
| 17.Electricity, gas and water supply | 76,949 | 35,511 | 348,809 | 4,310 | 5,486 | 23,275 | 1,647 | 1,512 | 11,676 |
| 18.Construction | 0 | 4,658 | 9,908 | 1,142 | 888 | 10,640 | 83 | 89 | 421 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 0 | 0 | 1,063 | 828 | 9,917 | 38 | 41 | 192 |
| 20.Wholesale trade and commission trade, | 0 | 7,189 | 24,191 | 1,167 | 908 | 10,881 | 202 | 217 | 1,027 |
| 21.Retail trade | 274 | 37 | 6,478 | 1,189 | 925 | 11,086 | 232 | 249 | 1,179 |
| 22.Hotels and restaurants | 0 | 2,718 | 9,102 | 1,194 | 929 | 11,130 | 77 | 83 | 393 |
| 23.Inland transport | 644 | 5,802 | 25,684 | 1,165 | 907 | 10,866 | 199 | 214 | 1,012 |
| 24.Water transport | 0 | 10,854 | 62,073 | 3,591 | 2,794 | 33,476 | 2,653 | 2,845 | 13,447 |
| 25.Air transport | 12,084 | 7,130 | 22,821 | 4,275 | 3,327 | 39,860 | 2,122 | 2,275 | 10,758 |
| 26.Other supporting and auxiliary transport | 0 | 3,849 | 2,111 | 1,247 | 971 | 11,627 | 188 | 202 | 957 |
| 27.Post and telecommunications | 0 | 2,479 | 3,304 | 1,169 | 910 | 10,905 | 83 | 89 | 424 |
| 28.Financial intermediation | 79 | 84 | 371 | 1,090 | 849 | 10,166 | 103 | 110 | 518 |
| 29.Real estate activities | 0 | 0 | 0 | 1,049 | 816 | 9,779 | 18 | 19 | 88 |
| 30.Renting of machinery and equipment | 27,833 | 8,084 | 12,023 | 2,535 | 1,974 | 23,625 | 718 | 771 | 3,638 |
| 31.Public administration and defense | 0 | 3 | 559 | 1,124 | 875 | 10,489 | 43 | 46 | 216 |
| 32.Education | 1 | 7 | 387 | 2,611 | 2,032 | 24,328 | 765 | 821 | 3,879 |
| 33.Health and social work | 361 | 4,517 | 31,404 | 2,733 | 2,128 | 25,460 | 488 | 523 | 2,471 |
| 34.Other community, social and personal services | 83 | 6,381 | 4,483 | 2,440 | 1,900 | 6,825 | 538 | 576 | 2,725 |
| Aggregated emissions by component | 305,371 | 329,260 | 1,554,582 | 63,033 | 81,042 | 701,367 | 40,581 | 42,574 | 202,596 |
| | 2,189,213 | | | 845,442 | | | 285,751 | | |

*Table 4.20: Projections of U.S. Exported and Imported Emissions Associated with P2, 2011; kt of $CO_2$*

| Industry | Breakdown of U.S. Exported Emissions | | | Breakdown of U.S. Imported Emissions | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Intermediate Import | | | Final Import | | |
| | CHN | EU 15 | ROW | CHN | EU15 | ROW | CHN | EU15 | ROW |
| 1.Agriculture, hunting, forestry and fishing | 1,936 | 1,088 | 26,473 | 10,752 | 10,752 | 10,752 | 10,752 | 10,752 | 10,752 |
| 2.Mining and quarrying | 12,574 | 7,479 | 31,015 | 6,714 | 6,714 | 6,714 | 6,714 | 6,714 | 6,714 |
| 3.Food, beverages and tobacco | 473 | 469 | 28,609 | 5,844 | 5,844 | 5,844 | 5,844 | 5,844 | 5,844 |
| 4.Textiles | 318 | 435 | 7,611 | 1,877 | 1,877 | 1,877 | 1,877 | 1,877 | 1,877 |
| 5.Leather and footwear | 6 | 9 | 182 | 6,623 | 6,623 | 6,623 | 6,623 | 6,623 | 6,623 |
| 6.Wood and cork | 597 | 438 | 2,456 | 1,165 | 1,165 | 1,165 | 1,165 | 1,165 | 1,165 |
| 7.Pulp, paper, printing and publishing | 1,256 | 2,878 | 28,020 | 30,866 | 30,866 | 30,866 | 30,866 | 30,866 | 30,866 |
| 8.Coke, refined petroleum and nuclear fuel | 701 | 10,091 | 62,902 | 14,314 | 14,314 | 14,314 | 14,314 | 14,314 | 14,314 |
| 9.Chemicals | 19,805 | 26,007 | 139,729 | 50,926 | 50,926 | 50,926 | 50,926 | 50,926 | 50,926 |
| 10.Rubber and plastics | 608 | 1,124 | 40,279 | 13,303 | 13,303 | 13,303 | 13,303 | 13,303 | 13,303 |
| 11.Other non-metallic mineral | 3,044 | 3,094 | 26,837 | 5,667 | 5,667 | 5,667 | 5,667 | 5,667 | 5,667 |
| 12.Basic and fabricated metals | 5,869 | 4,672 | 37,951 | 20,569 | 20,569 | 20,569 | 20,569 | 20,569 | 20,569 |
| 13.Machinery | 1,784 | 2,385 | 8,544 | 8,784 | 8,784 | 8,784 | 8,784 | 8,784 | 8,784 |
| 14.Electrical and optical equipment | 2,151 | 2,168 | 8,348 | 3,555 | 3,555 | 3,555 | 3,555 | 3,555 | 3,555 |
| 15.Transport equipment | 21,148 | 4,722 | 70,959 | 4,454 | 4,454 | 4,454 | 4,454 | 4,454 | 4,454 |
| 16.Manufacturing, nec; recycling | 229 | 420 | 3,039 | 3,884 | 3,884 | 3,884 | 3,884 | 3,884 | 3,884 |
| 17.Electricity, gas and water supply | 23,335 | 22,389 | 145,139 | 33,286 | 33,286 | 33,286 | 33,286 | 33,286 | 33,286 |
| 18.Construction | 0 | 220 | 26,195 | 1,381 | 1,381 | 1,381 | 1,381 | 1,381 | 1,381 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 0 | 138 | 167 | 167 | 167 | 167 | 167 | 167 |
| 20.Wholesale trade and commission trade, | 0 | 1,804 | 9,604 | 3,852 | 3,852 | 3,852 | 3,852 | 3,852 | 3,852 |
| 21.Retail trade | 3,120 | 800 | 27,954 | 1,022 | 1,022 | 1,022 | 1,022 | 1,022 | 1,022 |
| 22.Hotels and restaurants | 85 | 8 | 26,777 | 542 | 542 | 542 | 542 | 542 | 542 |
| 23.Inland transport | 1,856 | 11,478 | 34,958 | 3,367 | 3,367 | 3,367 | 3,367 | 3,367 | 3,367 |
| 24.Water transport | 13 | 1,867 | 25,713 | 7,616 | 7,616 | 7,616 | 7,616 | 7,616 | 7,616 |
| 25.Air transport | 6,117 | 13,668 | 33,633 | 17,447 | 17,447 | 17,447 | 17,447 | 17,447 | 17,447 |
| 26.Other supporting and auxiliary transport | 218 | 6,459 | 3,161 | 3,841 | 3,841 | 3,841 | 3,841 | 3,841 | 3,841 |
| 27.Post and telecommunications | 1,120 | 1,903 | 6,512 | 267 | 267 | 267 | 267 | 267 | 267 |
| 28.Financial intermediation | 87 | 468 | 6,592 | 374 | 374 | 374 | 374 | 374 | 374 |
| 29.Real estate activities | 0 | 43 | 20 | 310 | 310 | 310 | 310 | 310 | 310 |
| 30.Renting of machinery and equipment | 1,318 | 8,810 | 3,689 | 9,280 | 9,280 | 9,280 | 9,280 | 9,280 | 9,280 |
| 31.Public administration and defense | 2,853 | 1,544 | 28,538 | 83 | 83 | 83 | 83 | 83 | 83 |
| 32.Education | 2,576 | 1,125 | 4,098 | 84 | 84 | 84 | 84 | 84 | 84 |
| 33.Health and social work | 1,214 | 1,900 | 29,637 | 124 | 124 | 124 | 124 | 124 | 124 |
| 34.Other community, social and personal services | 634 | 1,439 | 1,739 | 974 | 974 | 974 | 974 | 974 | 974 |
| Aggregated emissions by component | 88,838 | 287,010 | 525,153 | 515,972 | 191,445 | 961,466 | 94,664 | 27,451 | 208,412 |
| | 901,001 | | | 1,668,883 | | | 330,528 | | |

*Table 4.21: Projections of China Exported and Imported Emissions Associated with P2, 2011; kt of $CO_2$*

| Industry | Breakdown of China Exported Emissions | | | Breakdown of China Imported Emissions | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Intermediate Import | | | Final Import | | |
| | USA | EU 15 | ROW | USA | EU15 | ROW | USA | EU15 | ROW |
| 1.Agriculture, hunting, forestry and fishing | 1,756 | 1,044 | 42,650 | 4,373 | 4,373 | 4,373 | 4,373 | 4,373 | 4,373 |
| 2.Mining and quarrying | 1,566 | 1,415 | 35,158 | 14,503 | 14,503 | 14,503 | 14,503 | 14,503 | 14,503 |
| 3.Food, beverages and tobacco | 344 | 461 | 35,890 | 2,768 | 2,768 | 2,768 | 2,768 | 2,768 | 2,768 |
| 4.Textiles | 16,118 | 13,123 | 75,391 | 1,543 | 1,543 | 1,543 | 1,543 | 1,543 | 1,543 |
| 5.Leather and footwear | 3,749 | 748 | 34,226 | 16,150 | 16,150 | 16,150 | 16,150 | 16,150 | 16,150 |
| 6.Wood and cork | 2,036 | 2,015 | 27,317 | 15,415 | 15,415 | 15,415 | 15,415 | 15,415 | 15,415 |
| 7.Pulp, paper, printing and publishing | 8,144 | 1,256 | 35,268 | 18,500 | 18,500 | 18,500 | 18,500 | 18,500 | 18,500 |
| 8.Coke, refined petroleum and nuclear fuel | 2,592 | 2,846 | 33,984 | 11,837 | 11,837 | 11,837 | 11,837 | 11,837 | 11,837 |
| 9.Chemicals | 29,745 | 29,975 | 191,331 | 20,366 | 20,366 | 20,366 | 20,366 | 20,366 | 20,366 |
| 10.Rubber and plastics | 11,688 | 13,599 | 82,101 | 18,247 | 18,247 | 18,247 | 18,247 | 18,247 | 18,247 |
| 11.Other non-metallic mineral | 11,597 | 10,331 | 64,158 | 18,506 | 18,506 | 18,506 | 18,506 | 18,506 | 18,506 |
| 12.Basic and fabricated metals | 39,660 | 52,968 | 282,450 | 4,356 | 4,356 | 4,356 | 4,356 | 4,356 | 4,356 |
| 13.Machinery | 14,471 | 15,649 | 186,220 | 815 | 815 | 815 | 815 | 815 | 815 |
| 14.Electrical and optical equipment | 84,760 | 84,296 | 181,974 | 3,787 | 3,787 | 3,787 | 3,787 | 3,787 | 3,787 |
| 15.Transport equipment | 10,788 | 11,099 | 97,129 | 882 | 882 | 882 | 882 | 882 | 882 |
| 16.Manufacturing, nec; recycling | 1,215 | 894 | 68,825 | 1,392 | 1,392 | 1,392 | 1,392 | 1,392 | 1,392 |
| 17.Electricity, gas and water supply | 101,249 | 45,715 | 470,854 | 11,451 | 11,451 | 11,451 | 11,451 | 11,451 | 11,451 |
| 18.Construction | 0 | 4,885 | 10,474 | 414 | 414 | 414 | 414 | 414 | 414 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 0 | 0 | 189 | 189 | 189 | 189 | 189 | 189 |
| 20.Wholesale trade and commission trade, | 0 | 7,846 | 26,795 | 1,010 | 1,010 | 1,010 | 1,010 | 1,010 | 1,010 |
| 21.Retail trade | 311 | 42 | 7,443 | 1,169 | 1,169 | 1,169 | 1,169 | 1,169 | 1,169 |
| 22.Hotels and restaurants | 0 | 2,851 | 9,622 | 388 | 388 | 388 | 388 | 388 | 388 |
| 23.Inland transport | 671 | 6,026 | 26,843 | 995 | 995 | 995 | 995 | 995 | 995 |
| 24.Water transport | 0 | 11,166 | 64,151 | 11,071 | 11,071 | 11,071 | 11,071 | 11,071 | 11,071 |
| 25.Air transport | 12,994 | 7,626 | 24,687 | 9,349 | 9,349 | 9,349 | 9,349 | 9,349 | 9,349 |
| 26.Other supporting and auxiliary transport | 0 | 3,959 | 2,182 | 941 | 941 | 941 | 941 | 941 | 941 |
| 27.Post and telecommunications | 0 | 2,600 | 3,493 | 420 | 420 | 420 | 420 | 420 | 420 |
| 28.Financial intermediation | 82 | 87 | 388 | 509 | 509 | 509 | 509 | 509 | 509 |
| 29.Real estate activities | 0 | 0 | 0 | 87 | 87 | 87 | 87 | 87 | 87 |
| 30.Renting of machinery and equipment | 30,586 | 8,822 | 13,318 | 2,730 | 2,730 | 2,730 | 2,730 | 2,730 | 2,730 |
| 31.Public administration and defense | 0 | 3 | 584 | 213 | 213 | 213 | 213 | 213 | 213 |
| 32.Education | 1 | 7 | 396 | 2,966 | 2,966 | 2,966 | 2,966 | 2,966 | 2,966 |
| 33.Health and social work | 410 | 5,084 | 36,080 | 1,779 | 1,779 | 1,779 | 1,779 | 1,779 | 1,779 |
| 34.Other community, social and personal services | 85 | 6,502 | 4,582 | 2,678 | 2,678 | 2,678 | 2,678 | 2,678 | 2,678 |
| Aggregated emissions by component | 328,357 | 342,980 | 1,706,472 | 64,346 | 83,575 | 687,743 | 39,313 | 43,480 | 176,634 |
| | 2,377,809 | | | 835,664 | | | 259,427 | | |

*Table 4.22: Projections of U.S. Exported and Imported Emissions Associated with P3, 2011; kt of $CO_2$*

| Industry | Breakdown of U.S. Exported Emissions | | | Breakdown of U.S. Imported Emissions | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Intermediate Import | | | Final Import | | |
| | CHN | EU 15 | ROW | CHN | EU15 | ROW | CHN | EU15 | ROW |
| 1.Agriculture, hunting, forestry and fishing | 1,878 | 1,060 | 25,600 | 20,235 | 2,085 | 34,398 | 4,666 | 330 | 14,325 |
| 2.Mining and quarrying | 12,323 | 7,350 | 30,333 | 3,952 | 2,734 | 19,653 | 612 | 751 | 8,157 |
| 3.Food, beverages and tobacco | 430 | 433 | 25,777 | 1,672 | 547 | 15,904 | 1,910 | 1,618 | 5,716 |
| 4.Textiles | 303 | 417 | 7,209 | 2,594 | 845 | 5,918 | 1,424 | 76 | 1,848 |
| 5.Leather and footwear | 6 | 9 | 176 | 135 | 75 | 1,690 | 5,167 | 30 | 6,521 |
| 6.Wood and cork | 578 | 426 | 2,370 | 1,320 | 434 | 2,067 | 50 | 43 | 1,127 |
| 7.Pulp, paper, printing and publishing | 1,231 | 2,828 | 27,403 | 46,802 | 13,366 | 26,110 | 11,049 | 366 | 24,077 |
| 8.Coke, refined petroleum and nuclear fuel | 617 | 9,050 | 54,599 | 8,394 | 2,731 | 20,233 | 1,539 | 9,878 | 18,812 |
| 9.Chemicals | 17,230 | 23,099 | 119,747 | 75,648 | 20,397 | 60,023 | 13,018 | 13,433 | 40,988 |
| 10.Rubber and plastics | 590 | 1,095 | 38,950 | 60,193 | 17,041 | 29,514 | 10,603 | 106 | 10,020 |
| 11.Other non-metallic mineral | 2,967 | 3,026 | 26,087 | 50,392 | 19,727 | 35,154 | 2,631 | 2,448 | 4,442 |
| 12.Basic and fabricated metals | 5,655 | 4,525 | 36,427 | 93,903 | 26,972 | 42,498 | 5,484 | 1,997 | 15,458 |
| 13.Machinery | 1,684 | 2,270 | 8,018 | 1,496 | 486 | 9,845 | 2,698 | 417 | 8,677 |
| 14.Electrical and optical equipment | 2,048 | 2,079 | 7,907 | 860 | 566 | 9,814 | 1,585 | 167 | 3,522 |
| 15.Transport equipment | 19,171 | 4,342 | 63,661 | 1,306 | 425 | 36,321 | 1,293 | 1,165 | 6,054 |
| 16.Manufacturing, nec; recycling | 214 | 397 | 2,825 | 1,660 | 1,802 | 6,510 | 1,018 | 2,336 | 3,848 |
| 17.Electricity, gas and water supply | 20,348 | 19,924 | 124,703 | 29,007 | 5,612 | 24,200 | 18,594 | 1,790 | 28,938 |
| 18.Construction | 0 | 211 | 24,884 | 469 | 153 | 2,036 | 297 | 257 | 1,360 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 0 | 132 | 196 | 63 | 1,441 | 141 | 20 | 166 |
| 20.Wholesale trade and commission trade, | 0 | 1,717 | 9,012 | 849 | 276 | 2,679 | 3,529 | 1,290 | 3,805 |
| 21.Retail trade | 2,802 | 730 | 24,818 | 412 | 355 | 3,270 | 224 | 147 | 1,012 |
| 22.Hotels and restaurants | 75 | 7 | 23,272 | 234 | 231 | 2,537 | 26 | 80 | 534 |
| 23.Inland transport | 1,652 | 10,392 | 30,729 | 312 | 514 | 10,597 | 103 | 45 | 3,326 |
| 24.Water transport | 12 | 1,801 | 24,547 | 50,411 | 9,082 | 32,611 | 5,681 | 375 | 10,273 |
| 25.Air transport | 5,505 | 12,493 | 29,933 | 10,882 | 3,540 | 51,114 | 5,525 | 6,652 | 22,931 |
| 26.Other supporting and auxiliary transport | 209 | 6,237 | 3,022 | 1,148 | 373 | 5,816 | 1,995 | 190 | 3,806 |
| 27.Post and telecommunications | 1,048 | 1,798 | 6,053 | 24,134 | 11,777 | 17,549 | 39 | 497 | 249 |
| 28.Financial intermediation | 81 | 442 | 6,128 | 1,318 | 429 | 7,992 | 19 | 54 | 369 |
| 29.Real estate activities | 0 | 40 | 18 | 184 | 60 | 499 | 20 | 90 | 308 |
| 30.Renting of machinery and equipment | 1,234 | 8,325 | 3,429 | 26,635 | 9,535 | 26,007 | 3,256 | 985 | 8,477 |
| 31.Public administration and defense | 2,568 | 1,411 | 25,399 | 200 | 65 | 426 | 79 | 6 | 82 |
| 32.Education | 2,411 | 1,063 | 3,809 | 5 | 49 | 329 | 2 | 5 | 83 |
| 33.Health and social work | 1,117 | 1,769 | 27,029 | 28,202 | 7,664 | 50,424 | 25 | 23 | 119 |
| 34.Other community, social and personal services | 598 | 1,370 | 1,632 | 1,395 | 453 | 4,277 | 95 | 105 | 968 |
| Aggregated emissions by component | 71,907 | 256,891 | 460,479 | 478,819 | 175,817 | 870,746 | 96,918 | 26,007 | 200,833 |
| | 789,277 | | | 1,525,382 | | | 323,757 | | |

*Table 4.23: Projections of China Exported and Imported Emissions Associated with P3, 2011; kt of $CO_2$*

| Industry | Breakdown of China Exported Emissions | | | Breakdown of China Imported Emissions | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Intermediate Import | | | Final Import | | |
| | USA | EU 15 | ROW | USA | EU15 | ROW | USA | EU15 | ROW |
| 1.Agriculture, hunting, forestry and fishing | 1,639 | 979 | 39,535 | 4,255 | 4,255 | 4,255 | 4,255 | 4,255 | 4,255 |
| 2.Mining and quarrying | 1,475 | 1,338 | 32,911 | 13,176 | 13,176 | 13,176 | 13,176 | 13,176 | 13,176 |
| 3.Food, beverages and tobacco | 330 | 444 | 34,311 | 3,351 | 3,351 | 3,351 | 3,351 | 3,351 | 3,351 |
| 4.Textiles | 14,990 | 12,260 | 69,586 | 1,914 | 1,914 | 1,914 | 1,914 | 1,914 | 1,914 |
| 5.Leather and footwear | 3,599 | 720 | 32,720 | 14,194 | 14,194 | 14,194 | 14,194 | 14,194 | 14,194 |
| 6.Wood and cork | 1,934 | 1,920 | 25,815 | 14,993 | 14,993 | 14,993 | 14,993 | 14,993 | 14,993 |
| 7.Pulp, paper, printing and publishing | 7,655 | 1,185 | 32,940 | 16,808 | 16,808 | 16,808 | 16,808 | 16,808 | 16,808 |
| 8.Coke, refined petroleum and nuclear fuel | 2,514 | 2,766 | 32,863 | 10,619 | 10,619 | 10,619 | 10,619 | 10,619 | 10,619 |
| 9.Chemicals | 27,663 | 28,003 | 176,599 | 20,317 | 20,317 | 20,317 | 20,317 | 20,317 | 20,317 |
| 10.Rubber and plastics | 11,104 | 12,960 | 77,585 | 15,814 | 15,814 | 15,814 | 15,814 | 15,814 | 15,814 |
| 11.Other non-metallic mineral | 11,365 | 10,137 | 62,747 | 15,676 | 15,676 | 15,676 | 15,676 | 15,676 | 15,676 |
| 12.Basic and fabricated metals | 38,014 | 50,902 | 269,556 | 4,533 | 4,533 | 4,533 | 4,533 | 4,533 | 4,533 |
| 13.Machinery | 13,991 | 15,161 | 179,419 | 783 | 783 | 783 | 783 | 783 | 783 |
| 14.Electrical and optical equipment | 78,827 | 78,749 | 167,962 | 4,490 | 4,490 | 4,490 | 4,490 | 4,490 | 4,490 |
| 15.Transport equipment | 10,356 | 10,682 | 92,855 | 879 | 879 | 879 | 879 | 879 | 879 |
| 16.Manufacturing, nec; recycling | 1,179 | 869 | 66,554 | 1,390 | 1,390 | 1,390 | 1,390 | 1,390 | 1,390 |
| 17.Electricity, gas and water supply | 95,174 | 43,137 | 439,778 | 11,344 | 11,344 | 11,344 | 11,344 | 11,344 | 11,344 |
| 18.Construction | 0 | 4,694 | 9,996 | 412 | 412 | 412 | 412 | 412 | 412 |
| 19.Sale, maintenance and repair of motor vehicles and motorcycles | 0 | 0 | 0 | 189 | 189 | 189 | 189 | 189 | 189 |
| 20.Wholesale trade and commission trade, | 0 | 7,477 | 25,321 | 1,006 | 1,006 | 1,006 | 1,006 | 1,006 | 1,006 |
| 21.Retail trade | 303 | 41 | 7,239 | 1,167 | 1,167 | 1,167 | 1,167 | 1,167 | 1,167 |
| 22.Hotels and restaurants | 0 | 2,740 | 9,183 | 387 | 387 | 387 | 387 | 387 | 387 |
| 23.Inland transport | 637 | 5,743 | 25,367 | 992 | 992 | 992 | 992 | 992 | 992 |
| 24.Water transport | 0 | 10,536 | 59,917 | 10,400 | 10,400 | 10,400 | 10,400 | 10,400 | 10,400 |
| 25.Air transport | 12,570 | 7,392 | 23,802 | 8,738 | 8,738 | 8,738 | 8,738 | 8,738 | 8,738 |
| 26.Other supporting and auxiliary transport | 0 | 3,866 | 2,122 | 938 | 938 | 938 | 938 | 938 | 938 |
| 27.Post and telecommunications | 0 | 2,499 | 3,334 | 420 | 420 | 420 | 420 | 420 | 420 |
| 28.Financial intermediation | 79 | 84 | 374 | 507 | 507 | 507 | 507 | 507 | 507 |
| 29.Real estate activities | 0 | 0 | 0 | 87 | 87 | 87 | 87 | 87 | 87 |
| 30.Renting of machinery and equipment | 29,363 | 8,490 | 12,732 | 3,296 | 3,296 | 3,296 | 3,296 | 3,296 | 3,296 |
| 31.Public administration and defense | 0 | 3 | 563 | 212 | 212 | 212 | 212 | 212 | 212 |
| 32.Education | 1 | 7 | 389 | 3,525 | 3,525 | 3,525 | 3,525 | 3,525 | 3,525 |
| 33.Health and social work | 390 | 4,845 | 34,096 | 2,249 | 2,249 | 2,249 | 2,249 | 2,249 | 2,249 |
| 34.Other community, social and personal services | 84 | 6,401 | 4,498 | 2,669 | 2,669 | 2,669 | 2,669 | 2,669 | 2,669 |
| Aggregated emissions by component | 311,939 | 336,120 | 1,577,019 | 61,063 | 80,198 | 647,782 | 38,890 | 42,574 | 190,214 |
| | | 2,225,078 | | | 789,043 | | | 271,678 | |

# CHAPTER 5: CONCLUSIONS

With globalization, there has been a rapid growth in international trade which has led to a widespread perception of increasing $CO_2$ embodied emissions within imports and exports. Globalization of modern trade has resulted in increased fragmentation of produced goods and services, such that production of goods and services often takes place at multiple locations around the globe. Links between embodied emissions as part of carbon transfers and international production fragmentation induced intermediate imports have rarely been addressed in the literature. Ignoring these connections leads to a misleading view of how to achieve worldwide $CO_2$ mitigation efforts. This dissertation sets out to quantify current carbon transfers and their linkages to worldwide mitigation policies. In addition, the consequences of various emission allocation systems is examined. Thus, these are fundamental themes throughout all three essays. This final chapter will present the research contributions of each essay, conclude the main findings, and discuss the directions for the future research.

The main research contributions of the first essay (Chapter 2) are:

- A new method for setting of consumption factors for LMDI II model; and
- Attribution technique of LMDI II to investigate the contributions of industrial sectors behind dynamic changes in PBE and CBE emissions.

Despite a sizable literature regarding LMDI decomposition for analyzing key factors behind energy consumption and GHG emission changes, existing studies have paid less attention to the contributions from changes in CBE emissions. According to a theory of fragmentation trade, increasing international trade has created networks of production that have repercussions on global emissions and can affect domestic emissions. Ignoring these connections can lead to a misleading picture of key contributors to $CO_2$ emissions.

In this respect, this essay included consumption factors as well as basic production factors in order to examine the effects of import demand on dynamic changes in both PBE and CBE emissions. It is important to note that computation of CBE emissions focuses on embodied $CO_2$ emissions in imports. The results of the U.S. economy confirmed that the decrease in U.S. PBE emissions could be partially explained by an increase in CBE emissions in terms of emissions embodied in imports.

The important policy strategies recommended in this essay are that: (1) climate policies that deal with U.S. embodied emissions should grow out of voluntary national reductions addressed as a goal of U.S. INDC because of the increasing importance of a structural effect where domestically produced inputs are replaced by intermediate imports; and (2) emission responsibility shared between trading partners could be established by a process international trade rather than by a focus on low-carbon and energy technology transfers. This is relevant because the structure effect surpassed the effects of emission coefficients and energy intensity to become the second largest contributor to increased imported emissions since 2004. In addition, U.S. import demand has been moving towards not only intermediate imports but also carbon intensive imports. However, an important challenge towards sharing emission responsibilities between importing and exporting economies is what weighting procedure should be designed. This is discussed further in essay two.

In essay one, an attribution technique of LMDI proposed by Choi and Ang (2012) was used to analyze the contributions of four industrial sectors. This technique led to an improved understanding of contributing factors and the structure of carbon transfers regarding emission performances of four sectors across the U.S. and its trading partners. There are several findings at the industrial sector level that can lead to a number of policy strategy recommendations. For example, the increase in emission coefficient effects of the foreign primary and secondary sectors contributed a rise in energy intensity effects on embodied emissions, but the reverse impact (energy intensity increases leading to emission coefficient increases) was not observed. In this essay, an enhancement of energy conversation in the primary and secondary sectors alone would not contribute significant reductions in U.S. embodied emissions. In turn, improvements in energy intensities of the U.S. primary and secondary sectors remain an important issue for the future of U.S. PBE reductions. These attribution results also pointed out that decreases in U.S. PBE would be limited by benefits from natural gas use regarding the emission coefficient effect.

The main contributions of the second essay (Chapter 3) are:

- A weighting procedure for establishing shares of the $CO_2$ emissions allocation; and
- Computation of three distinct emission burdens when examining industrial mitigation efforts and the consequence of emission allocations.

Global production fragmentation significantly affects the allocation of emissions embodied in international trade. Thus, differences between PBE and CBE increasingly produce the need for uneven policy actions in order to target emission reductions between exporting and importing economies. These differences may impact mitigation efforts across economies given the current level of carbon transfers. The SE allocation is an alternative distinct from the PBE and CBE allocations. The challenge facing the application of this allocation is how to define a weighting procedure. The weighting procedure proposed in this essay (see equation 3.13) complements a framework by Peters (2008) with the application of multilateral border tax adjustments. Value added in embodied emissions is derived from effective carbon tariffs calculated based upon the EE-MRIO and the use of value-added exports (VAX) by Johnson and Noguera (2012). Further, this weighting element can be represented by a quotient of value added on emissions embodied in exports.

Essay two proposed three aspects of emission burdens to examine industrial mitigation efforts and the consequence of emission allocations. The three aspects of emission burdens are: an industrial role change, industrial international trade change, and import content change. The main findings showed that the CBE of ten U.S. industries (agriculture, paper, chemicals, rubber and plastics, basic metals, transport equipment, water transport service, post telecommunications, health services, and renting of machinery and equipment) had discrepancies of 40% greater when comparing PBE and CBE for each of the three aspects. Five of them (paper, chemicals, rubber and plastics, transport equipment, and water transport service) were stronger in emission burdens on import content changes than those on international trade changes. This implies that a large proportion of imports are used to meet final demand. A CBE allocation would put these five industries at a major competitive disadvantage.

An adoption of the HCE allocation does not help solve this problem. This essay found that the HCE allocation reduces emission burdens on international trade changes if there exists growth in final imports, at least growth faster than those of intermediate imports. In turn, the SE allocation shows slight improvements to a competitive advantage of those industries. It declines emission burdens on both industrial international trade changes and changes in industrial import content to the five industries.

This essay explored that the composition of intermediate import to determine reductions in emission burdens with industrial international trade changes. The links between proportion of imports and the products exported are computed to document reductions in emission burdens due to industrial role changes. In light of global emissions as part of the fragmentation of international production, the SE allocation becomes more effective and even equitable than the HCE allocation. This judgment is made due to large declines in both aspects of emission burdens with the SE allocation due to high possibilities to encourage the commitment of importers that benefit from international trade to be involved the process of carbon transfer reductions. However, despite analyses of the consequences of four allocation approaches and examination of their advantages and disadvantages, there remains a need to create a balance between an appropriate emission allocation and a maintenance of international trade activities.

With the results of the first two essays, the main contributions of the third essay (Chapter 4) are:

- Proposing a method to compute production-demand elasticities for examining the strength of inter-industrial forward and backward relationships within trade structures and embodied emissions; and
- Using the production-demand elasticities to identify key industries for exported and imported emissions in order to assess climate policies impacts on emission reductions and trade activity losses.

Previous studies have used key industry analysis in production emissions within an economy. Departing from a single set of economic structure, an identification of key industries in embodied emissions requires demand-driven with a hierarchy of backward and forward linkages. To investigate key industries in embodied emissions, I used a simplified analysis by employing two assumptions: (1) no series expansions of backward and forward linkages (no higher order backward and forward linkages were considered in this essay); and (2) no internal multiplier effect (no backward and forward linkages impact embodied emissions with imported products from third parties).

In this third essay, the hierarchy of backward and forward linkages is calculated based on Rasmussen (1956) and terms key industries with production-demand elasticity introduced by Alcántara and Padila (2006). Further, Carvolho et al. (2013) demonstrated that the weighting structure for production-demand elasticity can be divided into each category of demand. In this sense, I apply a basic assumption of WIOD (the mirror flow) to the calculation of production-demand elasticity distinct between exported and imported emissions expressed as equations 4.12-4.14. This distinction leads to an improved understanding of key industries in the structure of carbon transfers in light of the fragmentation of international production. The main results for U.S. key industries pointed out that there is a gap of industrial policy designs between key industries in exported and imported emissions. For example, industrial coverage in reference to the U.S. INDC (exported emissions) should not have limited to category 1 industries, but also should involve category 3 industries. This is relevant because industries classified as category 3 under exported emissions are classified as category 1 industries for imported emissions. However, a gap of industrial coverage between exported and imported emissions is not an important issue in the Chinese economy because key industries in exported were covered by those in imported emissions.

The outcomes of key industries classification are used to evaluate the practical applications of climate policies. Due to the importance of carbon transfers, this essay considers three policy alternatives: an emission standard for the utility industry (P1); a unilateral border tax adjustment (P2); and a multilateral border tax adjustment (P3). The results show that a P1 policy will contribute a remarkable reduction in exported emissions, but would have a big effect on trade activity losses occurring within industries that have a high demand for utility products. The findings of a P2 policy indicate that there is a limited effect on emission reductions, but a strong effect on import activity losses because industries projected reductions are relevant not only to high carbon intensive industries, but also to category 2 and 3 industries. However, a large proportion of reductions occurs in category 3 industries. A P3 policy contributes large emission reductions, but has a limited effect on trade activity losses as the forward and backward linkage effects occur mainly within the key industries of category 1.

At the Paris climate conference in 2015, the participating 196 economies agreed on a global pact to reduce $CO_2$ emissions based on their PBEs as soon as possible. National governments submitted broad-based climate action plans, so-called INDCs, before the conference. These INDCs do not yet produce enough GHG reductions to keep the global average temperature increase below two degrees Celsius (Levin and Fransen, 2015). The final version of the Paris Agreement has not ever scaled up the mitigation efforts and support actions beyond the INDCs (Europa, 2016). To close the gap, the SE allocation can provide complement policies for enhancing global mitigation efforts. The discussions in this dissertation do not argue to use the SE allocation as the sole in climate policies for the U.S., China, and EU15 economies. However, until the goal of INDCs is achieved, the SE allocation can pave the way for a steady transition towards a low carbon future, at least in the middle term.

This dissertation provides an improved understanding of the structure of carbon transfers and the role of carbon transfers in affecting mitigation efforts across major economies: the U.S., China, and the EU15. It has several limitations which suggest directions for the future research. I classify these suggestions into two groups: (1) model modifications; and (2) data quality.

The following list is a guide to model modifications.

- ***Factor substitution for analyzing the effect of pricing carbon***. An input-output framework to analyze the effect of price changes captures an output effect, but usually ignores the possibility of factor substitution. Generally, the primary cost of pricing carbon consists of two economic consequences: (1) an output effect; and (2) a substitution effect. The output effect occurs where changes in energy price reduce the monetary value of economy’s output due to decline in industrial profits. The substitution effect occurs when capital and labor substitutes for energy input due to relative prices of energy changes. In this way, a change in relative prices of input factors also affects the monetary value of economy’s output due to consumer wage and industrial profit. Ignoring the substitution effect causes a misleading view of the consequence of carbon prices.
- ***The internal and external multiplier effects for the hierarchy of backward and forward linkages***. The hierarchy framework introduced in this dissertation centered on the external multiplier effect. The internal multiplier effect would become important if there is a possibility of factor substitutions across economies. However, this dissertation utilizes the Armington assumption to hold relative production technologies constant across economies.
- ***Cost efficiency of policy alternatives***. This dissertation examined the effectiveness of three policy alternative in response to tradeoff between emission reductions and trade activity losses.

However, the costs of achieving these reductions were not computed so questions about cost efficiency of these policies remain.

The following list is a guide to data quality.

- ***More detail industries***. The data set used in this dissertation were presented 34 industries. A greater disaggregation of industries to increase the number of sub-industrial sectors would provide more in-depth policy strategies for dealing with carbon transfers as part of the fragmentation of international production.
- ***More recent year of tax rates***. Carbon tax rates used to calculate effective carbon tariff were for 2004 and 2010. The social cost of carbon used to estimate carbon taxes must be updated to the most recent year.
- ***Database of trade in value added***. This database is required in the work of structural decomposition analysis regarding the fragmentation of international production induced by intermediate imports across economies at multiple times. This database will also extend to key industry analysis in relation to the supply-driven multiplier approach. The findings of the third essay will be complemented if a future study of the determination of key industries in exported and imported emissions are associated with supply-driven multipliers.

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