Three Papers on Input-Ouput Energy and Environmental Accounting

by

Sonya Huang

Bachelor of Science
Massachusetts Institute of Technology
Cambridge, Massachusetts (2005)

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Author____
Department of Urban Studies and Planning
Oct 11, 2012

Certified by____
Professor Karen R. Polenske
Department of Urban Studies and Planning
Dissertation Supervisor

Accepted by____
Professor JoAnn Carmin
Chair, PhD Committee
Department of Urban Studies and Planning

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ABSTRACT

The input-output model, a framework for national accounting and economic modeling, has been popular among regional economists for studying energy and emissions due to its focus on interindustry linkages. In a series of three papers, we apply the input-output model to three different aspects of fossil-fuel energy consumption and carbon dioxide emissions, using two temporally extensive datasets.

In the first paper, we construct detailed energy and emissions accounts of the United States from 1972 to 2002, and analyze the resulting time series from perspectives of household consumption and industrial production. The resulting accounts suggest that despite an overall decrease in energy intensity over the study period, the decrease was uneven across industry sectors and consumption goods, especially between manufacturing and services.

In the second paper, we perform a structural decomposition of CO_2 emissions growth in 36 countries over the years 1995-2009, using a newly published dataset. We compare the relative contributions to emissions growth from industrial efficiency improvements, interindustry linkage structure, and final demand levels and composition. We find that industrial efficiency and final demand predictably work against each other, but which effect dominates depends on geographic region. Analysis of specific energy-intensive industries sheds more light on the reasons for the geographic variation in emissions growth.

In the third paper, we focus on embodied CO_2 emissions in trade, using the same dataset as the second paper. Predictably, countries in the European Union tend to import more embodied emissions than they export, while large developing countries such as China, Russia, and India export more than they import. However, we find more nuanced trends in resource-rich developed countries including the United States, Canada, Mexico, and Australia. In particular, the United States became a net exporter of embodied CO_2 emissions only recently, which may mean that the relevance of the topic of emissions abatement responsibility to the United States has shifted in recent years.

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Chapter i

Introduction

Energy consumption and the emission of environmentally harmful substances – often the byproducts of fossil fuel consumption, are two key factors in determining the sustainability of living standards across the world. Recent scholarship has suggested that the world is headed in a direction of irreversible (by modern technology) climate change, which is inextricably linked to greenhouse gases emitted by human activity such as industrial processes and transportation. Slowing down the damage requires thorough accounting of the processes that lead to greenhouse gas accumulation on a global level.

To deal with the need for energy and emissions accounting, standards including the System of Environmental-Economic Accounts (SEEA) and National Accounting Matrix including Environmental Accounts (NAMEA) were developed to accompany the existing System of National Accounts (SNA) implemented by many countries. These standards intend to document, on an industry-by-industry basis, the environmental side effects of the economy including energy consumption, greenhouse gas (GHG) emissions, and other variables.

The SNA standard centers on the input-output framework designed by Leontief, which documents the dollar transactions between each pair of industries. The Leontief matrix derived from the table of industrial transactions, by chaining the transactions at each input stage, provides a proxy for life cycle analysis of each industry. When combined with emissions or energy consumption, the input-output framework becomes a very powerful way to decompose energy use and emissions along sector lines that are often used in trade and policy discussions.

Adoption and implementation of the SEEA and NAMEA standards vary widely across countries and thus their datasets are very hard to compare. In existing literature on hybrid I-O models, the leading complaints have been the lack of comparable data across years or geographies (especially sector definitions), and the aggregation of industry sectors – grouping smaller industries with very different input compositions has a drastic effect on the results concerning all sectors due to the linked nature of the I-O model.

In the spring of 2012 the World Input-Output Database (WIOD), a project funded by the European Commission, was released to the public. The WIOD is a NAMEA-compatible database that includes 40 countries (27 OECD and 13 non-OECD countries) in addition to the inter-country supply and use of commodities between them [Erumban et al., 2012]. Additionally, some countries including the United States have detailed input-output tables that can be linked with past detailed energy consumption statistics.

In the three papers in this series, we analyze the aforementioned datasets to explain energy consumption and CO_2 emissions by industry activity over the past few decades, with an emphasis on embodied energy and emissions in industrial products.

In Chapter 1, we combine U.S. benchmark supply and use tables with energy consumption data to create hybrid tables of energy consumption. Until recently the world's largest producer of emissions (see table i.1), in addition to having a large repository of historical data, the United States provides an informative case study of technological progress in energy and emissions efficiency. While the U.S. government does not currently publish NAMEA-compatible tables of energy use and emissions, the available data allows users to construct such satellite tables with certain assumptions. In addition to estimating emissions by sector from underlying data, in this paper we examine embodied energy of consumer goods and direct emissions in industry production.

Table i.1: CO_2 emissions, historical and projected, by selected world region (Million metric tons CO_2)

Region	2005	2006	2010	2012	2015	2020
OECD	13,651	13,606	12,861	12,929	13,031	13,252
OECD Americas	7,079	7,014	6,693	6,704	6,773	6,924
OECD Europe	4,400	4,428	4,094	4,115	4,115	4,147
OECD Asia	2,172	2,165	2,074	2,110	2,143	2,181
Non-OECD	14,530	15,152	18,445	19,184	20,426	21,958
United States	5,996	5,918	5,644	5,622	5,680	5,777
China	5,513	5,817	8,262	8,598	9,386	10,128

[a] Data source: U.S. Energy Information Administration

In Chapter 2, we take advantage of the time-invariant industry sector classification in the WIOD to conduct a structural decomposition analysis. In particular, we use the combination of industry linkage tables, final demand, and satellite environmental accounts throughout this series to estimate average per-sector environmental damages. Holding two of the three components fixed while varying the third over time can produce different hypothetical counterfactual time series of environmental damages. For most countries, changes in per-sector intensity explain the majority of variation in overall emissions intensity, with the variation being a general decrease in emissions intesity. However, a small number of countries have changes in the mix of final demand and/or changes in industry linkage structure that offset the decrease in per-sector intensity.

In Chapter 3, we examine trade between countries and the impact on other countries' emissions due to embodied emissions in imported goods. Due to the increasing trade in all countries, embodied emissions in traded products and possible avenues for reducing it has gained attention of analysts over the past decade. However, being able to calculate embodied emissions for imported products requires data from environmental accounts of the source country of imports, which until very recently were not widely available. In this paper, we examine trade balances in terms of embodied CO_2 in traded goods using the new WIOD data, and the results reveal how much we may be underestimating embodied emissions by assuming U.S. imports are produced using the same technology as domestic products.

i.1 Input-output framework basics

In all three papers in this series, we use the input-output framework to analyze total energy consumption and emissions by economic sectors, which is briefly reviewed here. The input-output framework models an open economy as follows:

All goods and services (which we call "goods" for brevity) are produced and consumed by a finite number of industry sectors (some implementations use commodity sectors instead). Each industry produces a certain good, which is its output, and to do so it must also consume a certain mix of goods and services, called *intermediate inputs*. Let $z_{i,j}$ be the amount of good i used by industry j in order to produce good j. Let Z be the transactions matrix, i.e., the result of entering all combinations of $z_{i,j}$ into a matrix whose rows and columns are the list of all industries involved in these exchanges.

All goods are also consumed by consuming sectors that do not produce; these sectors are called "final demand". Let $\mathbf{y}$ be the column vector of goods purchased by a sector of final demand. Usually there are several final demand sectors including households, government, capital investment, inventory changes, exports, and imports.

Sectors that contribute to goods production but do not consume goods in the process are known as "value added". Let this be the row vector $\mathbf{v}$.

The economy expressed in these simple components is as follows:

$$\begin{bmatrix} Z & \mathbf{y} \\ \mathbf{v} & \end{bmatrix}$$

The total output x_j of each industry j is the sum of sales to other industries plus the sum of sales to final demand. Because the economy is balanced (each industry produces as much as it consumes), the total output of each industry is also equal to the total consumption of intermediate inputs and value added. This may be expressed as

$$x_i = \sum_j z_{i,j} + y_j = \sum_i z_{i,j} + v_i \tag{i.1}$$

The above information allows us to calculate the *technical coefficient* $a_{i,j}$, or the average amount of intermediate input i required to produce each unit (usually a dollar) of output for industry j. This may be expressed as

$$a_{i,j} = \frac{z_{i,j}}{x_j} \tag{i.2}$$

or

$$A = Zdiag(\mathbf{x})^{-1}$$

The matrix A expresses the input-output technology of the economy and is also known as the *direct input requirements* matrix. Equations i.1 and i.2 can be combined into the following expression, which says that total output is the sum of final demand and intermediate inputs, which are proportional to the output produced.

$$\mathbf{x} = A\mathbf{x} + \mathbf{y} \tag{i.3}$$

Equation i.3 can be rewritten as:

$$\mathbf{x} = (I - A)^{-1}\mathbf{y} \tag{i.4}$$

$(I - A)^{-1}$, or L, which is known as the *Leontief inverse*, expresses total output as a linear combination of final demand. This matrix is also known as the *total requirements* matrix, in contrast to the direct requirements matrix. Total requirements is the sum of direct and indirect inputs, where indirect inputs are intermediate inputs requred to produce intermediate inputs to the final product, and so forth. Another way to see this is that $(I - A)^{-1}$ is the result of raising A to the infinite power. We often use the language "direct and indirect" to refer to results calculated from multiplying the Leontief inverse to a subset of final demand.

This expression is especially useful in applications to energy and environmental accounting because the same identities hold when dollar units of x are substituted with physical units such as Joules and tons. Furthermore, while total sales of all industries combined is not economically meaningful due to double-counting, energy consumption and emissions are one-way transactions and thus the concept of total output is meaningful.

i.2 Source code and additional data

Source code and selected results used for all analyses in these papers is included with the enclosed CD. At the time of this writing, the most updated code and data are available at the following URL: `https://github.com/sonya/eea`

Chapter 1

Embodied Energy and Emissions in U.S. Goods and Services

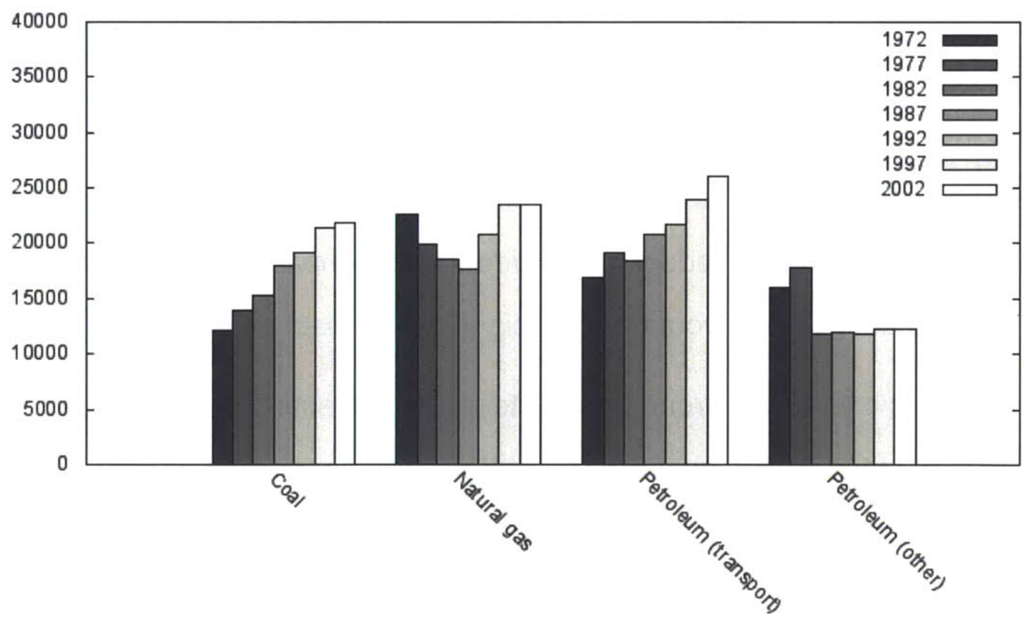
1.1 Introduction

Until 2006, the United States was the largest producer of CO_2 emissions worldwide, accounting for roughly 20% of total CO_2 emissions, based on a quick calculation from data on the U.N. Millennium Development Indicators [United Nations Statistics Division, 2012]. Yet a far more important statistic that is less apparent from public-oriented data sources like the United Nations is the consumption of embodied CO_2 emissions, in which the United States remains the largest. Understanding the components of embodied emissions and finding ways to reduce the environmental impact of consumption decisions in the United States would have a significant impact on world emissions.

At the most basic level, two trends characterize the trajectory of energy use and emissions in the United States over the last half century: increasing energy consumption (and until a few years ago, emissions) over time, but decreasing energy and emissions intensity over time (see Figures 1.1 and 1.2). We define energy and emissions intensity as energy consumed and emissions generated per dollar of GDP. These same trends are seen in countries all over the world as well as within the population: households with higher incomes consume more energy but less energy per dollar [Herendeen et al., 1981]. The trend of increasing emissions in the United States appears to have reversed in the last few years [U.S. Energy Information Administration, 2012], although given the variety of energy sources, decreasing emissions does not necessarily imply decreasing energy use.

Increasing energy use can be intuitively explained by the natural requirements of an increasing population, and higher purchasing power due to growing GDP. Decreasing energy intensity over time, however, has a number of possible explanations. An optimistic explanation, which is in fact a large reason for the decline, is technological progress making industries more energy efficient [Sue Wing, 2008]. A pessimistic explanation is that energy used to create the goods we consume, and emissions generated from the production process, are taking place outside of the United States. Determining the extent of both these explanations requires analysis of embodied emissions in products.

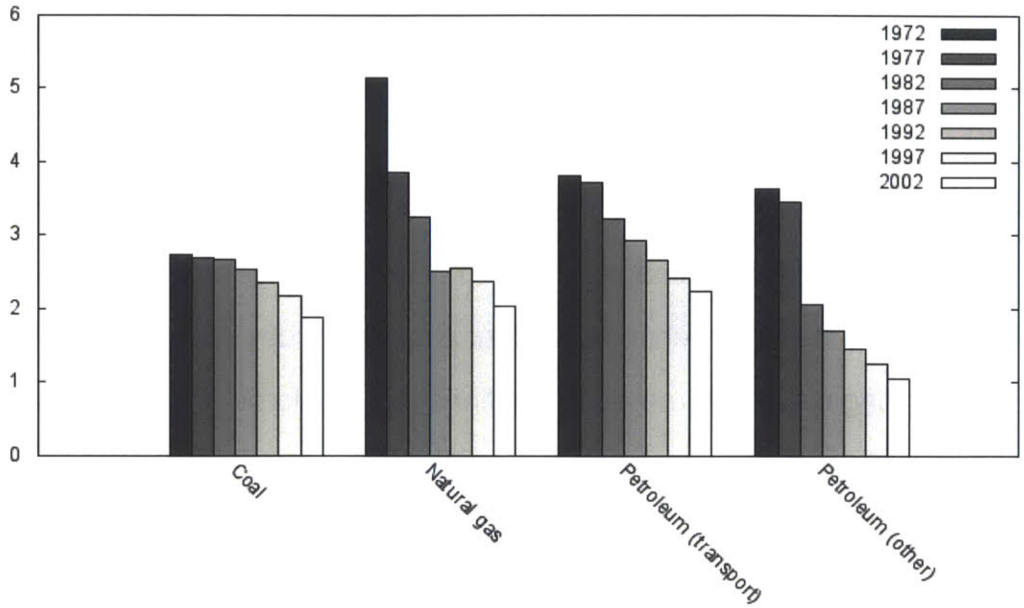
Figure 1.1: Total consumption of fossil fuels in the United States by energy source, trillion Btu, 1972-2002



[a] Fossil fuels accounted for 86% of total energy consumption in the United States in 2002, down from 93% in 1972. This percentage has continued to decrease through 2010. The remaining energy is supplied by nuclear power and renewables including (from most to least): hydropower, wood and waste, wind, and solar.
Data source: Energy Information Administration

For many years the United States has published detailed and well-documented data

Figure 1.2: U.S. Fossil Fuel Intensity, Btu per 2005 chained dollar of GDP, 1972-2002



Data source: Bureau of Economic Analysis, Energy Information Administration

sets on industry activity, energy use, and environmental emissions. However, official satellite tables that tabulate energy use and emissions by industry sector, as specified by the National Accounting Matrix including Environmental Accounts (NAMEA), do not exist for the United States. Researchers attempting to conduct cross-country analyses of energy and emissions involving the United States., or within the United States at a certain level of detail, are always required to estimate their own satellite tables, resulting in a lot of duplicated work that is not easily shared, and sometimes proprietary.

In this paper, we use input-output and energy consumption data to estimate energy use and emissions by commodity (products of U.S. industries) from 1972 to 2002. Full data tables of the resulting estimates are included with the software enclosed with this paper. We highlight results relevant to technological progress within sectors of the economy and the extent to which the results are complicated by offshoring.

1.2 Related work

1.2.1 U.S. environmental accounting

The U.S. government does not yet produce per-industry or per-commodity accounts of energy use and environmental damages that can be easily linked to economic data such as input-output accounts. However, independent attempts to construct such satellite tables from underlying data, or to answer questions that would be answered with satellite tables, are abundant.

Government agencies do produce some relevant but limited data sets. For instance, the Energy Information Administration (EIA) since 1985 has been collecting energy consumption data directly from manufacturing industries from the Manufacturing Energy Consumption Survey (MECS). Survey results are published every four years and have been incorporated into studies that attempt to estimate emissions from fuel combustion such as U.S. Department of Commerce, Economics and Statistics Administration [2010].

The Comprehensive Environmental Data Archive (CEDA) database is one of the most comprehensive environmental databases linked to commodities produced in the United States, covering over a thousand environmental interventions and nearly 500 product categories. The database is created from input-output tables from the Bureau of Economic Analysis (BEA), environment and emissions data from multiple public sources, and application of life cycle impact analysis [Suh, 2005]. While comprehensive, the proprietary data produced from laborious compilation and modeling do not include a time component, which limits their ability to shed light on the technological change associated with the environmental impact of U.S. industrial activity.

Weber [2009] compile energy and environmental data from the EIA in addition to separate sources for each of nine major sectors (government, services, trade and transportation, energy manufacturing, non-energy manufacturing, utilities and construction, electricity, raw materials, and agriculture). Their procedure includes allocating energy use among major sectors, then allocating individual industries' energy use based on the applicable data set. Energy consumption figures using this method should be trustworthy as this method takes advantage of the deeper knowledge of each major sector used to compile each separate dataset. However, a simpler and less labor-intensive method to get energy consumption by sector using only EIA takes advantage of the energy prices available in EIA data and dollar consumption data available in benchmark I-O accounts. This latter method was used by Bullard and Herendeen [1975], Bullard III and Herendeen [1975], Herendeen [1973], Herendeen et al. [1981], Canning et al. [2010] and is also the choice of method in this paper, primarily due to the availability of longitudinal data extending as far back as the mid 1900s.

Finally, the World Input-Output Database, whose environmental accounts were released to the public in May 2012, includes emissions of several GHG types by 35 industry sectors from the years 1995-2009. There is not yet any public documentation of the data sources used to construct each country's accounts, but this paper and the WIOD presumably have multiple U.S. data sources in common.

1.2.2 Explanations of U.S. energy and emissions trends

Results computed from the creation of satellite energy and environmental accounts are often then decomposed along lines of final demand and industries to compare the energy requirements of different household types [Herendeen et al., 1981], energy requirements over time of major economic sectors [Weber, 2009], or particular products [Canning et al., 2010].

The literature on U.S. emissions has been mixed in regard to the role of trade. U.S. Department of Commerce, Economics and Statistics Administration [2010] found that embodied emissions associated with imported goods in 1998 and 2006 accounted for 6% and 7% respectively of total U.S. emissions, concluding that imports only represent a "small fraction" and omitting trade from the chief findings in the report. In contrast, [Weber and Matthews, 2008] found that up to 30% of CO_2 embodied in household consumption was emitted overseas, and estimates that fail to account for differences in international production structure could underestimate consumption-based emissions by as much as 15%. One problem with the Department of Commerce study is the application of domestic technological assumptions to imports, as importing goods from less energy-efficient countries causes more emissions than the alternative where the same goods are produced domestically.

The United States has exhibited declining energy intensity for all years with available data, the reason being technological progress for the most part and only a small part due to the cost of energy inputs [Sue Wing, 2008], suggesting that the energy efficiency of imports could improve if other countries also experienced similar technological progress. Guo et al. [2010] found that imports to the United States from China in 2005 allowed the United States to prevent 193 metric tons of domestic CO_2 emissions, but causing 525 metric tons to be produced in China instead. Du et al. [2011] believe that policies limiting CO_2 production in the United States encourage activities that lead to carbon leakage, i.e., the emission of carbon in less regulated locations to prevent emissions in regulated locations. The literature on input-output environmental analysis has increasingly recommended studying environmental impacts of the economy from both perspectives of consumption and production, as consumption includes imports and (in general) excludes exports, while production does the opposite [Peters and Hertwich, 2006].

Although the United States, like most developed countries, has become more energy-efficient overall and in most industry sectors over time, some parts of the economy have not conformed to this trend and may be slowing overall progress towards energy reduction. Canning et al. [2010] found that energy requirements of the food sector had increased as a percentage of total energy use from 1997 to 2002; in the process of this research, which was not described in the report, we found that the majority of food commodities (agricultural products and manufactured foods) had increased in energy requirements per dollar of production, contrary to the rest of the economy.

Studies over the long term of energy and environmental impacts by industry and final demand sectors are available for many countries [Kander and Lindmark, 2006, Chang et al., 2008], but similar studies for the United States following Costanza and Herendeen [1984] have been rare. Given the difficulties in obtaining accurate environmental data by industry, comparing sectors over the long term provides a more complete view in deciding whether changes in a certain period are permanent or transitory. In this paper, we examine U.S. energy use by commodities at the finest possible level of detail over a span of 30 years; the public source code provided with this study can be used to generate the satellite tables of energy use and emissions estimates referenced here, as well as extended to additional years of data when they become available.

1.3 Methodology

Data All results in this paper are calculated from publicly available data published by the Bureau of Economic Analysis (BEA) and Energy Information Administration (EIA).

The data sets from the BEA are the Benchmark Input-Output tables from 1972, 1977, 1982, 1987, 1992, 1997, and 2002; and the Personal Consumption Expenditures (PCE) bridge tables associated with each of these years. The data from the EIA are the annual price and consumption tables from the State Energy Data System (SEDS). We only use the series corresponding to the entire United States.

Energy Satellite Tables We use a variation of Bullard III and Herendeen [1975] to construct a hybrid, commodity-by-commodity input-output table where all rows corresponding to energy commodities tracked by EIA data – coal, electricity, natural gas, and petroleum – are replaced with physical amounts in Btu. All commodities are manually assigned into one of five sectors that the EIA distinguishes: industry, commercial, residential, power generation, and transportation. The total amount of each fuel consumed is then allocated to each commodity in proportion to the dollar value of fuels required to produce each commodity, stratified by EIA sector.

Directly allocating petroleum use to the commodities using the procedure described above misrepresents the role of transportation in energy consumption. This is because motor gasoline, which EIA data records as being entirely used for transportation, is purchased as a direct input by industrial, commercial, and residential sectors; allocating all motor gasoline consumption to transportation commodities understates the role of private automobile transportation that is not captured in the NAICS commodity classification. Thus, in our hybrid table we manually split petroleum into two types: transportation-related and non-transportation-related. When petroleum products are clearly associated with a NAICS commodity, we allocate them directly (for example, we allocate all of jet fuel and aviation gas to the air transportation commodity), while we allocate the remaining petroleum products with primarily transportation uses (e.g. motor gasoline) to the industrial, commercial, and residential sectors. We then use dollar amounts spent on petroleum by these sectors to allocate the remaining non-transportation-related petroleum products.

We calculate energy use by personal consumption categories by creating final demand vectors for each consumption category from PCE bridge tables, and multiplying them by our hybrid Leontief matrix.

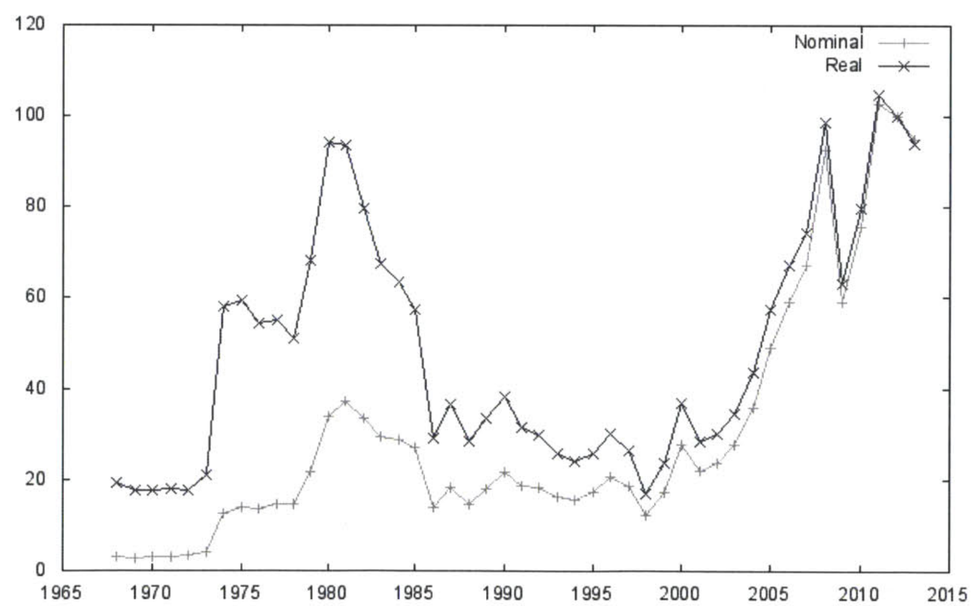
Emissions Satellite Tables Our emissions tables focus only on CO_2 generated via fuel combustion. We simply multiply each sector's petroleum, coal, and natural gas consumption by the associated emissions factors published by EIA. Emissions due to electricity generation are not included. This obviously ignores overall emissions reduction efficiency and thus should be seen as an overstatement of actual emissions.

More specific details about our account construction and calculations are included in the Appendix to this chapter.

1.4 Results and discussion

Because the results cannot be discussed without considering oil price fluctuations, we begin by reproducing a graph from EIA in Figure 1.3, which shows the rapid increase in oil prices beginning in 1973, peaking in 1981, and rapidly falling to a relatively stable price between 1986 and 2003. Oil prices are key to a number of results presented in the following tables.

Figure 1.3: U.S. historical crude oil import prices, current and real (1982-84 chained) dollars



Data source: Energy Information Administration

1.4.1 Embodied Energy in Consumer Good Categories

Table 1.1 shows the amount of energy from fossil fuel combustion that is caused directly or indirectly by consumer purchases. The consumption categories are defined in the BEA's National Income and Product Accounts, and unlike industry sector definitions, are comparable across years. Figure 1.4 displays fossil fuel energy consumption levels relative to levels in 1972.

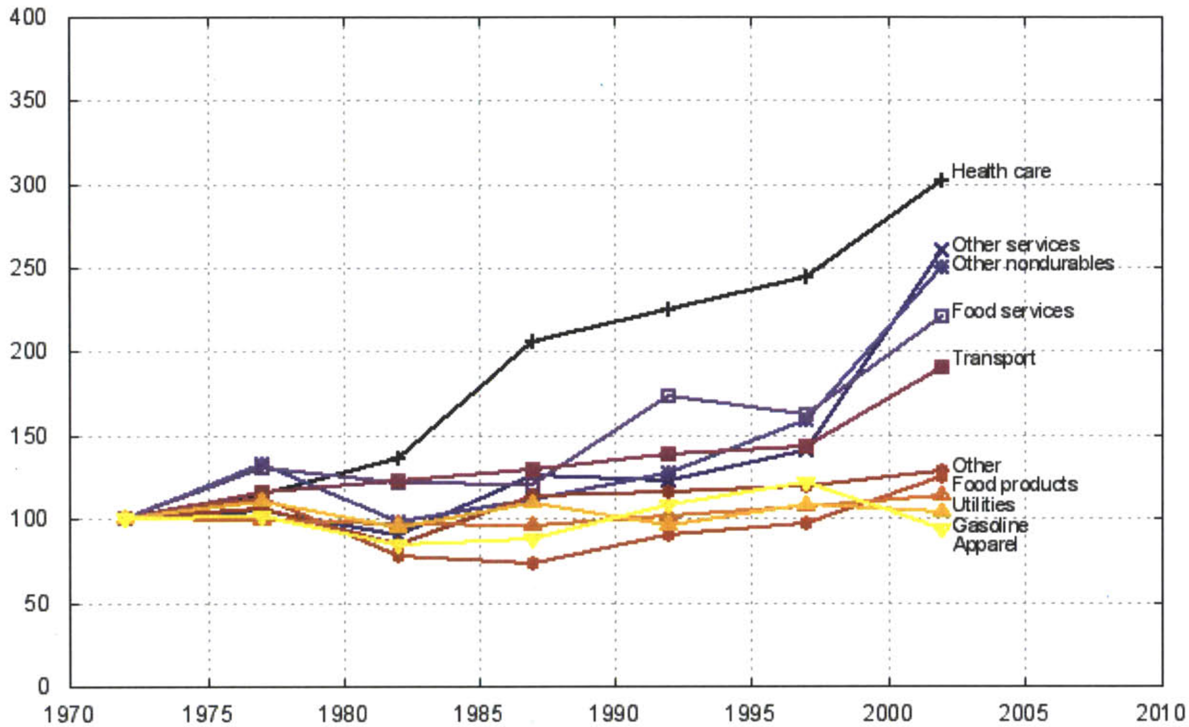
Table 1.1: Direct and indirect domestic fossil fuel energy due to household consumption by product category, trillion Btu

sector	1972	1977	1982	1987	1992	1997	2002
Clothing and footwear	1,236	1,259	1,038	1,081	1,344	1,503	1,154
Financial services and insurance	688	607	636	856	960	825	760
Food and beverages off-premise	4,040	4,531	3,130	2,966	3,639	3,925	5,058
Food services and accommodations	1,347	1,756	1,641	1,626	2,338	2,180	2,969
Durable household equipment	1,072	1,115	850	967	1,009	1,156	1,133
Gasoline and other energy goods	13,835	15,292	13,071	15,159	13,184	15,005	14,403
Nonprofit institutions	439	520	593	823	669	655	243
Health care	1,231	1,422	1,677	2,532	2,778	3,016	3,722
Housing and utilities	16,072	16,018	15,546	15,427	16,273	17,171	18,377
Motor vehicles and parts	1,596	1,696	957	1,745	1,480	1,570	1,749
Other durable goods	167	193	165	159	188	200	283
Other nondurable goods	1,199	1,587	1,169	1,332	1,520	1,905	2,996
Other services	1,705	1,790	1,530	2,146	2,086	2,409	4,441
Recreation services	734	822	818	760	933	981	1,377
Recreational goods and vehicles	341	379	248	447	582	613	936
Transportation services	1,620	1,884	1,991	2,106	2,244	2,315	3,089

[a] Data sources: Bureau of Economic Analysis, Energy Information Administration, author's calculations

For all consumption categories except health care and transportation services, total energy consumption decreased between 1977 and 1982, which were years shortly before and after then recession of the early 1980s recession. The years 1972 and 1977 have unusually large energy footprints in apparel, off-premise food, gasoline, and motor vehicles. Relatively high consumption of gasoline and motor vehicles can easily be attributed to low gas prices during this period; commodities associated with food are also closely linked to petroleum supply due to the use of petroleum in agriculture. Fruit farming was associated with the largest use of petroleum throughout the 30-year interval.

Figure 1.4: Direct and indirect domestic fossil fuel energy due to household consumption by product category relative to 1972 (1972 = 100)



Data source: Bureau of Economic Analysis, Energy Information Administration, author's calculations

Table 1.2 shows the energy intensities for the same consumption categories, while Figure 1.5 shows intensities relative to 1972.

Of the commodities shown in Figure 1.5, food products and apparel had the least improvement in energy efficiency over the 30-year study period. Energy intensity changes in the apparel category, which includes clothing and footwear, reflect a shift from petroleum to natural gas in the 1990s. We estimate that the composition of *direct* fossil fuel purchases was approximately 78% petroleum and 20% natural gas in 1972, 45% petroleum and 52% natural gas in 1992, and 8% petroleum and 91% natural gas in 2002. One possible explanation for this is a shift in the technology of textile production, but this is unlikely as synthetic fibers were already common in the 1970s, and the petroleum and natural gas ratios required in the production of cotton and polyester are

Table 1.2: Indirect and direct domestic fossil fuel energy intensity by product category, Btu per dollar purchased by households

sector	1972	1977	1982	1987	1992	1997	2002
Clothing and footwear	10.78	10.57	8.52	7.51	9.94	10.03	8.90
Financial services and insurance	4.58	3.42	2.93	2.55	2.20	1.44	1.24
Food and beverages off-premises	13.29	13.70	9.91	8.91	10.77	11.29	13.75
Food services and accommodations	8.76	8.84	7.67	5.79	7.14	6.17	6.30
Durable household equipment	13.55	12.66	9.47	9.44	10.38	10.05	9.37
Gasoline and other energy goods	256.88	141.06	88.42	158.70	188.42	216.24	194.36
Gross output of nonprofit institutions	10.26	7.77	6.76	6.96	4.59	4.23	2.75
Health care	6.87	5.91	4.51	4.48	3.51	3.19	3.27
Housing and utilities	30.22	25.05	20.59	17.13	16.03	14.65	12.08
Motor vehicles and parts	11.86	10.51	7.50	8.31	8.27	7.13	5.95
Other durable goods	10.03	7.23	5.90	6.59	7.29	6.62	5.24
Other nondurable goods	10.97	12.02	7.83	7.21	7.03	7.57	8.28
Other services	7.49	6.77	5.29	5.23	4.25	4.01	4.89
Recreation services	9.54	8.18	7.35	6.02	5.62	4.23	4.66
Recreational goods and vehicles	11.28	9.79	7.16	6.27	6.60	5.62	5.58
Transportation services	18.68	16.40	17.46	13.31	13.38	9.56	11.13

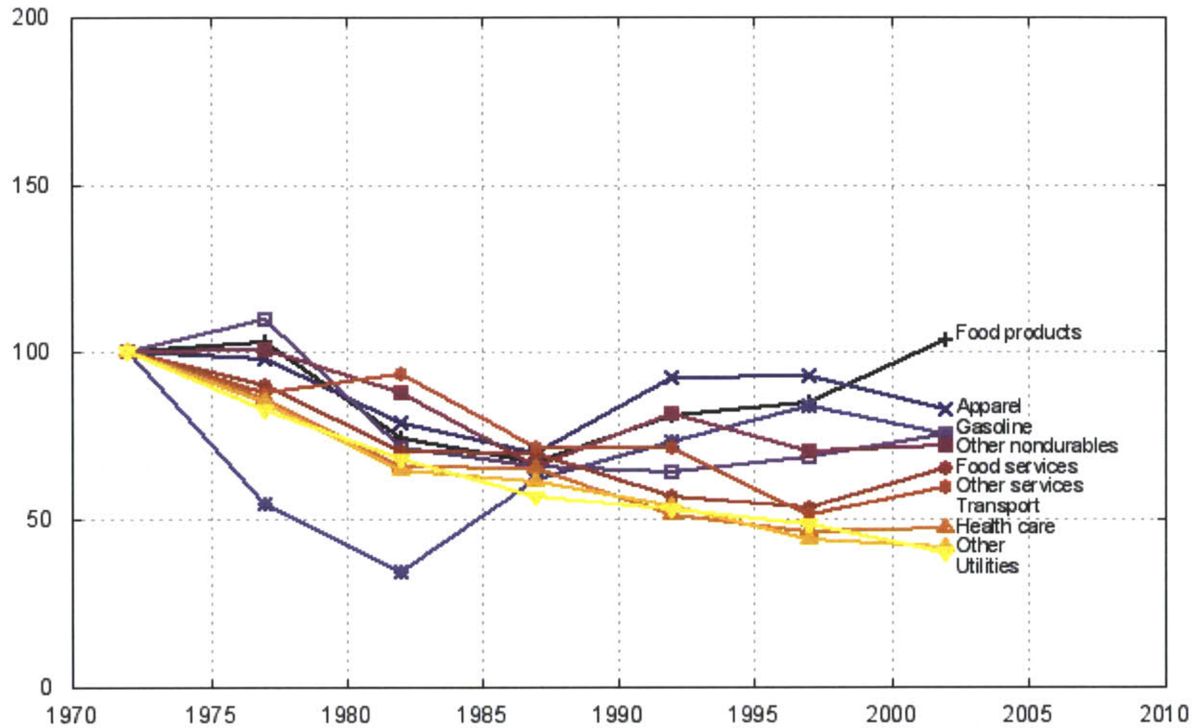
[a] Data sources: Bureau of Economic Analysis, Energy Information Administration, author's calculations

not drastically different [van Winkle et al., 1978, Kalliala and Nousiainen, 1999]. As the largest purchasers of natural gas are the cut-and-sew apparel manufacturing sectors (which purchase fabrics as an input), a more likely explanation is that textiles are increasingly offshored while energy used by the apparel industry increasingly consists of natural gas used in the cleaning/drying process. Table 1.5 shows a very clear increase in the share of clothing items imported from outside the United States, with imports making up a majority of consumer clothing purchases in 1997 and after.

Unlike all other consumption categories, clothing, food products, and to a certain extent the food service category, all showed increasing energy *intensity* in the 1987-2002 period when oil prices were relatively stable (table 1.2).

Although the clothing sector may have different energy profiles due to its declining status in the United States (and its energy and emissions intensities declined in 2002), increased energy intensity in the food sector may require further research. One possible culprit we can identify in our data is the meat industry: non-poultry meat production was consistently the food commodity on which consumers spent the most dollars every year;

Figure 1.5: Indirect + direct domestic fossil fuel energy intensity due to household consumption by product category relative to 1972 (1972 = 100)



Data source: Bureau of Economic Analysis, Energy Information Administration, author's calculations

meat and poultry combined constituted 18-25% of consumers' food spending each year. Between 1987 and 2002 the direct energy requirements of the meat and poultry processing industries increased steadily, with non-poultry slaughtering and processing increased from roughly 0.5 kBtu to 2.0 kBtu per dollar, and poultry processing increased from 1.2 to 1.7 kBtu per dollar (different sector definitions between years make these estimates very rough). Whether the technologies of the meat and poultry industries have become more energy intensive due to industry consolidation in the 1990s is a topic for research beyond the scope of this paper.

Tables 1.3 and 1.4 show rough estimates of CO_2 emissions due to fossil fuel combustion, based on emissions factors for coal, natural gas, motor gasoline, and middle distillate fuels provided by EIA. The emissions trends by consumption category are essentially parallel to the energy trends, although the shift from petroleum to natural gas may be seen in the emissions intensity of clothing (table 1.4) which has increased less fast than energy intensity. Note that our estimates do not account for emissions reduction efficiency, thus our figures are most likely higher than actual, especially for later years.

Table 1.3: Direct and indirect domestic emissions from fossil fuel combustion by due to household consumption by product category, kilotons CO_2

sector	1972	1977	1982	1987	1992	1997	2002
Clothing and footwear	90	92	76	79	98	110	84
Financial services and insurance	50	44	47	63	70	60	56
Food and beverages off-premise	296	331	229	217	266	287	370
Food services and accommodations	99	128	120	119	171	159	217
Durable household equipment	78	82	62	71	74	85	83
Gasoline and other energy goods	1,012	1,119	956	1,109	964	1,098	1,054
Nonprofit institutions	32	38	43	60	49	48	18
Health care	90	104	123	185	203	221	272
Housing and utilities	1,176	1,172	1,137	1,128	1,190	1,256	1,344
Motor vehicles and parts	117	124	70	128	108	115	128
Other durable goods	12	14	12	12	14	15	21
Other nondurable goods	88	116	85	97	111	139	219
Other services	125	131	112	157	153	176	325
Recreation services	54	60	60	56	68	72	101
Recreational goods and vehicles	25	28	18	33	43	45	68
Transportation services	119	138	146	154	164	169	226

[a] Data sources: Bureau of Economic Analysis, Energy Information Administration, author's calculations

Finally, Table 1.5 shows the share of each consumer category that is imported from outside the United States. So far, our estimates of energy consumption and CO_2 production have focused on domestically produced goods and services and domestic consumers. If there were no foreign trade, then Equation i.4, which was

$$\mathbf{x} = L\mathbf{y}$$

would simply represent the relationship between domestic total output and domestic final demand. Another way of reading Table 1.5 is to see each number as the share of a good that is subject to the production technology in another country, yet in our calculation we

Table 1.4: Direct and indirect domestic emissions intensities from fossil fuel combustion by product category, grams CO_2 per dollar

sector	1972	1977	1982	1987	1992	1997	2002
Clothing and footwear	0.79	0.77	0.62	0.55	0.73	0.73	0.65
Financial services and insurance	0.34	0.25	0.21	0.19	0.16	0.11	0.09
Food and beverages off-premises	0.97	1.00	0.72	0.65	0.79	0.83	1.01
Food services and accommodations	0.64	0.65	0.56	0.42	0.52	0.45	0.46
Durable household equipment	0.99	0.93	0.69	0.69	0.76	0.74	0.69
Gasoline and other energy goods	18.79	10.32	6.47	11.61	13.78	15.82	14.22
Gross output of nonprofit institutions	0.75	0.57	0.49	0.51	0.34	0.31	0.20
Health care	0.50	0.43	0.33	0.33	0.26	0.23	0.24
Housing and utilities	2.21	1.83	1.51	1.25	1.17	1.07	0.88
Motor vehicles and parts	0.87	0.77	0.55	0.61	0.60	0.52	0.44
Other durable goods	0.73	0.53	0.43	0.48	0.53	0.48	0.38
Other nondurable goods	0.80	0.88	0.57	0.53	0.51	0.55	0.61
Other services	0.55	0.50	0.39	0.38	0.31	0.29	0.36
Recreation services	0.70	0.60	0.54	0.44	0.41	0.31	0.34
Recreational goods and vehicles	0.83	0.72	0.52	0.46	0.48	0.41	0.41
Transportation services	1.37	1.20	1.28	0.97	0.98	0.70	0.81

[a] Data sources: Bureau of Economic Analysis, Energy Information Administration, author's calculations

have applied the same (domestic) production technology to the entire good. The categories of clothing, durable household equipment, motor vehicles, other durable goods, other nondurable goods, and recreational goods and vehicles all consisted of over 25% imports in 2002, and were all generally rising. Thus our estimates of the impact of consumption on emissions is less accurate (and increasingly less accurate over time) for these sectors.

1.4.2 Estimates of CO_2 Emissions by Industry Sectors

The previous section, which dealt with the impact of household consumption on energy and emissions, was based on direct and indirect impacts of consumption. In this section we examine the *direct* CO_2 emissions by industry sector as a way of gauging progress in industrial efficiency, by which we mean direct improvements to emissions intensity within each industry. Table 1.6 breaks down calculated emissions from fossil fuel combustion

Table 1.5: Share of consumer goods imported

sector	1972	1977	1982	1987	1992	1997	2002
Clothing and footwear	0.11	0.17	0.22	0.35	0.44	0.53	0.72
Financial services and insurance	0.00	0.01	0.01	0.01	0.00	0.01	0.03
Food and beverages off-premises	0.04	0.04	0.05	0.06	0.06	0.06	0.08
Food services and accommodations	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Durable household equipment	0.05	0.09	0.11	0.16	0.18	0.21	0.26
Gasoline and other energy goods	0.09	0.11	0.09	0.10	0.08	0.08	0.11
Gross output of nonprofit institutions	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Health care	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Housing and utilities	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motor vehicles and parts	0.11	0.14	0.23	0.28	0.26	0.24	0.29
Other durable goods	0.12	0.19	0.24	0.45	0.50	0.47	0.49
Other nondurable goods	0.04	0.05	0.06	0.11	0.13	0.17	0.25
Other services	0.12	0.08	0.08	0.11	0.09	0.10	0.06
Recreation services	0.09	0.11	0.10	0.00	0.00	0.00	0.00
Recreational goods and vehicles	0.17	0.10	0.13	0.37	0.33	0.33	0.33
Transportation services	0.01	0.02	0.02	0.02	0.02	0.02	0.03

[a] Calculated as weighted averages of import share by input-output sector
[a] Data source: Bureau of Economic Analysis, author's calculations

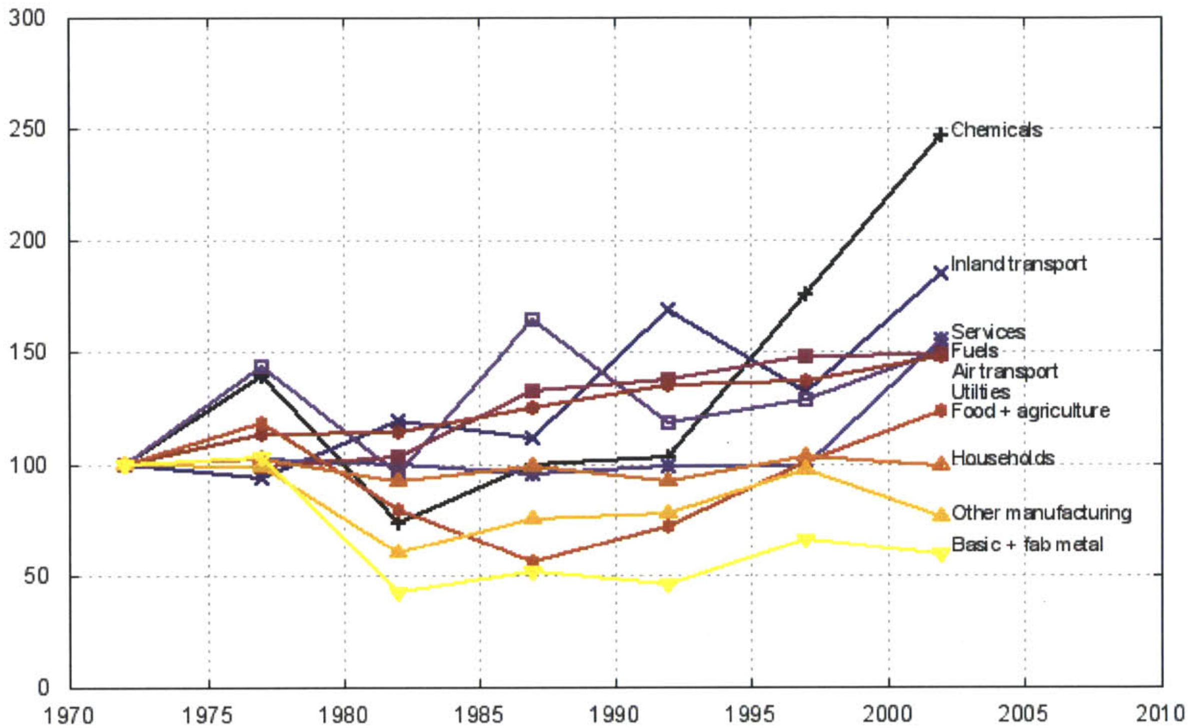
by industry sector.

Note that comparing industry sectors over time with BEA input-output data is considerably more difficult than comparing personal consumption goods over time due to frequent changes in industry classification. Many fluctuations in our estimates can be attributed to changes in sector assignments, which we explain further at the end of this section.

Direct fossil fuel-related emissions due to household consumption stayed relatively flat over the 30-year period, despite rising household consumption in dollars. This is because an increasing share of household energy was supplied via electricity, which calculated from our model increased from 1.8 quadrillion Btu (9.5% of all direct energy purchases) in 1972 to 4.3 quadrillion Btu (20%) in 2002.

Of the fossil fuels, direct purchases of coal – the most uncommon household fuel – by households dropped drastically from 115 trillion Btu (0.60%) in 1972 to 12 trillion Btu (0.056%) in 2002, while very little long-term change in levels was seen in natural gas and

Figure 1.6: Direct emissions by industry sector relative to 1972 levels (1972 = 100)

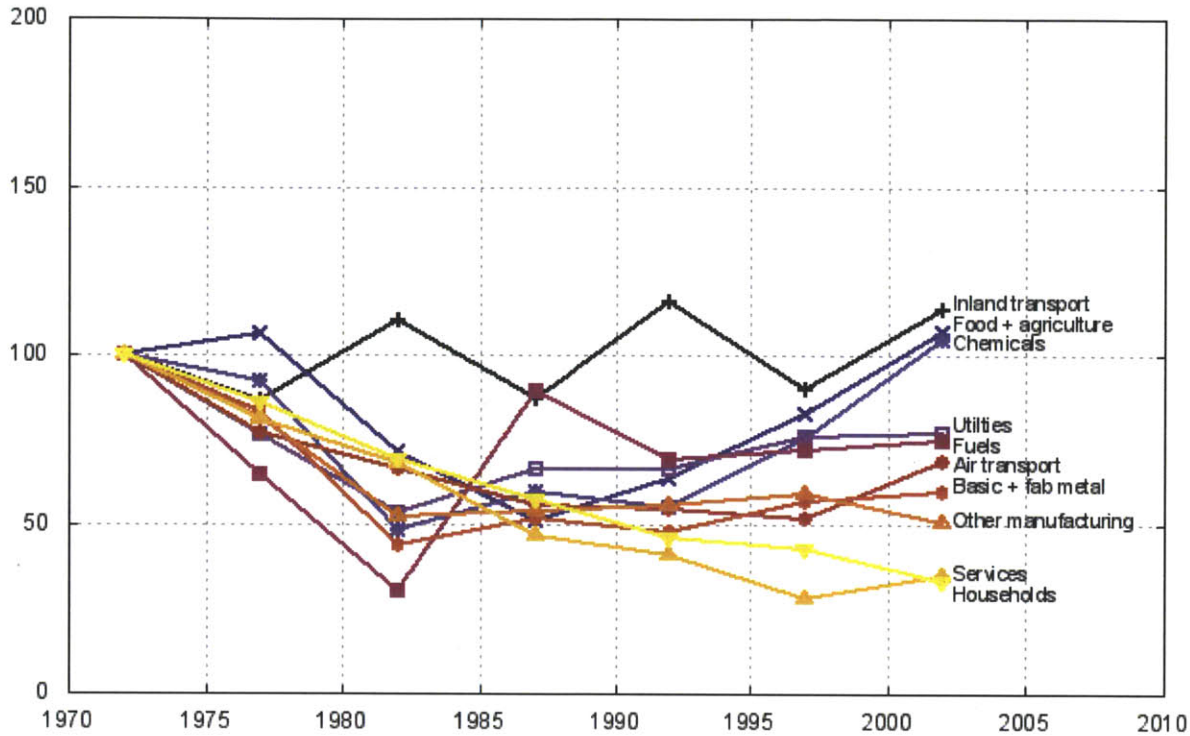


Data source: Bureau of Economic Analysis, Energy Information Administration, author's calculations

petroleum. Transport-related petroleum is by far the largest source of household direct energy purchases (47-55% of total energy over the 30-year period), followed by natural gas (23-27%). Thus, the impact of household consumption on emissions *growth* in the United States has been primarily through growth in purchases of electricity, which through 2002 was still mostly coal-powered (see Figure 1.8).

Table 1.7 presents emissions intensities based on the results in Table 1.6. As we found earlier, fossil fuel energy and therefore emissions intensities of the food and agriculture sectors dropped from 1972 to 1982 and grew from 1987 to 2000; a similar pattern is seen in the textiles industry. In general, emissions intensities decreased over time far more for the service sectors than for the manufacturing sectors, some of which saw no decrease. The large decline in service industries is likely due to the services taking up an increasing share of sales in the U.S. economy. Some differences between

Figure 1.7: Direct emissions intensity by industry sector relative to 1972 intensity (1972 = 100)

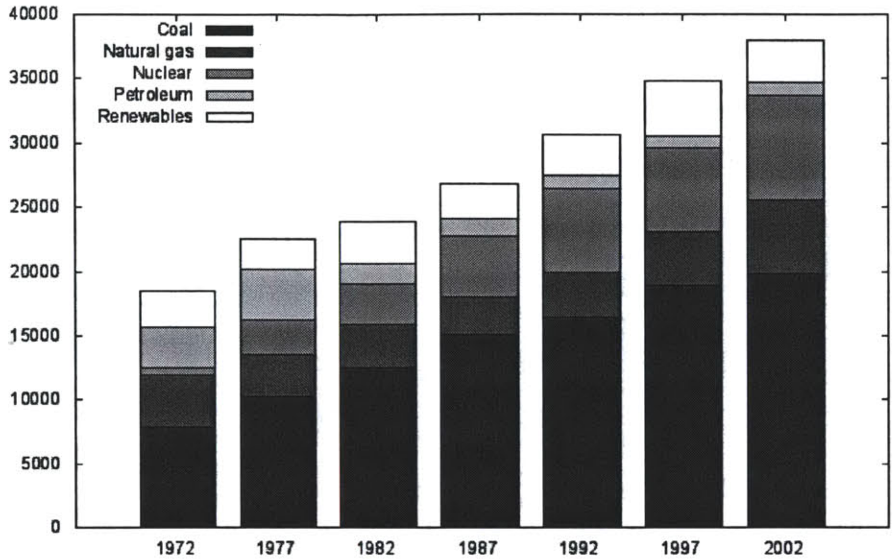


Data source: Bureau of Economic Analysis, Energy Information Administration, author's calculations

years before 1997 and years beginning with 1997 are due to sector redefinitions (starting in 1997 the BEA sectors were based on the North American Industrial Classification System, while previously they appear to have been the BEA's own coding system). In particular, postal and telecommunications included separate industries for post and couriers in the 1997 and 2002 codes, whereas for earlier years they were included in public administration. There were also many more general sectors associated with public administration in 2002 than any other year.

Table 1.8 compares our resulting CO_2 amounts with the World Input-Output Database (WIOD). A brief visual glance suggests our estimates are on the same order of magnitude as those of WIOD, and that some differences may be explained by interpretation of industry sectors. Within manufacturing, for example, we allocated more emissions to the fuel and chemicals sectors and less to the nonmetallic mineral, basic

Figure 1.8: Total energy consumption for electricity generation in the United States (including losses[a]) by energy source, trillion Btu, 1972-2002



[a] Power losses as a percentage of total energy consumed for power generation decreased from 70.6% to 68.9% over the 30-year period. In other words energy efficiency increased from 29.4% to 31.1%.
Data source: Energy Information Administration

metal, and mining sectors, compared to WIOD. Within transportation, we allocated too few emissions to the water transport sector (most likely due to an artifact – see Limitations section) and thus more emissions to all other transport modes. We allocated less emissions to many of the services like finance, health, education, and other services, while allocating more to post and telecommunications. As explained before, the large discrepancy between 1997 and 2002 public administration was due to the larger number of sectors associated with government in 2002. Finally, our large estimate of household consumption is based on direct purchases of coal, petroleum, and natural gas. Unfortunately we do not have information about how the household estimate was obtained for WIOD.

1.4.3 Limitations

Our method of allocating energy use to commodities is very simplified and involves heuristics for matching data between different sources such as proportional allocation. Studies such as Weber [2009] are likely more accurate due to the number of independent data sources.

Our measure of energy intensities and efficiencies, shared by many other analysts, is based on physical energy consumption per monetary units. The problem with this is that the resulting efficiency values are dependent on the price of energy inputs, especially for energy goods. For example, suddenly raising the price of oil twofold would make motor gasoline about twice as efficient in terms of Btus per dollar, although the available energy per gallon remains the same. This problem is less severe if fluctuations in energy prices are in line with prices of other goods in the economy, as the same inflation rates can be applied to all goods. Thus within our time series, the years 1987-2002 are perhaps more suitable (see Figure 1.3) to be examined for overall trends.

Another limitation is our choice of data sources. The BEA's Benchmark Input-Output Accounts currently offer the most detailed official figures available of transactions among industries, but the benchmark tables are not often updated and in some cases contain very different figures from more updated data. For example, we noticed that the water transportation industry had zero coal or petroleum requirements in the 2002 benchmark tables, although this was not the case in the more up-to-date annual accounts. Additionally, the benchmark accounts but not the annual accounts adjust for margins associated with imports by allocating the difference between purchaser and producer prices to the transportation and wholesale industries, resulting in a positive number for imports, complicating calculations involving imports. More accounting errors undoubtedly exist in the benchmark accounts. We confirmed through an email exchange with BEA staff the transportation inconsistencies we found in the benchmark accounts, and that the recently created annual accounts were the preferred source of these data. Unfortunately for our research, the annual accounts do not provide the level of detail required to associate energy with the fossil fuel sectors.

1.5 Conclusion

In this study, we went through the process of constructing hybrid and satellite tables of fossil-fuel consumption and associated CO_2 emissions for the United States for the years 1972-2002, based on benchmark input-output accounts. Although readers need to be wary of a number of issues related to the data and the assumptions of the Leontief framework, our estimates in aggregate can provide some insight into how energy and emissions in the U.S. break down by consumption category or production industry.

From both consumption and production perspectives, total energy and emissions generally increased over time while intensity decreased over time, but total energy impact of food and apparel notably increased in intensity on the consumption side, while direct emissions by manufacturing sectors did not visibly decline. An increasing share of manufactured products purchased by consumers consists of imports, for which we do not have the data to make accurate estimates about energy and emissions impact.

1.5.1 Further work

Although this study covers a span of three decades, we only had data through 2002. More relevant conclusions can be made with more recent data. Based on the BEA's publishing history, the 2007 benchmark input-output accounts are to be released by the spring of 2013. For this reason the code included with this paper that produces the time series was written to accommodate future additions to the data.

1.A Methodological Appendix

Constructing Input-Output from Supply and Use Tables

We use a commodity-based technology assumption [Miller and Blair, 1985], which means we assume all commodities are produced by the same technology (same proportion of inputs) regardless of the industry that produces them. This will result in us producing a commodity-by-commodity input-output table.

We use Make and Use (also known as Supply and Use) tables at the detailed level provided by BEA, which we denote as follows

$$\underset{N_I \times N_C}{M} \qquad \text{Industry-by-commodity Make table}$$

$$\begin{bmatrix} \underset{N_C \times N_I}{U} & \underset{N_C \times N_Y}{Y} \\ \underset{N_V \times N_I}{V} & \end{bmatrix} \qquad \text{Commodity-by-industry Use table}$$

where

N_C	Number of commodity sectors
N_I	Number of industry sectors
N_Y	Number of final demand sectors

Industry Output Proportions Each industry i produces a fraction c_{ki} of commodity k in its total output. We calculate c_{ki} by dividing output in commodity k by industry i's total output (which is obtained by summing all values of m_{ik} across commodities):

$$c_{ki} = \frac{m_{ik}}{\sum_j^{N_C} m_{ij}}$$

In matrix notation,

$$\underset{N_C \times N_I}{C} = \underset{N_C \times N_I}{M^T} \left[diag \left(\underset{N_I \times N_C}{M} \mathbf{e}_{N_C} \right) \right]^{-1}$$

Commodity-by-Commodity Transaction Matrix We construct the commodity-by-commodity transaction matrix, Z from the Use table and the industry output proportions matrix derived above using the Make table. The final demand columns, which are not producing industries and thus have no industry output proportions, are preserved in the reconstructed transactions table:

$$\begin{bmatrix} \underset{N_C \times N_C}{\hat{Z}} & \underset{N_C \times N_Y}{Y} \\ \underset{N_V \times N_C}{\hat{V}} & \end{bmatrix} = \begin{bmatrix} CU^T & Y \\ CV^T & \end{bmatrix} \tag{1.1}$$

where we $\hat{V}$ is an adjusted value-added matrix after accounting for industry output in other sectors.

Constructing Energy Hybrid Tables

The commodity-by-commodity use table contains interindustry transactions Z, (adjusted) value-added V, and final demand Y, denoted as follows:

$$\begin{bmatrix} Z & Y \\ V & \end{bmatrix} \tag{1.2}$$

In the hybrid table, rows representing dollar values of energy commodities sold are replaced with physical (Btu) units. (1.2):

$$\begin{bmatrix} Z^* & Y^* \end{bmatrix} = \begin{bmatrix} Z^{-E} & Y^{-E} \\ Z^E & Y^E \end{bmatrix}$$

where

Z^{-E}	Conventional transactions in dollar units
Z^E	Energy transactions in physical units
Y^{-E}	Conventional final demand in dollar units
Y^E	Energy final demand in physical units

The Leontief matrix created from this mixed-unit matrix can be multiplied with final demand as a regular Leontief matrix, as long as energy and non-energy rows are used separately. See the appendix of Bullard III and Herendeen [1975] for a full explanation.

Energy data We use the energy Price and Use tables published by the Energy Information Administration (EIA) in the State Energy Data System. Each observation in Price and Use table includes energy source (one of coal, petroleum, electricity, or natural gas), end-use sector (one of industrial, commercial, residential, transportation, or power generation), and either the total use in Btu or purchaser prices (including margins and taxes) from 1960 through 2009. Other energy sources and end-use sectors included in the data are subsets of the ones listed in parentheses above.

We assign commodity sectors in the input-output table to end-use sectors by the following rules. We assign all service sectors, wholesale and retail trade, and federal and state government activities other than transport and electricity, to the commercial sector. We assign personal consumption expenditures and household industry to the residential sector. We assign the power generation and distribution industry and government electric utilities to the electricity sector. We assign truck, rail, water, and air transport, auxiliary transport activities, and government transport to the transportation sector.

Non-petroleum energy allocation Based on the rules above, we obtain the total energy for coal, electricity, and natural gas consumed by each end-use sector and allocate the total to the assigned industries.

Suppose $\mathbf{z}$ is the row vector of coal usage extracted from the input-output matrix Z.

For example, suppose $\mathcal{C}$ represents the set of commodities in the commercial sector and $E_{i,\mathcal{C}}$ represents energy use by the commercial sector. The energy use in Btu $z_{i,o}^{E}$ of energy commodity i (coal, electricity, or natural gas) by commercial commodity o is

$$z_{i,o}^{E} = \frac{z_{i,o} E_{i,\mathcal{C}}}{\sum_{j \in \mathcal{C}} z_{i,j}}$$

Petroleum allocation We first allocate all petroleum that is not associated with the transport sector in the EIA data to all non-transportation commodities in the I-O table in the same way that other fuel sources are allocated. The amount thus allocated, when multiplied by EIA-published petroleum prices, is below each of the sectors' expenditures on petroleum, which is expected as non-tranportation petroleum is only a fraction of all petroleum consumed. Subtracting the expenditures allocated to non-transportation petroleum from expenditures in the I-O table[1] leaves us with a row of unallocated expenditures. We unconditionally allocate all avaiation gas and jet fuel to the air transportation sector. The remaining petroleum is proportionally allocated to the commercial and residential sectors. We assume the industrial and power generation sectors only purchase non-transportation-related petroleum.

[1] Energy prices published by the EIA are purchaser prices, whereas expenditures in the I-O table are in producer prices. We use a f.o.b. to c.i.f. ratio to convert between the two.

1.B Additional tables

Tables 1.6 and 1.7 contain detailed emission levels and intensities calculated using our methodology and aggregated into the same industries as the WIOD classification. Table 1.8 compares calculated emissions levels for 1997 and 2002 to data from WIOD.

Table 1.6: Direct emission by industry sector, metric tons CO_2

Sector	1972	1977	1982	1987	1992	1997	2002
Food, bev, tobacco	51,480	53,143	32,585	31,782	54,467	75,203	81,372
Textiles & products	20,684	23,668	14,794	12,212	19,472	24,120	14,427
Leather & footwear	1,924	1,307	657	489	1,624	842	451
Wood & products	40,388	25,285	14,167	24,936	23,167	11,334	9,542
Pulp, paper, printing	57,637	80,672	54,254	60,288	54,760	87,369	70,140
Coke, petrol, nucl Fuel	249,254	357,883	237,875	411,682	294,253	320,263	375,365
Chemicals & products	123,427	172,349	90,415	122,732	127,030	216,609	304,590
Rubber & plastics	12,095	17,699	7,906	12,944	13,549	18,671	21,410
Other nonmetall min.	49,460	55,301	25,494	35,721	39,444	54,932	44,950
Basic & fab metal	199,772	206,289	84,626	103,210	91,181	132,064	118,437
Machinery, n.e.c.	33,224	19,707	11,688	13,001	15,219	17,461	13,553
Electr & optical equip	30,950	26,335	21,046	22,303	23,606	17,568	13,465
Transport equipment	28,651	23,226	17,001	27,457	22,864	32,803	20,339
Manufacturing n.e.c.	8,051	6,557	3,961	3,320	5,370	10,030	6,525
Motor vehicle services	15,629	19,916	14,519	60,075	34,609	8,309	5,237
Wholesale trade	69,861	75,564	72,576	62,008	65,740	42,068	44,034
Retail trade	69,248	78,144	84,494	44,552	52,240	51,737	21,864
Inland transport	130,478	122,522	155,205	145,903	220,642	171,549	241,308
Water transport	27,235	28,758	24,888	11,924	17,256	6,336	2,698
Air transport	162,263	160,888	167,882	215,123	223,328	240,581	241,504
Transport services	9,572	8,684	4,336	5,377	2,468	77,487	67,725
Post & telecomm	1,664	5,728	3,298	1,948	4,003	40,155	81,284
Real estate	42,758	33,081	20,640	12,324	25,328	31,440	12,549
Other bus. activities	53,645	39,464	38,375	36,088	47,101	75,813	175,553
Agriculture etc.	124,908	155,551	107,464	65,904	72,662	101,553	136,844
Mining & quarrying	133,865	132,007	105,201	119,034	127,502	93,203	95,499
Utilities	1,550,989	1,761,252	1,765,360	1,937,636	2,095,516	2,129,535	2,290,119
Construction	147,724	177,697	135,478	157,917	44,221	155,728	236,706
Hotels & Restaurants	15,833	17,768	21,303	16,322	29,894	21,907	34,371
Finance	15,821	13,753	12,257	9,171	13,560	6,435	9,586
Public administration	12,919	10,777	22,711	15,201	19,853	12,860	318,299
Education	14,972	11,844	6,086	6,122	4,702	2,874	29,722
Health & social work	42,884	41,555	45,718	50,476	41,737	28,298	45,683
Other services	5,976	7,443	5,436	5,800	9,364	15,979	20,820
Household consumption	1,154,649	1,185,120	1,060,157	1,146,477	1,065,982	1,190,026	1,137,303

[a] Data sources: Bureau of Economic Analysis, Energy Information Administration, author's calculations

Table 1.7: Direct emissions intensity by sector, metric tons per dollar output

Sector	1972	1977	1982	1987	1992	1997	2002
Food, bev, tobacco	0.106	0.098	0.060	0.058	0.093	0.121	0.132
Textiles & products	0.093	0.104	0.079	0.059	0.103	0.134	0.123
Leather & footwear	0.092	0.065	0.040	0.036	0.130	0.069	0.071
Wood & products	0.325	0.172	0.121	0.147	0.137	0.109	0.099
Pulp, paper, printing	0.349	0.369	0.228	0.207	0.181	0.341	0.289
Coke, petrol, nucl Fuel	2.167	1.407	0.653	1.939	1.504	1.561	1.618
Chemicals & products	0.586	0.540	0.282	0.350	0.325	0.442	0.614
Rubber & plastics	0.153	0.168	0.079	0.097	0.093	0.102	0.116
Other nonmetall min.	0.627	0.600	0.319	0.388	0.501	0.550	0.450
Basic & fab metal	0.488	0.408	0.215	0.253	0.233	0.277	0.291
Machinery, n.e.c.	0.186	0.081	0.052	0.065	0.073	0.057	0.052
Electr & optical equip	0.100	0.070	0.047	0.042	0.042	0.028	0.028
Transport equipment	0.078	0.052	0.046	0.054	0.046	0.050	0.030
Manufacturing n.e.c.	0.189	0.130	0.082	0.069	0.104	0.053	0.031
Motor vehicle services	0.170	0.173	0.131	0.297	0.161	0.048	0.027
Wholesale trade	0.179	0.149	0.136	0.095	0.089	0.047	0.047
Retail trade	0.161	0.152	0.164	0.068	0.076	0.060	0.022
Inland transport	0.664	0.575	0.733	0.578	0.771	0.599	0.755
Water transport	0.984	0.647	0.602	0.319	0.385	0.218	0.091
Air transport	3.170	2.447	2.104	1.764	1.731	1.644	2.175
Transport services	0.902	0.543	0.162	0.150	0.065	0.947	0.798
Post & telecomm	0.014	0.041	0.019	0.008	0.015	0.081	0.134
Real estate	0.065	0.045	0.024	0.011	0.019	0.043	0.014
Other bus. activities	0.135	0.080	0.060	0.038	0.039	0.034	0.060
Agriculture etc.	0.411	0.467	0.317	0.215	0.236	0.301	0.464
Mining & quarrying	1.227	0.694	0.325	0.688	0.662	0.494	0.518
Utilities	7.082	5.434	3.810	4.702	4.692	5.402	5.462
Construction	0.237	0.254	0.171	0.165	0.050	0.175	0.211
Hotels & Restaurants	0.074	0.065	0.070	0.042	0.067	0.044	0.055
Finance	0.054	0.040	0.028	0.013	0.017	0.005	0.006
Public administration	0.024	0.018	0.034	0.019	0.018	0.011	0.174
Education	0.327	0.230	0.102	0.079	0.048	0.024	0.139
Health & social work	0.157	0.110	0.092	0.074	0.045	0.030	0.034
Other services	0.094	0.089	0.058	0.041	0.051	0.040	0.040
Household consumption	0.415	0.357	0.287	0.239	0.191	0.178	0.138

[a] Data sources: Bureau of Economic Analysis, Energy Information Administration, author's calculations

Table 1.8: Direct CO_2 emissions due to fuel combustion by sector, calculated here vs. WIOD

	1997		2002	
Sector	calculated	WIOD	calculated	WIOD
Food, bev, tobacco	75,203	57,040	81,372	60,388
Textiles & products	24,120	21,079	14,427	17,630
Leather & footwear	842	669	451	487
Wood & products	11,334	16,397	9,542	14,190
Pulp, paper, printing	87,369	63,129	70,140	72,182
Coke, petrol, nucl Fuel	320,263	224,008	375,365	198,007
Chemicals & products	216,609	130,001	304,590	181,973
Rubber & plastics	18,671	6,634	21,410	8,662
Other nonmetall min.	54,932	123,501	44,950	125,286
Basic & fab metal	132,064	198,008	118,437	161,967
Machinery, n.e.c.	17,461	18,932	13,553	21,509
Electr & optical equip	17,568	20,524	13,465	19,725
Transport equipment	32,803	26,440	20,339	29,369
Manufacturing n.e.c.	10,030	7,577	6,525	7,596
Motor vehicle services	8,309	8,732	5,237	8,742
Wholesale trade	42,068	43,999	44,034	45,209
Retail trade	51,737	110,062	21,864	116,057
Inland transport	171,549	164,388	241,308	168,142
Water transport	6,336	56,494	2,698	46,683
Air transport	240,581	163,096	241,504	159,385
Transport services	77,487	25,684	67,725	43,020
Post & telecomm	40,155	26,906	81,284	22,556
Real estate	31,440	13,478	12,549	13,449
Other bus. activities	75,813	120,718	175,553	132,091
Agriculture etc.	101,553	62,534	136,844	60,000
Mining & quarrying	93,203	160,474	95,499	114,463
Utilities	2,129,535	1,981,282	2,290,119	2,161,763
Construction	155,728	56,233	236,706	63,786
Hotels & Restaurants	21,907	68,459	34,371	76,009
Finance	6,435	38,541	9,586	42,284
Public administration	12,860	376,250	318,299	318,219
Education	2,874	15,307	29,722	19,424
Health & social work	28,298	94,307	45,683	105,865
Other services	24,594	94,723	26,553	65,397
Household consumption	1,190,026	661,965	1,137,303	688,529

[a] Data sources: Bureau of Economic Analysis, Energy Information Administration, World Input-Output Database, author's calculations

Chapter 2

Structural Decomposition of Emissions Growth

2.1 Introduction

Historically, uneven global development and industrialization has led to divergent living standards among countries. As developing countries become increasingly industrialized, the potential environmental impact of their economic activities becomes more pressing, especially in the area of CO_2 emissions where our ability to control emissions lags behind our capacity to generate it in ecologically harmful amounts.

Higher living standards are associated with increased CO_2 emissions (compare the PPP per capita and emissions per capita columns in Table 2.1), which makes intuitive sense as the more people consume, the more emissions will be embodied in their consumption. Simultaneously, technological progress (as well as demand for abatement technology due to higher living standards) includes cleaner production methods that allow countries to reduce emissions intensity as they advance. Whether or not the impact of better technology is enough to offset the emissions due to increased consumption is of vital importance in predicting emissions trends in the near future.

Some hope for technological advances dominating the impact of emissions can be found in the experience of more localized pollutants such as SO_x and NO_x. There has been evidence that these pollutants follow an environmental Kuznets curve – an inverted

Table 2.1: Total CO_2 emissions intensity by country, ranked by 1995 purchasing power parity (PPP) per capita

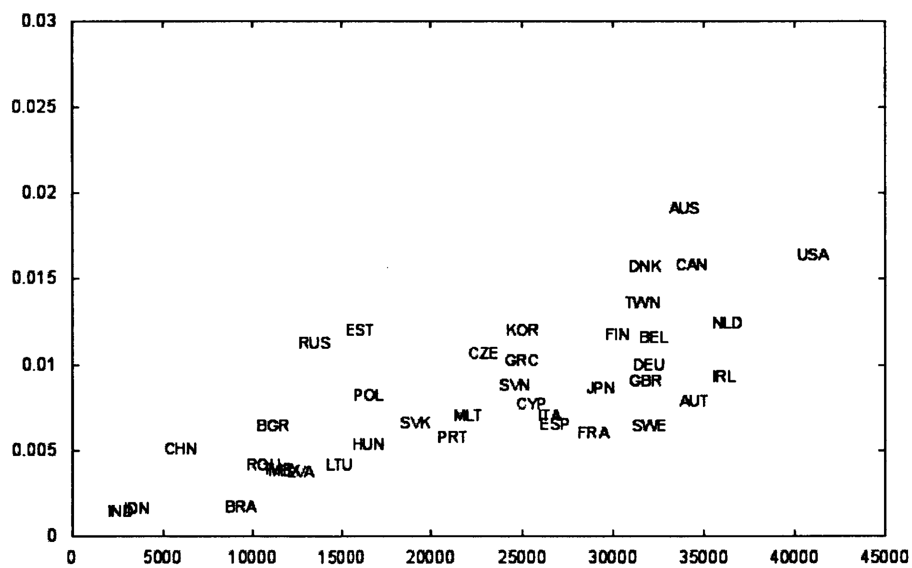
	PPP per capita[a]		GDP intensity[b]			Per capita emissions[c]		
Country	1995	2009	1995	2009	change	1995	2009	change
India	1,404	2,813	1.60	1.18	-0.42	0.88	1.42	0.54
China	1,849	6,206	2.86	1.53	-1.32	2.53	5.06	2.53
Indonesia	2,711	3,696	0.71	0.98	0.27	1.09	1.63	0.55
Latvia	6,182	12,902	0.94	0.44	-0.50	3.97	3.74	-0.22
Bulgaria	6,840	11,390	1.98	1.08	-0.90	7.53	6.46	-1.07
Romania	7,213	10,797	1.29	0.66	-0.63	5.74	4.15	-1.58
Lithuania	7,386	15,089	0.86	0.42	-0.44	4.49	4.17	-0.32
Brazil	7,716	9,468	0.31	0.30	-0.01	1.42	1.66	0.25
Russia	7,851	13,615	2.58	1.75	-0.83	10.81	11.22	0.41
Estonia	7,938	16,246	1.88	0.88	-1.00	12.61	11.99	-0.62
Turkey	8,711	11,655	0.48	0.47	-0.00	2.89	3.86	0.97
Poland	8,997	16,711	1.61	0.68	-0.93	9.53	8.23	-1.29
Mexico	9,846	11,936	0.45	0.42	-0.04	3.29	3.84	0.54
Slovak Republic	10,820	19,354	1.05	0.43	-0.62	8.34	6.61	-1.73
Hungary	11,691	16,710	0.63	0.33	-0.30	5.92	5.29	-0.63
Taiwan	15,075	31,840	0.62	0.56	-0.06	9.11	13.60	4.49
Czech Republic	15,746	23,077	0.96	0.55	-0.41	11.49	10.63	-0.86
Korea	15,761	25,299	0.64	0.44	-0.20	9.07	12.04	2.97
Slovenia	15,976	24,820	0.48	0.35	-0.13	7.48	8.81	1.33
Malta	17,072	22,204	0.35	0.32	-0.02	5.81	7.00	1.19
Portugal	17,521	21,376	0.31	0.27	-0.04	5.38	5.73	0.35
Greece	17,605	25,162	0.47	0.39	-0.08	8.27	10.25	1.97
Ireland	18,600	36,273	0.24	0.13	-0.11	9.74	9.29	-0.45
Cyprus	20,100	25,790	0.44	0.41	-0.03	6.34	7.68	1.34
Spain	21,022	27,083	0.29	0.22	-0.07	6.38	6.48	0.10
Finland	21,907	30,503	0.37	0.25	-0.12	11.85	11.77	-0.08
United Kingdom	24,007	32,026	0.30	0.20	-0.10	10.14	9.01	-1.12
Sweden	24,641	32,300	0.19	0.12	-0.07	7.14	6.39	-0.76
France	25,234	29,161	0.21	0.15	-0.06	6.79	5.97	-0.81
Italy	25,263	26,729	0.26	0.21	-0.05	7.93	7.03	-0.90
Australia	25,385	34,184	0.53	0.43	-0.09	16.95	19.07	2.12
Belgium	26,706	32,414	0.31	0.22	-0.09	12.99	11.58	-1.41
Austria	27,426	34,681	0.22	0.16	-0.06	7.65	7.82	0.17
Canada	27,778	34,527	0.48	0.39	-0.09	15.67	15.79	0.12
Germany	27,809	32,176	0.34	0.24	-0.10	11.63	9.98	-1.65
Japan	28,026	29,625	0.27	0.23	-0.03	9.11	8.63	-0.48
Denmark	28,054	31,961	0.30	0.27	-0.03	14.14	15.74	1.60
Netherlands	28,464	36,570	0.30	0.23	-0.07	12.49	12.41	-0.07
United States	33,874	41,188	0.51	0.36	-0.15	18.60	16.38	-2.22
Luxembourg	48,419	68,188	0.22	0.06	-0.16	18.96	9.77	-9.19

[a] Purchasing power parity in 2005 chained US dollars
[b] Emissions intensity in kilotons per million USD (2005 chained dollars)
[c] Emissions intensity in tons per capita
[a] Data source: World Input-Output Database; IMF World Economic Outlook Database, April 2012; World Bank Open Data.

U-shape when emissions is plotted against a region's wealth – due to increasing emissions production in poorer regions and increasing emissions abatement in richer countries [Stern et al., 1996, Selden and Song, 1994]. Support for a Kuznets curve in CO_2 emissions, however, has been mixed at best, with some studies finding positive evidence [Zaim and Taskin, 2000] and others being inconclusive [He and Richard, 2010] or highly sensitive to specifications, including whether emissions are consumption or production based [Aldy, 2005].

A simple plot of per-capita emissions against purchasing power parity (PPP), a measure of living standards (figure 2.1, using the sample of countries from the World Input-Output Database (WIOD), appears to say that either the Kuznets curve does not exist, or that the world is still on the increasing side of the inverted U.

Figure 2.1: Emissions intensity (kilotons per capita) vs. purchasing power parity (PPP) per capita, chained 2005 US dollars, 2009



Data source: World Input-Output Database, World Bank Open Data.

However, simple plots of emissions intensity with as emissions over GDP (a measure of production technology) versus PPP lend some support to the idea of technological convergence. In figure 2.2, not only do the countries emissions intensities appear to converge above a certain threshold of PPP (around $15,000), the overall range of emissions intensities in 2009 has also decreased while all countries in our sample were slightly richer. Even more interestingly, the change in emissions intensities over the 14-year period was much more similar among the countries with a PPP above $15,000 in 1995 than those below (figure 2.3).

We seek to understand the evolution of emissions in different countries, and to what extent the observed changes are due to different types of technological progress, or a shift in consumption toward less energy-intensive goods. We use a structural decomposition analysis using the input-output model to compare the relative impact of changes in inter-industry linkages, efforts within each industry to decrease emissions within the industry (we adopt the term "industrial efficiency" from Wood [2009] to represent per-industry decreases in emissions intensity independent of intermediate inputs), and changes in the mix of household consumption and exports. We also compare emissions intensities across countries for selected sectors with the largest contribution to global emissions.

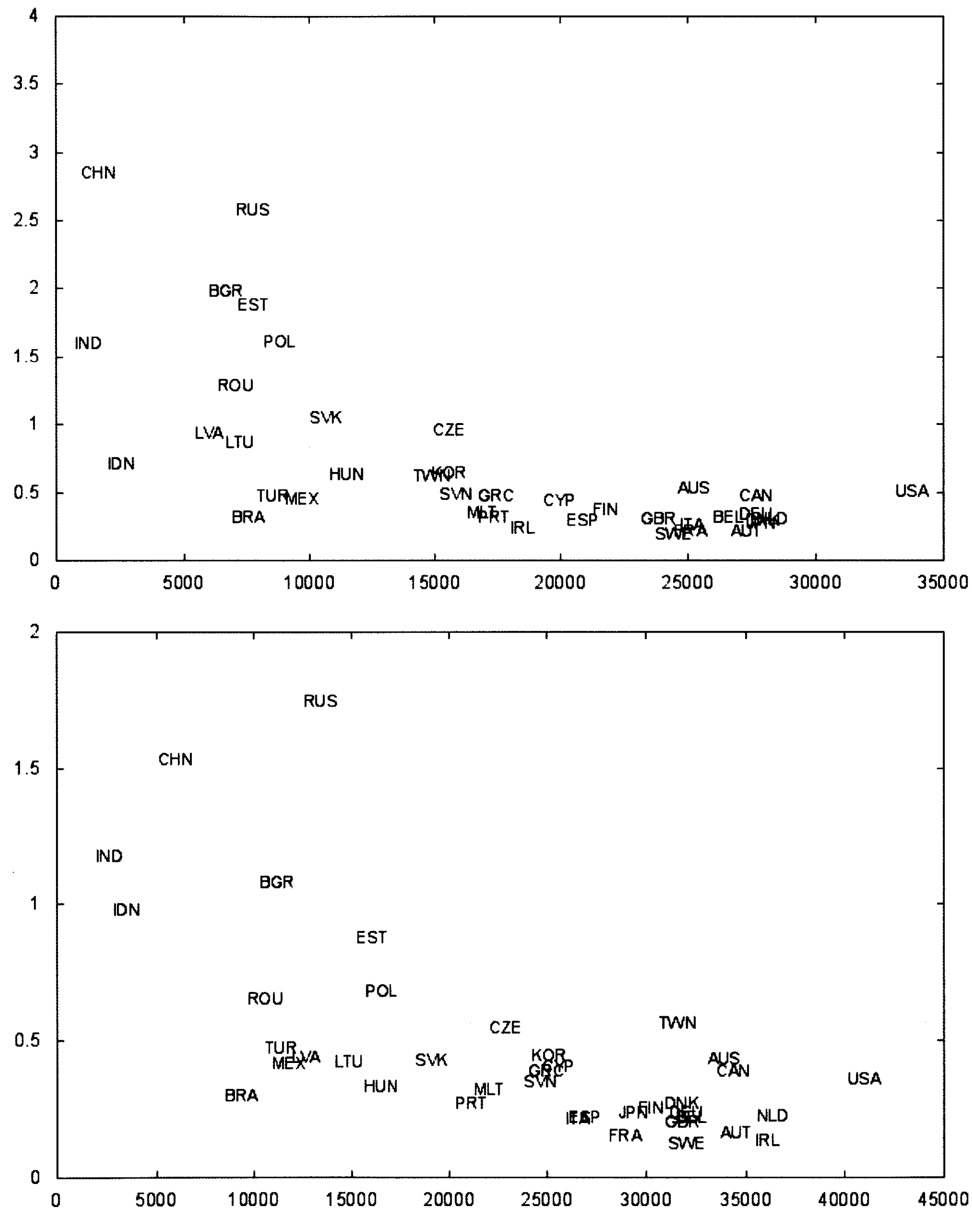
2.2 Hypothesis

Despite the elusiveness of a Kuznets curve for CO_2 emissions, the theory predicting it lends to some concrete hypotheses:

In all countries we expect the increase in emissions to be mostly due to increases in final demand. In general we also expect industrial efficiency to contribute negatively to both emissions levels and intensity. However, the offsetting effect of industrial efficiency should be larger in developed countries.

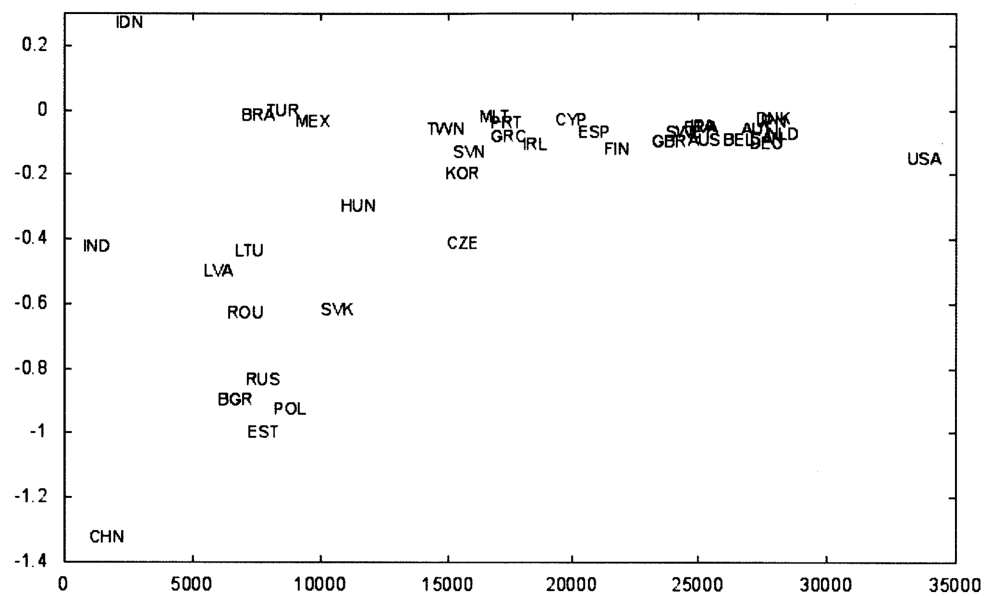
In developing countries, although we expect demand for energy-intensive goods to

Figure 2.2: Emissions intensity (kilotons per million dollars) vs. purchasing power parity (PPP) per capita, chained 2005 US dollars. Top: 1995; bottom: 2009.



Data source: World Input-Output Database, World Bank Open Data.

Figure 2.3: Change in emissions intensity 1995-2009 vs. 1995 purchasing power parity (PPP) per capita



Emissions intensity in kilotons CO_2 per dollar GDP, 2005 chained USD.
PPP in thousands, 2005 chained USD.
Data source: World Input-Output Database, World Bank Open Data.

increase with income, there is no reason for the *mix* of goods consumed to contain more energy goods than non-energy goods. Thus, emissions intensity changes on the household consumption side should mostly be attributable to changes in industrial efficiency and interindustry linkages. Developing countries may tend to specialize in energy-intensive exports, however, which would cause the export mix to contribute an increasing effect to emissions intensity.

In developed countries, which are able to afford more technologically advanced production and goods with more immaterial requirements, changes to the mix of household consumption may be reflected in a shift to the less emissions intensive service industries, so contributions to emissions intensity from household consumption mix are expected to be negative.

2.3 Related work

Comparative static analysis by way of structural decomposition of hybrid Leontief matrices is not unprecedented. Many similar studies were done on single countries over time periods before or in the beginning of WIOD coverage, and provide a fuller context for the results found in this paper.

Several studies, like ours, attempted to break down changes in emissions into components related to technology and final demand, though they have tended to be on single countries. China is one of the most studied countries for using structural decomposition analysis on environmental impacts. Lin and Polenske [1995] compares energy use in China between 1981 and 1987 while Garbaccio et al. [1999] compares 1987 to 1992. Lin and Polenske [1995] found changes in final demand to be the main force leading to increased energy use, while "changes in production technology... reduced the energy requirement." Examining per-yuan energy intensity changes, Garbaccio et al. [1999] found that technical change accounted for most of the decrease in energy intensity, with changes in demand working in the opposite direction.

Studies of other countries have generally found industrial efficiency to be the largest contributor to decreasing emissions levels, while final demand pushes emissions upwards. The impacts of interindustry linkages tend to be mixed. Wachsmann et al. [2009] studied CO_2 emissions in Brazil between 1970 and 1996, finding that both final demand and inter-industry linkages have a positive impact on energy use and energy-related CO_2 emissions, while industrial efficiency had a negative impact. Chang et al. [2008] did a study of fuel-based CO_2 emissions in Taiwan for three five-year periods between 1989 and 2004, finding that industrial efficiency contributed to larger and larger decreases in emissions throughout the three periods, while industry linkages contributed negatively for the first two periods and positively for the last. The analysis by Sue Wing [2008] covers the United States from 1958 to 1998, a long period of time in which the primary contributor to declining energy intensity shifted from “inter-sectoral structural change” to “intra-sectoral efficiency change”. Lim et al. [2009] found “industry structure” to have small contributions to CO_2 emissions in Korea from 1990 to 2005, with signs that varied depending on the years chosen, although industrial efficiency and final demand mix did not show downward contributions until after 1995. Wood [2009] study Australia’s emissions between 1976 and 2005, consistently finding a negative impact from industrial efficiency, industry linkages, and final demand mix, although the size of the impact decreased over time. Zhang [2012] also found sector energy intensity to be the predominant downward force against growing carbon emissions in China, spurred by increasing final demand, with input mix having different results over different years between 1987 and 2007.

The key takeaway from preceding structural decomposition studies is that the opposing forces of increasing final demand and decreasing industrial emissions intensity have so far always yielded to final demand, despite a wide variation in each country’s individual numbers. In our analysis, by decomposing many countries’ data at once, we seek to compare the differences in in technology, input mix, and final demand trends across countries for a better understanding of the geography of emissions production.

Our method of multiplying final demand with production technologies of different years is very similar to the method used in Lin and Polenske [1995]. Unlike their approach we separate per-sector intensity from final demand by assuming energy and emissions are directly proportional to total output. Similar methods are used in Lim et al. [2009], Kagawa and Inamura [2001], Jacobsen [2000], Chang et al. [2008].

Garbaccio et al. [1999] present a follow-up study to Lin and Polenske [1995] using Divisia approximations, which unlike Lin and Polenske [1995] and our study, are not sensitive to the choice of base year. Divisia indices are used by structural decomposition studies of energy use by Wachsmann et al. [2009], Wood [2009], Weber [2009], Sue Wing [2008] mentioned above. Wood [2009] also decomposed the Leontief matrix into forward linkages, backward linkages, and industrial structure, although his results focus mainly on the offsetting effects of industrial efficiency and inter-industry linkages overall.

Many of the papers include detailed methodological descriptions about the process of converting data sources into usable forms, ranging from the attainability of trustworthy data [Garbaccio et al., 1999] to the construction of rectangular input-output tables from "make" and "use" tables [Kagawa and Inamura, 2001]. Some similar processes were covered in the appendix of Chapter 1. While the construction of usable data forms involves certain assumptions (e.g. commodity-based technology vs. industry-based technology), which are incorporated into the WIOD data, the WIOD data provides the appealing option of foregoing the painstaking and error-prone process of making data compatible with models.

Compared to most of the works cited, our method is relatively simple. We only decompose energy or emissions change into three factors at a time: final demand, within-sector intensity, and inter-industry linkages. We present our results mainly as graphs so that the relative contribution of each component can be clearly illustrated.

2.4 Data sources and methodology

The main data source is the National Input-Output Tables (NIOT) and the Environmental Accounts from the World Input-Output Database. The NIOT accounts were last updated for most countries in January 2012, with the remaining minority updated in February 2012. All environmental accounts were last updated and released to the public in May 2012.

2.4.1 Caveats in data interpretation

The environmental accounts were the latest dataset to be completed in the WIOD, and in many cases it is ostensibly incomplete, with missing values for the measurements required in our analysis. The following list documents the deficiencies in the data from visual inspection. Depending on the degree of the deficiency, some countries' data cannot be used to draw realistic conclusions.

- Half the sectors in Luxembourg are missing CO_2 data starting from 2000.
- Most service sectors in Slovenia are missing CO_2 data for all years.
- All transport-related sectors in Malta except inland transport are missing CO_2 data for all years.
- Wholesale and retail trade are missing CO_2 data for all years in Sweden. Leather and footwear is also missing in 2009, although emissions for this sector are very low in all prior years.
- All emissions data are missing from all years for the supporting and auxiliary transport activities sector in Hungary, and water transport is missing emissions data starting from 2004.
- The leather and footwear sector in Finland is missing CO_2 data starting from 2004; however, the emissions quantity steadily decreased in prior years and was 0.4 kilotons out of a total of 68,140 for the country's emissions from intermediate consumption. Data for the hotel and restaurant sector, which accounts for just above 1% of total output, is missing for all years.
- Data are missing from both the input-output and environmental accounts for the coke, refined petroleum, and nuclear fuel sector in Latvia in 2009.
- Netherlands is missing emissions data for the leather and footwear sector for all years. The leather and footwear sector accounted for about 0.1% of Netherlands'

total output in all years of the study period.

Based on these points, we will discard Luxembourg, Slovenia, Malta, and Hungary from the remainder of the analysis in this paper. Results for Finland, Sweden, Latvia, and Netherlands must be interpreted with these caveats taken into account.

2.4.2 Structure of imports in WIOD data

For symmetric input-output tables we use the National Input-Output Table (NIOT) series in the WIOD. Unlike most symmetric I-O tables that account for imports as a negative column in final demand, the NIOT tables separate imported intermediate inputs to each industry from domestic inputs, making imports collectively an addend to value added. To illustrate, the conventional I-O matrix looks like

$$\left[\begin{array}{c|c} Z & Y \\ \hline V & \end{array}\right]$$

where Z is intermediate transactions, Y is final demand, and V is value added. Y includes household consumption, governemnt consumption, etc., as well as exports and imports. Imports are recorded as negative values, so that when summing all columns in Y, one is left with the total domestic output of each good.

The NIOT structure looks like

$$\left[\begin{array}{c|c} Z_d & Y_d \\ \hline Z_i & Y_i \\ \hline V_d & \end{array}\right]$$

where Z_d is intermediate transactions with domestic inputs, Y_d is domestic final demand of domestic inputs, Z_i is intermediate transactions with imported inputs, Y_i is domestic final demand of imported products, and V_d is value-added of domestic inputs. The structure of Z_d and Z_i are the same, and the structure of Y_d and Y_i are the same.

To determine how to construct a Leontief matrix from these data, in the conventional case we have

$$\mathbf{x} = Z\mathbf{e}_{||} + Y\mathbf{e}_{||}$$

where $\mathbf{e}_{||}$ is a column vector of ones (multiplying a matrix M by $\mathbf{e}_{||}$ creates a vector that is the sum of all columns in M).

In the NIOT version, the following equation is equivalent to the above:

$$\mathbf{x} = Z_d\mathbf{e}_{||} + Y_d\mathbf{e}_{||} \tag{2.1}$$

This is because while the negative column of imports is not included in Y_d, the sum of values in Z_d are smaller exactly by the amount that is imported for each good. We can decompose Equation 2.1 as

$$\mathbf{x} = (Z_d + Z_i)\mathbf{e}_{||} + (Y_d + Y_i)\mathbf{e}_{||} - (Z_i\mathbf{e}_{||} + Y_i\mathbf{e}_{||})$$

The last term in parentheses is the same as the import column in final demand.

Thus, to construct a Leontief matrix using data in the NIOT, the matrix is simply

$$L = (I - A_d)^{-1}$$

where A_d is $Z_d diag(\mathbf{x})^{-1}$.

2.4.3 Structural decomposition

The standard Leontief identity for an output vector $\mathbf{x}$, technical coefficient matrix A, and final demand vector or matrix $\mathbf{y}$ is

$$\mathbf{x} = (I - A)^{-1}\mathbf{y}$$

We use L to represent the Leontief matrix $(I - A)^{-1}$.

Consumption of energy and production of emissions by each industry is represented in satellite tables as another form of value-added [Erumban et al., 2012]. We assume energy inputs and emissions are directly proportional to industry output, in the same manner as all other intermediate inputs in the I-O framework. For each embodied measurement, CO_2 for example, create an intensity vector we call $\mathbf{j}$, which is (for example) tons of CO_2 divided by total output for each industry.

When estimating the marginal impact on output of a small change in consumption, it is common to use this approximation:

$$\Delta\mathbf{x} \approx L\Delta\mathbf{y}$$

The change in emissions, assumed to be directly proportional to the change in $\mathbf{x}$, is thus

$$\Delta\mathbf{j} \odot (L\Delta\mathbf{y}) \tag{2.2}$$

where $\odot$ represents element-wise multiplication.

2.4.4 Counterfactuals

The approximation in Equation 2.2 includes three variables: the intensity vector $\mathbf{j}$, the direct and indirect industry linkages L, and the final demand vector $\mathbf{y}$. We construct counterfactuals by holding all but one of these variables constant. For example, a counterfactual emission value $\mathbf{e}_t$ at year t obtained by varying intensity would be

$$\mathbf{e}_t = \mathbf{j}_t \odot (L_0 \Delta \mathbf{y}_0)$$

where L_0 and $\Delta \mathbf{y}_0$ are the Leontief and marginal final demand variables for the base year.

Marginal final demand vectors are normalized vectors that sum to one dollar where the value for each industry is the share of that industry in total final demand. We construct separate marginal vectors for household consumption (PCE) and gross exports.

Note that normalizing all final demand vectors shows changes only due to the substitution effect between goods while completely ignoring the income effect. We choose to normalize final demand for the most part because we assume consumption of embodied energy and emissions is always positively related with income. We include results using final demand levels (rather than shares) where noted.

2.5 Results

In the first part of this section, we present the results of decomposing domestic emission levels and intensities into contributions from the structure of industry linkages, efficiency improvements within each industry, and levels and mix of final demand. In our result we isolate the two largest components of domestic final demand: household consumption and exports.

In the second part, we selectively examine changes across countries in the most emissions-intensive industry sectors to determine shifts in specialization in these industries.

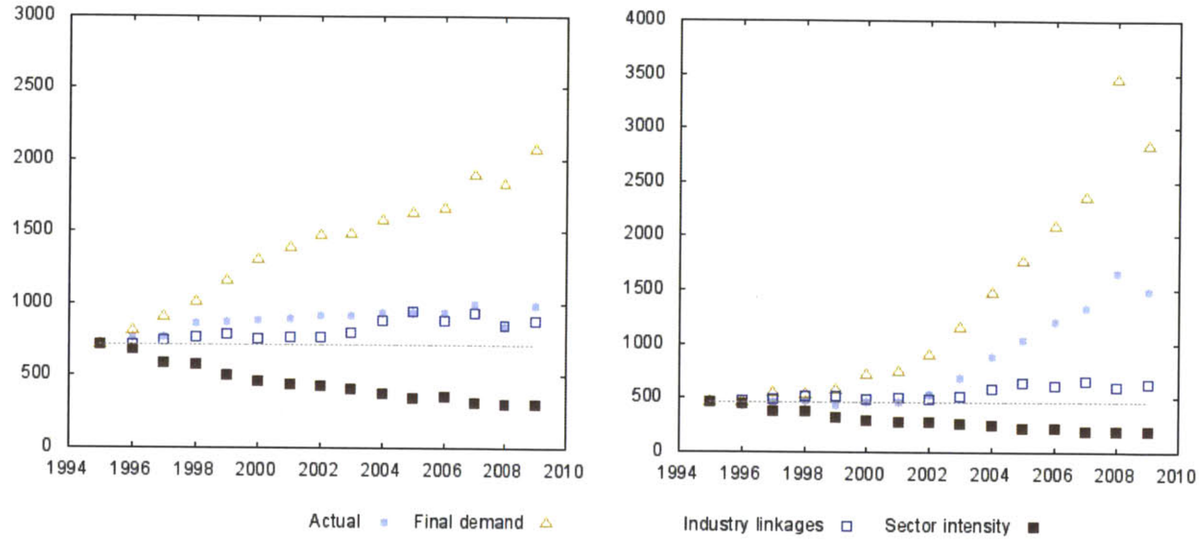
2.5.1 Counterfactuals of decomposed series

We begin with an example of a full time series to demonstrate its interpretation. The components that affect changes in emissions are final demand, industry linkages, and sector intensity which is the reverse of industrial efficiency. If the series where changes are isolated to sector intensity is increasing, this means industries themselves are becoming less efficient in the process of producing their own goods. If the series where changes are isolated to industry linkages is increasing, this means direct energy inputs are being substituted for non-energy inputs in the production process [Wood, 2009]. If the series isolating final demand is increasing, this means consumers (households or trading partners) are purchasing more embodied energy. For emissions intensity decompositions, the final demand component means a larger representation of emissions-intensive goods in the mix of goods consumed.

Figure 2.4 shows an example of a time series of CO_2 emissions in China decomposed into changes due to industrial efficiency, input structure, and final demand. Household consumption and exports are treated as separate partitions of the economy. Figure 2.5 shows the decomposition of CO_2 emissions intensity in China per dollar of final demand, where the series isolating changes in final demand represent the mix of final demand.

Figure 2.4 shows that industrial efficiency (the series named "Sector Intensity") was steadily contributing to decreasing emissions embodied in both household consumption and exported goods in China over the 14-year period. These decreases were more than

Figure 2.4: Counterfactual estimates of CO_2 emissions (million tons) in China at base year 1995.



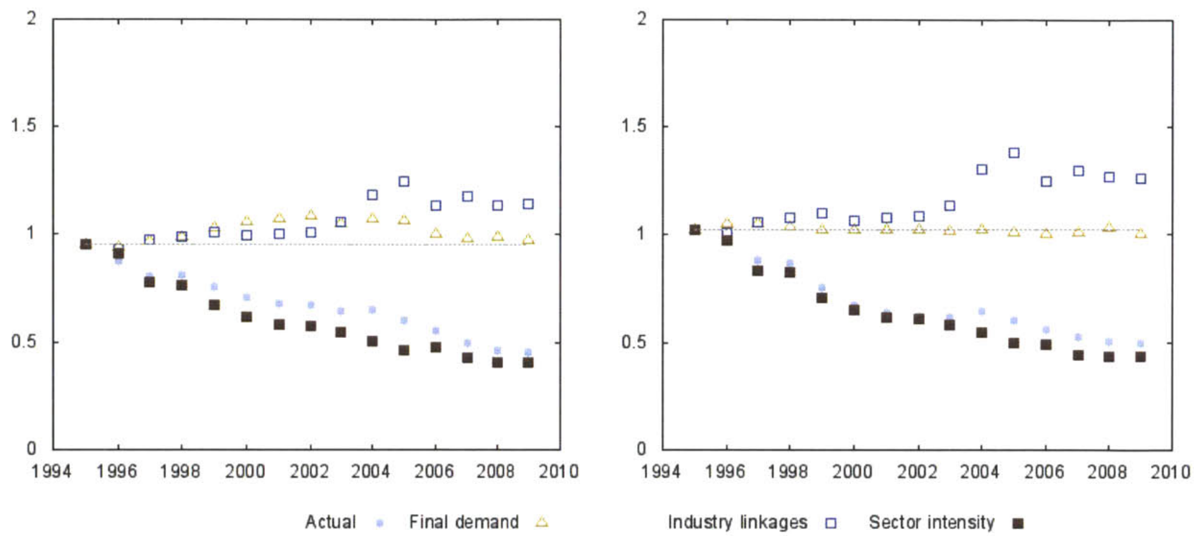
Left: household consumption; right: exports.
Data source: World Input-Output Database, author's calculations.

offset by the emission increases due to final demand changes. In the case of household consumption, increased final demand combined with decreased sector intensity and a smaller increase in the energy intensity of intermediate inputs led to a small increase (37% over 1995 levels by 2009) in CO_2 emissions. In the case of exports, the increase in emissions due to final demand was much larger. Although the interindustry linkage structure appears to have become less efficient in the early 2000s, its impact was overshadowed by the large changes in final demand and industrial efficiency.

The changes due to interindustry linkages in China are more apparent in Figure 2.5, which presents emissions intensities per dollar of final demand instead of levels. The increase in energy intensity that would have resulted from changes in the interindustry linkages alone are more than offset by the decreases resulting from industrial efficiency. Contrary to our hypotheses, neither the mix of household consumption nor exports has a visible positive or negative impact on emissions intensity.

The figures in the rest of this section show the relative contributions to emissions

Figure 2.5: Counterfactual estimates of CO_2 emissions intensities (kilotons per million dollars) in China at base year 1995.



Left: household consumption; right: exports.
Data source: World Input-Output Database, author's calculations.

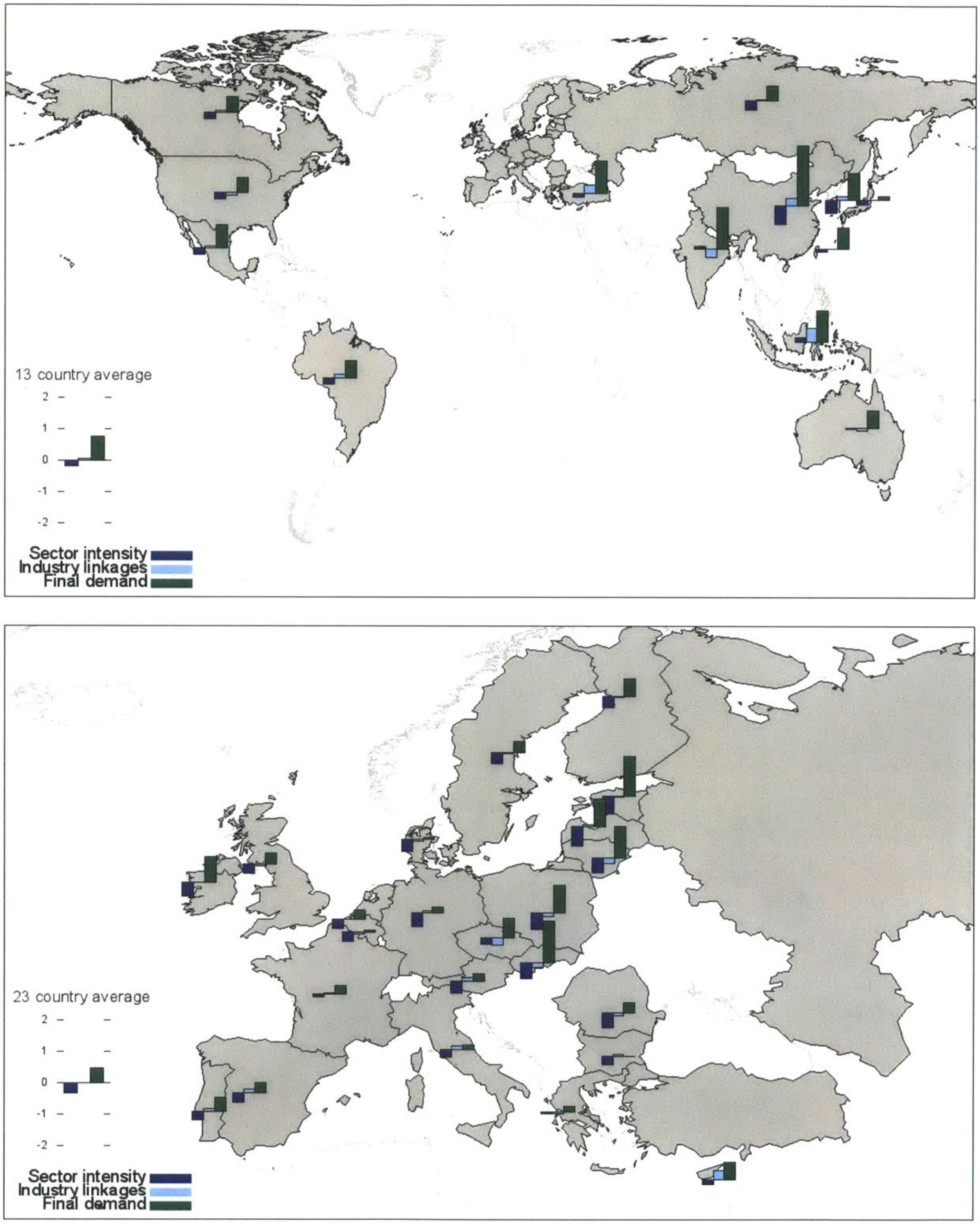
growth from final demand, final demand mix, and industrial efficiency. Contributions from interindustry linkages are not shown due to space constraints, but these and more detailed statistics for the structural decomposition results can be found in Tables 2.14 through 2.17 in the Appendix. We sort the data in Tables 2.14 through 2.17 by 1995 PPP so that the reader may note similarities based on living standards.

Figure 2.6 shows changes in emissions levels associated with household consumption of domestic products. Figure 2.7 shows the analogous breakdown using emissions intensities instead of levels. Although total emissions levels have gone up in most countries, emissions due to household consumption have actually decreased in about half the countries in our sample. With the exception of Japan, these countries are all members of the European Union, and primarily the richest countries. This set of countries where emissions from household consumption decreased also largely overlaps with the countries that committed to the strictest emissions target in the Kyoto Protocol (8% below 1990 levels), with the exceptions of Slovakia, Portugal, and Finland whose household consumption-based emissions did not decrease, and Japan and Poland who committed to slightly less stringent emissions targets. Also noteworthy is the EU Emissions Trading Scheme, a CO_2 trading program that began in 2005 and includes all countries shown in the bottom half of Figures 2.6 and 2.7. The upward force of final demand is visibly lower in the EU countries than the non-EU countries.

The largest downward contributions to emissions, as expected, were generally from improved industrial efficiency. Contributions from changes in interindustry linkage structure were for the most part largely overshadowed by industrial efficiency (generally negative) and final demand (always positive), although some countries including India, Romania, Lithuania, Poland, Czech Republic, and Ireland experienced some sizable decreases in emissions intensity due to industry linkages, implying a general shift to less emissions-intensive raw inputs. The largest upward contributions from final demand (where increases in household consumption of all goods would contribute an increase over 80% to 1995 emissions levels) took place in China, India, Slovakia, Estonia, Turkey, Brazil, Indonesia, Latvia, Poland, and Korea; these countries are notably all in the lower half of the 1995 PPP rankings of our sample.

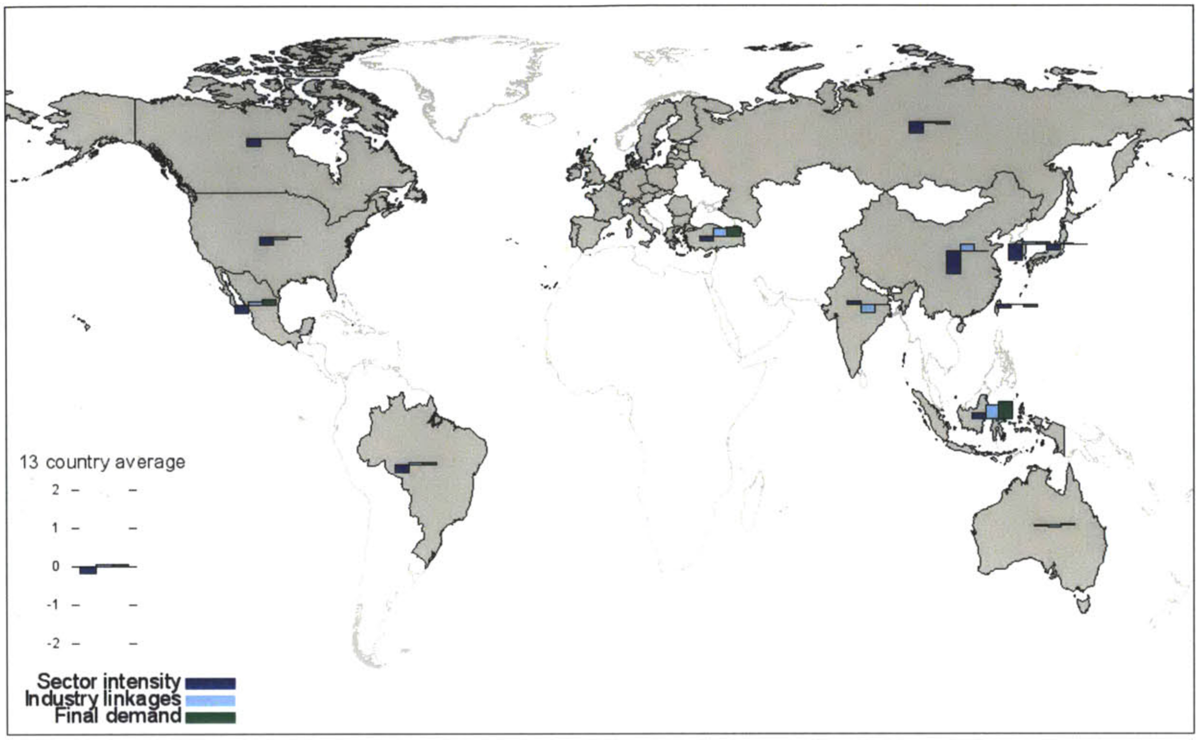
One explanation for a decline in emissions levels due to household consumption is that the mix of domestic goods sold to domestic consumers has become less energy intensive. For example if all service industries are produced and consumed locally, and all other goods traded, this could result in very low emissions from consumption of domestic goods. Table 2.15 (page 104), which breaks down energy intensity per dollar of household consumption of domestic products, shows that the mix of final demand contributed negatively to emissions intensity in several of the countries where emissions levels decreased: Greece, Ireland, Spain, United Kingdom, Belgium, Austria, and Denmark, suggesting that these countries avoided domestic emissions by switching domestic consumption to non energy-intensive goods. However, the large negative

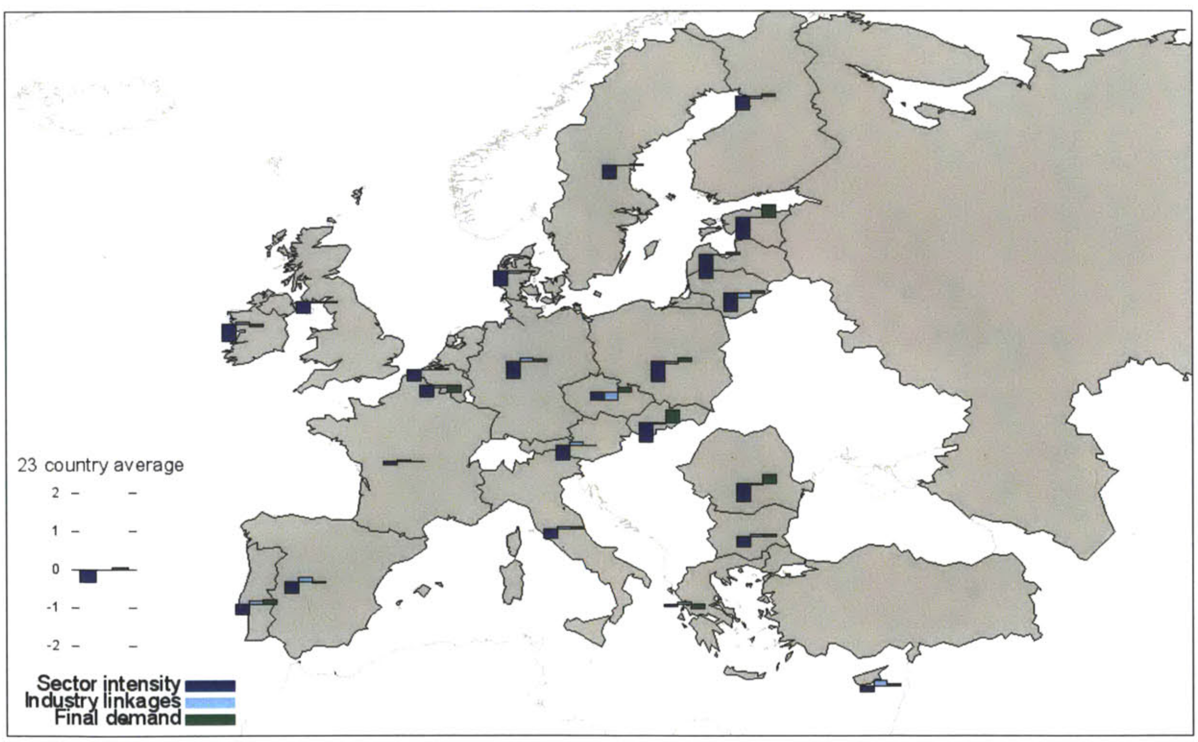
Figure 2.6: Contributions of sector intensity, industry linkages, and final demand to growth of CO_2 emissions embodied in household consumption of domestic products, 1995-2009. Top: non-EU countries, bottom: EU countries.



Data source: World Input-Output Database, author's calculations. Geographic boundary data from ESRI.

Figure 2.7: Contributions of sector intensity, industry linkages, and final demand to growth of CO_2 emissions intensity per dollar of household consumption of domestic products, 1995-2009. Top: non-EU countries, bottom: EU countries.





Data source: World Input-Output Database, author's calculations. Geographic boundary data from ESRI.

Table 2.2: Household consumption satisfied by imports, ranked by share of imported household consumption as a share of total household consumption.

	Imports (MM$)		Share (%)			Imports (MM$)		Share (%)	
Country	1995	2009	1995	2009	Country	1995	2009	1995	2009
Malta	1,030	1,536	36.5	37.2	UK	106,995	201,924	10.4	13.8
Luxembourg	3,706	4,818	37.5	36.7	Germany	136,791	222,804	9.9	13.6
Slovakia	2,555	8,360	15.7	24.1	Finland	6,992	13,333	10.4	13.0
Slovenia	2,875	5,106	20.4	24.0	Poland	7,965	26,954	6.7	12.1
Ireland	11,883	23,169	22.9	23.8	Taiwan	18,801	28,563	13.7	11.9
Estonia	1,006	1,648	27.2	23.5	Romania	4,300	8,062	7.5	11.6
Belgium	39,114	46,948	24.2	23.5	Greece	11,618	20,012	9.1	11.0
Lithuania	2,078	4,177	22.7	22.5	France	95,320	133,321	10.0	10.8
Czech Rep.	8,399	14,094	18.0	20.2	Spain	35,379	70,675	7.6	10.7
Netherlands	47,364	60,645	19.7	20.0	Australia	23,656	44,567	7.9	9.8
Hungary	3,855	11,350	9.3	19.9	Italy	68,151	92,030	7.6	8.9
Cyprus	1,883	2,359	24.5	18.6	Korea	14,479	42,000	5.2	8.1
Austria	19,842	31,032	15.3	18.4	Mexico	20,579	45,142	5.6	7.9
Latvia	851	1,665	16.2	17.8	China	16,557	67,966	4.1	5.8
Denmark	17,428	21,257	16.4	17.5	Japan	81,765	127,284	3.8	5.1
Bulgaria	1,361	3,340	8.1	17.3	Indonesia	7,618	9,965	5.3	4.9
Sweden	15,400	29,752	11.6	16.5	USA	261,448	442,228	4.3	4.9
Russia	45,871	75,906	15.5	16.2	Turkey	5,121	18,148	2.1	4.4
Portugal	12,130	18,977	13.2	15.6	Brazil	12,868	17,751	3.0	2.8
Canada	72,081	101,055	15.5	14.8	India	6,366	19,117	2.2	2.8

[a] Data source: World Input-Output Database. Import amounts in 2005 chained U.S. dollars.

components of sector intensity in Sweden, Germany, Ireland, and Denmark may also be achievements of switching to cleaner power generation, which we discuss in a later section.

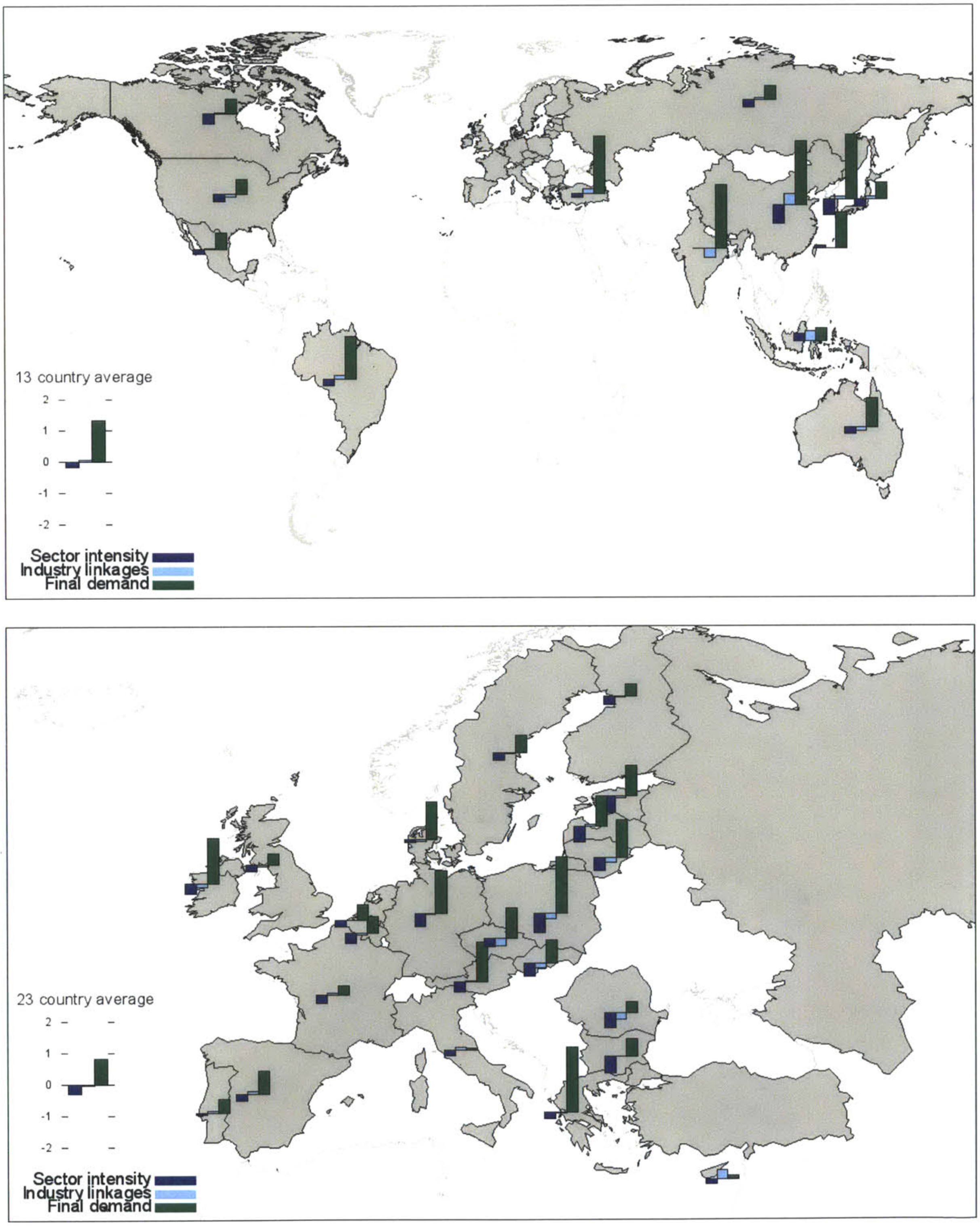
There were still several countries where the mix of domestic consumption became more energy-intensive, despite decreasing corresponding emissions levels. Besides Germany, Japan, Italy, France, and Sweden, these countries are all in Eastern Europe (Czech Republic, Poland, Estonia, Lithuania, Romania, Bulgaria, Latvia) on the lower half of the PPP spectrum.

That the final demand mix contributed positively to emissions intensity in lower income countries was expected by our hypothesis. That emissions levels would decrease despite a more energy-intensive final demand mix can have a number of reasons, including: very strong decreases in sector intensity (true for example in Latvia, Lithuania, Romania, Estonia, Poland, and Germany); slow GDP growth (Japan and Italy's GDP grew respectively by 0.7% and 0.9% annually, the slowest of the sample, followed by Germany and France at 1.6% and 1.9%); or an increase in the share of household consumption satisfied by imports (Poland, Bulgaria, Sweden, and Germany all greatly increased their share of imports – see Table 2.2).

In contrast to household consumption, changes in emissions levels due to exports (Figure 2.8, details in Table 2.16) tell a less optimistic story. Only a third of the countries in our sample saw decreases in emissions levels associated with exports; a handful (China, Brazil, Turkey, Taiwan, and Denmark) saw increases of over 100% above 1995 levels. Final demand was the main culprit; it appears that exports have generally grown more than household consumption. In the next two tables we examine whether exports have also grown in more emissions-intensive ways than household consumption.

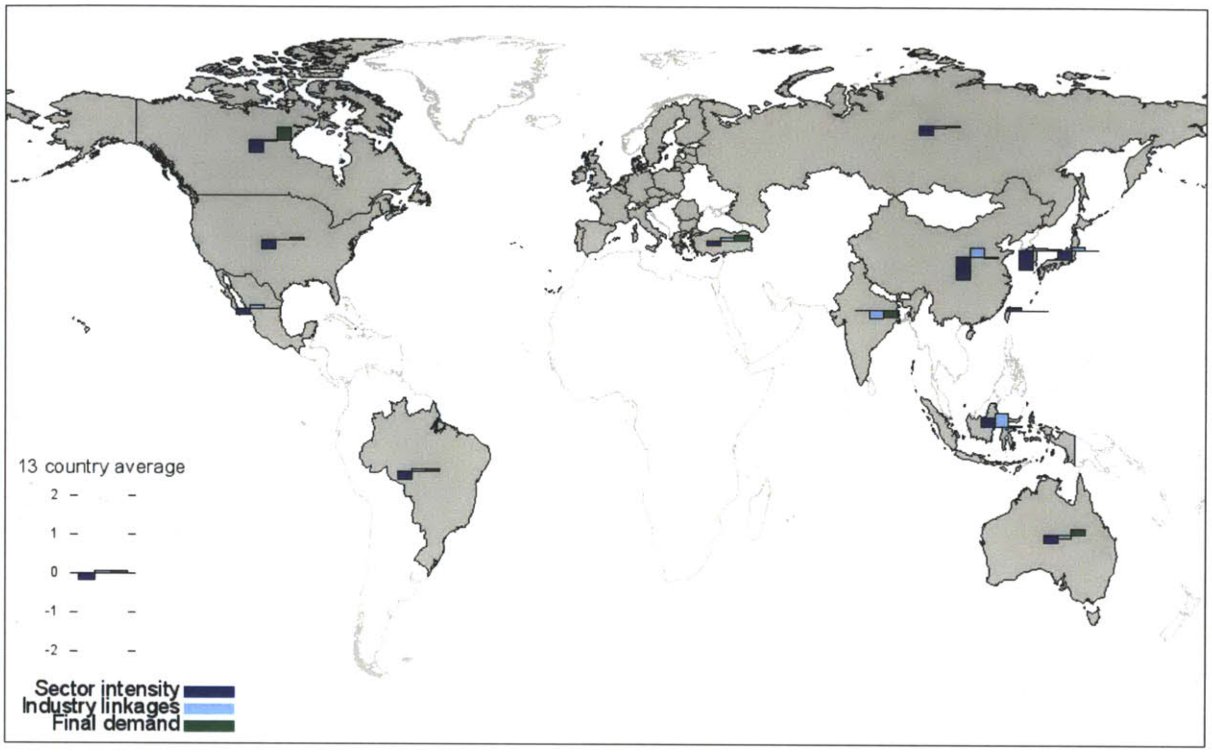
Figure 2.9 (details in Table 2.17) shows changes in emissions intensity associated with exports. Increased overall emissions intensity is seen in a number of locations not

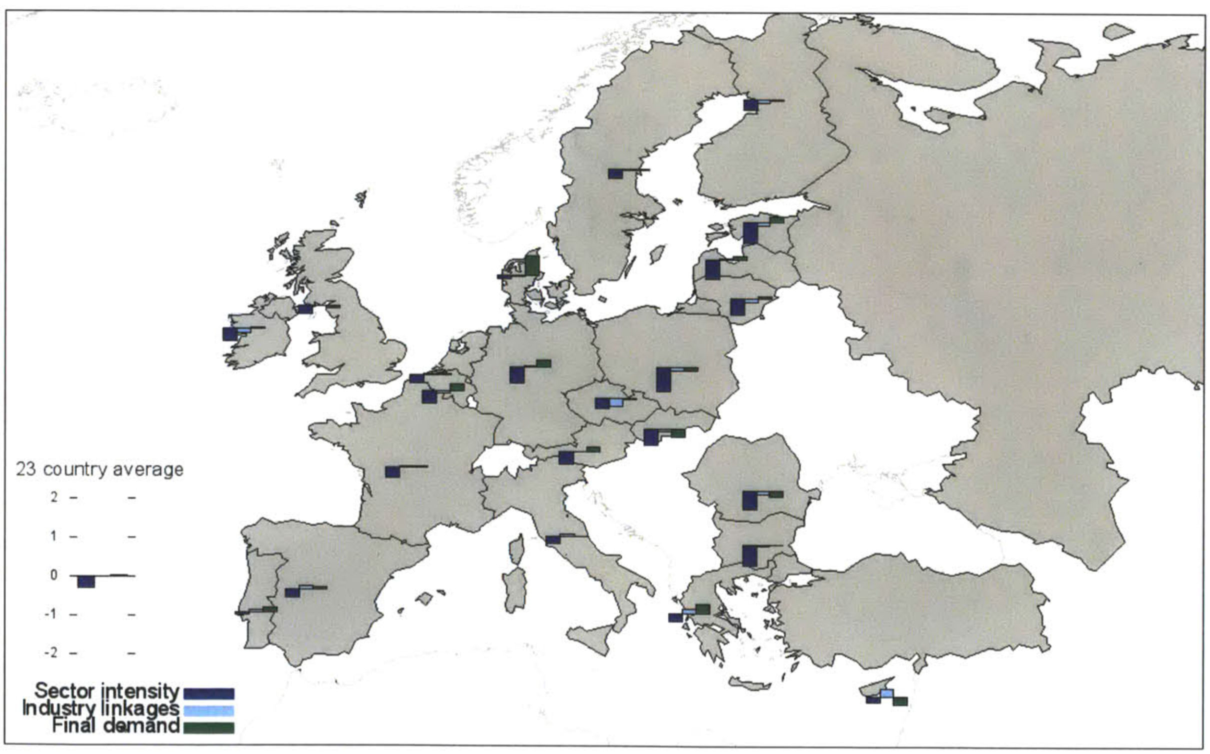
Figure 2.8: Contributions of sector intensity, industry linkages, and final demand to growth of CO_2 emissions embodied in exports, 1995-2009. Top: non-EU countries, bottom: EU countries.



Data source: World Input-Output Database, author's calculations. Geographic boundary data from ESRI.

Figure 2.9: Contributions of sector intensity, industry linkages, and final demand to growth of CO_2 emissions intensity per dollar export, 1995-2009. Top: non-EU countries, bottom: EU countries.

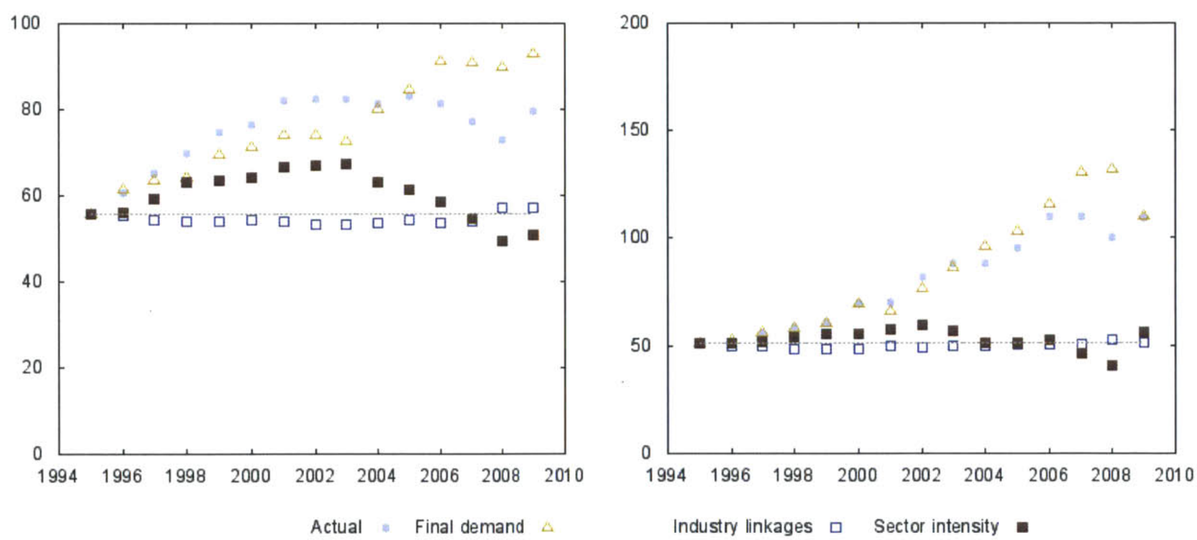




Data source: World Input-Output Database, author's calculations. Geographic boundary data from ESRI.

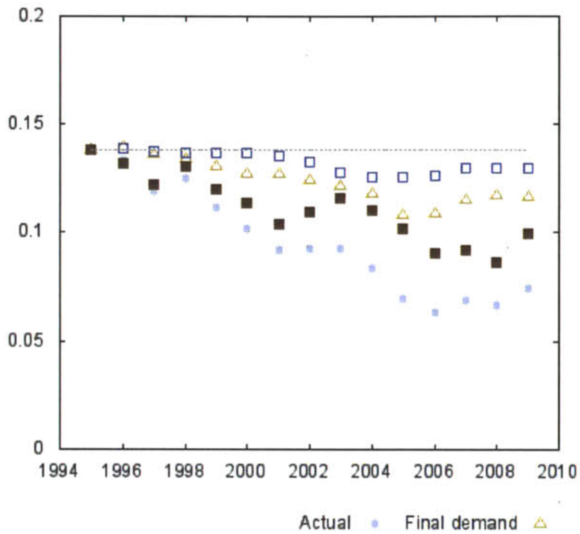
mentioned before: Taiwan, Portugal, and Denmark. In the latter two, the change is driven primarily by final demand, whereas in Taiwan the industrial efficiency for exported goods has become worse, unlike almost all other countries. One possible explanation is that the global recession in 2009 led to temporary or permanent structural shifts in the industrial landscape. Exports from Taiwan fell sharply in 2009 as a result of the recession, as seen in Figure 2.10, following a trend through 2008 that appeared to consist of falling sector intensity and increasing final demand; this trend is echoed in other export-oriented countries (see Figures 2.4 and 2.14). However, we also have reasons to believe that the environmental data for Taiwan in the WIOD are uniquely inaccurate (see section 2.6), despite being complete.

Figure 2.10: Counterfactual estimates of CO_2 emission levels in Taiwan at base year 1995. Left: household consumption; right: exports.



Contrary to our hypothesis, countries where the mix of exports contributed to an increase or decrease in emissions intensity appears unrelated to whether the country is developing or not. A closer look at the full time series is somewhat revealing. The graphs of Austria (Figure 2.12), Belgium (Figure 2.11, and Japan (Figure 2.13) show that sometime in the early 2000s these three countries suddenly started to specialize in emissions-intensive exports, while the industrial efficiency of exported goods simultaneously decreased.

Figure 2.11: Counterfactual estimates of CO_2 emission intensities in Belgium at base year 1995. Left: household consumption; right: exports.



A common characteristic of these three countries is that they each have large automotive industries, which are recorded as large exports in the transport equipment sector. Transport equipment was the second largest exporting industry in Belgium until 2005, after which the metal industry – another emissions intensive industry and a large input to the transport equipment sector – became second. Chemicals was the top exporting sector for all years.

In Austria, transport equipment exports increased sharply between 2001 and 2004, bringing it from the second to the largest export sector. Similarly in Japan, electrical equipment was the top export sector followed closely by transport equipment until 2006, when transport equipment exceeded the electrical equipment sector.

In Germany, where transport equipment was by far the largest export sector across all years, we see a similar graph (figure 2.14) where the product mix of exports contributed to increasing emissions intensity beginning in the early 2000s, coupled with a slightly accelerating decrease in sector intensity. cfact-co2-DEU

Figure 2.12: Counterfactual estimates of CO_2 emission intensities in Austria at base year 1995. Left: household consumption; right: exports.

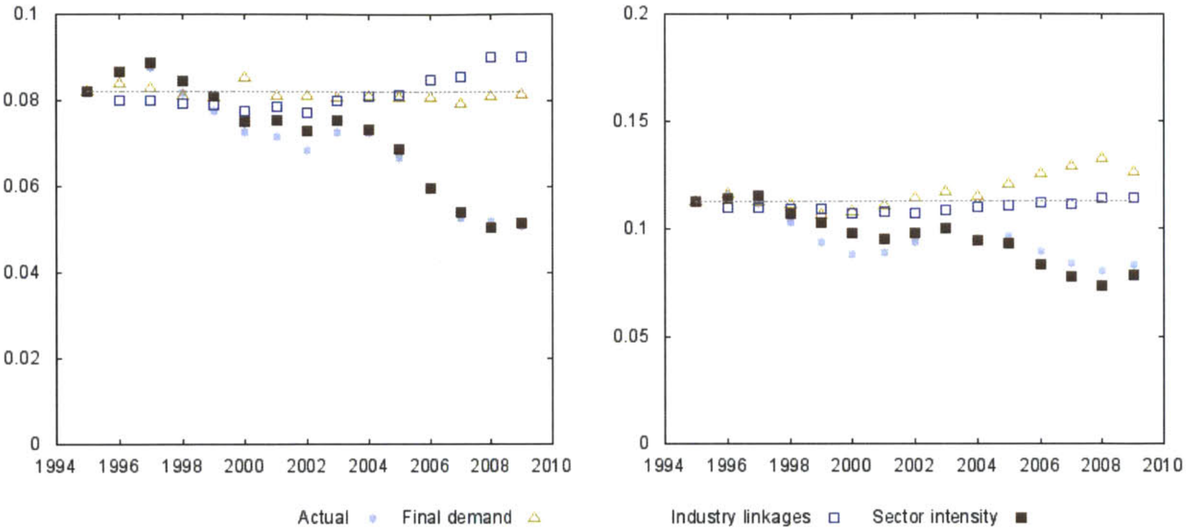


Figure 2.13: Counterfactual estimates of CO_2 emission intensities in Japan at base year 1995. Left: household consumption; right: exports.

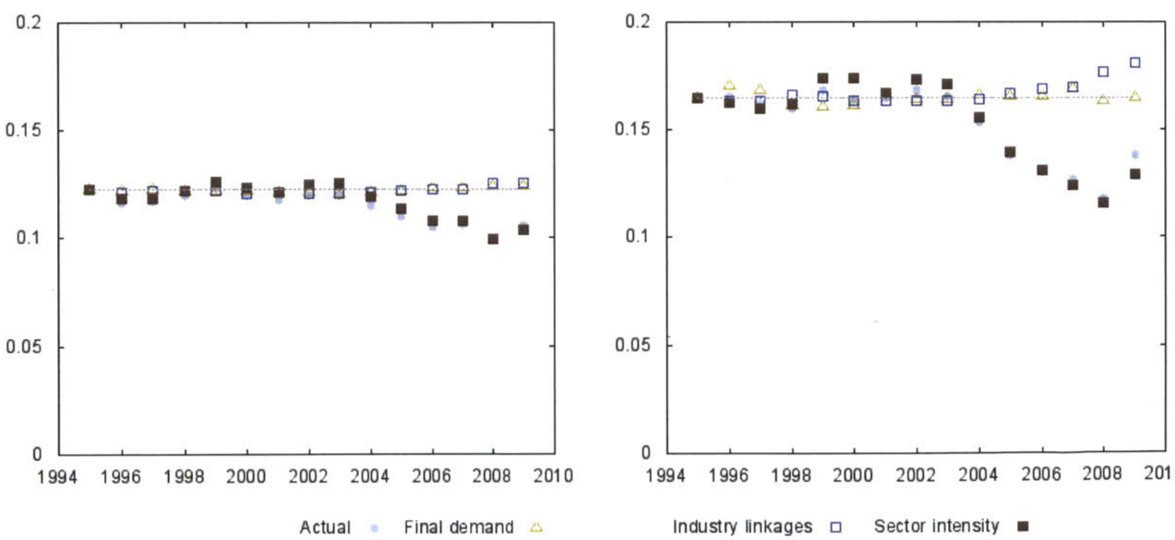
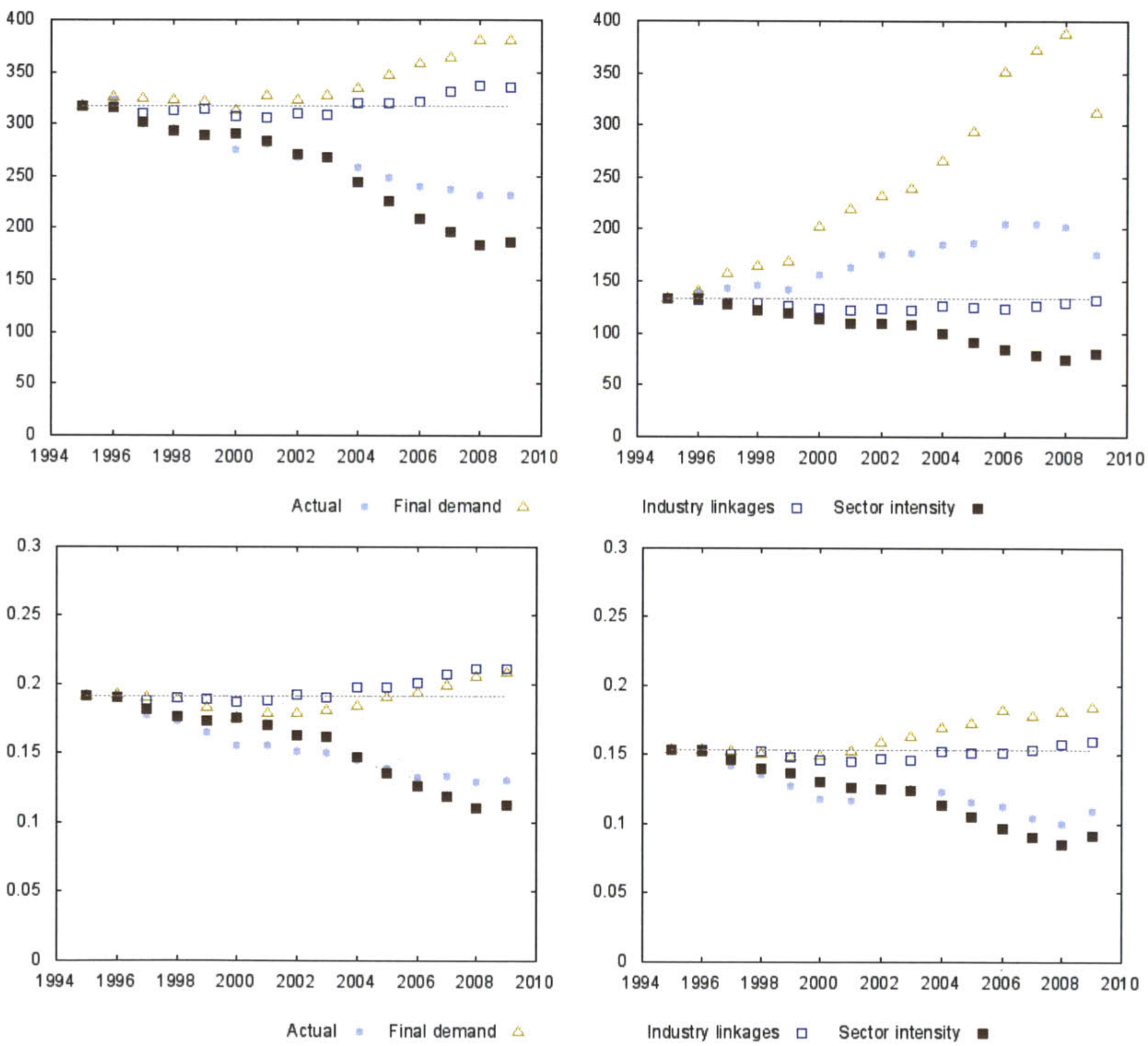


Figure 2.14: Counterfactual estimates of CO_2 emissions in Germany at base year 1995. Top row: emissions levels; bottom row: emissions intensities. Left column: household consumption; right column: exports.



The explanation for the changes in these countries simply appears to be a worldwide increase in motor vehicle demand, which experienced a growth spurt after 2001. Foregoing exchange rate and GDP calculations, we estimate from WIOD data that worldwide sales (not necessarily final demand) of motor vehicles increased from 1.885 trillion nominal dollars in 1995 to 2.182 trillion nominal dollars in 2000, but grew over the next five years to 3.113 trillion in 2005.

2.5.2 Emissions by industry sector

In this section we examine CO_2 emissions levels by industry sector across all countries in our sample. Emissions figures presented in this section come directly from raw WIOD data; intensities are kilotons CO_2 per million US dollars.

One fact to note is that we have chosen the two endpoints of our time series, 1995 and 2009. Recorded emissions levels in 2009 in the dataset are lower across the board in 2009 than 2008, with exceptions including China. This is a reflection of the recession, as lower nominal GDP values are also present in the data. Despite this anomaly, we believe that presenting results from the most recent year available still allows us to reasonably observe the average technical change that took place in the 14-year period.

When ranking sectors in each country by total CO_2 emissions, the sectors that appear most frequently in the top five are: electricity, gas, and water supply; basic and fabricated metals; other nonmetallic minerals; chemicals and chemical products; coke, petroleum, and nuclear fuel; inland transport; air transport; agriculture. We discuss these sectors in groups.

Utilities

Table 2.3 shows CO_2 emissions levels and intensities associated with the electricity, gas, and water supply industry (which we call "utilities" for short). Utilities account for nearly 50% or more of all intermediate industrial CO_2 emissions in about half the countries shown in table 2.3, and account for over 20% for almost all countries.

Utilities also has the highest emissions intensity of all industry sectors in the WIOD classification, though the intensity has fallen over the 1995-2009 period for most countries. The emissions intensities vary widely among countries due to the variation in energy sources used in power generation. China, India, Poland, Indonesia, and Estonia, who have exceptionally high emissions intensities, consume 80% of their electricity from thermal generation, according to electricity consumption statistics by the EIA. Although power generation basically became more efficient across the board, some countries made notable changes in their composition of power sources. Czech Republic and Slovakia both sizably increased share of nuclear electricity (from 20% to 34%, and 44% to 54% respectively), while countries that made large shifts to renewable energy include Sweden (49% to 60%), Denmark (6% to 30%), Germany (6% to 17%), and Ireland (5% to 15%). All countries just listed saw a large negative contribution from sector intensity to household consumption of domestic products in the structural decomposition. As power generation is a local good, it makes sense that these improvements would be reflected in the consumption of domestic products.

One caveat to note is that the dramatic declines in some countries can be attributed partially to increasing energy prices. If energy demand is inelastic, then high energy prices will simply lead to lots of dollars spent on energy with little change in emissions.

According to European Commission statistics [Communication Department of the European Commission, 2012], industrial prices for electricity in Poland were €.0492 per

Table 2.3: CO_2 emissions in kilotons from electricity, gas, and water supply industry

	1995		2009		
Country	level	intensity	level	intensity	growth rate[c]
China	1,051,685 (38.6%)	23.185	3,326,279 (53.5%)	9.858	0.086
United States	1,835,228 (42.3%)	6.241	2,033,025 (48.5%)	5.699	0.007
India	370,603 (51.4%)	11.794	813,610 (54.2%)	15.796	0.058
Russia	820,960 (58.1%)	14.674	713,693 (50.6%)	9.077	-0.010
Germany	351,462 (48.5%)	3.893	324,063 (50.9%)	2.018	-0.006
Japan	242,121 (23.6%)	1.243	322,816 (33.8%)	1.394	0.021
Korea	79,502 (21.4%)	4.341	226,668 (42.5%)	4.046	0.078
Australia	132,978 (49.1%)	5.669	206,646 (56.7%)	5.956	0.032
Poland	165,832 (52.8%)	11.049	154,032 (56.0%)	5.117	-0.005
United Kingdom	166,721 (37.0%)	1.755	153,862 (36.4%)	1.182	-0.006
Taiwan	60,714 (34.2%)	5.957	114,579 (39.5%)	6.540	0.046
Italy	118,081 (32.8%)	1.801	113,538 (34.5%)	1.099	-0.003
Mexico	75,377 (29.0%)	5.857	107,813 (30.7%)	3.712	0.026
Indonesia	47,675 (27.6%)	16.820	104,859 (31.7%)	10.910	0.058
Turkey	38,409 (27.6%)	4.580	90,665 (37.8%)	2.743	0.063
Canada	82,242 (20.6%)	2.657	88,383 (20.1%)	2.554	0.005
Spain	71,354 (35.1%)	1.792	74,189 (32.2%)	0.927	0.003
Romania	70,563 (58.6%)	7.001	42,720 (55.6%)	3.581	-0.035
Czech Republic	59,009 (55.4%)	4.195	53,785 (55.6%)	3.308	-0.007
Netherlands	47,595 (31.0%)	1.674	55,361 (33.3%)	1.173	0.011
Greece	44,770 (59.4%)	6.980	55,118 (58.8%)	5.643	0.015
France	33,879 (11.9%)	0.225	35,408 (13.6%)	0.378	0.003
Bulgaria	25,798 (45.2%)	11.195	28,233 (67.7%)	9.640	0.006
Belgium	24,132 (24.0%)	1.585	22,619 (24.8%)	0.988	-0.005
Finland	21,078 (39.6%)	3.472	22,463 (40.7%)	2.340	0.005
Denmark	30,208 (47.5%)	4.295	20,950 (26.8%)	2.338	-0.026
Portugal	16,927 (36.5%)	1.853	17,430 (33.4%)	1.054	0.002
Brazil	9,559 (5.5%)	0.320	16,817 (6.7%)	0.329	0.041
Ireland	13,057 (51.0%)	3.809	12,661 (45.9%)	1.435	-0.002
Estonia	14,154 (83.3%)	20.699	10,062 (70.6%)	8.843	-0.024
Austria	9,937 (22.8%)	0.699	9,558 (19.9%)	0.261	-0.003
Sweden	9,372 (20.0%)	0.804	8,834 (18.7%)	0.467	-0.004
Slovak Republic	9,268 (23.2%)	1.785	8,375 (25.2%)	0.806	-0.007
Cyprus	2,117 (48.5%)	5.625	4,011 (59.7%)	4.423	0.047
Lithuania	5,564 (42.2%)	2.629	2,969 (25.8%)	1.274	-0.044
Latvia	3,624 (41.7%)	4.446	2,075 (28.9%)	1.335	-0.039

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions.
[b] Growth rate represents compound annual growth rate in emissions levels.
[a] Data source: World Input-Output Database.

kWh in 2001 (roughly €.055 in 2005 chained euros) and €.0857 per kWh in 2009 (roughly €.080). Although the data documentation mentions a break in measurement method before and after 2007, the over twofold price increase is large compared to other countries in same price dataset. Similarly in Romania, prices were €.0405 (€.042) in 2003 and €.0811 (€.0757) in 2009. In contrast, an example where prices did not drop is France, where the price was €.0567 (€.0632) in 2000 and €.0667 (€.0622) in 2009.

Mining, metals, and nonmetallic minerals

We discuss the mining and quarrying industry, the basic and fabricated metals industry, and the nonmetallic minerals industry as a group because they show similar trends in terms of the countries that experienced emissions growth and reductions.

Tables 2.6, 2.7, and 2.8, in the Appendix show detailed information about these sectors. In this section we include simplified graphs that show changes in emissions levels and intensities between 1995 and 2009. Figures 2.15, 2.16, and 2.17 show that China and India, and to a certain extent Russia, Brazil, and other parts of Asia (Korea, Taiwan, and Indonesia) generally had large increases in CO_2 emissions (shown as solid circles in the graph), while the United States and European countries generally had decreases (shown as empty circles in the graph).

Emissions intensity fell for most of the countries shown, although the countries with the largest increases in emissions levels tended to have larger reductions in emissions intensity (points farther below the $y = x$ line had larger reductions in intensity). Decreasing emissions intensity means the growth rate in dollar output of these industries is higher than the growth rate of emissions.

China's exceptionally large growth in emissions from all these sectors highlights a general shift to China as the primary location of production of these materials. However, in the countries where emissions decreased, dollar output also increased (this can be calculated from the emissions amounts and intensities in Tables 2.8, 2.7, and 2.6). Thus, although China is providing an increasing share of raw materials, this fact is more likely a reflection of increased worldwide demand, rather than a substitution from one group of locations to another.

Transport

Figures 2.18 and 2.19 present the inland and air transportation sectors (see Tables 2.9 and 2.10 for details). Not only are transport sectors frequently among the top emitting sectors across countries (water tranport, not shown, is in the top five for Sweden, Japan, and Denmark), the total emissions from transportation have been increasing globally. Even in the EU countries where emissions were generally decreasing, air transport emissions grew by a large amount while emissions intensities also seemed to increase. The largest contributor to these increases was household consumption, which means increased passenger travel (as opposed to freight) is responsible for a large part of the increase. For inland transport, emissions intensities declined on average, but the declines are not as obvious from Figure 2.18, compared to other sectors discussed in this section. This may indicate a technological barrier in motor fuel efficiency.

Although the technology of the air travel industry should be similar across countries, and the WIOD applies the same emissions factors for jet fuel (almost the exclusive source of CO_2 emissions attributed to the air transport sector), Figure 2.19 shows large differences in the per dollar emissions intensities of the air transportation industry for some countries. Historical airline performance statistics are difficult to obtain, but a few research reports hint at a combination of operating costs and average trip length as possible explanations for inflated emissions intensity figures. In 2005, among a group of 16 European air carriers including traditional long-haul carriers such as British Airways and KLM, and shorter distance low-cost carriers such as Ryanair and Easyjet, Turkish

Figure 2.15: CO_2 intensity changes in mining industry, 2009 vs. 1995

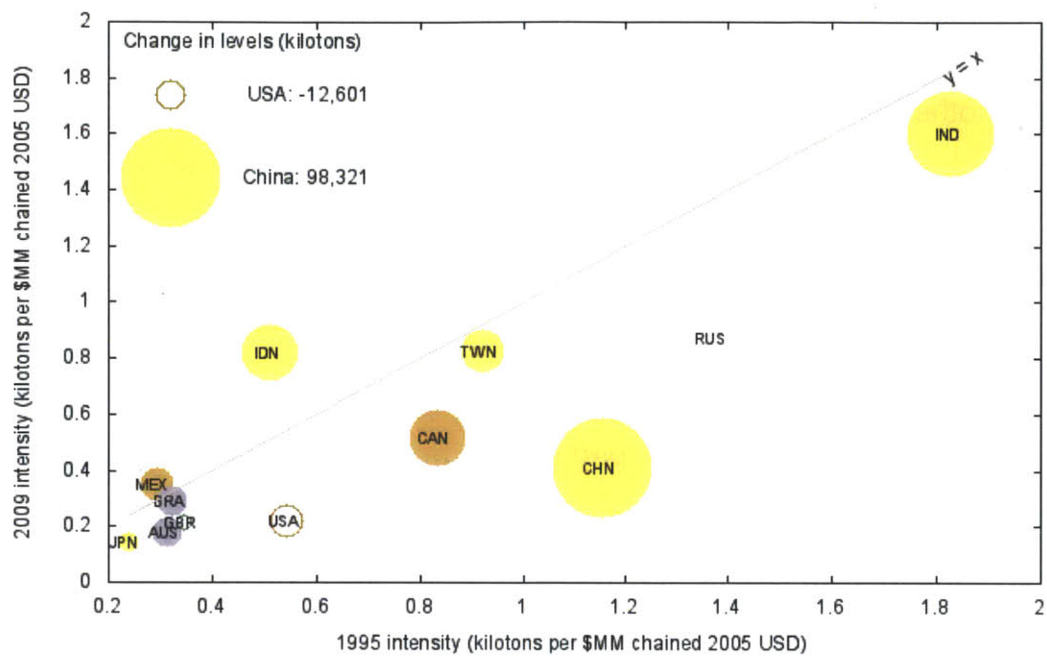
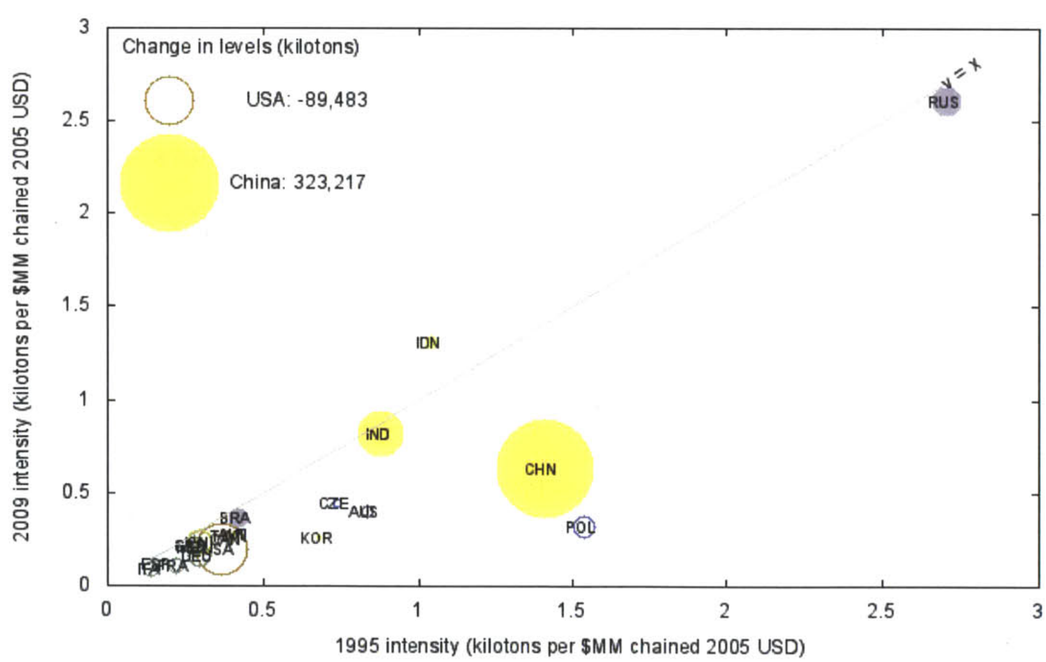


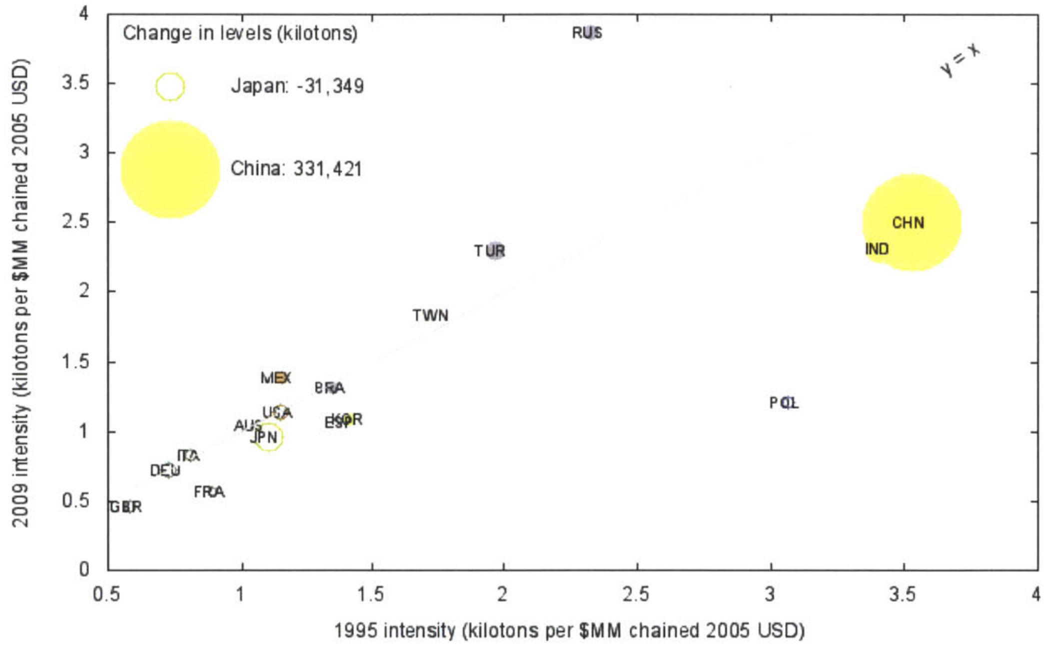
Figure 2.16: CO_2 intensity changes in basic and fabricated metals industry, 2009 vs. 1995



Circle sizes represent relative changes in emissions level; hollow circles represent negative values. Colors distinguish rough geographic regions. Countries emitting less than 10 megatons in 2009 not shown.

Data source: World Input-Output Database, author's calculations.

Figure 2.17: CO_2 intensity changes in nonmetallic minerals industry, 2009 vs. 1995

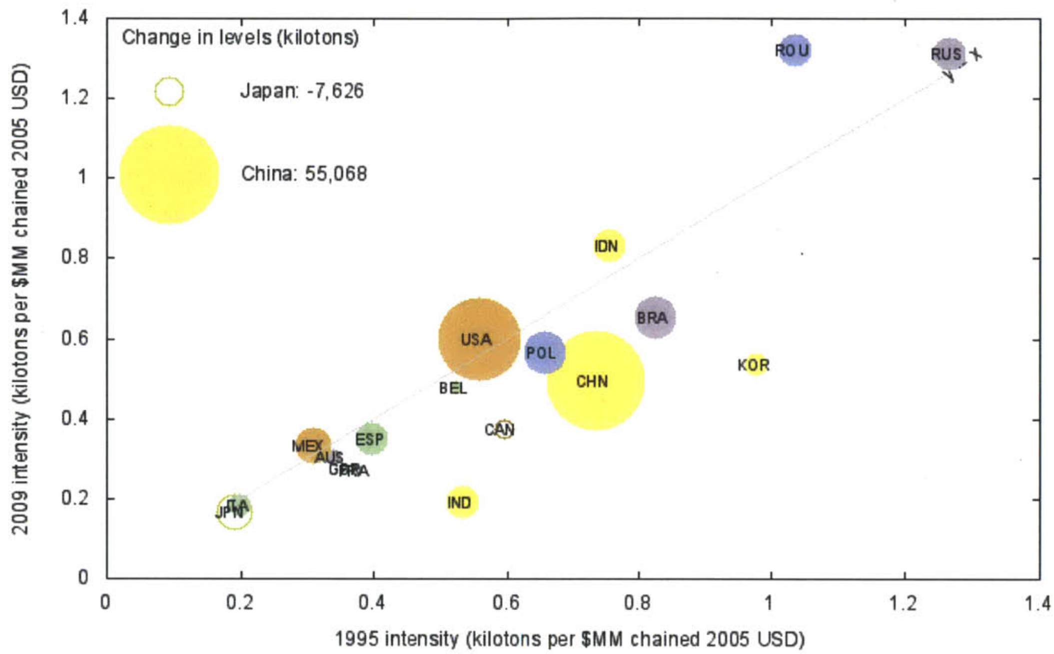


Circle sizes represent relative changes in emissions level; hollow circles represent negative values. Colors distinguish rough geographic regions. Countries emitting less than 10 megatons in 2009 not shown.
Data source: World Input-Output Database, author's calculations.

Airlines had the lowest operating costs per available ton-kilometer and the fourth longest trip lengths [Williams, 2008]. A few years earlier, [Dietlin, 2004] found that airlines operating in the Asia-Pacific region on average had lower unit costs per available seat-kilometer as well as longer average passenger hauls than their European and North American counterparts; within Asia, the two Taiwan-based carriers also had lower costs and longer hauls than their Japanese and Korean counterparts. Among major carriers in other parts of the world, Russia-based Aeroflot also had low unit costs and passenger hauls compared to North American and EU airlines. If jet fuel costs are roughly the same across countries, then lower operating costs and longer flights (implying lower costs to the customer per mile traveled) would imply that a larger fraction of the airline's expenses were on fuel.

Another possibility is that jet fuel consumption figures in the WIOD are inaccurate for some countries. Jet fuel consumption figures by country provided by the U.S. Energy

Figure 2.18: CO_2 intensity changes in inland transport industry, 2009 vs. 1995



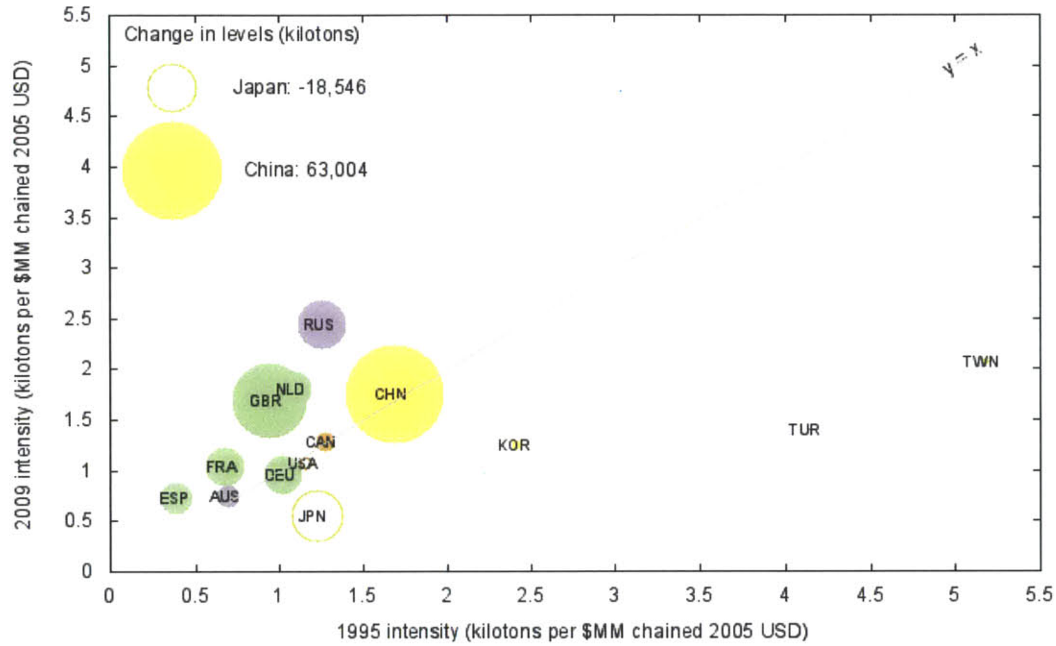
Circle sizes represent relative changes in emissions level; hollow circles represent negative values. Colors distinguish rough geographic regions. Countries emitting less than 10 megatons in 2009 not shown.
Data source: World Input-Output Database, author's calculations.

Information Administration (EIA), while roughly proportional to the jet fuel emissions in the WIOD data, have some large relative differences. For instance, the EIA data records Taiwan's consumption of jet fuel at roughly 55% of Korea's consumption, instead of being more than Korea's as recorded in WIOD data.

Fuels and chemicals

Emissions data for coke, petroleum, and nuclear fuels and chemicals and chemical products (many of which are petroleum-based) are shown in Figures 2.20 and 2.21 respectively (details in Tables 2.11 and 2.12). These sectors show similar patterns to the metals, minerals, and mining sectors with generally declining emissions levels for developed countries and rising emissions levels for developing countries (multiplying the emissions levels in Tables 2.11 and 2.12 by the intensities will reveal higher

Figure 2.19: CO_2 intensity changes in air transport industry, 2009 vs. 1995



Circle sizes represent relative changes in emissions level; hollow circles represent negative values. Colors distinguish rough geographic regions. Countries emitting less than 10 megatons in 2009 not shown.
Data source: World Input-Output Database, author's calculations.

expenditures, showing that the drop is in emissions levels mostly due to better industrial efficiency). Russia's increasing intensity makes it an outlier in the chemicals industry. While more specific sub-industries of the chemical industry are not available in the WIOD data, the intermediate input structure of the Russian chemical industry in 2009 includes a higher percentage (5.7%, vs. 2.8% in 1995) of fuels and a lower percentage (1.9% vs. 3.5%) from mining. This is possibly evidence that the chemical products being produced are more complex as more refined inputs are required, but more information is needed to determine whether this is true.

Agriculture, hunting, forestry, and fishing

Although the size of the agriculture, hunting, forestry, and fishing sector is relatively small in the developed world, it is one of the five largest emitting sectors in several countries

Figure 2.20: CO_2 intensity changes in coke, refined petroleum, and nuclear fuel industry, 2009 vs. 1995

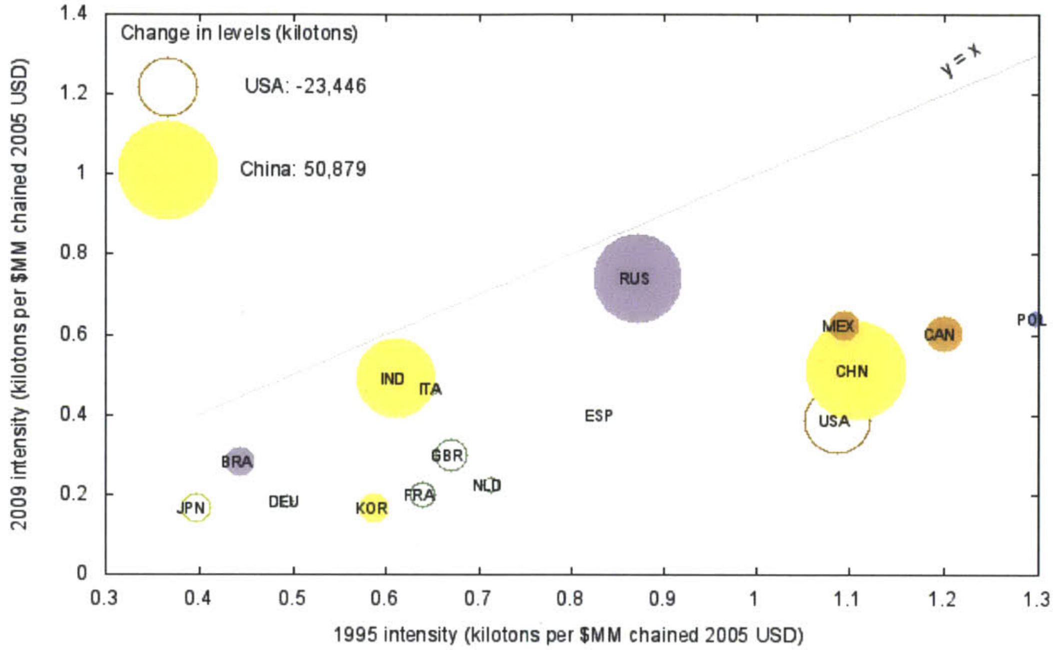
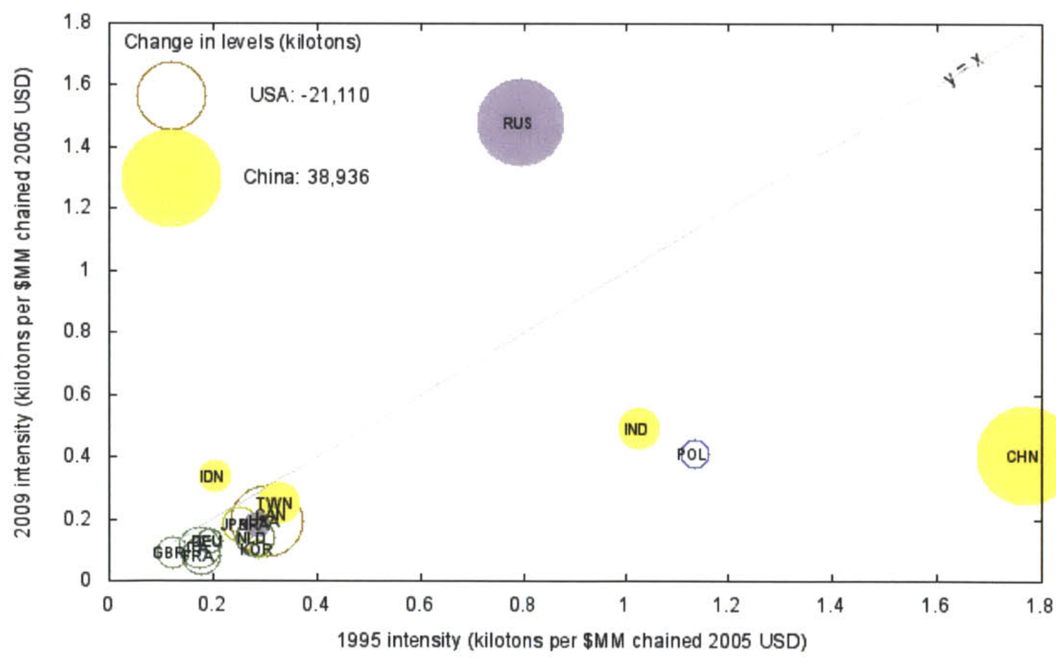


Figure 2.21: CO_2 intensity changes in chemicals and chemical products industry, 2009 vs. 1995

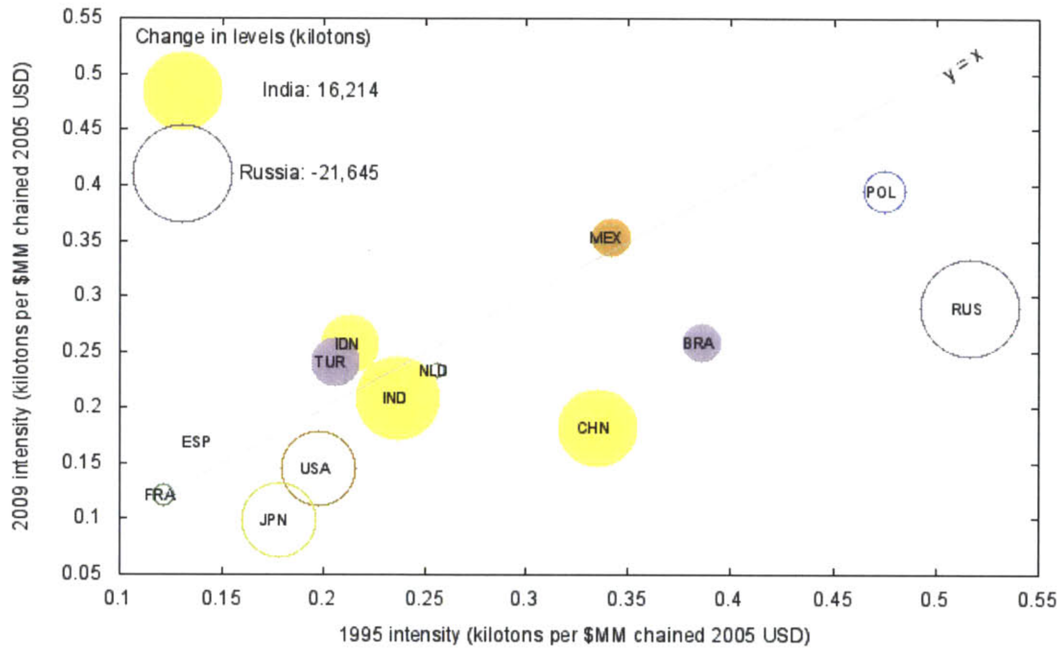


Circle sizes represent relative changes in emissions level; hollow circles represent negative values. Colors distinguish rough geographic regions. Countries emitting less than 10 megatons in 2009 not shown.

Data source: World Input-Output Database, author's calculations.

including Brazil, China, India, Poland, Mexico, and Turkey.

Figure 2.22: CO_2 intensity changes in agriculture, hunting, forestry, and fishing industry, 2009 vs. 1995



Circle sizes represent relative changes in emissions level; hollow circles represent negative values. Colors distinguish rough geographic regions. Countries emitting less than 10 megatons in 2009 not shown.
Data source: World Input-Output Database, author's calculations.

The BRIC countries (Brazil, Russia, India, and China), with a small number of exceptions, rank high in the production of emissions associated with several of the sectors presented, and also show positive emissions growth. Some surpassed the U.S. level of emissions between 1995 and 2009. Emissions intensities in these countries are also for the most part higher than the counterpart industries in the United States, especially the raw materials sectors, suggesting that these sectors are candidates for policy interventions. As the majority of Brazil's electricity is supplied by renewable energy, the high ranking of Brazil as an emitter in the raw materials, fuels, and chemical industries suggests that these sectors independently cause a large amount of CO_2 emissions.

2.6 Discussion

In this paper we take apart three components contributing to change in CO_2 emissions over time to understand the mechanisms behind the apparent convergence in emissions intensity as living standards increase across countries.

From our input-output based structural decomposition, we find that large improvements to industrial efficiency, coupled with modest increases in final demand, actually result in respectable decreases in emissions levels due to household consumption in most EU countries – particularly those with the most stringent commitments in the Kyoto Protocol. In Table 2.4, we can see comparatively large decreases in emissions embodied in household consumption of domestic products in both the first 15 countries in the EU, and all current EU countries. The EU countries have notably lower positive contributions from final demand to emission levels, in contrast to the group of non-EU countries, whose upward contribution from final demand was twice as high, and the Kyoto non-participants whose final demand contribution was roughly fourfold. The group consisting of all Kyoto Protocol non-participants in our sample experienced the largest positive growth in emissions from household consumption, which is unsurprising as this group consists of high-growth countries like China, India, Russia, and Brazil. However, the growth rates of emissions due to exports in these countries greatly exceed domestic consumption.

The decreases in embodied emissions from household consumption were accompanied by increases in embodied emissions in exports, as summarized in Table 2.5. Note that the embodied emissions calculated in this chapter do not include imports, so the contrasting growth directions due to household consumption and exports may suggest that the decline in emissions in household consumption is simply due to domestic products becoming a smaller fraction of domestic consumption. Exports have

Table 2.4: Summary of structural decomposition changes in of CO_2 emission levels due to household consumption of domestic products, 1995-2009

Country	Actual	Sector Intensity	Industry Linkages	Final Demand
USA	0.024	-0.204	-0.081	0.456
N. America + Australia	0.059	-0.196	-0.069	0.472
EU15	-0.140	-0.290	0.027	0.248
EU	-0.144	-0.321	0.002	0.341
Non-EU	0.176	-0.234	-0.003	0.712
Kyoto participants	-0.012	-0.233	-0.037	0.401
Kyoto (without USA)	-0.049	-0.263	0.009	0.345
Kyoto (without Russia)	-0.019	-0.229	-0.044	0.395
Kyoto non-participants	0.508	-0.312	0.112	1.395

[a] Data sources: World Input-Output Database author's calculations

also taken up an increasing share of final demand in all countries, with some countries exporting more than domestic household consumption. We further note that while emissions due to household consumption in the Kyoto non-participant group grew by roughly 50% over our study period, as shown in Table 2.4, emissions embodied in exports grew at over three times the rate of household consumption.

Table 2.5: Summary of structural decomposition changes in of CO_2 emission levels due to household consumption of domestic products, 1995-2009

Country	Actual	Sector Intensity	Industry Linkages	Final Demand
USA	-0.046	-0.226	-0.091	0.456
N. America + Australia	0.011	-0.234	-0.061	0.500
EU15	0.116	-0.257	0.002	0.660
EU	0.061	-0.305	-0.029	0.755
Non-EU	0.747	-0.292	0.084	1.833
Kyoto participants	0.068	-0.260	-0.016	0.598
Kyoto (without USA)	0.098	-0.269	0.004	0.636
Kyoto (without Russia)	0.049	-0.273	-0.035	0.635
Kyoto non-participants	1.630	-0.377	0.203	3.598

[a] Data sources: World Input-Output Database author's calculations

In our structural decomposition of emissions intensities (Tables 2.15 and 2.17), we find some evidence of household consumption in rich countries shifting toward a mix where energy-intensive goods are less represented, consistent with the reasoning of the environmental Kuznets hypothesis. For exports, we see no relationship between the mix of goods and the wealth of the country.

Our examinations of changes in specific industry sectors provides some details behind our observation of technological convergence. Emissions intensities in all sectors shown are generally lower and span a smaller range in 2009 than in 1995. The mining, metals, and nonmetallic minerals industries in general show decreases in emissions levels in developed countries and increases in developing countries. Although this suggests a shift in the locations of production, it is likely that the reduced emissions levels are due more to increased industrial efficiency than actual reduction in industry output.

Due to China's very large and increasing role in the global production of carbon-intensive sectors, a number of studies have urged policymakers to focus on bringing in cleaner production technologies from more developed countries [Guo et al., 2010, Liu et al., 2010] and reducing coal dependence [Weber et al., 2008]. The same arguments can be applied to India and Russia. Japan's overall industrial efficiency has been a recommended by some as target of technological emulation [Ackerman et al., 2007, Liu et al., 2010]. It is clear that switching from coal to cleaner sources of power generation, including renewable energy and nuclear power, can go a long way in curbing emissions due to household consumption of domestic products.

The problem we have not solved is the lack of comparable improvements in exported products, and the unknown emissions associated with imports. Emissions from the transportation industries, which includes exports of air and water transportation services, have grown in most countries, while using petroleum as their main source of fuel. The growing raw material industries in the developing countries are also primarily traded. Although consumer education is important, the focus of policy attention will increasingly have to be on the contents of traded goods. Additionally, recommendations for China to emulate Japan are essentially proposals to accelerate technological convergence among countries. Given that GDP is expected to rise rapidly in the developing world, further improvements to industrial efficiency in the most efficient are still needed to provide a more efficient target towards which the developing countries can converge.

2.6.1 Limitations

This study has several limitations that the reader should be aware of when making conclusions about global trends in emissions and technology.

Government expenditures

Although our domestic final demand breakdown focused on households and exports, governments constitute the third largest component of final demand in most countries; in our sample governments accounted roughly between 5% and 20% of total consumption of domestic products. There were small shifts in the proportion of government spending in some countries over our study period, but we found similar results when running the decomposition with combined household and government consumption to using households alone.

Aggregation biases

In studies where data are available for large numbers of sectors (e.g. over 100), sensitivity analyses of models can be done by varying the level of sectoral aggregation. These are done in Weber [2009] Jacobsen [2000].

Jacobsen [2000] finds differences of up to 19% in total calculated energy demand when decreasing the number of industry sectors from 117 to 27, including a sign change within the transportation sector. Since sub-industries within a general industry category can have very different technologies, this is a caveat we need to take into account in the WIOD data, which is currently available in 35 industry sectors, but aggregates all utilities.

To aid in the analysis of environmental impacts, the WIOD data would be greatly aided if disaggregated data were available for the industry sector with the largest emissions: utilities. Utilities consists of electricity, gas, and water supply; electricity itself is generated from different sources including coal, natural gas, nuclear, renewables, etc. Emissions intensities among these different utility suppliers are different and would more detailed data would allow for more informed policy responses targeting emissions by the different suppliers.

Accounting errors

As the environmental accounts are apparently not complete (see section 2.4), it is very likely that inaccuracies in the data could have significant impact on the conclusions.

As a check for data quality, we downloaded official input-output tables and environmental accounts from the government statistical agencies of Canada, Japan, Taiwan, and the UK, performing the same decomposition analyses on each dataset as we did on WIOD data. Results for Canada, Japan, and UK were qualitatively consistent for all overlapping years between national data and the WIOD. The government of Taiwan does not publish data on CO_2 emissions by industry sector, but data for NO_x and SO_x are in both datasets for select years. The results for Taiwan were visibly inconsistent, with overall NO_x and SO_x industrial intensities rising during the early 2000s in WIOD data but declining in the government data. It may be worth noting that statistics about Taiwan are not included in data published by the U.N. or World Bank, both of which have programs dedicated to recording industry and emissions data. For other countries, we were not able to locate time series of input-output tables and emissions tables at consistent levels of detail at more than 20 sectors and over more than two time period. Based on our small sample of comparisons, we believe that WIOD data may be reliable for the majority of countries, particularly those that have a tradition of publishing national accounts.

If we can agree on the methodology to test hypotheses, it will be relatively easy to redo the calculations on revised data. Fortunately, datasets created for public benefit tend to be adjusted over time as more relevant information is found. For example, the BEA always publishes “advance statistics” a few months before publishing “revised statistics” where the former involve a lot more guesswork. As the data used in this study is the first public release of the WIOD database including environmental accounts, we can expect likely revisions to the data that will make it more complete in future studies.

Imports

Our biggest concern regarding the completeness of this study is imports. This study has explicitly ignored the parts of the economy that consume imports, as their separation in the WIOD has made this possible. While we have found that the household consumption of domestic products in many EU countries are associated with less overall emissions, the share of household consumption satisfied by imports has increased in almost all countries (see table 2.2). Our analysis so far has not been able to estimate the growth or decline of emissions associated with imported consumption.

By removing imports altogether, the approach taken in this study departs from our approach in Chapter 1 which was to assume embodied energy of imported goods had the same production technology as domestic goods. The implications of these approaches are discussed in Chapter 3, which focuses on embodied emissions in trade.

2.A Appendix

This Appendix contains several tables referenced in the results and discussion.

Tables 2.14 through 2.17 (pages 103-106) show detailed results from the structural decomposiion discussed in Section 2.5.1.

Tables 2.6 through 2.13 (pages 98-102) show, as discussed in Section 2.5.2, emissions levels and intensities for the industry sectors that produce the most emissions in the countries in the WIOD dataset.

Table 2.6: CO_2 emissions in kilotons from basic and fabricated metals industry

	1995		2009		
Country	level	intensity	level	intensity	growth rate[c]
China	305,037 (11.2%)	1.408	628,254 (10.1%)	0.632	0.053
Russia	148,950 (10.5%)	2.703	177,108 (12.6%)	2.608	0.012
India	54,825 (7.6%)	0.878	122,465 (8.2%)	0.820	0.059
Japan	131,667 (12.9%)	0.293	110,812 (11.6%)	0.231	-0.012
United States	190,539 (4.4%)	0.366	101,057 (2.4%)	0.194	-0.044
Korea	62,121 (16.7%)	0.678	64,509 (12.1%)	0.257	0.003
Germany	65,620 (9.1%)	0.295	47,987 (7.5%)	0.161	-0.022
Australia	37,884 (14.0%)	0.831	31,146 (8.5%)	0.405	-0.014
Brazil	16,192 (9.3%)	0.418	27,964 (11.1%)	0.361	0.040
Canada	28,216 (7.1%)	0.395	24,208 (5.5%)	0.253	-0.011
Taiwan	16,904 (9.5%)	0.401	20,482 (7.1%)	0.265	0.014
United Kingdom	34,859 (7.7%)	0.282	20,227 (4.8%)	0.214	-0.038
France	25,451 (9.0%)	0.220	16,935 (6.5%)	0.110	-0.029
Italy	25,481 (7.1%)	0.139	14,813 (4.5%)	0.091	-0.038
Indonesia	9,598 (5.6%)	1.036	14,786 (4.5%)	1.305	0.031
Mexico	14,848 (5.7%)	0.290	14,054 (4.0%)	0.203	-0.004
Poland	28,097 (8.9%)	1.538	12,399 (4.5%)	0.324	-0.057
Spain	11,500 (5.7%)	0.161	10,974 (4.8%)	0.116	-0.003
Czech Republic	14,140 (13.3%)	0.735	10,396 (10.7%)	0.441	-0.022
Austria	9,374 (21.5%)	0.415	10,261 (21.4%)	0.277	0.006

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.7: CO_2 emissions in kilotons from other nonmetallic minerals industry

	1995		2009		
Country	level	intensity	level	intensity	growth rate[c]
China	381,064 (14.0%)	3.531	712,485 (11.5%)	2.499	0.046
United States	117,827 (2.7%)	1.149	109,713 (2.6%)	1.140	-0.005
India	56,254 (7.8%)	3.411	89,080 (5.9%)	2.317	0.033
Russia	58,683 (4.2%)	2.324	70,114 (5.0%)	3.867	0.013
Japan	91,067 (8.9%)	1.100	59,717 (6.3%)	0.959	-0.030
Spain	37,542 (18.5%)	1.376	37,115 (16.1%)	1.065	-0.001
Korea	31,188 (8.4%)	1.409	36,252 (6.8%)	1.089	0.011
Germany	45,952 (6.3%)	0.727	34,559 (5.4%)	0.723	-0.020
Italy	39,808 (11.1%)	0.808	34,123 (10.4%)	0.835	-0.011
Turkey	20,598 (14.8%)	1.967	33,989 (14.2%)	2.303	0.036
Indonesia	23,400 (13.5%)	3.890	33,228 (10.0%)	5.326	0.025
Mexico	16,997 (6.5%)	1.150	24,279 (6.9%)	1.383	0.026
Brazil	15,984 (9.1%)	1.348	22,916 (9.1%)	1.318	0.026
France	24,833 (8.7%)	0.887	20,323 (7.8%)	0.571	-0.014
Taiwan	15,748 (8.9%)	1.736	15,434 (5.3%)	1.840	-0.001
Poland	20,058 (6.4%)	3.067	14,809 (5.4%)	1.216	-0.021
Austria	5,153 (11.8%)	0.667	5,495 (11.5%)	0.607	0.005
United Kingdom	17,203 (3.8%)	0.583	11,264 (2.7%)	0.463	-0.030

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.8: CO_2 emissions in kilotons from mining industry

	1995		2009		
Country	level	intensity	level	intensity	growth rate[c]
China	97,151 (3.6%)	1.155	195,472 (3.1%)	0.411	0.051
United States	123,592 (2.8%)	0.542	110,990 (2.7%)	0.221	-0.008
India	32,787 (4.5%)	1.827	108,791 (7.2%)	1.604	0.089
Russia	97,335 (6.9%)	1.369	95,439 (6.8%)	0.873	-0.001
Canada	43,901 (11.0%)	0.833	76,923 (17.5%)	0.515	0.041
Indonesia	12,140 (7.0%)	0.510	44,641 (13.5%)	0.818	0.097
Mexico	15,505 (6.0%)	0.293	28,501 (8.1%)	0.353	0.044
Taiwan	7,009 (3.9%)	0.919	25,889 (8.9%)	0.824	0.098
Australia	14,208 (5.2%)	0.313	24,083 (6.6%)	0.177	0.038
Japan	15,671 (1.5%)	0.239	22,053 (2.3%)	0.143	0.025
United Kingdom	25,129 (5.6%)	0.346	20,809 (4.9%)	0.213	-0.013
Brazil	5,829 (3.3%)	0.322	17,119 (6.8%)	0.288	0.080

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.9: CO_2 emissions in kilotons from inland transport industry

Country	1995 level	1995 intensity	2009 level	2009 intensity	growth rate[c]
United States	153,409 (3.5%)	0.558	192,153 (4.6%)	0.599	0.016
China	43,161 (1.6%)	0.735	98,229 (1.6%)	0.496	0.060
Russia	90,023 (6.4%)	1.264	96,500 (6.8%)	1.313	0.005
Brazil	24,406 (13.9%)	0.826	34,827 (13.9%)	0.654	0.026
India	26,656 (3.7%)	0.531	33,463 (2.2%)	0.191	0.016
Japan	40,398 (3.9%)	0.191	32,771 (3.4%)	0.168	-0.015
Korea	22,837 (6.1%)	0.978	25,971 (4.9%)	0.537	0.009
United Kingdom	26,095 (5.8%)	0.361	25,924 (6.1%)	0.276	-0.000
France	25,202 (8.9%)	0.373	24,456 (9.4%)	0.270	-0.002
Italy	20,433 (5.7%)	0.198	23,960 (7.3%)	0.184	0.011
Mexico	15,468 (6.0%)	0.308	23,690 (6.7%)	0.333	0.031
Spain	16,430 (8.1%)	0.395	22,642 (9.8%)	0.351	0.023
Canada	24,438 (6.1%)	0.595	21,937 (5.0%)	0.374	-0.008
Poland	8,668 (2.8%)	0.658	18,954 (6.9%)	0.565	0.057
Indonesia	8,752 (5.1%)	0.755	15,195 (4.6%)	0.831	0.040
Romania	8,191 (6.8%)	1.035	14,398 (18.7%)	1.320	0.041
Australia	9,558 (3.5%)	0.339	10,995 (3.0%)	0.305	0.010
Belgium	9,063 (9.0%)	0.523	10,327 (11.3%)	0.477	0.009

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.10: CO_2 emissions in kilotons from air transport industry

Country	1995 level	1995 intensity	2009 level	2009 intensity	growth rate[c]
United States	159,303 (3.7%)	1.155	155,830 (3.7%)	1.083	-0.002
China	15,170 (0.6%)	1.682	78,174 (1.3%)	1.761	0.124
United Kingdom	24,346 (5.4%)	0.934	61,140 (14.5%)	1.696	0.068
Germany	21,468 (3.0%)	1.013	33,799 (5.3%)	0.960	0.033
Russia	6,017 (0.4%)	1.249	24,528 (1.7%)	2.447	0.106
France	12,784 (4.5%)	0.668	24,314 (9.3%)	1.038	0.047
Canada	18,051 (4.5%)	1.271	22,436 (5.1%)	1.282	0.016
Japan	38,607 (3.8%)	1.222	20,061 (2.1%)	0.549	-0.046
Netherlands	9,017 (5.9%)	1.081	20,243 (12.2%)	1.811	0.059
Korea	14,319 (3.8%)	2.417	17,406 (3.3%)	1.253	0.014
Taiwan	19,387 (10.9%)	5.171	16,750 (5.8%)	2.076	-0.010
Australia	10,923 (4.0%)	0.688	16,565 (4.5%)	0.748	0.030
Spain	3,440 (1.7%)	0.386	12,638 (5.5%)	0.734	0.097
Turkey	12,600 (9.1%)	4.141	10,264 (4.3%)	1.397	-0.015

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.11: CO_2 emissions in kilotons from coke, petroleum, and nuclear fuel industry

	1995		2009		
Country	level	intensity	level	intensity	growth rate[c]
United States	209,883 (4.8%)	1.087	186,437 (4.5%)	0.386	-0.008
China	49,989 (1.8%)	1.106	100,868 (1.6%)	0.510	0.051
Russia	22,856 (1.6%)	0.872	64,257 (4.6%)	0.741	0.077
India	15,259 (2.1%)	0.610	47,798 (3.2%)	0.490	0.085
Canada	25,863 (6.5%)	1.200	32,858 (7.5%)	0.603	0.017
Mexico	25,610 (9.9%)	1.094	31,113 (8.9%)	0.622	0.014
Japan	33,303 (3.3%)	0.396	27,819 (2.9%)	0.165	-0.013
Italy	25,540 (7.1%)	0.649	24,053 (7.3%)	0.464	-0.004
Korea	16,021 (4.3%)	0.586	20,576 (3.9%)	0.166	0.018
France	23,356 (8.2%)	0.638	19,609 (7.5%)	0.201	-0.012
Spain	18,169 (8.9%)	0.832	18,638 (8.1%)	0.400	0.002
Germany	19,845 (2.7%)	0.493	18,362 (2.9%)	0.184	-0.006
Brazil	12,843 (7.3%)	0.443	17,782 (7.1%)	0.281	0.024
United Kingdom	22,743 (5.0%)	0.670	16,217 (3.8%)	0.299	-0.024
Poland	9,043 (2.9%)	1.297	11,169 (4.1%)	0.641	0.015
Netherlands	12,012 (7.8%)	0.712	10,395 (6.3%)	0.224	-0.010

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.12: CO_2 emissions in kilotons from chemicals and chemical products industry

	1995		2009		
Country	level	intensity	level	intensity	growth rate[c]
China	230,291 (8.5%)	1.772	269,228 (4.3%)	0.407	0.011
United States	154,673 (3.6%)	0.304	133,563 (3.2%)	0.194	-0.010
Russia	26,206 (1.9%)	0.794	58,187 (4.1%)	1.479	0.059
Japan	57,238 (5.6%)	0.250	51,364 (5.4%)	0.182	-0.008
India	39,297 (5.5%)	1.027	47,076 (3.1%)	0.490	0.013
Germany	35,851 (4.9%)	0.195	32,075 (5.0%)	0.128	-0.008
Taiwan	12,126 (6.8%)	0.326	20,513 (7.1%)	0.249	0.038
Brazil	12,460 (7.1%)	0.283	15,899 (6.3%)	0.184	0.018
Korea	17,697 (4.8%)	0.287	15,547 (2.9%)	0.102	-0.009
Canada	15,604 (3.9%)	0.319	14,860 (3.4%)	0.212	-0.003
France	20,868 (7.3%)	0.177	13,889 (5.3%)	0.080	-0.029
Italy	21,073 (5.9%)	0.173	13,113 (4.0%)	0.105	-0.033
Poland	17,446 (5.6%)	1.136	12,950 (4.7%)	0.411	-0.021
United Kingdom	16,154 (3.6%)	0.124	11,151 (2.6%)	0.090	-0.026
Indonesia	5,579 (3.2%)	0.203	10,499 (3.2%)	0.335	0.046
Netherlands	16,987 (11.1%)	0.281	10,466 (6.3%)	0.138	-0.034

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.13: CO_2 emissions in kilotons from agriculture, hunting, forestry, and fishing industry

	1995		2009		
Country	level	intensity	level	intensity	growth rate[c]
China	104,619 (3.8%)	0.335	118,136 (1.9%)	0.182	0.009
India	34,240 (4.8%)	0.236	50,454 (3.4%)	0.209	0.028
United States	62,506 (1.4%)	0.197	50,208 (1.2%)	0.145	-0.016
Brazil	21,606 (12.3%)	0.386	25,358 (10.1%)	0.259	0.012
Russia	46,026 (3.3%)	0.517	24,380 (1.7%)	0.290	-0.044
Mexico	17,519 (6.7%)	0.342	20,829 (5.9%)	0.355	0.012
Indonesia	10,653 (6.2%)	0.213	18,407 (5.6%)	0.258	0.040
Turkey	11,705 (8.4%)	0.205	16,921 (7.1%)	0.241	0.027
Japan	26,176 (2.6%)	0.178	13,253 (1.4%)	0.100	-0.047
France	13,944 (4.9%)	0.121	12,886 (4.9%)	0.121	-0.006
Poland	16,703 (5.3%)	0.475	12,666 (4.6%)	0.395	-0.020
Netherlands	11,221 (7.3%)	0.256	10,498 (6.3%)	0.234	-0.005
Spain	10,123 (5.0%)	0.139	10,160 (4.4%)	0.169	0.000

[a] Numbers in parentheses represent percentage of total intermediate industrial emissions by the respective country.
[b] Only countries with over 10 megatons in 2009 are shown.
[c] Data source: World Input-Output Database.

Table 2.14: Structural decomposition of changes (1995-2009) in CO_2 emissions levels as a fraction of 1995 levels due to household consumption of domestic products.

Country	Actual	Sector Intensity	Industry Linkages	Final Demand
India	0.781	0.091	-0.238	1.316
China	0.370	-0.574	0.235	1.880
Indonesia	1.275	0.138	0.420	0.975
Latvia	-0.204	-0.583	0.070	0.869
Bulgaria	-0.306	-0.260	0.070	0.012
Romania	-0.305	-0.456	-0.089	0.321
Lithuania	-0.063	-0.449	-0.169	0.985
Brazil	0.363	-0.193	0.120	0.537
Russia	0.062	-0.271	0.033	0.470
Estonia	-0.008	-0.546	-0.019	1.238
Turkey	0.856	-0.124	0.263	0.996
Poland	-0.162	-0.514	-0.100	0.872
Mexico	0.396	-0.197	0.062	0.742
Slovakia	0.018	-0.484	-0.152	1.297
Taiwan	0.430	-0.086	0.024	0.667
Czech Republic	-0.026	-0.208	-0.222	0.593
Korea	0.330	-0.405	0.126	0.818
Portugal	0.073	-0.249	0.083	0.420
Greece	-0.029	-0.059	-0.052	0.166
Ireland	-0.116	-0.428	-0.001	0.788
Cyprus	0.654	-0.131	0.292	0.552
Spain	-0.061	-0.297	0.101	0.304
Finland	0.003	-0.342	-0.021	0.549
United Kingdom	-0.106	-0.275	-0.068	0.351
Sweden	-0.153	-0.351	-0.018	0.334
France	-0.016	-0.096	0.022	0.260
Italy	-0.070	-0.226	0.102	0.155
Australia	0.357	-0.019	-0.075	0.539
Belgium	-0.305	-0.282	-0.055	0.053
Austria	-0.206	-0.372	0.127	0.222
Canada	0.158	-0.202	0.048	0.475
Germany	-0.269	-0.410	0.058	0.200
Japan	-0.045	-0.154	0.014	0.125
Denmark	-0.399	-0.372	-0.051	0.070
Netherlands	-0.076	-0.285	0.003	0.286
United States	0.024	-0.204	-0.081	0.456

[a] Data source: World Input-Output Database; Author's calculations.

Table 2.15: Structural decomposition of changes (1995-2009) in CO_2 emissions intensity of household consumption of domestic products as a fraction of 1995 intensity.

Country	Actual	Sector Intensity	Industry Linkages	Final Demand
India	-0.190	0.091	-0.187	0.006
China	-0.523	-0.574	0.196	0.022
Indonesia	0.527	0.138	0.357	0.422
Latvia	-0.585	-0.583	0.005	0.082
Bulgaria	-0.331	-0.260	0.047	0.060
Romania	-0.319	-0.456	-0.015	0.220
Lithuania	-0.483	-0.449	-0.111	0.052
Brazil	-0.116	-0.193	0.068	0.046
Russia	-0.347	-0.271	-0.014	-0.048
Estonia	-0.428	-0.546	-0.014	0.306
Turkey	0.060	-0.124	0.194	0.235
Poland	-0.482	-0.514	-0.036	0.108
Mexico	-0.047	-0.197	0.104	0.145
Slovakia	-0.386	-0.484	-0.035	0.303
Taiwan	-0.186	-0.086	0.028	-0.051
Czech Republic	-0.314	-0.208	-0.207	0.120
Korea	-0.268	-0.405	0.067	0.060
Portugal	-0.164	-0.249	0.094	0.110
Greece	-0.192	-0.059	0.058	-0.125
Ireland	-0.517	-0.428	0.056	-0.055
Cyprus	0.030	-0.131	0.161	0.085
Spain	-0.306	-0.297	0.109	-0.037
Finland	-0.328	-0.342	-0.034	0.058
United Kingdom	-0.329	-0.275	-0.030	-0.017
Sweden	-0.345	-0.351	-0.009	0.024
France	-0.207	-0.096	0.031	0.002
Italy	-0.181	-0.226	0.063	0.054
Australia	-0.083	-0.019	-0.065	0.032
Belgium	-0.461	-0.282	-0.064	-0.159
Austria	-0.381	-0.372	0.099	-0.009
Canada	-0.257	-0.202	0.008	-0.013
Germany	-0.319	-0.410	0.104	0.086
Japan	-0.138	-0.154	0.022	0.012
Denmark	-0.474	-0.372	-0.062	-0.041
Netherlands	-0.271	-0.285	0.003	0.019
United States	-0.294	-0.204	-0.062	-0.011

[a] Data source: World Input-Output Database; Author's calculations.

Table 2.16: Structural decomposition of changes (1995-2009) in CO_2 emissions levels as a fraction of 1995 levels due to exports.

Country	Actual	Sector Intensity	Industry Linkages	Final Demand
India	0.796	0.020	-0.266	2.084
China	2.175	-0.573	0.351	5.044
Indonesia	0.956	0.234	0.301	0.387
Latvia	0.098	-0.464	0.077	0.973
Bulgaria	-0.289	-0.502	-0.003	0.543
Romania	-0.409	-0.469	-0.195	0.338
Lithuania	0.166	-0.400	-0.149	1.174
Brazil	1.012	-0.189	0.102	1.321
Russia	0.140	-0.210	0.058	0.459
Estonia	-0.038	-0.510	-0.070	0.930
Turkey	1.648	-0.118	0.153	1.784
Poland	-0.084	-0.603	-0.153	1.762
Mexico	0.342	-0.123	0.053	0.525
Slovakia	-0.226	-0.408	-0.143	0.709
Taiwan	1.142	0.103	0.006	1.149
Czech Republic	0.049	-0.246	-0.235	0.943
Korea	0.820	-0.475	0.094	2.253
Portugal	0.323	-0.055	0.055	0.442
Greece	0.898	-0.188	-0.026	2.444
Ireland	-0.015	-0.313	-0.128	1.410
Cyprus	0.407	-0.120	0.300	0.140
Spain	0.368	-0.200	0.099	0.726
Finland	-0.029	-0.249	-0.025	0.390
United Kingdom	-0.076	-0.207	-0.061	0.335
Sweden	0.096	-0.233	-0.029	0.547
France	-0.146	-0.264	0.049	0.295
Italy	-0.123	-0.171	0.082	0.046
Australia	0.241	-0.204	-0.101	0.904
Belgium	-0.090	-0.308	-0.052	0.521
Austria	0.503	-0.303	0.031	1.242
Canada	-0.021	-0.312	0.020	0.453
Germany	0.314	-0.403	-0.014	1.331
Japan	0.244	-0.218	0.072	0.516
Denmark	1.037	-0.076	-0.066	1.177
Netherlands	0.071	-0.213	0.006	0.487
United States	-0.046	-0.226	-0.091	0.456

[a] Data source: World Input-Output Database; Author's calculations.

Table 2.17: Structural decomposition of changes (1995-2009) in CO_2 emissions intensity of exports as a fraction of 1995 export emissions intensity.

Country	Actual	Sector Intensity	Industry Linkages	Final Demand
India	-0.418	0.020	-0.189	-0.146
China	-0.515	-0.573	0.231	-0.024
Indonesia	0.424	0.234	0.330	0.025
Latvia	-0.410	-0.464	0.034	0.115
Bulgaria	-0.547	-0.502	-0.016	0.014
Romania	-0.584	-0.469	-0.084	-0.145
Lithuania	-0.410	-0.400	-0.086	0.053
Brazil	-0.125	-0.189	0.043	0.066
Russia	-0.288	-0.210	-0.035	-0.011
Estonia	-0.450	-0.510	-0.081	0.152
Turkey	0.058	-0.118	0.081	0.145
Poland	-0.663	-0.603	-0.058	-0.084
Mexico	-0.068	-0.123	0.100	0.014
Slovakia	-0.608	-0.408	-0.066	-0.214
Taiwan	0.005	0.103	0.023	0.003
Czech Republic	-0.457	-0.246	-0.208	-0.043
Korea	-0.455	-0.475	0.058	0.026
Portugal	0.012	-0.055	0.063	0.112
Greece	-0.181	-0.188	0.128	0.217
Ireland	-0.574	-0.313	-0.110	0.015
Cyprus	-0.055	-0.120	0.227	-0.174
Spain	-0.161	-0.200	0.098	0.056
Finland	-0.335	-0.249	-0.059	-0.019
United Kingdom	-0.319	-0.207	-0.004	-0.062
Sweden	-0.306	-0.233	-0.017	-0.041
France	-0.337	-0.264	0.033	0.018
Italy	-0.172	-0.171	0.069	-0.001
Australia	-0.230	-0.204	-0.073	0.152
Belgium	-0.295	-0.308	-0.055	0.176
Austria	-0.262	-0.303	0.011	0.118
Canada	-0.143	-0.312	-0.022	0.311
Germany	-0.291	-0.403	0.039	0.197
Japan	-0.162	-0.218	0.097	0.000
Denmark	0.455	-0.076	-0.028	0.486
Netherlands	-0.239	-0.213	0.026	0.031
United States	-0.261	-0.226	-0.007	0.044

[a] Data source: World Input-Output Database; Author's calculations.

Chapter 3

Accounting for Emissions Embodied in Trade

3.1 Introduction

Over the last few decades, decreasing energy and emissions intensity of goods and services (measured as energy consumed and emissions generated per chained dollar) has been the norm in developed (particularly OECD) countries; in some countries emission levels have also begun to decline. This is largely due to improvements in production technology that allow goods to be produced with less energy inputs and cleaner energy. Another reason for decreasing emissions intensity in developed countries is a shift in final demand from primary and secondary manufacturing to services, whose energy use and emissions do not tend to scale up in the same way as goods production.

However, global emissions continues to rise, and at a higher rate in developing countries. Pressure from the international community calls on developing countries to improve emissions efficiency has resulted in debates about assigning the burden of emissions "responsibility" to developing countries. One problem is the theory of pollution havens, in which tight environmental regulation in a country simply causes firms to locate polluting plants in countries with loose environmental regulation, resulting in an apparent decrease in emissions in the firm's home country, while increasing emissions in the country that hosts the plants.

Another problem is that consumption needs of developed countries continue to rise, yet public-facing emissions statistics, such as those distributed by the World Bank and the U.S. Energy Information Administration (EIA), only give information about territorial emissions produced by each country. Domestic emissions is produced by a combination of industrial production and household activity (such as driving), but industrial products are often exported, which creates the argument that the the recipient of exported products should be held responsible for emissions generated during their production. Likewise, domestic consumption includes imported products which are produced while increasing emissions in another country. These problems are of concern to developed and developing countries alike, and as global trade increases, carbon imbalances and their incongruence with existing agreements like the Kyoto Protocol are likely to intensify.

The United States, once the largest domestic producer of carbon emissions, and now the largest importer, plays a key role in the future of carbon emissions. The United States is also the country with the largest trade deficit (the difference between imports and exports) in emissions, and there are two broad reasons for this deficit that apply to other developed countries. The first is that United States imports tend to be either raw materials, which come from an industry (mining) that releases large amounts of pollutants into the air and water during extraction, and manufactured goods that make use of raw materials. Table 3.1 ranks industries by the proportion of demand in the U.S. that is imported.

The second reason for a large trade deficit in emissions is cross-country differences in emissions intensity. If an emissions-intensive country trades with an emissions-efficient country with equal imports and exports, the emissions-intensive country will create more emissions for the same dollar amount of trade, resulting in a trade surplus. This relationship can be seen in figure 3.1, which plots emissions trade balance as a fraction of domestic emissions against emissions intensity (more details

Table 3.1: Percentage of U.S. domestic demand (intermediate and final) satisfied by imports, 2009.

Industry	Percent imported
Leather and footwear	92.9
Textile Products	67.8
Electrical and optical equipment	51.3
Manufacturing n.e.c.; recycling	41.0
Mining and quarrying	38.2
Machinery, n.e.c.	35.7
Transport equipment	27.7
Chemical products	24.4
Air Transport	19.4
Rubber and plastics	18.2
Basic and fabricated metal	18.0
Other nonmetallic mineral	14.3
Wood and products	13.0
Coke, petroleum, nuclear fuel	11.8
Agriculture, hunting, forestry, fishing	10.9
Food, beverages, tobacco	7.5
Paper, printing, publishing	6.8
Other business activities	5.8
Water transport	5.2
Inland transport	3.6
Financial intermediation	2.3
Wholesale trade	1.3

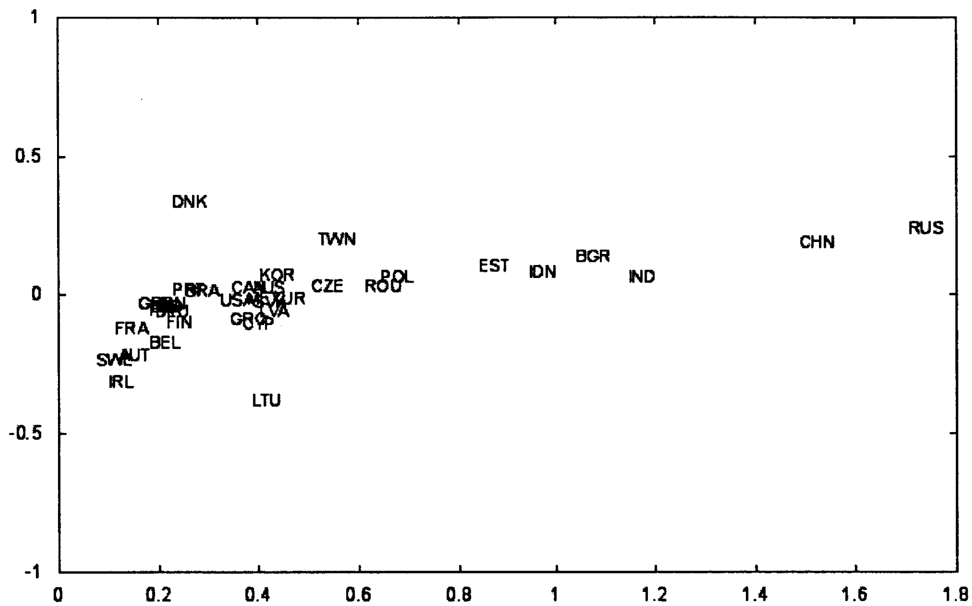
[a] Under 1%: utilities; other services; education; auxiliary transport; retail trade; post and telecommunications; hotels and restaurants; motor vehicle services; construction; real estate; health and social work; public administration.

[b] Source: World Input-Output Database

about the numbers in figure 3.1 are described in section 3.4.2).

The upshot of growing imbalances in traded embodied emissions is a need to review existing international policies on carbon emissions in addition to the way international emissions data is publicly presented. Using the very recently updated data provided by the World Input-Output Database, this paper estimates embodied emissions in imports and exports in a sample of 40 countries, and describes geographical and sectoral trends in emissions over the period between 1995 and 2009.

Figure 3.1: Emissions trade balance as a fraction of total emissions vs. emissions intensity (kilotons per million chained US dollar), 2009



Data source: World Input-Output Database, author's calculations

3.2 Related work

Accounting for embodied energy and emissions in traded products has been a topic of interest in international communities, especially the implications on who should bear the responsibility of reducing emissions.

Closely accompanying the topic of responsibility is that of methodology: assigning responsibility of consumption emissions requires data and models that can accurately estimate the amount of embodied emissions consumed by countries [Wiedmann, 2009].

3.2.1 Implications on international emissions agreements

One recurring topic of concern is the effectiveness of agreements like the Kyoto Protocol and EU Emissions Trading Scheme at controlling global emissions, given the ability of committed countries to import goods with high embodied CO_2 while reducing emissions domestically [Ahmad and Wyckoff, 2003, Peters and Hertwich, 2008a, Nakano et al., 2009, Wiebe et al., 2012, Sinden et al., 2011].

This concern is a modern manifestation of the "pollution haven" hypothesis [Bommer, 1999], which emphasizes firms' motivations to move plants to locations with lax environmental regulation. Empirical support for the pollution haven hypothesis has been mixed, with studies as Eskeland and Harrison [2003] finding no evidence in U.S. international trade, Cole [2004] finding weak and localized evidence in groups of countries, and Millimet and List [2004], Levinson and Taylor [2008] finding affirmative evidence in the United States and North America. The problem with the pollution haven hypothesis is that its description has encouraged studies to focus on observations at the firm or plant level, making measurement of the actual pollutants secondary. Additionally, the non-confined nature of CO_2 emissions makes less relevant the environmental regulations that these studies were focused on.

A large number of studies using input-output methods to analyze carbon emissions in trade have found results that should add to skepticism about the efficacy of agreements that limit domestic emissions. Sinden et al. [2011] find that of aluminum products (including secondary products containing aluminum) purchased in the EU, 65% of embodied emissions are associated with imports, which they also found was on average more carbon intensive than domestic aluminum. Peters and Hertwich [2008a], using data from GTAP, conduct a survey similar to the current paper of CO_2 trade balances across countries in 2001. They find that trade accounted for 21-23% of global embodied CO_2 emissions, but more importantly that 10-11% of embodied emissions represents carbon leakage, i.e. embodied carbon that is offshored to non-participating countries of the Kyoto Protocol and thus offsetting carbon reduction in participating countries. An early survey by Ahmad and Wyckoff [2003] found that in 1995 many countries had CO_2 trade surpluses or deficits near 10% of their domestic emissions levels. These findings are particularly important in the context of the Kyoto Protocol, since countries agree to achieve emissions based on a percentage of domestic emissions at a certain time For the Kyoto Protocol the target percentages were offsets within $\pm$ 8% of 1990 emissions levels, a smaller percentage than some carbon leakage proportions found in these studies.

Adding to the problem of carbon leakage is the possibility that carbon-exporting countries are producing more CO_2 for the same output than the importing countries would produce. Evidence suggests that this has been the case for China and Brazil, which tend to export energy-intensive goods while producing them in more energy-intensive ways than the destination countries [Machado et al., 2001, Xu et al., 2009]. The fact that a large amount of territorial emissions in China are produced for exports to other countries and not the consumption of citizens has also raised questions of fairness and equity [Zhang and Li, 2011, Li and Hewitt, 2008, Pan et al., 2008].

A frequently proposed amendment to address the problem of carbon leakage in agreements like the Kyoto Protocol is to compile and publish data for both consumption and production-based emissions, instead of focusing on the latter [McMillan and Keoleian, 2009, Nakano et al., 2009, Peters and Hertwich, 2008b, Pan et al., 2008, Peters et al., 2011, Wang and Watson, 2008, Yunfeng and Laike, 2010]. Du et al. [2011] point out the obvious implication of carbon leakage on carbon tax schemes: domestic carbon taxes simply lead to production of carbon-intensive products where production is cheaper. They simulate various alternatives for U.S. trade which all lead to theoretically better outcomes, including combining domestic carbon taxes with import tariffs, and combining domestic taxes with export subsidies.

3.2.2 Difficulties in allocating emissions

A universal characteristic of published papers on emissions trade balances is the inclusion of large sections detailing lack of comparable data across countries and the quality of existing data. Frequently cited problems include: lack of data about the technology of trading partners, forcing researchers to use the domestic country's technology as a proxy (domestic technology assumption); harmonization of sectors and aggregation problems; and the intractability of international transportation.

Domestic technology assumption

When multi-regional data are not available, researchers often use coefficients from one country to proxy for its trading partners, applying the assumption that the foreign country has similar technology to the domestic [Andrew et al., 2009]. At the time of writing of a review by Peters and Hertwich [2009], this assumption was still applied to "most IO studies of environmental issues," despite researchers' awareness of inaccuracies in the results.

One study found embodied imports to account for only 6% of total U.S. emissions in 1998 and 7% in 2006, pointing out that these percentages are much lower than the corresponding percentages in dollar terms, as imports accounted for 16.7% of GDP in 2006 [U.S. Department of Commerce, Economics and Statistics Administration, 2010]. This study uses the same per-sector intensity values for both domestic and imported products (described in their Appendix), which understates emissions.

When estimating the amount of emissions China avoided by importing goods, Weber et al. [2008] resorted to using estimating this using China's emissions intensities, which unlike studies of developed countries, is biased upward.

Sector harmonization and aggregation

Many studies complain about industry or product sectors being too highly aggregated in the available data, though few studies have produced concrete recommendations. Lenzen et al. [2004] constructed a five region multiregional input-output (MRIO) model based on separate national statistics, which required significant manual work to reclassify and aggregate industry and product sectors. As a test of the possibility of aggregating to fewer sectors to save time in research, they found that aggregating to ten sectors resulted in unreasonable shifts of the causes of emissions between imports, exports, and domestic consumption. Very relevant to the WIOD dataset is their analysis of aggregation effects in the "electricity, water, and gas" sector, which is represented as a single industry sector in WIOD data. Although the number of industry sectors in WIOD is far greater than ten, we have noted elsewhere that studies of emissions would be far more useful if the sector representing half of all territorial emissions was split into its more detailed components.

In a study specifically to investigate the effects of sector aggregation on CO_2 trade analysis using hybrid input-output tables, Su et al. [2010] discover that having 40 sectors harmonized between input-output and environmental accounts is sufficient to yield stable results, although there is no specification of what the sectors should be.

International transportation

As global trade volume increases, so does the overhead of shipping goods between countries, including the emissions-intensive activity of freight transportation. This leads to concern about which country should bear the responsibility of producing the emissions while goods are in transit [Cadarso et al., 2010]. Also, due to potential differences in the technology of freight and passenger transport, Weber and Matthews [2007] believe that missing freight statistics may lead their estimates of emissions embodied in U.S.

international trade to be underestimated by a small amount (not more than 10%).

3.2.3 Summary

The idea that carbon emissions is increasingly being produced by developing countries and embodied in imports to developed countries has been studied by many, resulting in a call for consumption-based carbon accounting by many researchers.

There is a general tendency for multi-country studies to group net importers and net exporters along the lines of developed vs. developing countries [Liu and Wang, 2009] or OECD vs. non-OECD countries [Peters and Hertwich, 2009, Wiebe et al., 2012]. While these groupings work as generalizations, they may shift attention away from countries deviating from this pattern. Furthermore, results vary widely among studies [Liu and Wang, 2009], indicating a general need for more research in this area. For this reason, our analysis focuses on select countries and large geographic regions, particularly the changes in emissions trade that occurred in recent years.

3.3 Methodology

3.3.1 Data sources

This paper uses the International Supply and Use Tables, National Input-Output Tables, and Environmental Accounts series from the World Input-Output Database.

Due to the recency of the WIOD release, the data should be treated with caution. The WIOD is the result of a compilation of data from other sources, and for many indicators, other easily accessed public data can be compared. Although it is difficult to know which data source is correct when they disagree, these disagreements give us a sense of how much trust to put in a particular set of records.

Table 3.3 contains descriptive statistics of emissions levels and intensities for all countries in the WIOD database. Comparable emissions intensities from the U.S. Energy Information Administration are shown for comparison. When ranked by emissions intensity – calculated as kilotons CO_2 per million chained dollars – there is a rough geographical pattern in the rankings: Western Europe forms a group of the most efficient countries; followed by the Baltic region and a subset of Eastern Europe; North America and Australia; other Eastern European countries; Asian countries excluding Japan; and India, China, and Russia.

Table 3.2 compares percent changes in emissions for all countries listed in Annex B of the Kyoto Protocol. The column "target" is the target change in emissions compared to 1990 that the countries aim to achieve between 2008 and 2012 [United Nations, 2012]. As data for 1990 is not (yet) available in WIOD, the percent change from 1995-2009 is shown in the next column. The percent changes from the same period, based on United Nations data, is shown in the next column. The 1990-2009 change, which is directly comparable to the Kyoto Protocol timeframe, is shown where available. (Emissions levels from the U.N. data are not shown due to space constraints, but differences in levels appear to be small based on visual inspection.)

Although multi-region input-output (MRIO) models are plagued with complications of calculating exchange rates, CO_2 emissions are in standard units and differences across data sets are more surprising. In table 3.2 we find some countries whose emissions changes are very much in agreement between the two sources, and some (Denmark, Luxembourg) where the changes are large and in opposite directions. Based on the list in the methodology section of Paper II, it is likely that emissions levels for six footnoted countries are understated in 2009, yet the U.N. data generally shows larger reduction percentages than WIOD.

Table 3.2: Current progress of Kyoto Protocol Annex B countries

	emissions			change		
Country	1995	2009	target	95-09	95-09 (UN)	90-09 (UN)
EU-15	3,421,449	3,300,138	-8%	-3.5%	-7.6%	-7.6
Austria[c]	61,592	64,202	-8%	4.2%	0.9	2.6
Belgium[c]	131,934	120,625	-8%	-8.6%	-8.3	-4.5
Bulgaria	62,146	46,526	-8%	-25.1%	-26.2	-43.5
Czech Republic	118,622	108,591	-8%	-8.5%	-13.5	
Denmark[c]	73,975	86,558	-8%	17.0%	-17.1	-8.1
Estonia	18,241	15,584	-8%	-14.6%	-4.8	
France[c]	405,902	385,683	-8%	-5.0%	-7.6	-8.9
Finland[c]	60,472	61,796	-8%	2.2%	1.4	3.5
Germany[c]	949,454	816,627	-8%	-14.0%	-15.1	
Greece[c]	86,523	110,032	-8%	27.2%	19.9	30.5
Ireland[c]	35,217	42,556	-8%	20.8%	26.7	32.6
Italy[c]	454,346	424,765	-8%	-6.5%	-8.6	-5.7
Latvia[a]	9,866	8,347	-8%	-15.4%	-31.0	
Lithuania	16,506	14,826	-8%	-10.2%	-20.8	
Luxembourg[a,c]	7,769	4,807	-8%	-38.1%	21.5	1.3
Netherlands[c]	193,231	204,698	-8%	5.9%	-3.8	3.4
Portugal[c]	54,138	61,320	-8%	13.3%	10.5	36.0
Romania	130,157	91,451	-8%	-29.7%	-37.5	-50.0
Spain[c]	253,767	299,987	-8%	18.2%	19.2	31.7
Slovak Republic	44,694	36,088	-8%	-19.3%	-22.1	
Slovenia[a]	14,989	17,673	-8%	17.9%	6.3	
Sweden[a,c]	63,398	57,852	-8%	-8.7%	-13.8	-14.4
United Kingdom[c]	589,734	558,629	-8%	-5.3%	-15.9	-16.8
United States[b]	4,953,562	5,025,427	-7%	1.5%	1.2	8.6
Canada	465,258	528,885	-6%	13.7%	11.8	14.2
Hungary[a]	60,884	52,986	-6%	-13.0%	-18.9	-22.7
Japan	1,141,202	1,101,926	-6%	-3.4%	-7.0	0.6
Poland	367,719	316,876	-6%	-13.8%	-13.8	-18.5
Russia	1,608,211	1,598,286	0%	-0.6%	-5.3	
Australia	304,708	405,468	8%	33.1%	30.2	39.3

[a] Missing data in some sectors.
[b] The United States has not ratified the Kyoto Protocol.
[c] Member of EU-15, which has committed to a collective target of -8% regardless of individual countries.
[d] Data sources: World Input-Output Database (except where specified), United Nations Millenium Development Goals Indicators (where specified).

Table 3.3: GDP and CO_2 emissions of all countries in WIOD sample ranked by 2009 efficiency.

	GDP ($MM USD)[a]		CO_2 (ktons)		intensity[b]		intensity (EIA)[c]	
Country	1995	2009	1995	2009	1995	2009	1995	2009
Luxembourg[d]	38,013	96,793	7,769	4,807	0.20	0.05	0.380	0.257
Sweden[d]	377,489	466,082	63,398	57,852	0.17	0.12	0.235	0.135
Ireland	117,610	321,104	35,217	42,556	0.30	0.13	0.313	0.203
France	2,159,646	2,762,503	405,902	385,683	0.19	0.14	0.216	0.180
Austria	343,388	433,738	61,592	64,202	0.18	0.15	0.247	0.204
Italy	1,554,260	2,214,557	454,346	424,765	0.29	0.19	0.279	0.237
Spain	807,948	1,517,574	253,767	299,987	0.31	0.20	0.310	0.277
Belgium	486,920	606,208	131,934	120,625	0.27	0.20	0.459	0.335
Brazil	996,652	1,569,865	229,363	322,726	0.23	0.21	0.415	0.406
Netherlands	674,221	971,710	193,231	204,698	0.29	0.21	0.454	0.371
Germany	3,519,015	3,675,875	949,454	816,627	0.27	0.22	0.364	0.268
Japan	6,748,397	4,859,207	1,141,202	1,101,926	0.17	0.23	0.274	0.251
Finland	191,310	270,970	60,472	61,796	0.32	0.23	0.367	0.262
United Kingdom	1,666,419	2,374,314	589,734	558,629	0.35	0.24	0.329	0.227
Denmark	264,287	358,235	73,975	86,558	0.28	0.24	0.325	0.193
Portugal	164,957	249,895	54,138	61,320	0.33	0.25	0.341	0.291
Malta[d]	6,251	9,959	2,188	2,836	0.35	0.28	0.553	0.478
Latvia[d]	7,647	28,946	9,866	8,347	1.29	0.29	1.119	0.555
Slovenia[d]	32,801	58,476	14,989	17,673	0.46	0.30	0.638	0.447
Slovakia	32,029	116,154	44,694	36,088	1.40	0.31	1.335	0.593
Hungary[d]	69,567	170,403	60,884	52,986	0.88	0.31	0.784	0.459
Greece	173,689	337,400	86,523	110,032	0.50	0.33	0.511	0.386
Lithuania	10,913	43,623	16,506	14,826	1.51	0.34	1.230	0.590
Cyprus	11,451	23,262	5,372	8,332	0.47	0.36	0.565	0.504
United States	9,682,196	13,842,639	4,953,562	5,025,427	0.51	0.36	0.585	0.421
Canada	866,669	1,431,302	465,258	528,885	0.54	0.37	0.623	0.472
Australia	530,767	1,038,149	304,708	405,468	0.57	0.39	0.570	0.501
Turkey	334,428	681,843	179,141	296,440	0.54	0.43	0.540	0.492
Czech Rep.	90,153	247,531	118,622	108,591	1.32	0.44	1.152	0.663
Mexico	463,787	942,233	306,024	426,681	0.66	0.45	0.540	0.492
Romania	56,002	183,208	130,157	91,451	2.32	0.50	1.517	0.717
Korea	788,385	1,046,828	409,041	584,059	0.52	0.56	0.697	0.555
Poland	193,615	496,827	367,719	316,876	1.90	0.64	1.541	0.826
Taiwan	443,425	474,260	193,957	313,741	0.44	0.66	0.769	0.692
Indonesia	346,965	593,572	214,712	392,862	0.62	0.66	0.984	1.175
Estonia	6,465	22,832	18,241	15,584	2.82	0.68	2.043	1.257
Bulgaria	22,639	57,859	62,146	46,526	2.75	0.80	2.529	1.380
India	511,772	1,444,290	806,420	1,642,719	1.58	1.14	1.925	1.434
China	1,025,488	5,717,130	3,074,350	6,695,928	3.00	1.17	3.053	2.074
Russia	456,106	1,175,742	1,608,211	1,598,286	3.53	1.36	3.061	1.674

[a] GDP in millions of 2005 chained dollars
[b] Intensity in tons per thousand 2005 chained dollars
[c] Intensity in same units from Energy Information Administration for comparison
[d] Missing data for some sectors in WIOD
[e] Data sources: World Input-Output Database, U.S. Energy Information Administration

3.3.2 Calculation of trade balances

The CO_2 trade balance of a country is the difference between exported embodied CO_2 and imported embodied CO_2. A country is said to have a trade surplus in CO_2 if the amount of CO_2 embodied in exports exceeds that of imports, and a trade deficit otherwise.

We use the Leontief framework to decompose total emissions based on types of final demand. We focus primarily on imports and exports, but we also use household consumption to comparison trade to domestic activity.

As in paper II, we begin with the standard Leontief identity for output $\mathbf{x}$, technical coefficients A, and final demand $\mathbf{y}$:

$$\mathbf{x} = L\mathbf{y}$$

where $L = (I - A)^{-1}$.

Multiplying L by any subset of $\mathbf{y}$ produces the total output associated with the selected subset of final demand. Is is straightforward to decompose total output into the amount attributable to household consumption, government, etc.

Given an emissions intensity vector $\mathbf{j}$, let

$$\mathcal{L} = diag(\mathbf{j})L$$

This hybrid $\mathcal{L}$ multiplied by any subset of $\mathbf{y}$ then produces the total emissions associated with the selected subset.

"Total output" and "total emissions" includes direct, indirect, and induced effects of final demand. To get only the direct emissions associated with a final demand vector, we use

$$\mathbf{y} \odot \mathbf{j}$$

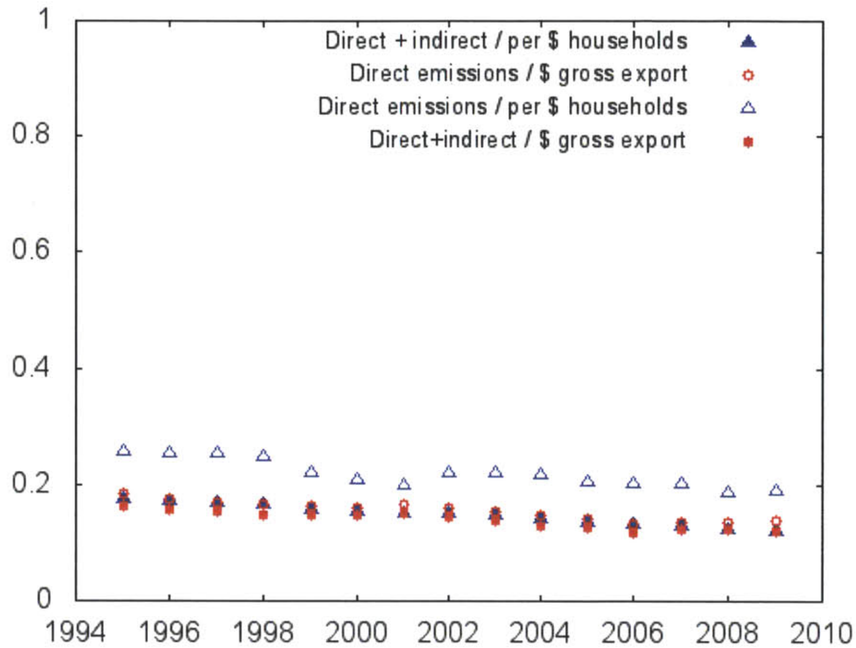


Figure 3.2: Marginal CO_2 increase per dollar of exports and household consumption, USA. Data source: World Input-Output Database.

The difference between direct and total effects has important implications on the structure of an economy. In U.S. input-output models, total effects usually just look like a larger version of direct effects, as seen in figure 3.2. In contrast, our Chinese data show that the direct marginal CO_2 emitted per dollar of household consumption is generally higher than that per dollar of export – China's citizens appear to be purchasing more emissions-intensive products than trading partners. The opposite is true when direct and indirect impacts are both included (see figure 3.3).

3.4 Results

In this section we present our estimates of CO_2 emissions embodied in gross imports and imports. We analyze these results from the following perspectives: a) the extent to which traded emissions are mis-counted due to the domestic technology assumption; b) changes in emissions trade balances in our sample of 40 countries over the period from

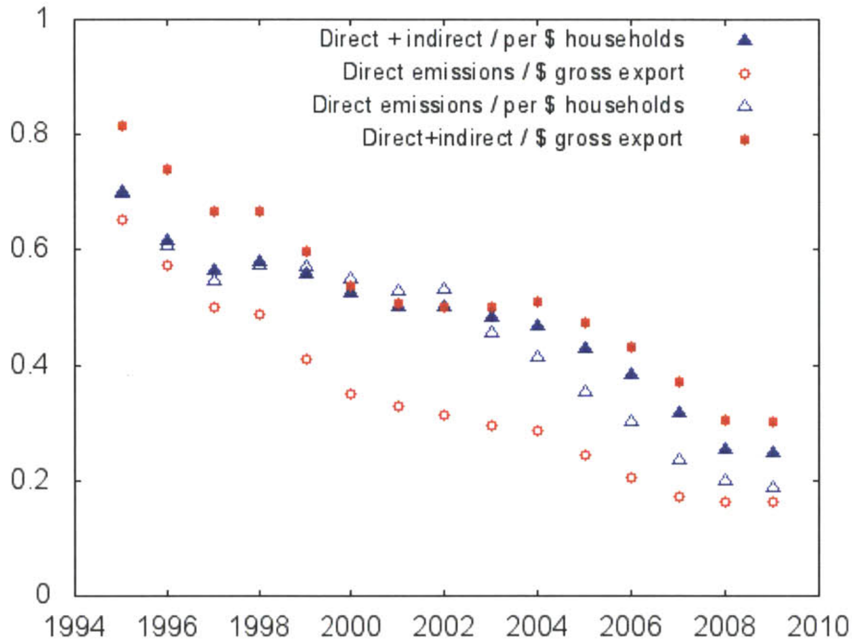


Figure 3.3: Marginal CO_2 increase per dollar of exports and household consumption, China. Data source: World Input-Output Database.

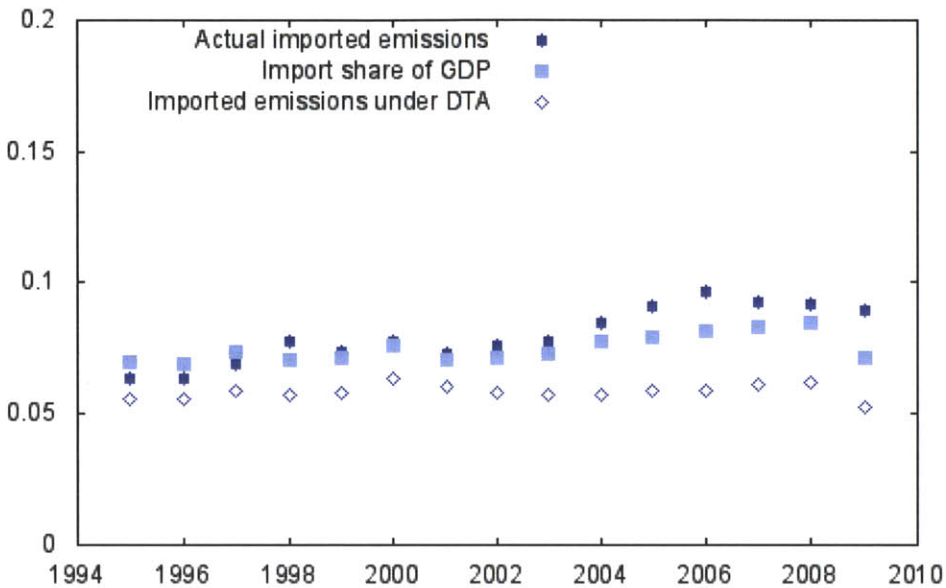
1995-2009; and c) changes in the composition of traded embodied emissions from the most emissive industry sectors by geographic region.

3.4.1 Differences in emissions with and without domestic technology assumption

In this section we compare imported and exported emissions calculated using the domestic technology assumption (DTA), against those calculated using Leontief tables from the country of origin.

Figure 3.4 illustrates this comparison for imports to the United States from 1995 to 2009. The ratio of imports to GDP in dollar terms is included to provide a rough idea of the emissions intensity of the import mix. The series labeled "Imported emissions under DTA" represents the amount of embodied emissions that we would estimate in imports if imported products were assumed to be produced using U.S. technology, while the series labeled "Actual imported emissions" is calculated using the technology of trading partners. We will henceforth use "Non-DTA" to refer to imported emissions calculated using country-of-origin technology.

Figure 3.4: Embodied emissions in imports under domestic technology assumption (DTA) and foreign technology calculation for the United States as a fraction of total domestic emissions.

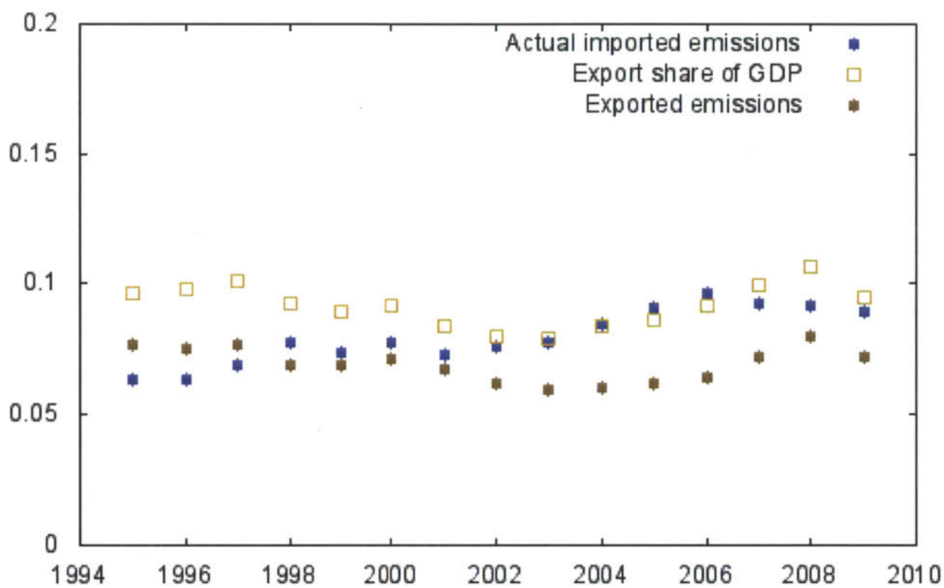


The widening gap between the emissions calculated with and without the DTA is evidence that the United States has been importing products that are becoming on average less emissions efficient relative to the United States. Thus, while Andrew et al. [2009] argue, and we agree, that applying the DTA to imports is better than ignoring imports altogether, the costs of applying the DTA (in terms of inaccurate emissions calculations) have been increasing over time.

Figure 3.4 also shows the dollar amount of imports as a fraction of U.S. GDP, which is higher than the share of imported emissions under DTA, but (starting from 1998) below the share of emissions under Non-DTA. If the ratio of dollar imports to GDP is higher than the ratio of imported to total emissions, as the DTA series suggests, this would imply that the mix of goods imported is on average more emissions efficient than the mix of goods produced domestically. If the dollar ratio is lower than the emissions ratio, as the Non-DTA series suggests, then the mix of goods imported are more emissions intensive than the mix of domestic goods.

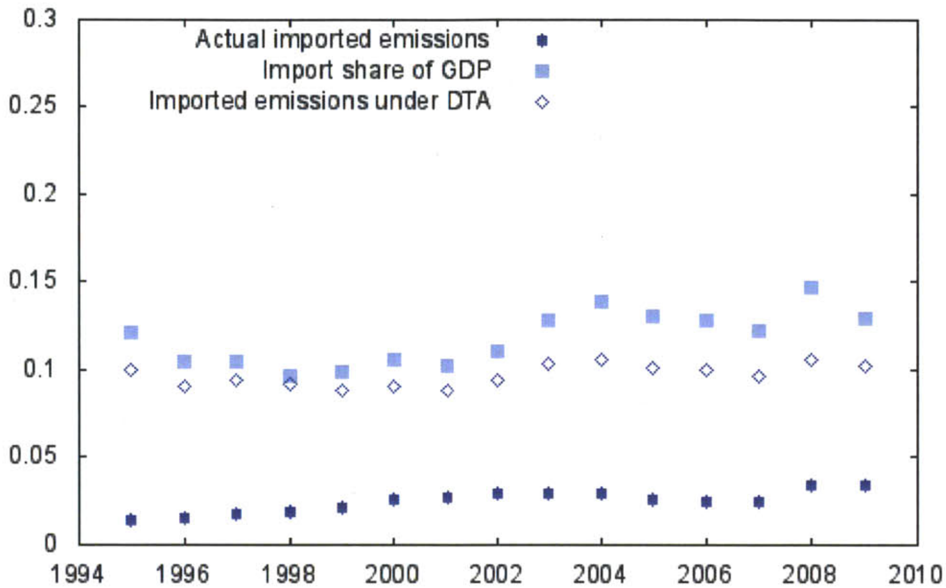
By this same reasoning, figure 3.5 shows that the mix of goods exported by the United States is on average more emissions efficient than the mix of goods produced and consumed domestically, since the export share of GDP in dollar terms is higher than the export share of domestic emissions. Imported emissions calculated under the Non-DTA are also shown in figure 3.5 for comparison, clearly indicating that imports of emissions have exceeded exports since 1998.

Figure 3.5: Embodied emissions in exports as a share of total domestic exports, and exports as a share of GDP in the United States



As the United States is the largest net importer of embodied emissions, the most interesting country to contrast with the United States is China, the largest net exporter. The comparison of embodied emissions calculated under the DTA and Non-DTA is shown in figure 3.6. Very clearly, China shows the opposite relationship to the United States between the two series: applying the DTA results in large overestimates of the amount of embodied emissions imported into China. From this standpoint, importing goods is preferable to producing goods domestically in China because China's trading partners on average have more efficient technology.

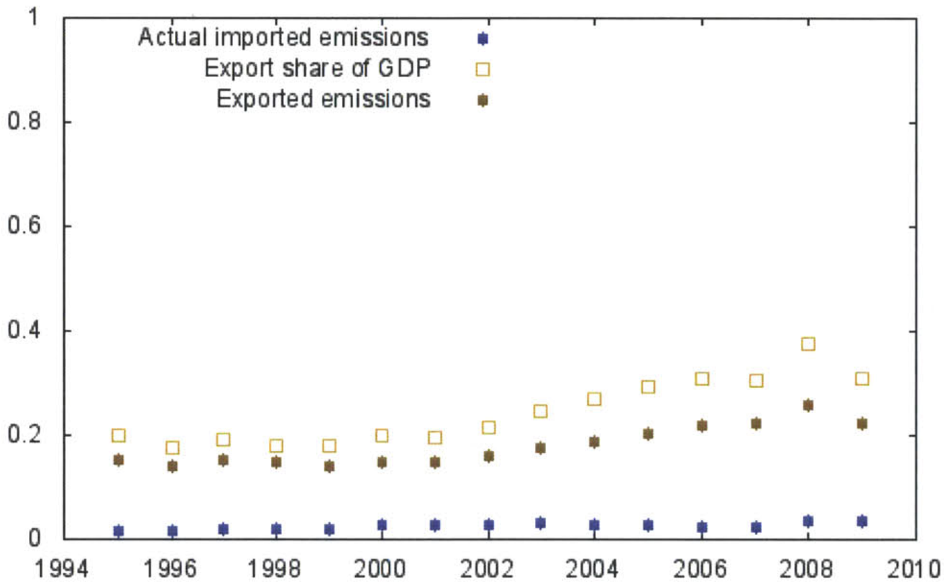
Figure 3.6: Embodied emissions in imports under domestic technology assumption (DTA) and foreign technology calculation for the China as a fraction of total domestic emissions.



In China, the relative position of the ratio of dollar imports to GDP is higher than the ratio of imported emissions to total domestic emissions, suggesting that the mix of goods imported is more energy efficient than the average mix of goods produced domestically. The same relationship is found for exports (see figure 3.7): the mix of exported goods is also more emissions efficient than the mix of goods produced and consumed domestically.

Across countries, we find in general that the dollar import ratio exceeds the emissions import ratio for less developed countries and major producers of primary resource (Australia, Bulgaria, Canada, China, Estonia, India, Indonesia, Mexico, Poland, Portugal, Romania, Russia, Taiwan), while the emissions import ratio is higher for all EU-15 countries besides Denmark (Austria, Belgium, France, Finland, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, UK), Brazil, Cyprus, Czech Republic, Japan, Korea, Latvia, Lithuania, Turkey, and the United States. Denmark, Greece, Hungary, Malta, Slovakia, and Slovenia do not show a clear difference. Those countries with higher import dollar than emissions ratios may be seen

Figure 3.7: Embodied emissions in exports as a share of total domestic exports, and exports as a share of GDP in China.



to be less emissions efficient, since the goods they import are on average more efficient than the goods produced domestically. These countries will also predominantly fall into the "net exporter" category in the next section. Conversely, countries with lower import dollar than emissions ratios will tend to fall into the "net importer" category.

However, the export dollar share of GDP is higher than the export share of emissions in almost all countries. The few exceptions are Brazil, Denmark, Japan, and Russia. This would suggest that most countries export a mix of goods that is more efficient than what domestic consumers consume on average, or in other words, that domestic emissions is borne at a higher rate per dollar by consumers than by foreign countries. The four exceptional countries most likely specialize in exports of emissions-intensive industries with less domestic consumption: Brazil in food products; Denmark in water transportation; Japan in automobiles, chemicals, and electrical equipment; Russia in mining and inland transport.

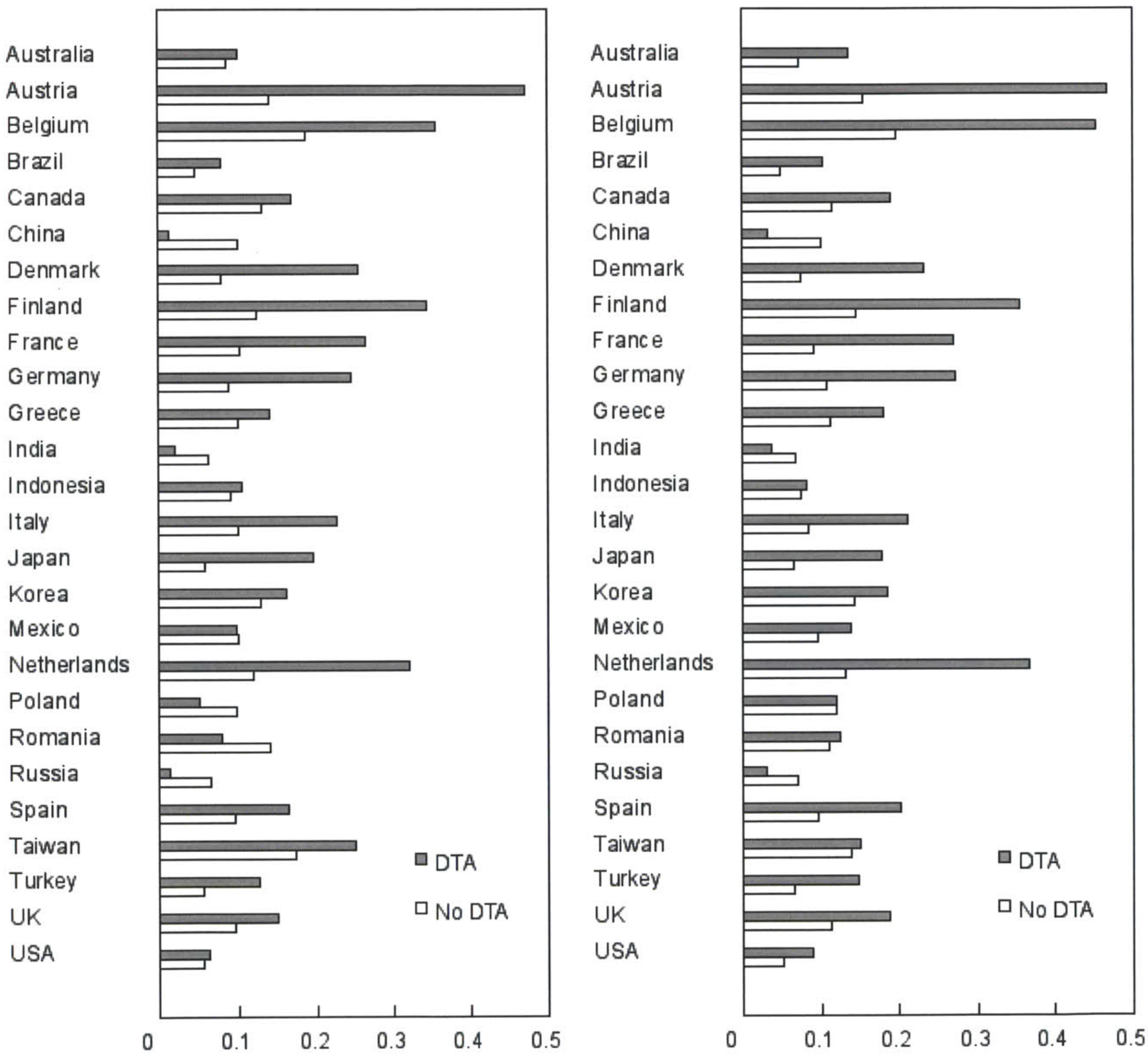
The differences between imported embodied emissions calculated with and without the DTA are summarized figure 3.8 (see table 3.9 for detailed numbers and suppressed countries). A number of patterns are worth highlighting in these results. In 1995, countries in Western Europe and Japan all imported a few times more embodied emissions than the DTA would suggest, while China, India, and Russia imported many times less emissions than those calculated under the DTA. The pattern for Western Europe and Japan continued into 2009, although the difference for China, India, and Russia became less pronounced. Canada, Mexico, the United States, and Australia all had relatively small gaps between DTA and non-DTA emissions imports, but in 2009 all these gaps widened in the direction where non-DTA exceeded DTA emissions.

3.4.2 Trade balances

In the previous section, we highlighted four countries whose embodied emissions from imports would be underestimated by larger amount in 2009 under the domestic technology assumption than in 1995. In other words, the emissions profiles between imported and domestic products was more similar in these countries in 1995, but as time progressed, the emissions intensity of domestic production improved relative to imports, or imports became more emissions intensive relative to domestic production. These relative changes in technology have a dramatic effect on the emissions trade balances of these countries. In figure 3.9, the most obvious changes are the trade positions of the North American countries and Australia.

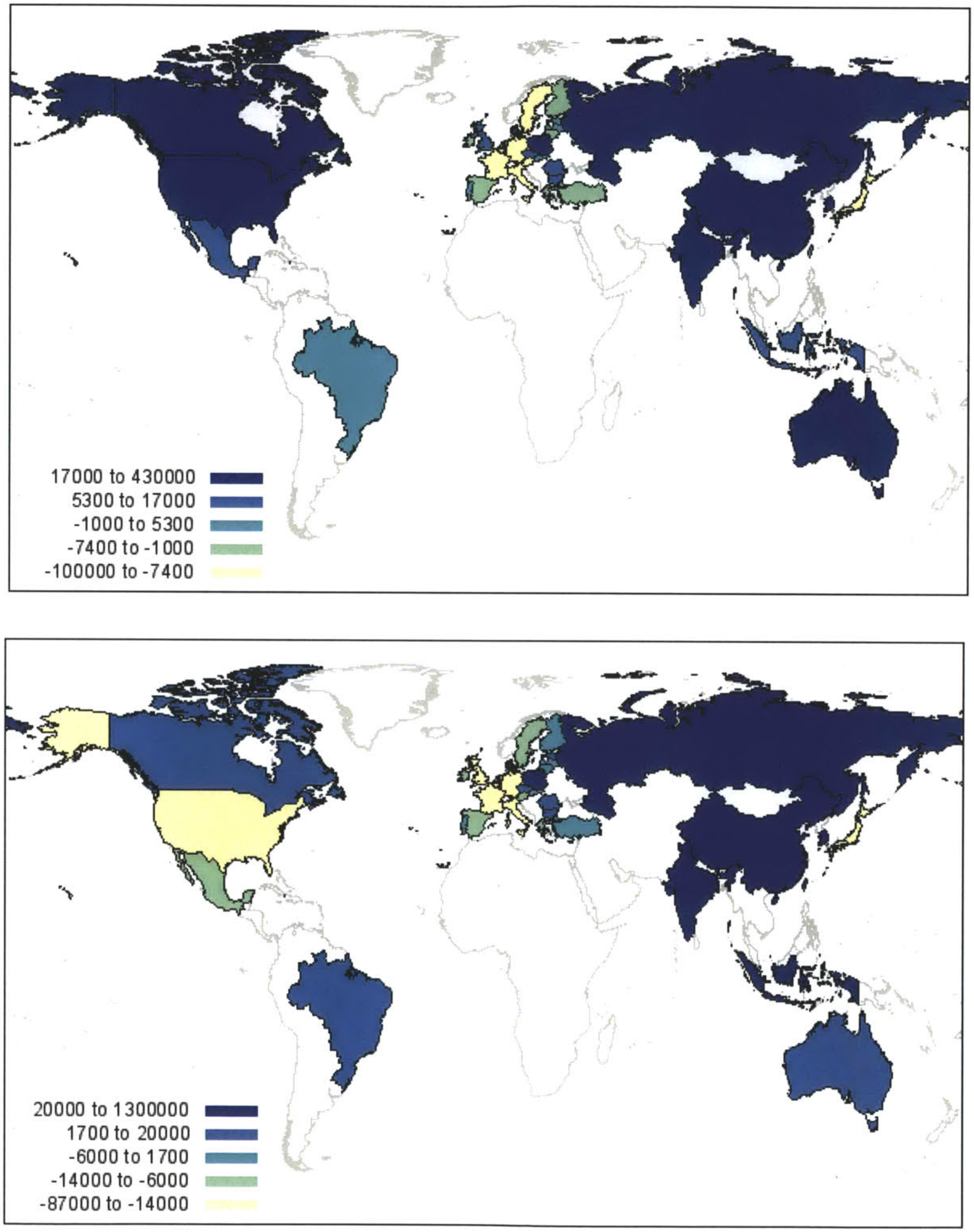
Tables 3.4 and 3.5 show the countries with the largest trade surpluses or deficits in CO_2 ranked by 2009 trade balance. Since the sample of countries is roughly the same size as the full set of OECD members, which account for three quarters of world trade [U.S. Department of State, 2012], one quarter of world trade is not accounted for in these results. Nevertheless, we are able to confirm some known facts: the United States is the country with the largest CO_2 trade deficit, while China is the country with the largest surplus, with China's surplus being almost an order of magnitude greater than the the

Figure 3.8: Embodied emissions in imports as a fraction of domestic emissions, calculated with and without domestic technology assumption. Left: 1995, right: 2009.



Data source: World Input-Output Database, author's calculations.

Figure 3.9: CO_2 trade balances (kilotons) for selected countries, 1995 vs. 2009



Data source: World Input-Output Database, author's calculation. Geographic boundary data from ESRI

Table 3.4: Countries with largest CO_2 trade deficits, ranked by 2009 deficit.

Country	1995	1997	1999	2001	2003	2005	2007	2009
U.S.A.	63,976	39,149	-25,611	-29,148	-96,816	-161,917	-114,357	-86,508
France	-39,412	-34,285	-41,158	-37,520	-42,488	-41,472	-51,961	-46,460
Germany	-99,587	-60,820	-85,930	-38,094	-50,240	-48,767	-55,107	-46,346
Japan	-96,257	-58,215	-46,378	-30,031	-8,155	-25,351	-423	-36,232
Italy	-26,610	-19,752	-43,581	-30,298	-25,169	-19,574	-19,785	-22,497
Belgium	-9,519	-10,570	-8,310	-9,055	-12,606	-20,084	-24,396	-20,470
U.K.	5,608	-7,115	-21,763	-13,241	-10,227	-20,351	-31,875	-18,401
Austria	-18,282	-16,517	-15,940	-17,448	-20,779	-17,097	-15,113	-13,795
Sweden	-7,679	-7,679	-7,289	-5,034	-13,677	-15,213	-17,177	-13,623
Ireland	-2,651	-3,406	-6,177	-6,048	-8,309	-9,618	-15,634	-13,352
Spain	-6,154	-3,978	-11,298	-3,487	-8,144	-10,314	-23,283	-12,142
Greece	-6,478	-6,749	-6,923	-14,676	-16,260	-14,231	-14,156	-9,314
Netherlands	-121	906	-1,575	-2,439	-4,627	-7,825	-11,951	-8,881
Mexico	9,123	-3,558	-7,824	-15,643	-7,437	-7,583	-14,098	-6,589
Finland	-4,301	-2,457	-12,462	-7,607	-8,375	-10,861	-7,365	-6,010
Turkey	-7,428	-257	-15,029	-1,661	-570	-13,347	-18,027	-3,673
Slovakia	4,939	2,468	417	-3,686	-2,322	-62	-2,288	-983
Cyprus	-1,942	-1,951	-2,518	-1,843	-1,704	-931	-1,045	-872

[a] Countries suppressed due to missing data: Luxembourg, Malta, Hungary, Latvia, Slovenia
[a] Data source: World Input-Output Database, author's calculation.

United States' deficit. Of the countries in our sample, 24 have trade deficits and 16 have trade surpluses, but the total tonnage of the CO_2 surplus (1899 million tons) is several times higher than the total deficit (391 million tons). The remaining balance is supplied by countries in the rest of the world.

Tables 3.7 and 3.8 show trade surpluses and deficits as a fraction of the country's total domestic emissions. When countries are ranked by this fraction, Denmark is shown as the largest net exporter per ton of domestic CO_2 emissions; this exceptional ranking merits some discussion. The most likely explanation for this calculated result is that the water transportation sector is recorded in the national input-output table as 100% exported as well as the largest export sector in Denmark. According to WIOD data, emissions from the water transport sector accounted for 47% of all CO_2 emissions produced by Denmark in 2009. These facts stand in stark contrast to the general literature on Denmark, which has generally found Denmark to be neutral or net-importing

Table 3.5: Countries with largest CO_2 trade surplus, ranked by 2009 surplus.

Country	1995	1997	1999	2001	2003	2005	2007	2009
China	425,437	414,524	366,005	380,377	567,126	902,637	1,177,681	1,263,415
Russia	355,161	311,605	552,955	517,462	527,865	507,555	445,338	382,011
India	78,150	85,507	96,933	106,923	99,493	113,896	111,774	110,389
Taiwan	2,713	1,632	7,734	26,566	39,902	40,195	53,951	62,234
Korea	17,031	25,151	49,327	50,209	30,700	16,656	5,122	41,586
Indonesia	10,949	8,477	39,853	45,502	49,685	48,269	52,987	32,825
Denmark	5,308	6,484	14,334	15,950	21,494	23,501	38,155	28,974
Poland	44,749	32,394	12,956	15,886	23,939	24,730	17,658	20,190
Canada	37,634	33,689	39,511	51,267	46,402	32,281	27,376	13,169
Australia	21,842	21,375	26,543	41,571	26,037	23,006	18,524	9,517
Bulgaria	12,398	18,050	-1,033	14,427	13,230	10,031	13,598	6,494
Brazil	74	-2,256	11,486	14,160	26,109	27,424	16,525	4,076
Czech Rep,	7,205	5,577	-149	779	1,012	3,084	2,106	3,607
Romania	13,791	13,382	6,478	6,120	5,950	2,460	650	2,805
Estonia	2,061	1,949	-519	163	968	-869	1,159	1,654
Portugal	-1,030	-2,104	-925	-3,391	-1,956	1,031	2,049	1,192

[a] Data source: World Input-Output Database, author's calculation.

in carbon trade [Jacobsen, 2000], and exports are usually attributed to manufacturing. The CIA World Factbook [U.S. Central Intelligence Agency, 2012] lists shipping neither under the list of notable industries nor export commodities. This may be a reflection of the world's general lack of monitoring over shipping industry emissions.

The large impact of water transport may be a recent phenomenon. Considering the reports of A.P. Moller - Maersk Group, a Danish company that leads the world's shipping container industry at 16% market share [International Chamber of Shipping, 2011, A.P. Moller - Maersk Group, 2011]. According to p. 53 of the company's own report, Maersk Line, the company's shipping container arm, made $18,288 million in revenue in 2009 while producing 32,438 kilotons of direct and indirect CO_2 emissions. WIOD data have $26,354 in output and 36,721 kilotons for the Danish water transport sector in 2009.

3.4.3 Gross imports and exports by sector

In this section we examine gross trade of embodied emissions broken down by industry sector. Tables 3.10 through 3.25 present embodied emissions in traded goods by industry sector for several large geographic regions. Note that these figures represent emissions from each sector embodied in traded goods and not the traded goods themselves. In other words, the electricity sector in these tables represents the electricity used in the process of creating all traded goods and not just electricity that was traded.

There is a fairly consistent pattern that emerges across all geographic regions: an increasing share of embodied emissions in traded goods comes from the utilities (electricity, water, and gas) and all forms of transportation (ground, water, air). The remaining emissions-intensive sectors, especially manufacturing, have mostly lost share in emissions trade to utilities and transportation. The increase in emissions utilities may have a few explanations. The first, and predominant cause, is that the composition of traded goods shifted toward a mix that is more utilities-intensive. The utilities-intensive commodities of raw materials (metal ores, secondary raw materials) and primary fuels (crude petroleum, natural gas, coke, refined petroleum and nuclear fuels) were among the commodities that experienced the largest increases in trade in dollar terms between 1995 and 2009, taking up four of the top six traded commodities with the highest growth rate.

A second explanation for the increase in both utilities and transportation is the complexity of goods traded. Of the commodities produced by manufacturing industries, those that experienced the fastest growth were items like medical, precision and optical instruments; radio, television and communication equipment. Manufactured commodities that experienced low or negative growth tended to be secondary products of agriculture and forestry such as wood, paper, textiles, apparel, food and tobacco. The shift from simpler manufactured products toward more complex manufactured products is likely to result in longer supply chains and more steps in the manufacturing process, each of which is associated with additional transportation and utilities overhead. Electrical and optical equipment is the non-service industry with the largest intermediate expenditures on air transport.

A third explanation involves increasing trade in the service sectors. More so than advanced manufacturing, the commodities that grew the most alongside metal ores and fuels were service sectors including health, research and development, finance, and other business services. While the service sectors themselves do not generate a large amount of direct emissions, their facilities make use of electricity and transportation. The industry named “other business services” is in fact the largest intermediate purchaser of air transport, and likely explains a lot of the increase in emissions due to air transport seen in most of the regions. Financial intermediation is another large intermediate user of air transport. Total gross exports of other business services in our 40 countries grew from 4.7% of all exports in 1995 to 6.5% in 2009, while imports grew from 3.7% to 6.0%. Finance in 2009 accounted for 2.4% of exports and 3.9% of imports, up from 1.7% and 2.2% in 1995.

The EU-15 countries (tables 3.10 and 3.11) best illustrate the overall trend described above, where for both imports and exports, not only the share but also the total amount of emissions associated with most of the raw materials and manufacturing sectors decreased, while that of utilities and transportation increased. Since the Western European countries are not large direct importers or exporters of metal ores and secondary raw materials, the means embodied emissions from mining, metals, and minerals were almost entirely indirect. Use of raw materials increased globally, so decreasing emissions from the metals, minerals, and mining sectors are likely signs of the increasing efficiency in these sectors shown by the results in Chapter 2.

The group of countries in Eastern Europe and the Baltic region (tables 3.12 and 3.13) are most distinct in the decrease in imported embodied emissions share from utilities. We noted in Chapter 2 that several countries in Eastern Europe such as Poland, Romania, Czech Republic, and Slovakia had considerable decreases in emissions intensity of of the utilities sector. If these countries tend to import from each other, this may have slowed down the increase in embodied utilities emissions in imports to these countries. Although the share of embodied utilities emissions increased for exports, the total tons of emissions decreased due to a decrease in total exported emissions (this is consistent with the results of structural decomposition of exports in Chapter 2 – see table 2.16 – which shows emissions levels associated with total exports to have decreased for Bulgaria, Romania, Estonia, Poland, and Slovakia).

Along with Russia (tables 3.14 and 3.15), the Eastern European countries also experienced decreases in imported embodied emissions share from inland transport, and the largest increase in exported embodied emissions from inland transport. Russia is the world's largest exporter of inland transport services, most likely because of its geographic extent and the distance required for freight to travel in and out of its borders. Nearby countries such as Poland are also large exporters of inland transport. Russia's largest export in dollar terms is products of mining, which may be harvested in inland locations away from dense industrial centers. Russia is the only region where embodied exports of utilities emissions decreased, likely reflecting increased efficiency in the utilities sector.

Australia (tables 3.16 and 3.17) and the North American countries (tables 3.18 and 3.19), despite being in different continents, are resource-rich developed economies and share similar patterns in emissions trade. Between 1995 and 2009, Mexico and the United States both went from having trade surpluses to trade deficits in emissions, while Australia and Canada went from large net exporters to small net exporters. The changes in imported embodied utilities emissions to Australia and North America can be explained by a combination of a) composition of imports: in dollar terms, mining, fuels, and chemical products, which are among the industries requiring the most utilities per dollar of output (which can be seen in technical coefficients), accounted for a larger share of total imports; and b) a slight increase in the utilities intensity of these products between 1995 and 2009.

While utilities emissions accounted for a larger share of exported embodied emissions in most regions, none of the increases were as pronounced as China's (tables 3.20 and 3.21). Over one half of embodied emissions in Chinese exports are produced by the utilities sector, again underscoring the desirability of more efficient electric power in China.

3.5 Discussion

This study has shown that while the relative trade balances of developed countries and developing countries are consistent with expectations, with developed countries tending to import embodied emissions and developing countries tending to export emissions, there are geographical and sectoral differences in the growth trends of traded emissions.

Trade balances not only indicate the difference between exports and imports, but also the difference between production and consumption. Focusing exclusively on territorial emissions ignores the ability of developed countries to indirectly consume embodied emissions from imports, and thus discussions about which country should be responsible for paying for emissions reduction are necessarily incomplete. Our results, summarized in Table 3.6 show that this problem is particularly important to the United States due to changes at the turn of the millennium.

As we found in sections 3.4.1 and 3.4.2, in 1995 the European countries in general already had large trade deficits and more efficient production technology for domestic than imported goods. Thus, while consumption-based emissions exceeds production-based emissions by the largest percentage in EU countries (see last two columns of Table 3.6), this difference did not change over the study period. Growth in consumption-based emissions declined slightly slower than production-based emissions across EU countries. In contrast, growth in consumption-based emissions in the United

Table 3.6: Total CO_2 emissions by country group, production vs. consumption

	Territorial emissions (production-based)			Embodied emissions (consumption-based)			Difference[a]	
Country group	1995	2009	change	1995	2009	change	1995	2009
USA	4,954	5,025	1.45%	4,890	5,112	4.55%	-1.29%	1.72%
N. America + Australia	6,030	6,386	5.92%	5,897	6,457	9.49%	-2.20%	1.10%
EU15	3,414	3,295	-3.47%	3,625	3,496	-3.54%	6.18%	6.10%
EU	4,161	3,919	-5.81%	4,288	4,086	-4.72%	3.07%	4.27%
Non-EU	13,886	19,335	39.24%	12,968	17,549	35.33%	-6.61%	-9.24%
Kyoto participants	12,628	12,570	-0.46%	12,372	12,456	0.68%	-2.03%	-0.91%
Kyoto (without USA)	7,675	7,545	-1.69%	7,482	7,344	-1.85%	-2.51%	-2.67%
Kyoto (without Russia)	6,066	5,947	-1.97%	6,229	6,128	-1.63%	2.68%	3.04%
Kyoto non-participants	5,418	10,683	97.17%	4,884	9,179	87.93%	-9.86%	-14.08%

[a] Difference: percent difference between consumption and production-based calculations
[b] Units: million tons
[c] Data sources: World Input-Output Database author's calculations

States, North America, and Australia was significantly higher than production-based emissions. In fact, emissions growth for all Kyoto Protocol participants in our sample is very similar for consumption- and production-based emissions if the United States is removed. Not only did production-based emissions exceed consumption-based emissions the most in the Kyoto Protocol non-participants in our sample (Mexico, Turkey, Cyprus, China, India, Indonesia, Korea, Taiwan, Brazil), this difference also widened between 1995 and 2009, consistent with fast-growing exports from areas with less efficient production technology.

We also found notable differences in embodied emissions growth in trade across industry sectors. In particular, the electricity, gas, and water supply sector, despite many countries' efforts to reduce emissions intensity, has taken up an increasing share of embodied emissions in trade. The transport sectors, including land, water, and air, all account for an increasing share of embodied emissions as well. These trends are likely due to the complexity of traded products and geographic specialization in raw materials. In Chapter 2 we showed that the transport sectors did not improve emissions efficiency as much as other industry sectors; reducing emissions intensity of transport will become increasingly important as transport becomes a larger part of the global supply chain.

Between 1995 and 2009, a number of countries that were previously net exporters of emissions became net importers, including a few countries in Eastern Europe, Mexico, and the United States Changes that took place in the United States around the turn of the century are of particular importance. First, the United States changed from being a net exporter of embodied emissions to a net importer in 1998, a fairly recent change. Yet by 2003 the United States had the world's largest deficit in CO_2 emissions, and the deficit may continue to increase. Second, as figure 3.8 shows, embodied emissions in imports were a small fraction of domestic emissions in 1995 regardless of whether the domestic technology assumption was applied or not (which suggests U.S. production technology at this time was not much more emissions efficient than its trading partners). In 2009 the difference had become large enough that imported embodied emissions would be underestimated by almost one half without considering foreign technology. These changes are important to highlight due to their appearance in recent data. Studies of embodied emissions involving U.S. trade using older data are unlikely to have captured the large changes in imported emissions that occurred since 1998. As the United States debates policies to address emissions, it is increasingly important to include consumption-based emissions among the metrics evaluated.

3.A Appendix

This section contains more detailed tables referenced in the Results section of this chapter.

Tables 3.7 and 3.8 show the ratios of each country's emissions trade balance to total domestic emissions, as discussed in section 3.4.2.

Table 3.9 shows the full results, discussed in section 3.4.1, from comparing imported emissions calculated under the domestic technology assumption ("DTA") and using the technology of the country of origin ("No DTA").

Tables 3.10 through 3.25 show total (direct and indirect) emissions embodied in imports and exports broken down by sector of origin, discussed in section 3.4.3. For brevity, only sectors that account for at least 1% of total embodied emissions in either imports or exports are shown.

Table 3.7: Countries with largest CO_2 trade deficits as a fraction of domestic CO_2 emissions, ranked by 2009 share.

Country	1995	1997	1999	2001	2003	2005	2007	2009
Lithuania	-0.10	-0.16	-0.41	-0.45	-0.56	-0.37	-0.31	-0.38
Ireland	-0.08	-0.09	-0.15	-0.13	-0.19	-0.20	-0.33	-0.31
Sweden	-0.12	-0.12	-0.12	-0.08	-0.21	-0.24	-0.28	-0.24
Austria	-0.30	-0.25	-0.25	-0.26	-0.29	-0.23	-0.22	-0.21
Belgium	-0.07	-0.08	-0.06	-0.07	-0.09	-0.15	-0.20	-0.17
France	-0.10	-0.08	-0.10	-0.09	-0.10	-0.10	-0.13	-0.12
Cyprus	-0.36	-0.33	-0.34	-0.24	-0.23	-0.12	-0.13	-0.10
Finland	-0.07	-0.04	-0.20	-0.12	-0.11	-0.17	-0.10	-0.10
Greece	-0.07	-0.07	-0.07	-0.14	-0.15	-0.13	-0.12	-0.08
Germany	-0.10	-0.06	-0.09	-0.04	-0.05	-0.05	-0.06	-0.06
Italy	-0.06	-0.04	-0.09	-0.06	-0.05	-0.04	-0.04	-0.05
Netherlands	-0.00	0.00	-0.01	-0.01	-0.02	-0.04	-0.06	-0.04
Spain	-0.02	-0.02	-0.04	-0.01	-0.02	-0.03	-0.06	-0.04
Slovakia	0.11	0.06	0.01	-0.09	-0.06	-0.00	-0.06	-0.03
United Kingdom	0.01	-0.01	-0.04	-0.02	-0.02	-0.03	-0.05	-0.03
Japan	-0.08	-0.05	-0.04	-0.03	-0.01	-0.02	-0.00	-0.03
Mexico	0.03	-0.01	-0.02	-0.04	-0.02	-0.02	-0.03	-0.02
United States	0.01	0.01	-0.00	-0.01	-0.02	-0.03	-0.02	-0.02
Turkey	-0.04	-0.00	-0.07	-0.01	-0.00	-0.05	-0.06	-0.01

[a] Countries suppressed due to missing data: Luxembourg, Malta, Hungary, Latvia, Slovenia

[a] Data source: World Input-Output Database, author's calculation.

Table 3.8: Countries with largest CO_2 trade surpluses as a fraction of domestic CO_2 emissions, ranked by 2009 share.

Country	1995	1997	1999	2001	2003	2005	2007	2009
Denmark	0.07	0.08	0.19	0.21	0.25	0.27	0.36	0.33
Russia	0.22	0.21	0.36	0.33	0.32	0.31	0.26	0.24
Taiwan	0.01	0.01	0.03	0.10	0.14	0.13	0.16	0.20
China	0.14	0.13	0.12	0.12	0.15	0.18	0.20	0.19
Bulgaria	0.20	0.30	-0.02	0.28	0.25	0.19	0.24	0.14
Estonia	0.11	0.11	-0.03	0.01	0.06	-0.05	0.06	0.11
Indonesia	0.05	0.03	0.14	0.15	0.15	0.14	0.14	0.08
India	0.10	0.10	0.10	0.11	0.09	0.10	0.08	0.07
Korea	0.04	0.05	0.11	0.10	0.06	0.03	0.01	0.07
Poland	0.12	0.09	0.04	0.05	0.07	0.08	0.05	0.06
Czech Rep.	0.06	0.05	-0.00	0.01	0.01	0.03	0.02	0.03
Romania	0.11	0.11	0.07	0.06	0.05	0.02	0.01	0.03
Canada	0.08	0.07	0.08	0.10	0.08	0.06	0.05	0.02
Australia	0.07	0.07	0.08	0.11	0.07	0.06	0.05	0.02
Portugal	-0.02	-0.04	-0.01	-0.05	-0.03	0.01	0.03	0.02
Brazil	0.00	-0.01	0.04	0.05	0.09	0.09	0.05	0.01

[a] Data source: World Input-Output Database, author's calculation.

Table 3.9: Imported embodied emissions calculated with and without DTA

	1995				2009			
	DTA		No DTA		DTA		No DTA	
Country	level	ratio	level	ratio	level	ratio	level	ratio
Australia	26,543	0.09	30,641	0.10	29,300	0.07	55,603	0.14
Austria	8,576	0.14	29,062	0.47	9,983	0.16	30,000	0.47
Belgium	24,587	0.19	46,976	0.36	23,925	0.20	54,567	0.45
Bulgaria	9,606	0.15	8,445	0.14	6,249	0.13	8,321	0.18
Brazil	10,689	0.05	18,435	0.08	15,562	0.05	33,165	0.10
Canada	60,745	0.13	78,207	0.17	60,224	0.11	100,296	0.19
China	308,553	0.10	43,626	0.01	681,843	0.10	226,038	0.03
Cyprus	824	0.15	2,345	0.44	906	0.11	1,439	0.17
Czech Rep.	19,830	0.17	18,692	0.16	16,860	0.16	23,550	0.22
Germany	84,470	0.09	233,046	0.25	87,974	0.11	221,699	0.27
Denmark	5,959	0.08	18,844	0.25	6,574	0.08	20,215	0.23
Spain	24,025	0.09	41,492	0.16	28,673	0.10	60,498	0.20
Estonia	3,112	0.17	1,962	0.11	2,081	0.13	2,218	0.14
Finland	7,539	0.12	20,734	0.34	8,956	0.14	21,966	0.36
France	41,297	0.10	107,093	0.26	35,110	0.09	104,293	0.27
UK	56,796	0.10	87,945	0.15	63,268	0.11	104,890	0.19
Greece	8,726	0.10	12,118	0.14	12,456	0.11	20,017	0.18
Indonesia	19,457	0.09	22,461	0.10	29,751	0.08	32,524	0.08
India	51,510	0.06	17,476	0.02	110,914	0.07	61,368	0.04
Ireland	4,436	0.13	9,581	0.27	6,490	0.15	20,178	0.47
Italy	45,349	0.10	103,372	0.23	35,741	0.08	89,827	0.21
Japan	66,284	0.06	224,955	0.20	73,671	0.07	196,275	0.18
Korea	52,412	0.13	65,485	0.16	84,244	0.14	108,629	0.19
Lithuania	2,429	0.15	5,039	0.31	1,948	0.13	9,576	0.65
Latvia	1,537	0.16	2,673	0.27	938	0.11	2,568	0.31
Mexico	30,774	0.10	29,700	0.10	41,023	0.10	58,695	0.14
Netherlands	23,153	0.12	61,722	0.32	26,963	0.13	74,870	0.37
Poland	36,014	0.10	18,970	0.05	38,084	0.12	38,188	0.12
Portugal	6,875	0.13	9,676	0.18	7,256	0.12	10,248	0.17
Romania	18,168	0.14	10,231	0.08	10,158	0.11	11,395	0.12
Russia	106,187	0.07	22,699	0.01	111,971	0.07	48,618	0.03
Slovakia	8,022	0.18	9,914	0.22	5,741	0.16	12,486	0.35
Sweden	7,649	0.12	22,223	0.35	9,938	0.17	29,561	0.51
Turkey	10,164	0.06	22,544	0.13	19,528	0.07	43,708	0.15
Taiwan	33,500	0.17	48,391	0.25	43,444	0.14	47,254	0.15
USA	277,307	0.06	316,510	0.06	263,468	0.05	449,633	0.09

[a] Columns below "DTA" refer to emissions calculated under domestic technology assumption. Columns under "No DTA" are calculated from country of origin technology. Levels are in kilotons. Ratio refers to ratio of imported emissions to total domestic emissions.

[b] Hungary, Luxembourg, Malta, and Slovenia omitted due to missing data.

[c] Data source: World Input-Output Database, author's calculation.

Table 3.10: Embodied (direct + indirect) CO_2 emissions in gross exports from EU-15 countries[a]

Sector	1995		2009	
	kilotons	% of total	kilotons	% of total
Electricity, Gas and Water Supply	120,836	20.4	154,801	23.4
Water Transport	48,294	8.1	73,449	11.1
Air Transport	36,435	6.1	72,849	11.0
Basic and Fabricated Metal	82,163	13.9	61,857	9.3
Chemical Products	58,609	9.9	52,144	7.9
Other Non-Metallic Mineral	54,515	9.2	47,199	7.1
Coke, Refined Petroleum, Nuclear Fuel	35,980	6.1	42,732	6.5
Inland Transport	23,379	3.9	29,515	4.5
Agriculture, Hunting, Forestry, Fishing	20,423	3.4	20,001	3.0
Food, Beverages, Tobacco	16,357	2.8	16,677	2.5
Pulp, Paper, Printing, Publishing	13,972	2.4	12,766	1.9
Mining and Quarrying	14,381	2.4	10,557	1.6
Other Business Services	7,085	1.2	9,574	1.4

[a] Austria, Belgium, Denmark, France, Finland, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, UK. Luxembourg omitted due to missing data.

[b] Data source: World Input-Output Database, author's calculation.

Table 3.11: Embodied (direct + indirect) CO_2 emissions in gross imports to EU-15 countries[a]

Sector	1995		2009	
	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	275,205	34.2	344,706	40.0
Basic and Fabricated Metal	109,893	13.7	89,784	10.4
Other Non-Metallic Mineral	55,459	6.9	51,956	6.0
Inland Transport	44,409	5.5	51,399	6.0
Chemical Products	53,140	6.6	46,180	5.4
Mining and Quarrying	55,115	6.9	45,753	5.3
Air Transport	26,099	3.2	41,152	4.8
Coke, Refined Petroleum, Nuclear Fuel	35,568	4.4	39,467	4.6
Water Transport	12,498	1.6	24,421	2.8
Agriculture, Hunting, Forestry, Fishing	24,291	3.0	21,482	2.5
Food, Beverages, Tobacco	13,041	1.6	13,196	1.5
Pulp, Paper, Printing, Publishing	13,625	1.7	10,690	1.2
Textile Products	15,138	1.9	10,422	1.2
Other Business Services	8,110	1.0	10,092	1.2
Auxiliary Transport Activities	4,671	0.6	9,765	1.1

[a] Austria, Belgium, Denmark, France, Finland, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, UK. Luxembourg omitted due to missing data.

[b] Data source: World Input-Output Database, author's calculation.

Table 3.12: Embodied (direct + indirect) CO_2 emissions in gross exports from other European countries[a]

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	61,346	38.7	57,019	42.0
Inland Transport	6,438	4.1	15,749	11.6
Basic and Fabricated Metal	31,732	20.0	15,521	11.4
Other Non-Metallic Mineral	10,714	6.8	8,607	6.3
Chemical Products	13,897	8.8	8,551	6.3
Coke, Refined Petroleum, Nuclear Fuel	6,205	3.9	7,250	5.3
Agriculture, Hunting, Forestry, Fishing	3,922	2.5	4,487	3.3
Mining and Quarrying	4,113	2.6	2,269	1.7
Air Transport	1,447	0.9	2,237	1.6
Food, Beverages, Tobacco	2,065	1.3	2,179	1.6

[a] Bulgaria, Czech, Estonia, Latvia, Lithuania, Poland, Romania, Slovakia, Hungary.
[b] Data source: World Input-Output Database, author's calculation.

Table 3.13: Embodied (direct + indirect) CO_2 emissions in gross imports to other European countries[a]

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	31,218	41.1	43,576	40.2
Basic and Fabricated Metal	7,111	9.4	11,813	10.9
Mining and Quarrying	12,370	16.3	10,048	9.3
Inland Transport	7,573	10.0	9,131	8.4
Other Non-Metallic Mineral	3,013	4.0	7,012	6.5
Chemical Products	3,570	4.7	5,280	4.9
Coke, Refined Petroleum, Nuclear Fuel	3,834	5.0	4,733	4.4
Air Transport	966	1.3	3,548	3.3
Agriculture, Hunting, Forestry, Fishing	937	1.2	1,940	1.8
Water Transport	716	0.9	1,872	1.7
Food, Beverages, Tobacco	601	0.8	1,290	1.2

[a] Bulgaria, Czech, Estonia, Latvia, Lithuania, Poland, Romania, Slovakia, Hungary.
[b] Data source: World Input-Output Database, author's calculation.

Table 3.14: Embodied (direct + indirect) CO_2 emissions in gross exports from Russia

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	170,816	45.2	174,120	40.4
Basic and Fabricated Metal	73,141	19.4	72,307	16.8
Mining and Quarrying	60,303	16.0	70,686	16.4
Inland Transport	41,105	10.9	52,198	12.1
Coke, Refined Petroleum, Nuclear Fuel	7,198	1.9	22,931	5.3
Chemical Products	8,149	2.2	16,439	3.8
Other Non-Metallic Mineral	5,340	1.4	5,703	1.3
Air Transport	1,313	0.3	5,255	1.2

[a] Data source: World Input-Output Database, author's calculation.

Table 3.15: Embodied (direct + indirect) CO_2 emissions in gross imports to Russia

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	7,333	32.3	22,563	46.4
Basic and Fabricated Metal	2,169	9.6	4,170	8.6
Other Non-Metallic Mineral	2,166	9.5	3,637	7.5
Chemical Products	2,119	9.3	3,220	6.6
Textile Products	711	3.1	2,985	6.1
Inland Transport	1,324	5.8	2,487	5.1
Agriculture, Hunting, Forestry, Fishing	1,215	5.4	1,854	3.8
Coke, Refined Petroleum, Nuclear Fuel	754	3.3	980	2.0
Food, Beverages, Tobacco	1,331	5.9	885	1.8
Mining and Quarrying	418	1.8	754	1.6
Transport Equipment	264	1.2	599	1.2
Water Transport	198	0.9	591	1.2
Pulp, Paper, Printing, Publishing	456	2.0	553	1.1
Machinery, n.e.c.	324	1.4	484	1.0

[a] Data source: World Input-Output Database, author's calculation.

Table 3.16: Embodied (direct + indirect) CO_2 emissions in gross exports from Australia

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	15,020	28.6	19,690	30.2
Mining and Quarrying	8,984	17.1	14,214	21.8
Basic and Fabricated Metal	12,061	23.0	11,314	17.4
Air Transport	3,162	6.0	6,704	10.3
Water Transport	1,381	2.6	1,946	3.0
Agriculture, Hunting, Forestry, Fishing	1,842	3.5	1,906	2.9
Inland Transport	1,444	2.8	1,861	2.9
Chemical Products	971	1.8	1,470	2.3
Coke, Refined Petroleum, Nuclear Fuel	3,288	6.3	1,305	2.0
Other Non-Metallic Mineral	720	1.4	1,017	1.6
Food, Beverages, Tobacco	943	1.8	787	1.2

[a] Data source: World Input-Output Database, author's calculation.

Table 3.17: Embodied (direct + indirect) CO_2 emissions in gross imports to Australia

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	8,301	27.1	21,475	38.6
Air Transport	4,280	14.0	9,301	16.7
Basic and Fabricated Metal	3,129	10.2	5,906	10.6
Other Non-Metallic Mineral	2,472	8.1	3,047	5.5
Chemical Products	2,327	7.6	2,797	5.0
Mining and Quarrying	1,124	3.7	1,989	3.6
Inland Transport	914	3.0	1,686	3.0
Coke, Refined Petroleum, Nuclear Fuel	1,151	3.8	1,391	2.5
Water Transport	988	3.2	1,202	2.2
Textile Products	1,047	3.4	851	1.5
Agriculture, Hunting, Forestry, Fishing	513	1.7	738	1.3
Pulp, Paper, Printing, Publishing	635	2.1	693	1.2
Food, Beverages, Tobacco	425	1.4	592	1.1

[a] Data source: World Input-Output Database, author's calculation.

Table 3.18: Embodied (direct + indirect) CO_2 emissions in gross exports from North American countries

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	119,225	22.3	121,144	22.9
Mining and Quarrying	45,624	8.5	62,358	11.8
Coke, Refined Petroleum, Nuclear Fuel	37,115	6.9	41,196	7.8
Air Transport	35,676	6.7	37,707	7.1
Basic and Fabricated Metal	53,665	10.0	37,298	7.1
Chemical Products	39,318	7.3	36,446	6.9
Inland Transport	29,243	5.5	36,062	6.8
Water Transport	29,915	5.6	29,606	5.6
Other Non-Metallic Mineral	19,918	3.7	18,278	3.5
Agriculture, Hunting, Forestry, Fishing	18,332	3.4	14,497	2.7
Other Business Services	13,304	2.5	12,275	2.3
Auxiliary Transport Activities	4,828	0.9	11,098	2.1
Pulp, Paper, Printing, Publishing	16,789	3.1	10,371	2.0
Transport Equipment	7,524	1.4	6,953	1.3
Food, Beverages, Tobacco	6,116	1.1	6,895	1.3
Wholesale Trade	9,671	1.8	6,852	1.3
Machinery, n.e.c.	4,863	0.9	5,419	1.0

[a] Data source: World Input-Output Database, author's calculation.

Table 3.19: Embodied (direct + indirect) CO_2 emissions in gross imports to North American countries

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	118,264	27.9	250,084	41.1
Basic and Fabricated Metal	68,827	16.2	75,306	12.4
Mining and Quarrying	22,715	5.4	46,599	7.7
Other Non-Metallic Mineral	38,483	9.1	39,383	6.5
Chemical Products	33,633	7.9	37,672	6.2
Air Transport	21,749	5.1	28,354	4.7
Coke, Refined Petroleum, Nuclear Fuel	18,207	4.3	26,399	4.3
Inland Transport	11,029	2.6	14,253	2.3
Agriculture, Hunting, Forestry, Fishing	11,600	2.7	12,078	2.0
Textile Products	13,109	3.1	10,623	1.7
Pulp, Paper, Printing, Publishing	10,811	2.5	8,787	1.4
Other Business Services	4,752	1.1	7,108	1.2
Water Transport	3,016	0.7	6,821	1.1
Food, Beverages, Tobacco	4,895	1.2	6,723	1.1

[a] Data source: World Input-Output Database, author's calculation.

Table 3.20: Embodied (direct + indirect) CO_2 emissions in gross exports from China

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	173,990	37.1	782,976	52.6
Basic and Fabricated Metal	65,139	13.9	180,383	12.1
Other Non-Metallic Mineral	44,260	9.4	97,136	6.5
Chemical Products	40,897	8.7	83,170	5.6
Water Transport	6,554	1.4	60,729	4.1
Air Transport	6,174	1.3	45,421	3.0
Mining and Quarrying	18,627	4.0	33,916	2.3
Textile Products	26,774	5.7	30,631	2.1
Coke, Refined Petroleum, Nuclear Fuel	8,644	1.8	27,673	1.9
Inland Transport	7,306	1.6	23,632	1.6
Agriculture, Hunting, Forestry, Fishing	11,903	2.5	21,102	1.4

[a] Data source: World Input-Output Database, author's calculation.

Table 3.21: Embodied (direct + indirect) CO_2 emissions in gross imports to China

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	12,392	28.4	68,313	30.2
Basic and Fabricated Metal	9,929	22.8	37,400	16.5
Mining and Quarrying	2,067	4.7	25,958	11.5
Chemical Products	5,273	12.1	19,765	8.7
Air Transport	1,079	2.5	15,897	7.0
Other Non-Metallic Mineral	1,079	2.5	10,726	4.7
Inland Transport	1,147	2.6	9,672	4.3
Coke, Refined Petroleum, Nuclear Fuel	1,707	3.9	6,640	2.9
Agriculture, Hunting, Forestry, Fishing	1,632	3.7	5,854	2.6
Water Transport	513	1.2	2,934	1.3
Electrical and Optical Equipment	527	1.2	2,724	1.2
Other Business Services	292	0.7	2,342	1.0
Pulp, Paper, Printing, Publishing	900	2.1	2,266	1.0

[a] Data source: World Input-Output Database, author's calculation.

Table 3.22: Embodied (direct + indirect) CO_2 emissions in gross exports from other East Asian economies[a]

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	39,963	15.2	107,213	25.5
Water Transport	52,177	19.9	90,563	21.6
Basic and Fabricated Metal	51,568	19.7	76,823	18.3
Chemical Products	20,730	7.9	31,419	7.5
Other Non-Metallic Mineral	17,667	6.7	24,563	5.9
Air Transport	20,125	7.7	21,263	5.1
Coke, Refined Petroleum, Nuclear Fuel	8,139	3.1	16,714	4.0
Inland Transport	7,389	2.8	9,580	2.3
Transport Equipment	3,070	1.2	5,605	1.3
Electrical and Optical Equipment	5,471	2.1	4,833	1.2

[a] Japan, Korea, Taiwan.
[b] Data source: World Input-Output Database, author's calculation.

Table 3.23: Embodied (direct + indirect) CO_2 emissions in gross imports to other East Asian economies[a]

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	92,675	27.4	134,973	38.3
Basic and Fabricated Metal	57,887	17.1	49,262	14.0
Water Transport	15,117	4.5	37,058	10.5
Mining and Quarrying	21,953	6.5	28,788	8.2
Chemical Products	23,612	7.0	19,988	5.7
Other Non-Metallic Mineral	20,639	6.1	19,982	5.7
Air Transport	16,424	4.8	8,716	2.5
Coke, Refined Petroleum, Nuclear Fuel	16,575	4.9	8,380	2.4
Inland Transport	9,283	2.7	7,562	2.1
Agriculture, Hunting, Forestry, Fishing	14,279	4.2	7,120	2.0
Textile Products	10,574	3.1	4,579	1.3
Food, Beverages, Tobacco	8,411	2.5	4,382	1.2

[a] Japan, Korea, Taiwan.
[b] Data source: World Input-Output Database, author's calculation.

Table 3.24: Embodied (direct + indirect) CO_2 emissions in gross exports from selected Kyoto Protocol non-participants[a]

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	260,753	32.4	979,031	46.3
Basic and Fabricated Metal	106,953	13.3	259,415	12.3
Other Non-Metallic Mineral	77,130	9.6	135,081	6.4
Water Transport	30,325	3.8	121,373	5.7
Chemical Products	63,080	7.8	115,381	5.5
Mining and Quarrying	34,452	4.3	90,156	4.3
Air Transport	25,210	3.1	65,767	3.1
Coke, Refined Petroleum, Nuclear Fuel	28,663	3.6	57,482	2.7
Textile Products	39,979	5.0	44,129	2.1
Inland Transport	19,066	2.4	41,332	2.0
Agriculture, Hunting, Forestry, Fishing	23,908	3.0	38,626	1.8
Food, Beverages, Tobacco	13,274	1.7	21,341	1.0

[a] Brazil, Turkey, Mexico, Korea, Taiwan, Indonesia, India, China.
[b] Data source: World Input-Output Database, author's calculation.

Table 3.25: Embodied (direct + indirect) CO_2 emissions in gross imports to selected Kyoto Protocol non-participants[a]

	1995		2009	
Sector	Tons	% of total	Tons	% of Total
Electricity, Gas and Water Supply	79,309	29.5	229,633	37.5
Basic and Fabricated Metal	52,931	19.7	100,417	16.4
Mining and Quarrying	15,357	5.7	49,276	8.0
Chemical Products	26,643	9.9	48,628	7.9
Other Non-Metallic Mineral	15,791	5.9	35,789	5.8
Air Transport	6,794	2.5	22,256	3.6
Inland Transport	10,203	3.8	20,932	3.4
Coke, Refined Petroleum, Nuclear Fuel	13,544	5.0	19,966	3.3
Water Transport	2,762	1.0	15,215	2.5
Agriculture, Hunting, Forestry, Fishing	7,798	2.9	12,298	2.0
Pulp, Paper, Printing, Publishing	5,009	1.9	6,407	1.0

[a] Brazil, Turkey, Mexico, Korea, Taiwan, Indonesia, India, China.
[b] Data source: World Input-Output Database, author's calculation.

Chapter 4

Conclusion

In the three studies in this dissertation, we use input-output analysis to study fossil fuel energy consumption and emissions from three perspectives. From each study we can draw a number of lessons about energy and emissions trends in the United States and globally. In this chapter we summarize findings from the three studies, and discuss several themes that emerge from the different perspectives of viewing emissions.

4.1 Summary of findings

In Chapter 1, we found through historical analysis of U.S. industrial energy consumption and production, that direct emissions by different industries and total emissions embodied in different consumer goods have progressed at different rates despite overall decreasing energy and emissions intensity per dollar GDP.

Growth in total embodied energy (both fossil fuel and total) consumed by households increased the most in service sectors from 1972 to 2002, while embodied energy intensities fell the most in service sectors. The largest consumer-driven sources of embodied energy and emissions – utilities and gasoline – experienced very little growth in energy and emissions levels (see Figure 1.4), driven largely by efficiency improvements, especially in utilities (see Figure 1.5). Growth patterns were similar from the production side. Service industries, especially transport, among the largest contributors to energy and emissions growth, although service sectors also declined the most in energy and emissions intensity, while manufacturing industries were mixed. The worst performing sectors from both consumption and production perspectives were food products, apparel, and chemicals, which are all downstream sectors from petroleum.

In Chapter 2 we applied an old structural decomposition technique to a new dataset. Consistent with the plethora of studies comparing the relative contributions to emissions from final demand, sectoral emissions intensity, and industry input structure, we found that the opposing forces of higher final demand and lower emissions intensity tended to result in favor of final demand and thus higher emissions. However, by analyzing more recent cross-country data, we found some patterns of note.

First, the total level of emissions due to household consumption decreased in the majority of European Union (EU) countries that were participants to the Kyoto Protocol, due to a combination of industrial efficiency and the average mix of goods consumed (see bottom of Figure 2.6). Total levels of emissions due to exports decreased in a smaller set of these countries (Figure 2.8), as this has been more difficult to achieve for highly export-oriented countries like Germany and Japan. Second, our complementary analysis of emissions by industry sector shows that the progress of emissions intensity varies widely by sector and geography, with a large amount of emissions reductions due to utilities in Eastern Europe (Table 2.3), and emissions increases in raw material and basic manufacturing sectors of Russia, China, and India. The most effective industry to target globally is power generation, the largest component of the electricity, gas, and water supply sector that accounts for roughly half of emissions in the majority of countries studied. Third, there is some evidence of technological convergence in the cross-sector analyses, lending some hope to the possibility that developing countries can adopt cleaner technologies used by developed countries.

In Chapter 3, our analysis of embodied emissions in imports and exports answers questions about imported embodied emissions that were left open in Chapters 1 and 2. Our comparison of embodied emissions calculated with and without assuming production technology similar to the importing country shows that applying the domestic technology assumption indeed leads to large underestimations of embodied energy in imports to developed countries. This result is particularly important to the United States (as well as Canada, Mexico, and Australia) because the large difference is only apparent in data from very recent years (see Figure 3.8). In Chapter 1, our estimates of embodied energy and emissions relied on the domestic technology assumption; the results from Chapter 3 imply that underestimation is unlikely for all but one year of our time frame. For 2002 and beyond, environmental accounts built using the methodology of Chapter 1 are increasingly likely to be underestimated.

Similar to our findings in Chapter 2, within imports and exports we also found large variations in embodied emissions growth depending on geography and industry. Embodied emissions from utilities increased as a share of embodied emissions in both imports and exports in almost all countries in our sample, with the few exceptions being Russia and Eastern Europe. In Chapter 2 we found Russia and Eastern Europe to have greatly reduced emissions intensity in the utilities sector, but in most countries, energy intensity improvements in the utility sector did not keep up with those of downstream production, which may be a reflection of high capital costs in power generation leading to inflexible production curves. Also increased globally were emissions from land, water, and air transport industries, which may be due to increased trade in services that use more air travel, and complex manufactured products like precision instruments and optical equipment, which involve longer supply chains. Emissions from mining and basic manufacturing industries decreased as a share of total embodied emissions in trade for most countries, although the dollar value of traded mining products increased in share, especially as imports to North America, which may have resulted indirectly in emissions from utilities and inland transport.

4.2 Consumption vs. production and the importance of embedded energy and emissions

In Chapter 3, we demonstrated how the difference between calculating direct and total (direct + indirect) emissions by industry can varies by geographic region (see Figures 3.2 and Figures 3.3). More importantly, direct emissions captures industrial activity while total embodied emissions captures consumption activity. In pre-21st century United States, the emissions trends of industry sectors and consumption goods followed similar trends, with emissions from services industries growing but simultaneously becoming less energy intensive the fastest. However, the similarity between production and consumption is greatly altered as trade increases (total production is the sum of domestically consumed domestic production and exports, while consumption is domestically consumed domestic production plus imports).

For example, we found in Chapter 1 that the share of imported apparel in the United States grew rapidly (see Table 1.5) from 11% in 1972 to 72% in 2002, meaning consumption vastly exceeded production by 2002. If the countries that produce most of U.S. clothing use inefficient upstream inputs, then embodied emissions in apparel is likely to be much higher than we calculated.

In Chapter 3 we discussed providing emissions data by country based on embodied emissions consumed, in addition to emissions production data that is widely available. Since the emissions trade balance is equivalent to the difference between emissions production and consumption, the trade balances we calculated in Chapter 3 (see Tables 3.4 and 3.5) are also representative of the differences between a consumption- and production-based dataset. By publicizing only territorial emissions data, which are tied to domestic production, the amount of emissions for which each country is ultimately responsible may be distorted. We show in Table 3.6 that production-based emissions understates emissions responsibility the most for EU countries, and overstates responsibility for the Kyoto Protocol non-participants in our sample. Additionally, recent changes in the trade positions of the United States and North America suggest that the gap between production- and consumption-based emissions in these areas is widening.

4.3 Industrial and geographical shifts

The global landscape of emissions is closely tied to the shifting geography of industrial production and trade, in a way that highlights distinctions between developed and developing countries.

The first trend we saw in Chapter 1 is the steadily increasing share of consumer goods imported to the United States, especially apparel, vehicles, and other durable goods. For these goods, input-output analyses that apply the domestic technology assumption produce results that are probably underestimated, especially after 2000.

The United States is just one of many developed countries whose trade volume and net imports of emissions increased relative to domestic production. In Chapter 3 we found that all North American countries and Australia have exhibited similar trends, with the notable increases being in imports of utilities, transport, and mining (including natural gas). The countries whose exported emissions grew the most were China and Russia, which in 2009 were responsible for a combined 63% of utilities emissions embodied in gross exports from our sample of countries, and 44% of mining emissions in exports.

EU countries, while also importing more embodied emissions from utilities, generally reduced embodied emissions from raw material and primary manufacturing sectors in both imports and exports. Their largest non-utility emissions increases came from transport, which may be a side effect of increased trade as more transportation of goods is required.

Tables 2.4 and 2.5 in Chapter 2 show that the group of countries with the highest emissions growth – China, Russia, India, Brazil, and other Asian countries – increased emissions more rapidly to supply exports to foreign countries than domestic household consumption. While this is not enough to conclude that these developing economies are serving as pollution havens to the more strictly regulated EU countries, it shows that production of emissions has shifted geographically in the same direction that pollution haven theories predict.

4.3.1 Power generation and transportation

In all the three studies, power generation and transportation sectors stood out as large industrial sources of emissions. Between 1995 and 2009, traded goods that contained embodied emissions from utilities and transportation grew in almost all regions, both in absolute levels and as a share of total emissions. We suggest two explanations for this result. First, emissions efficiency in other industry sectors improved more than electricity, which requires large and inflexible capital investments to change, and transportation, which currently is a function of fuel economy (much of transportation beyond personal vehicles is also capital intensive and lasts for long terms). Our second explanation is that technological advances have led to higher demand of more complex products, as evidenced by products like precision instruments and optical equipment taking up a larger share of trade dollars. The increase in product complexity necessitates more complex supply chains, which include the electricity and transportation embodied in a more geographically diverse array of upstream inputs. The large increase in business travel may be largely responsible for the air transport industry's failure to improve emissions efficiency (as seen in Figure 2.19).

4.3.2 Permanent economic and technological shocks

In Chapter 1 we show that the energy intensity of goods is highly sensitive to current oil prices, especially goods directly downstream from, or complementary to petroleum products. The oil shocks of 1973-79 had a permanent reducing effect on energy intensity in all sectors, but especially in household consumption of gasoline and motor vehicles.

Although we do not yet have data beyond 2009 to evaluate the effects of the recent recession, we have preliminary results to see that the recession seriously hurt final demand from exports, but with less impact on emissions levels (see Figures 2.4, 2.10, 2.14). However, as oil prices fell during the recession and have rebounded to new highs in recent years, there is a possibility that new technological shifts will occur in the next few years.

4.4 Methodological contributions

In highly data-driven studies including national accounting, having better data is often more important than better models. A major common theme we found in all literature related to embodied emissions is a desire for more accessible, complete, and harmonized data on trade, technology, energy and emissions data, economic indicators, etc.

The World Input-Output Database is a comprehensive multi-regional input-output dataset whose scope and detail exceed that of the OECD and GTAP statistics. The data are organized in a format amenable to the structural decomposition analysis and trade balance calculations designed and applied in Chapters 2 and 3. To our knowledge, this is the first dissertation that applies input-output analysis to environmental accounts in the newly published WIOD data, with publicly available source code. Based on our positive experience with this dataset, which other researchers are likely to also find, we anticipate future improvements to data accuracy and scope.

In this dissertation we describe three approaches to analyze time series of emissions accounts: consumption vs. production, structural decomposition, and imports vs. exports. These methods can be easily replicated on later versions of WIOD data, as well as any NAMEA-compatible dataset. We also provide a method to create NAMEA-like environmental satellite tables from input-output and fuel consumption data, which we anticipate will be applicable to forthcoming BEA releases the 2007 and 2012 benchmark input-output accounts.

One of the lessons learned in Chapter 3 was the importance of having recent data, as the change in the United States' trade position may not be easily discovered without the correct time frame. For this reason, we emphasize the repeatability of our methods on future datasets, as longer-term changes to the global emissions landscape may not be predictable by simple extrapolation of our current results.

4.5 Reflections on current policy alternatives

In Chapters 2 and 3 we made references to the Kyoto Protocol and EU Emissions Trading Scheme, both of which are highly relevant to emissions policy debates today. Our studies can shed light on some aspects of these programs.

The EU Emissions Trading Scheme is a 15-year long program in which participants voluntarily enter a cap-and-trade scheme for CO_2 emissions. Our findings in Chapters 2 show that EU countries were able to reduce emissions from 1995 levels due to relatively small increases in household consumption. Our analysis of emissions trade in Chapter 3 (in particular Tables 3.11 and 3.10 on page 140) show that embodied emissions from imported goods increased, but only by 7% over the 14-year period, and thus the EU is the best prepared among the world to meet emissions reduction targets without imposing large emissions growth on the rest of the world.

Similar cap-and-trade schemes and carbon taxes on fossil fuels have been proposed for the United States, which has the advantage of being able to study the EU experience. One reasonable objection to a U.S. cap-and-trade scheme currently is the state of the post-recession economy, which may suffer further declines if domestic production is made costly by high fuel prices. We noted in Chapter 2 that many of the countries with emissions declines, such as Italy, Germany, and France, also experienced very slow GDP growth over the 14-year period. Furthermore, by voluntarily taxing domestic fuel, the United States could lose competitiveness over other countries that do not make efforts to reduce emissions.

The argument about reduced competitiveness would be mitigated if all countries were required to tax carbon emissions instead of just the United States. The Kyoto Protocol was an attempt to achieve such an international agreement, but through setting emissions targets rather than explicit taxes or tradable credits. Our studies highlight a few related problems with the Kyoto Protocol specification. First, the protocol does not provide a solution for countries that do not participate in the agreement, and we found that among the countries in the WIOD sample, non-participating countries experienced the largest growth in emissions, but much more so through exports than domestic consumption.

Second, the protocol focuses on reducing territorial emissions, which are produced by domestic industries. However, trade continues to grow as a share of the international economy, and more household consumption needs are being met by products that include embodied emissions from other countries. Table 3.6 shows the lopsided difference between production-based and consumption-based emissions, where EU countries consume 6% more emissions than they produce, and non-Kyoto countries produce around 10% more than they consume. Although the differences are smaller for the United States, the change in trade position before and after 2000 mean that previously, consumption-based emissions looked more favorable to the United States, whereas territorial emissions look more favorable now.

In this dissertation we focus on accounting of world emissions, and thus our recommendation to the policy community is also one of accounting. Emissions targets need to involve consumption-based emissions, as these are in some ways a better reflection of who is responsible for creating emissions. Consumption-based emissions are much more difficult to estimate than territorial emissions due to the complexity of geographies and upstream industries involved in the production process. However, if the WIOD and similar datasets improve, the creation of consumption-based datasets should become more accessible.

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