Energy Embodied in Trade, 1970–2014

Viktoras Kulionis

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Abstract

Ongoing globalisation combined with the rapid pace of technological change have generated significant growth in economic activities and have improved the welfare and living standards of many people around the world. The opening up of the world economy has also led to unprecedented surges in international trade and has fundamentally transformed the way that goods and services are produced, exchanged and consumed. In addition, the increasing separation of production and consumption activities has been accompanied by an increase in energy, resource and carbon content embodied in international trade. In general all economic activity requires the use of energy, which has a variety of environmental impacts. This dissertation examines how the relationship between energy use and economic growth evolved in high-income countries from 1970 to 2014 and the role of trade in this. The approach involves looking at the factors driving the change, how the importance of these factors has changed over time and how it differed across countries.

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Economic Growth, Energy Use, Trade, Footprint, Carbon Emissions, Input-Output Analysis, Structural Decomposition Analysis

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List of Papers

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III Kulionis, V. (2019) Constructing Energy Accounts for WIOD 2016 Release. *Unpublished manuscript*.

IV Jiborn, M., Kander, A., Kulionis, V., Nielsen, H., and Moran, D. (2018) Decoupling or Delusion? Measuring Emissions Displacement in Foreign Trade, *Global Environmental Change*, 49:27–34.

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Introduction

1 Motivation and Aim

Since the days of the Industrial Revolution, energy has played an essential role in economic development, human well-being and poverty alleviation. Substantial improvements in energy-driven technologies allowed labour to be diverted from primary activities such as agriculture towards more sophisticated manufacturing and services and facilitated a dramatic growth of population and income.

Advances during the twentieth century have been closely linked with an unprecedented rise of energy consumption in general and hydrocarbons in particular. Today modern economies are dependent on large and uninterrupted flows of energy like at no other time in history.

This dependence has critical environmental consequences. Energy systems in the past and still today are dominated by fossil fuels (e.g. oil and gas). All fossil fuels are carbon-based, and their combustion generates carbon dioxide (CO_2) and other greenhouse gases. There is now an almost universal agreement among climate scientists that greenhouse gas emissions are the primary driver of global climate change.

Overcoming the climate change challenge requires a better understanding of the relationship between economic growth and energy use. Long-term trends show that the relationship between fossil fuel energy use and economic growth has been both dynamic and complex. This relationship changes with shifts in development stages and differs across countries. Typically, energy intensities rise during the early stages of industrialisation, peak, and then decline as economies mature and use energy more efficiently. This pattern resembles the so-called Kuznets type curve. Often individual country trends may have very different slopes, and peaks can be sharp or can appear as extended plateaus (Smil, 2000). Energy intensity in England peaked in the late nineteenth century (Warde, 2007) in the US around 1920 (Schurr and Netschert, 1960), on the aggregate European level and globally around 1970 (Kander et al., 2013; Smil, 2016).

Declining energy intensity implies decoupling, which could be relative or absolute. Relative decoupling occurs when the growth rate of GDP is higher than the growth rate of energy consumption and environmental impact. As a result, relative decoupling implies a gain in efficiency but not the removal of the link between impact and economic growth. Absolute decoupling, on the other hand, occurs when the environmentally relevant variable is stable or decreasing while the output is growing. From an environmental perspective, absolute decoupling is a more desirable goal because it indicates sustainable growth without increasing environmental pressure.

Relative decoupling is a widespread phenomenon occurring at country and global levels. Often it is a result of steady upward economic growth and its relationship with technological (efficiency gains) and structural change (more services). Examples of absolute decoupling are less frequent and are only evident in a few highly developed economies since about 1970.

Decoupling may be presented as reality when in fact it is not taking place and seems to occur simply as the result of production relocation. In other words, countries may displace their production elsewhere by importing things they could otherwise produce themselves. Grossman and Krueger (1995) noted that the downward sloping part of an inverted U-shape curve might arise because as countries develop, they cease to produce energy-intensive products and import these goods from other countries with less restrictive environmental regulations. However, the empirical evidence does not support the hypothesis that environmental regulation is an important determinant of the global pattern of international trade (Grossman and Krueger, 1995). Instead, decisions to relocate are driven mainly by global differences in the prices of capital, labour and materials. If the differences in production methods and energy structures are significant between countries, then the relocation of production activities across countries may result in an overall increase in energy use and the related environmental impact.

Ongoing globalisation has led to unprecedented surges in international trade and fundamentally transformed the way that goods and services are produced, exchanged and consumed. Between 1980 and 2015, the value of exports grew by a factor of nine and, on average, exports made up 29% of a country's GDP in 2016 (Wiedmann and Lenzen, 2018). The increasing separation of production and consumption activities has been accompanied by an increase in factor content embodied in international trade.

The nature of international trade has changed, particularly with the emergence of global value chains and the trade of intermediary goods they involve. A significant proportion of total global impacts are now associated with trade, and this trend is rising. When answering the question as to whether human society can decouple economic growth from energy use and environmental impacts, it is essential to quantify the environmental factors embodied in trade.

The principal aim of this dissertation is to contribute empirically and theoretically to the analysis of the relationship between energy use and economic growth in developed economies. Specifically, it aims to determine what share of energy use is embodied in exports and what part is embodied in imports and how this developed over time. The overarching research question is:

To what extent does the energy content embodied in trade affect the relationship between energy use and economic growth?

The dissertation consists of an introductory chapter and four individual papers. The introductory chapter presents an overview of the factors that underpin the relationship between energy and economic growth in the long term. This chapter is set to establish the background for the subsequent papers.

Paper 1 measures the content of energy embodied in the trade of advanced economies between 1970 and 2009. Paper 2 examines the factors that explain the change in energy footprint over that time. Paper 1 and Paper 2 provide a firm understanding of energy-growth relationship in four advanced economies (Denmark, France, the UK and the USA) at the aggregate and disaggregate level. Studying these countries over an extended period informs how the relationship between energy and growth has evolved and what was the role of trade in this.

Paper 3 constructs energy accounts for the WIOD 2016 database and presents global energy use trends from 2000 to 2014. Paper 3 is a continuation of the two preceding papers. It provides a global, and most recent, perspective on the energy content embodied in trade.

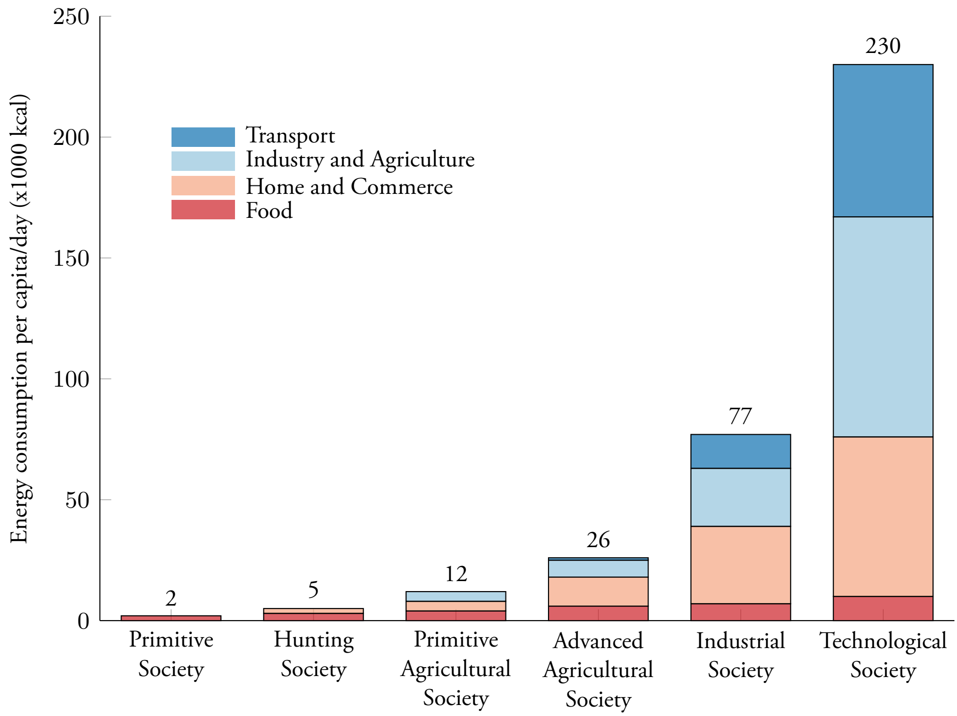
Paper 4 presents a method to detect and measure structural CO_2 emissions outsourcing. It complements the previous papers that focus on energy use by giving an additional perspective on CO_2 emissions which are directly related to energy use.

2 Historical context

2.1 A Brief History of Energy Use

Individual energy needs have changed dramatically over the years. Estimates of daily per capita energy requirements at six periods of societal development by Cook (1971) are shown in Figure 1. The first four refer to the pre-industrial age, often termed as the organic economy (Wrigley, 2006). In such economies, land was the main source of food and also the main source either directly or indirectly of all the material products needed, i.e. all the raw materials which entered into production were mainly of animal or vegetable origin. In primitive societies, per capita energy needs averaged 2,000 kcal per day. Energy consumption at this point was mostly in the form of food. The domestication of fire raised consumption to about 4,000 kcal per day. A large part of the non-food energy for heating and cooking came from harvesting biomass, primarily wood, peat and animal dung. Fire was an important discovery. It created light and improved safety in human settlements,

Figure 1: Daily Energy Use at Different Stages of Societal Development



Notes: Adapted from Cook (1971). *Primitive Society* (East Africa about 1,000,000 years ago) no use of fire, only the energy of the food. *Hunting Society* (Europe about 100,000 years ago) more food and energy for heat and cooking. *Primitive Agricultural Society* (Fertile Crescent in 5000 B.C.) growing crops and using animal energy. *Advanced Agricultural Society* (northwestern Europe in A.D. 1400) using coal for heating, some water power and wind power and animal transport. *Industrial Society* (e.g. England in 1875) using the steam engine. *Technological Society* (e.g. the U.S in 1970) using electricity and the internal combustion engine.

which promoted the expansion of habitation (Fouquet, 2009).

The introduction of agriculture increased energy demands to about 12,000 kcal per day in primitive agricultural societies. This was achieved through the domestication of animals which enabled humans to grow more food than was needed for personal use. During the advanced agricultural period, energy consumption increased to 26,000 kcal. The harnessing of water and wind power represented important inventions at this time. Wind was used to push sailing ships, water to drive mills for flour production, leather tanning, iron smelting and so on. In the agricultural period, dependence on land set physical and biological limits to the possible scale of production because each type of production was in competition with every other for the access of land products.

The invention of the steam engine ushered in the industrial revolution and initiated the transition from the organic economy to the fossil fuel based economy. The steam engine allowed the transformation of chemical energy (heat) into mechanical energy (motion). The first steam engine invented in 1698 was inefficient and expensive to use in any sites distant from coal supplies. Efficiency improvements by James Watt in 1769 finally rendered the steam engine a ground-breaking technology. It allowed the extraction of more coal from mines that were not exploitable in an earlier age and for this coal then to be used as a fuel source for locomotives and steam ships to transport raw materials, machinery and coal to sites across the continent and beyond (Kander et al., 2013). The increased use of coal was a symptom of technological change, and the primary driver of the Industrial Revolution (Fernihough and O'Rourke, 2014).

Coal provided 'ghost acres'[1] allowing escape from the constraints imposed by the previous dependence on land (Pomeranz, 2000). These virtual landscapes permitted specialisation, international trade and higher quality consumer goods and leading to increased consumption of energy. During the first Industrial Revolution, energy consumption increased to 70,000 kcal per capita/per day in England, Germany and the US.

After the invention of the steam engine and the growing use of coal, two other key inventions that have enhanced the energy system emerged in the nineteenth century, namely electricity and the Internal Combustion Engine (ICE). The use of electricity expanded in two phases (Kander et al., 2013). Firstly, it was introduced in the cities, initially as a substitute for other energy sources for specific applications such as light and cooking. In industry, electric motors replaced the factory system with one big steam engine that operated several individual machines. Electric motors did not revolutionise the way factories were organised, but they improved working conditions as they were operating more silently and did not emit smoke. The second phase of the electricity expansion was more dynamic and had a more significant impact on society. As opposed to the first phase, electric motors in factories were installed on each machine. This allowed greater flexibility of work and was more economical, as the machines could be started or shut down when it was needed. Household electric appliances also diffused more quickly during the second phase, and most of the appliances were new devices, not substitutes as was common during the first phase. These appliances not only acted as labour-saving tools but also helped to improve quality of life and thus devices such as vacuum cleaners, refrigerators, washing machines and others rapidly diffused across households. As a result, energy consumption rose steadily since 1900 and by circa 1970 per capita energy consumption in the USA amounted to 230,000 kcal per day, roughly 115 times higher than that of primitive societies.

The third Industrial Revolution, with Information Communication Technology (ICT) at the centre

[1] Ghost acres is a term used to refer to the area of land abroad that is needed to produce a product for consumption in a given country.

of it, emerged in the 1970s. Arguably, the ICT revolution was more energy-saving than the two previous revolutions. Energy savings came in various forms. Automation of manufacturing based on semiconductors enabled significant material and energy savings in traditional industries. Various e-services (e-bank, e-government, etc.) reduced the need for travel and ordinary letter and invoices. The outsourcing of the production of more energy-intensive products, such as steel and iron also played a role in reducing energy demands. Despite the growth in all kinds of energy-consuming devices, from air conditioners to computers to air travel, per capita, energy consumption remained relatively stable since the 1980s in most industrialised countries .

2.2 Factors Affecting Energy Use

Figure 2 displays energy use per capita and GDP per capita for Western Europe during the period from 1861 to 2008. Over the long-term, average energy consumption per capita in Western Europe increased four-fold and GDP rose eleven-fold. However this was not a universal phenomenon. On a global level between 1900 and 2000 energy use increased by about 17-fold (from 22 EJ to 380 EJ), and gross output rose 16 fold from 2 trillion to 32 trillion US dollars (Smil, 2000, 2013).

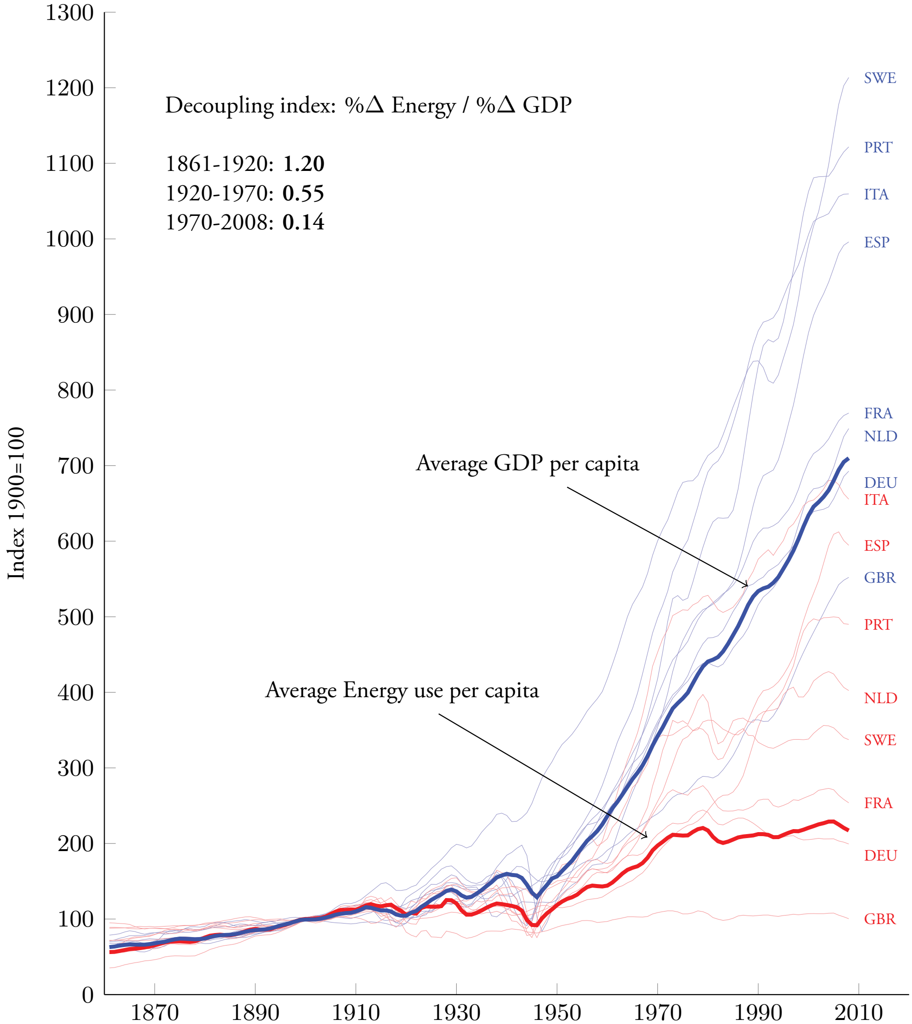
Expansion in energy use has been affected by many different factors such as population, income and technological change. The importance of these factors differed among countries and time. The IPAT identity (Commoner et al., 1972; Ehrlich and Holdren, 1972; Chertow, 2000) employed in this section can help understand how much of the change in energy consumption over a specific period has been due to a particular factor and how its importance has changed over time.

The IPAT identity represents specific impact (I), in this case it is energy use, as the product of three variables: population (P); affluence (A, expressed as GDP per capita); and technology (T, measured as energy use per GDP). The IPAT identity can be expressed as:

$$\underbrace{I}_{\text{Energy use}} = \underbrace{P}_{\text{Population}} \times \underbrace{A}_{\text{GDP / Population}} \times \underbrace{T}_{\text{Energy use / GDP}}$$

The IPAT decomposition results for Western Europe over the period 1861-2008 are given in Table Table 1 on page 9. From 1861 to 2008, energy use (I) in Western Europe increased on average by 1.39% per annum. The components of the IPAT identity show that the two main drivers of increasing energy use over this period were population growth (P) and growth in GDP per capita (A). Changes in income per capita accounted for 1.68% and were about three times as large as the population factor 0.53%. In contrast, technological change (P) worked in the opposite direction and had a negative impact on energy use, on average accounting for -0.82% per annum.

Figure 2: Energy Use in Western Europe 1861-2008



Notes: GDP from Bolt et al. (2018) and Energy data from Kander et al. (2013). DEU – Germany, ESP – Spain, FRA – France, GBR – Great Britain, ITA – Italy, NLD – the Netherlands, PRT – Portugal, SWE – Sweden. GDP per capita and Energy use per capita are weighted averages. The decoupling index shows average yearly percentage change in Energy use per capita given one percentage change in GDP per capita. For example, the decoupling index for the period 1970–2008 is 0.14, implying that 1% change in GDP per capita is associated with 0.14% change in Energy use per capita.

Energy use grew at different rates in different periods, and the importance of factors affecting its use also differed over time. Between 1861 and the onset of the First World War, there was a big leap in energy use mainly due to the increasing use of coal (Kander et al., 2013). All factors during this period including (T) had a positive impact on energy use. Technology (T) had a positive effect because during a period of industrialisation in Western Europe energy consumption had to grow faster than GDP in order to build infrastructures: roads, bridges, houses and heavy industry (Reddy and Goldemberg, 1990). These industrial activities generally required more energy than traditional agriculture. The overall effect of structural changes towards a larger share of high-energy activities in the economy is an increase in energy intensity.

During the interwar period, energy consumption stayed fairly constant. To a large extent, this was due to declining energy intensity (T) which helped to counterbalance the positive impact of increasing population (P) and income per capita (A). Energy consumption increased the greatest extent in the period 1950–1970, driven mainly by increases in income per capita (A). The post World War II period also saw a breakthrough in oil consumption. During the 'golden decades' of the 1950s and 1960s, cheap oil flooded European markets, and the oil share rose from 10% to 50% of total energy use (Kander et al., 2013).

Despite the increases in income per capita and population, the rate of increase in energy consumption was modest between 1970 and 2008 compared to the postwar period. During this period, energy intensity declined by 1.5% – 2%, the largest decline since 1861. Although the declining energy intensity was not sufficient to counterbalance the positive effects of income and population, it limited the increase in energy use. This rapid decline in energy intensity embodies two features of economic development: more efficient use of fuels (making more with the same amount of energy) and a structural shift from manufacturing towards services.

The historical link between energy flows and economic output for the high-income countries appears different in the post-1970 period in the sense that there is an apparent weakening in the long-term relationship between energy and GDP. Although so-called relative decoupling has been evident in some countries already since the beginning of the nineteenth century, the post-1970 period is marked by signs of absolute decoupling. It seems that at the end of the twentieth century the relationship between energy and economic growth entered a new phase, characterised by modest or even declining use of energy relative to economic growth.

2.3 Trade in Historical Perspective

International trade has changed drastically over the last few centuries, both in terms of the scale and also the nature of what and how it is traded. Baldwin (2006) explains globalisation as the process of two great unbundlings. The first unbundling occurred in two waves, one from roughly 1820/1870 to 1914 and the other from the 1960s to the present. The second unbundling (also termed frag-

Table 1: IPAT Decomposition for Western Europe, 1861-2008 (Annual Rate of Change)

Period	**I** (%)	**P** (%)	**A** (%)	**T** (%)
1861–1890	2.14	0.68	1.13	0.33
1890–1910	2.10	0.87	1.33	0.10
1910–1930	-0.02	0.36	0.88	-1.25
1930–1950	0.67	0.52	0.84	-0.69
1950–1970	3.53	0.77	4.20	-1.43
1970–1990	0.73	0.37	2.34	-1.98
1990–2008	0.51	0.31	1.72	-1.52
1861–2008	1.39	0.53	1.68	-0.82

Notes: Western Europe sample includes: Sweden, the Netherlands, England, Germany, France, Italy, Spain and Portugal. I - Impact (Energy use per capita), P - Population, A - Affluence (GDP per capita), T - Technology (Energy Use/GDP).

mentation, offshoring, vertical specialisation and slicing up the value-added chain) began around the mid-1980s and continues today. The first unbundling meant the separation of factories and consumers (or production and consumption) and the second unbundling meant that the production process itself could be split into different parts (factories shift from making things to making pieces) which could be outsourced (made in the same country) or offshored (made abroad). This section presents some of the main features of trends in trade from 1800 to 2014.

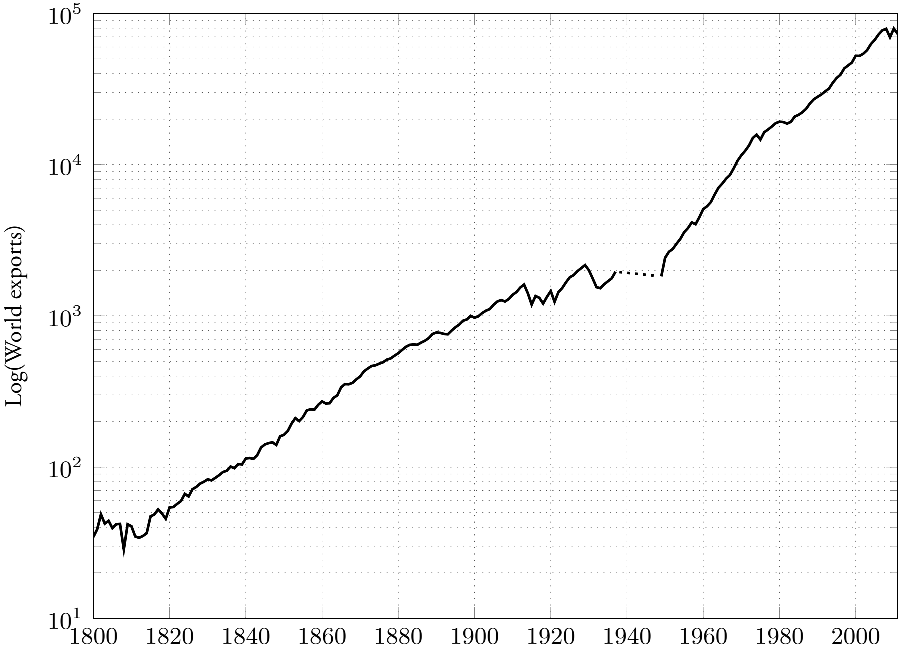
2.3.1 First Wave

The evolution of world exports is shown in Figure 3. Between 1800 and 2014 world exports grew at an annual rate of 4.2% (Federico and Tena-Junguito, 2017). Since the mid nineteenth century (the beginning of the first unbundling) world trade has grown over 140-fold. At the same time, the world's population has grown roughly six-fold, and world output has grown 60-fold (WTO, 2013).

In the pre-globalisation world, production and consumption activities were isolated by distance to such an extent that each village's consumption was supplied by its own production. The arrival of the first Industrial Revolution in the early nineteenth century initiated a massive expansion of trade, capital and technology. Breakthroughs in steam-related transport technologies (steamship and railways) reduced transportation costs and opened national economies to trade. The geographical separation of production and consumption activities led to the globalisation's first unbundling (Baldwin, 2006). The first wave of globalisation continued until World War I. The outbreak of World War I led to a fall in world exports by about a quarter.

A new global economic landscape – defined by an advanced industrial 'core' and a raw-material

Figure 3: Evolution of World Exports, 1800–2014



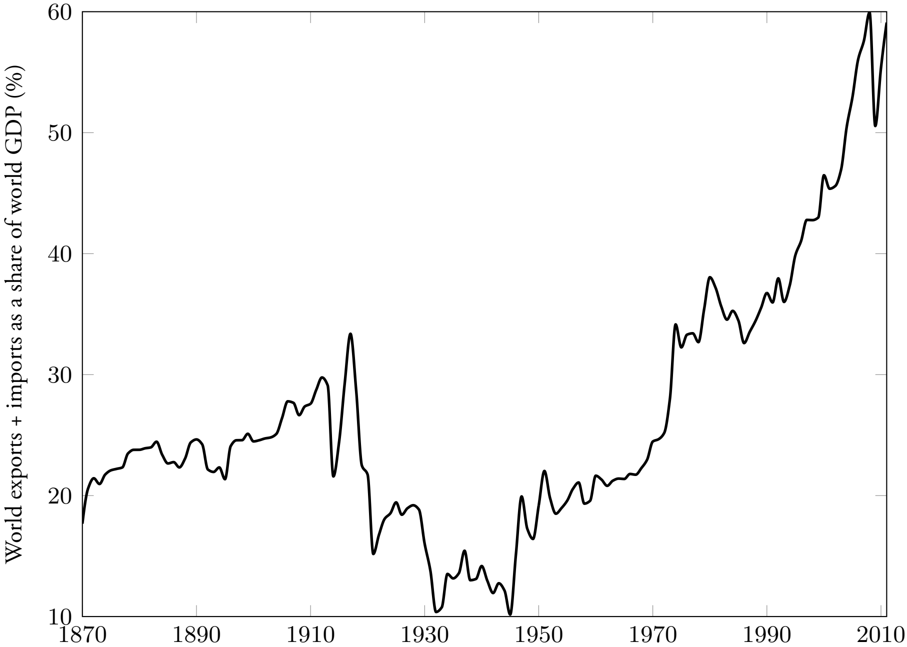
Notes: Data source: Federico and Tena-Junguito (2017). Data retrieved from `ourworldindata.org`. Dotted line represents missing data points.

supplying 'periphery' – gradually took shape over the course of the nineteenth century, reflecting the increasing international division of labour (Findlay and O'Rourke, 2007).

As the nineteenth century progressed the nature and geographical pattern of world trade changed to one in which the core exported manufactured goods throughout the world and imported raw materials especially from the colonies and other less developed nations. Exports of textiles led the way, followed in the second half of the nineteenth century by heavy manufactured goods, such as iron, steel and coal.

The roles of core and periphery in the geographical division of labour became clearly defined. Industrial production became pre-eminently a core activity. Industrial goods were both traded between core nations and exported to the periphery. Conversely, the periphery's role was a dual one. Firstly, it supplied the core with primary commodities- raw materials for transformation into manufactured products in the core; foodstuffs to help feed the industrial nations. Secondly, it purchased manufactured goods from the core, particularly capital goods in the form of machinery and equipment. This international division of labour in some cases led to the 'de-industrialisation' of the developing

Figure 4: World Trade as a Share of World GDP, 1870–2011



Notes: Data sources for the period: 1870-1949 from Klasing and Milionis (2014); 1849-2011 from Feenstra et al. (2015). Data retrieved from `ourworldindata.org`.

world (Bairoch and Kozul, 1996).

The global economic structure dominated by the core economies of northwest Europe and the United States persisted until the Second World War. About 70% of world manufacturing was concentrated in just five countries (US, Japan, Germany, France and the UK) and roughly 90% in only eleven countries (Dicken, 1998). The core industrial countries exported about 65% of the manufacturing output to the periphery and imported 80% of the periphery's primary products (Dicken, 1998). Trade was massively disrupted by the Second World War and the political chaos that followed.

2.3.2 Second Wave

The Second World War shattered the well established core-periphery trade structure. The vast majority of the world's industrial capacity was destroyed and had to be rebuilt. The post-war world economic system was in many ways a new beginning that has undergone a process of re-globalisation.

During the period between 1950 and 1973, world trade grew at roughly 8% a year, far faster than the 3% growth shown before the First World War (Federico and Tena-Junguito, 2017).

The growth of trade during the Golden Age was unprecedented. However, even more, important was the fact that trade increased more rapidly than GDP (and also faster than in the period 1870–1950) which was an indication of increased internationalisation of economic activities and greater integration (see Figure 4). Growing international economic cooperation and deepening integration built on a foundation of multilateral institutions (The Bretton Woods system) have come to characterise the second wave of globalisation.

The growth of international trade slowed markedly in the 1970s but resumed again from the mid-1980s. A significant change during the second wave of globalisation was the shift of manufacturing to new centres of production mainly in east and southeast Asian countries (the Republic of Korea, Singapore, and other 'Asian Tigers'). Their collective share of total world manufacturing exports grew from 1.5% in 1963 to nearly 20% in 1995.

Significant technological advances that improved the speed of transportation and communication have been responsible for driving globalisation since the mid twentieth century. These innovations included the development of commercial and civil aviation, the containerisation of international shipping and the invention of the internet. Newer technologies – automobiles, aeroplanes, telecommunications – enabled the next wave of industrialisers.

Increases in manufacturing trade stimulate the expansion and development of commercial, financial and business services. In the 1970s, trade in services grew more slowly than trade in manufacturing but that trend was reversed from the 1980s. Growing trade integration reflects the information communication technology (ICT) revolution of the 1980s, which enabled an even more global division of labour and specialisation (Dicken, 1998).

As stated above, the period from around the mid-1980s is termed by Baldwin (2006) as the second unbundling. The unique feature of this period was the unbundling of the whole production process or supply chains, which were previously bundled together in one enterprise. The ICT revolution radically reduced the cost of moving ideas. Internet and high-speed international communication networks allowed cheaper and easier coordination of production units in different locations. Productive functions no longer had to be confined within proximate spaces. Tasks that were previously not-traded became freely traded when communication costs dropped to almost zero (Baldwin, 2006), with some tasks being offshored across borders to exploit the cost differentials of production factors in various countries.

Production of goods and services by combining inputs from different countries is related to the emergence and development of complex and sophisticated global value chains (GVCs) (WTO, 2013). This is best illustrated with an example from WTO: “In the 1980s, Toyota produced cars that were ‘Made in Japan’ today it produces cars that are ‘Made in the World’ and the workforce that was once mainly employed on assembly lines is now increasingly engaged in running a highly integrated and technologically complex system of global production taking in everything from research, design and marketing to finance, logistics and information and communications technology (ICT) coordination” (WTO, 2017, p.14). The rise of such sophisticated and increasingly complex production networks marks a transition from local production systems to a ‘Factory World’ (Los et al., 2015) or as others argue to production systems organised within regional blocks such as ‘factory Asia’, ‘factory Europe’ and ‘factory North America’ (Baldwin and Lopez-Gonzalez, 2015).

3 Energy Use and Growth

3.1 Theory and Previous Research

Standard economic theory recognises capital, labour and land as the main factors of production (Solow, 1956). It is assumed that GDP growth per capita is driven by technological progress and capital investment (including human capital). Energy is assumed to have a relatively minor role in economic production in the mainstream theory of growth. This view has been criticised by resource and ecological economics, which is grounded in the biophysical theory of the role of energy. Increasing concerns about environmental conditions and resource scarcity triggered interest in resource economics. Solow (1974) among others has provided a theory of economic growth that includes an exhaustible resource.

The limited natural resource base of the planet as the limiting source of growth is not new. It was a central theme in Malthus (1798) famous work on population growth in which he argued that population increases geometrically (1, 2, 4, 8) while food supply increases arithmetically (1, 2, 3, 4) and therefore food supply would at some point run up against the limit of finite land. So far, as history has shown Malthus's predictions proved inaccurate.

Malthusian ideas re-emerged in the early 1970s, in the context of absolute limits on resources and energy. Resource scarcity was a central theme in two famous books: *The Population Bomb* by Ehrlich (1968) and *The Limits to Growth* by Meadows et al. (1972). These books emphasised that too many people were consuming too many natural resources and this would eventually lead to global shortages of natural resources and pollution. *The Limits to Growth* was criticised for unrealistic assumptions, methodology, weak data foundation, and underlying concepts (Cole et al., 1973).

With hindsight one can say that the argument about resource scarcity has been overstated. Technology and innovation continue to transcend the limits of supply by exploiting existing energy sources in new ways (e.g. shale gas) or inventing new substitutes. However, another argument about Earth's limited ability to act as a sink for human waste turns out to be correct and received positive reviews. Nordhaus (1992, p.2) pointed out: "...to dismiss today's ecological concerns out of hand would be reckless. Because boys have mistakenly cried 'wolf' in the past does not mean that the woods are safe".

Nature acts as a source of raw materials, oil and valuable minerals and also as a sink for unwanted by-products of economic activity such as greenhouse gas pollution. The mass-balance principle introduced by Ayres and Kneese (1969) means that economic systems are not isolated from ecological systems and can be understood as operating within a wider system: the ecological system. The economic system takes natural resources (matter, organic and inorganic, and energy) from the ecological system (environment) and returns waste and pollution to the latter in order to maintain and expand its own system organisation. Since all production involves the transformation or movement of matter in some way, energy is therefore necessary for economic production and, as a result, economic growth (Stern, 2010). Under such a view, energy becomes the main input and focus of attention, while labour and capital represent intermediate inputs since they cannot be produced or maintained without energy.

Extensive research has been carried out on the factors affecting the link between energy and growth in developed economies, especially since the two oil price shocks of the 1970s which triggered concerns about the availability of primary resources. As shown in Figure 2 average energy consumption per capita in western Europe has hardly changed since the 1970s, while at the same time, average GDP per capita has increased. Given this evidence, it is often claimed that there has been a decoupling of economic output and resources, which implies that the limits to growth are less restrictive over time.

A number of factors could affect the relationship between energy use and economic growth over time. According to Stern (2004a), the key factors are substitution between energy and other inputs, technological change, shifts in the composition of the energy input and shifts in the composition of economic output.

The linkage between energy use and economic growth has important environmental implications. As noted earlier, all forms of economic activity require energy use which has a variety of impacts. Extraction and processing of energy always involve some form of environmental disruption such as pollution or/and land use impacts. Thus, energy use is sometimes seen as a proxy for the environmental impact of human activity Stern (2004a). This means that the factors that affect the amount of energy required to produce one unit of GDP also act to reduce the environmental impact in the same way.

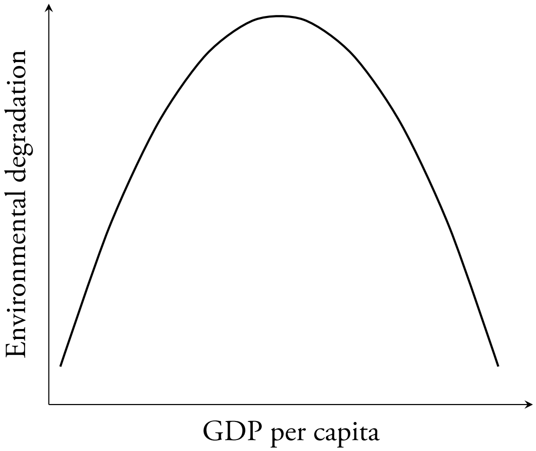
Energy exists in many different forms and not all energy sources are equally damaging for the environment. It is true that all energy methods are environmentally disruptive; for instance hydroelectric dams affect aquatic ecosystems. Nevertheless, energy sources such as wind, solar and nuclear are less polluting (in terms of emissions) than fossil fuels such as coal and oil. Furthermore, some energy sources are of higher quality than others which means that they can be used for a large number of activities and/or for more valuable activities (Stern, 2010). A shift from poorer quality fuels such as coal to the use of higher quality fuels such as natural gas not only reduces the total energy required to produce a unit of GDP but also produces less carbon dioxide per unit of energy derived.

The shift from lower to higher quality fuels is often known as climbing up the 'energy ladder' (Hosier, 2004). Initially, low-income economies are heavily reliant on biomass and animate power to meet their energy needs. As they develop the share of biomass in energy mix declines and the share of fossil fuels and some hydroelectricity increases. At high income levels, the reliance on hydroelectricity, oil and coal decreases while dependence on natural gas, nuclear power and modern renewables (e.g. wind, solar) increases (Burke, 2011).

Despite the strong link between energy use and economic activity, there are several pathways through which environmental impact can be reduced. In the 1990s, the relationship between economic growth and environmental degradation has been put to empirical tests (Stern, 2004b). Most of the literature sought to test the so-called Environmental Kuznets Curve (EKC) hypothesis, which posits that an inverted U-shape relationship exists between the level of pollution and economic growth (Grossman and Krueger, 1991). The general idea behind EKC shown in Figure 5 is that as a country develops, the pollution level in that country increases to a certain point after which environmental degradation starts to decrease. The decreasing point of EKC is often explained by the factors mentioned previously which include: more efficient use of available resources; shift in composition of output; and a shift in the composition of energy supplies towards cleaner fuels.

However, the EKC hypothesis has received considerable criticism on both empirical and theoretical grounds Dasgupta et al. 2002. Stern (2004b) argues that the EKC applies only for a subset of pollutants such as sulphur dioxide and that there is little empirical evidence for a common EKC that countries follow as their income rises. One of the most common theoretical critiques of the EKC is that if such a relationship exists it might be partly or largely a result of the effects of trade. Reductions in one pollutant in one country may involve increases in other pollutants in the same country or transfers of pollutants to other countries (Arrow et al., 1995). This argument is based on the assumption that relatively high environmental standards in high income countries impose

Figure 5: Environmental Kuznets Curve (EKC)



high costs on polluters which creates an incentive for some highly polluting industries to relocate. And if environmental standards are not uniform around the world, then industries will relocate to 'pollution havens', i.e. countries that are unable or unwilling to enforce high environmental standards (Dasgupta et al., 2002). Empirical literature does not support the pollution haven hypothesis (PHH) that environmental regulation is an important determinant of the global pattern of international trade (Levinson, 1996). Instead, decisions to relocate are driven mainly by global differences in the prices of capital, labour and materials (Grossman and Krueger, 1995). Although the empirical evidence does not provide support for the PHH, changes in trade patterns and significant growth in the volume of trade have had a considerable effect on the distribution of the environmental impacts. These changes have resulted in a growing spatial separation of production and consumption activities, and have led to a shift of resource use and associated environmental burden from one country to another (Wiedmann et al., 2015).

This phenomenon is commonly known as 'carbon leakage' and came to light during the signing of the Kyoto Protocol Convention. Peters (2010) provides a broader version of the term carbon leakage by splitting it into its 'strong' and 'weak' subdivisions. Weak carbon leakage corresponds to greenhouse gas (GHG) emissions that occur abroad in order to satisfy consumption in a given country. It takes into account all emissions embodied in international trade flows regardless of whether these flows were induced by climate policy. Strong carbon leakage corresponds to GHG emissions that occur outside a given country due to climate policy in that country. Strong carbon leakage is equivalent to PHH and the existing evidence shows that environmental regulations do not drive investment decisions and strong carbon leakage is negligible Peters (2010). The effect of weak carbon leakage has been assessed by quantifying balances of CO_2 and GHG emissions embodied in trade using input-output analysis (Wiedmann et al., 2007; Peters, 2008). Broad literature at the global and individual country level finds that developed countries are net importers of GHG emissions and that developing countries are net exporters (Davis and Caldeira, 2010; Peters et al., 2011). Furthermore, emissions embodied in international trade have grown over the past couple of decades (Wood et al., 2018). It is important to note that weak carbon leakage uses attributional models which do not say what caused the changes in international trade that led to the increase in weak carbon leakage (Peters, 2010; Peters and Solli, 2010). For example, Jakob and Marschinski (2012) note that weak carbon leakage can occur simply because exports are produced with a cleaner technology and not because the production of carbon-intensive goods has been offshored. The contribution of international trade to the growth in country-specific and global emissions and resource use remain relatively scarce. Only recently several studies (Arto and Dietzenbacher, 2014; Xu and Dietzenbacher, 2014; Hoekstra et al., 2016; Kaltenegger et al., 2017) have quantified its impacts. This thesis aims to contribute to this line of research by estimating the effect of international sourcing (and other factors) on changes in the energy footprint of high income countries over the long term.

3.2 Decoupling framework

Decoupling is a term used to describe a situation in which two or more factors are separated, or do not develop in the same way. In the energy-GDP framework, the term decoupling refers to the process whereby aggregate economic activity can grow without corresponding increases in energy use (and consequently environmental problems). Decoupling between energy use and economic growth can take different forms. Vehmas et al. (2003) illustrates all possible scenarios between environmental stress and economic growth in a quadrant diagram, distinguishing weak and strong forms of de-linking and re-linking. Building on Vehmas et al. (2003) work, Zhang et al. (2017) presents a framework for analysing the relationship between material use and output. Based on different elasticity and intensity measures they distinguish eight possible decoupling and coupling combinations. Building on previous work by Vehmas et al. (2003), (Tapio, 2005), (Zhang, 2012) and Akizu-Gardoki et al. (2018), I present a framework for analysing the relationship between energy use (E) and economic activity (Y) measured by GDP.

Relative change in E and Y from point in time 0 ($t = 0$) to point in time 1 ($t = 1$) can be expressed as:

$$\frac{\triangle E}{E_0} = \frac{E_1 - E_0}{E_0} \text{ and } \frac{\triangle Y}{Y_0} = \frac{Y_1 - Y_0}{Y_0} \tag{1}$$

Given (1) the elasticity of energy use to economic activity can be expressed:

$$\frac{\triangle E/E_0}{\triangle Y/Y_0} \tag{2}$$

The elasticity of energy use to GDP is also referred to as a decoupling index (Diakoulaki and Mandaraka, 2007; Fischer-Kowalski et al., 2011; Chen et al., 2017) that shows the rate at which energy use increases/decreases given one percentage change in GDP.

Change of energy use per unit of economic output between two points in time can be expressed as:

$$\triangle\left(\frac{E}{Y}\right) = \frac{E_1}{Y_1} - \frac{E_0}{Y_0} \tag{3}$$

Given the above information, all possible combinations of different decoupling and coupling scenarios are displayed in Figure 6 where the horizontal axis denotes a change in output $\frac{\triangle Y}{Y_0}$ and the vertical axis a change in energy use $\frac{\triangle E}{E_0}$. A constant relationship between E and Y ($\frac{\triangle E/E_0}{\triangle Y/Y_0} = 1$ and $\frac{\triangle E/E_0}{\triangle Y/Y_0} = -1$), is presented by dotted diagonal lines. From this diagram, eight different combinations of decoupling and coupling processes can be distinguished. Four of these combinations located on the left-hand side of the diagram refers to a situation of negative economic growth $\frac{\triangle Y}{Y_0} < 0$ which are rare occurrences. The four combinations located on the right-hand side of the diagram relate to positive economic growth $\frac{\triangle Y}{Y_0} > 0$ and are common across the world.

The decoupling index shown in Equation (2) is the most important metric in this framework because it shows the strength of decoupling. However, as can be seen in Figure 6 the decoupling index can take the same value but occur in different areas of the graph, for example $\frac{\triangle E/E_0}{\triangle Y/Y_0} > 1$ in both expansive coupling (**A**) and recessive decoupling (**E**) regions. In order to distinguish unique cases, it is necessary to look at the change in energy intensity (i.e. Equation 3) which is positive $\triangle\left(\frac{E}{Y}\right) > 0$ for expansive coupling but negative $\triangle\left(\frac{E}{Y}\right) < 0$ for recessive decoupling (**E**). This implies that in order to distinguish a unique case of decoupling, at least two conditions must be satisfied. Four unique cases that are characterised by positive economic growth (located on the right-hand side in Figure 6) are discussed in more detail below.

3.2.1 Expansive Coupling

Expansive coupling occurs when one percentage change in GDP (Y) is related to more than one percent increase in energy use (E). This situation refers to the upward part of the Environmental Kuznets Curve (EKC). In Western Europe, expansive decoupling took place in the period 1861–1910. This can be seen in Table 1 in which T has a positive value, indicating that energy use increased faster than GDP. Formally expansive coupling occurs when the following two conditions are satisfied:

Condition 1: The change in energy intensity between two points in time has to be greater than zero:

$$\triangle\left(\frac{E}{Y}\right) > 0$$

This condition indicates that energy intensity is increasing over time.

Condition 2: The change in energy use has to be greater than the change in output:

$$\frac{\triangle E/E_0}{\triangle Y/Y_0} > 1$$

3.2.2 Relative Decoupling

Relative decoupling occurs when energy use (E) per unit of economic GDP (Y) activity declines, meaning that less energy is required to produced one unit of output.. At the present time, relative decoupling is the norm, it is evident in most countries around the world. Formally relative decoupling occurs when the following two conditions are satisfied:

Condition 1: The change in energy intensity between two time points has to be less than zero:

$$\triangle\left(\frac{E}{Y}\right) < 0$$

This condition indicates that energy intensity is decreasing over time.

Condition 2: The change in output has to be greater than the change in energy use:

$$0 < \frac{\triangle E/E_0}{\triangle Y/Y_0} < 1$$

3.2.3 Absolute Decoupling

Absolute decoupling occurs when energy use declines in absolute terms while economic output continues to increase. It implies that economic growth no longer depends on the increasing use of energy. There are several countries (mainly highly developed economies) that display signs of absolute decoupling. However, these occurrences are still rare. Formally absolute decoupling must satisfy two conditions.

Condition 1: The change in energy intensity between two time points has to be less than zero:

$$\triangle\left(\frac{E}{Y}\right) < 0$$

Condition 2: The positive change in output has to be associated with a negative change in energy use:

$$-1 < \frac{\triangle E/E_0}{\triangle Y/Y_0} < 0$$

3.2.4 Strong Absolute Decoupling

Strong absolute decoupling refers to a situation where a one per cent increase in GDP is related to more than one per cent decrease of energy use, i.e. the elasticity of energy use to GDP is -1. This situation is different from the absolute decoupling case where elasticity is between -1 and 0. Formally strong absolute decoupling must satisfy two conditions.

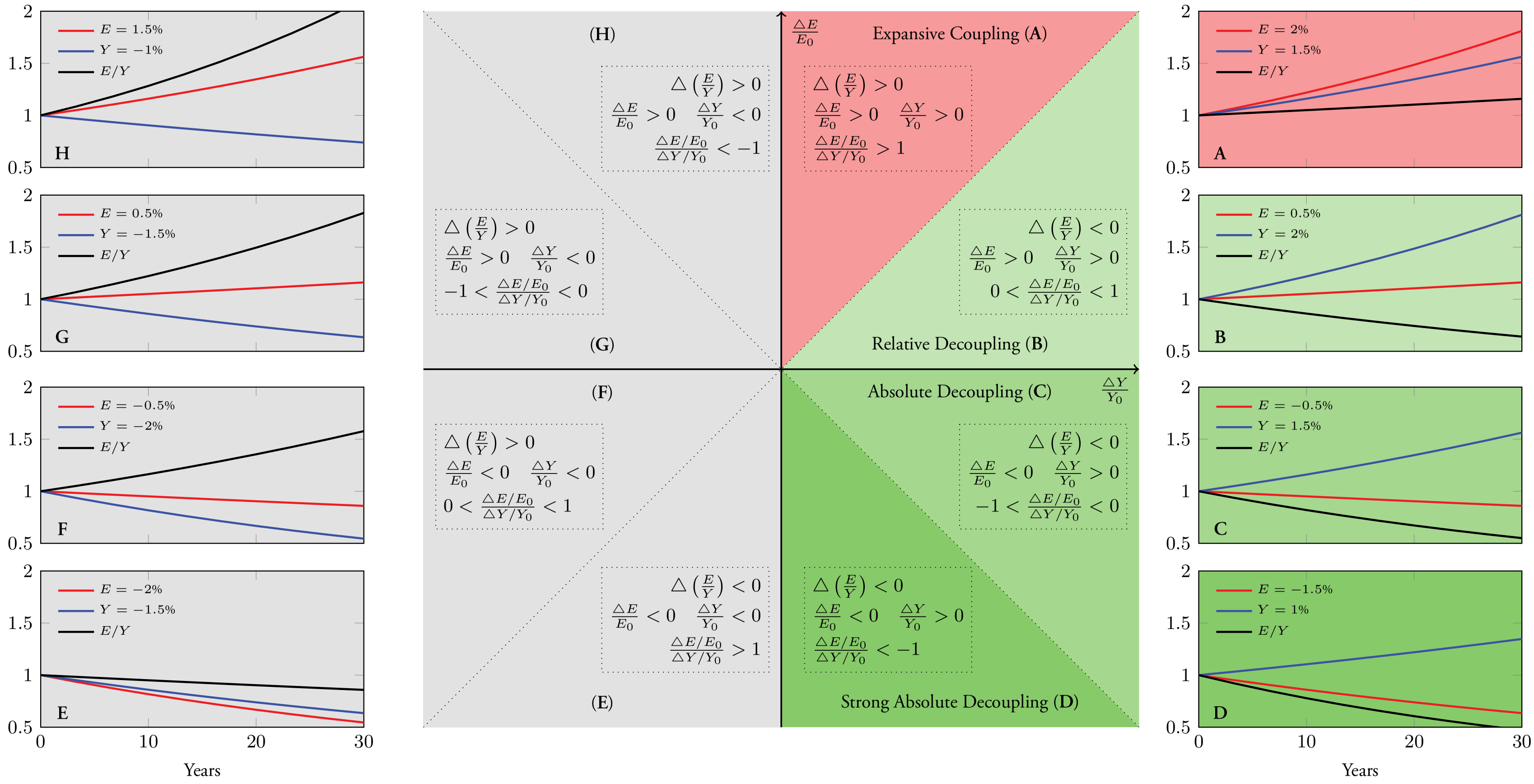
Condition 1: The change in energy intensity between two time points has to be less than zero:

$$\triangle\left(\frac{E}{Y}\right) < 0$$

Condition 2: The positive change in output has to be associated with more than a proportional negative change in energy use:

$$\frac{\triangle E/E_0}{\triangle Y/Y_0} < -1$$

Figure 6: Decoupling Framework



Note: E – environmental indicator and Y – GDP. The area shaded in grey contains all possible combinations of E and Y when the change in Y is negative. All possible combinations of E and Y when the change in Y is positive are shaded in red and green. The change in E and Y over time is exemplified (using arbitrary yearly growth rates of E and Y) in the surrounding graphs. For example, *Expansive Coupling* (shaded in red) occurs when a positive change in E is greather than a positive change in Y. Panel A displays how E (red line), Y (blue line) and their intensity E/Y (black line) develop over 30 year period (x-axis) assuming that the yearly change in E=2% and Y=1.5%. In all panels y-axis = 1 at time 0.

3.3 Accounting Principles

Several approaches are commonly used to allocate environmental responsibility. Two of the most commonly used perspectives are known as the production-based (PB) approach and the consumption-based (CB) approach (Peters, 2008). Data compiled according to the PB perspective is mainly used by statistical offices, whereas environmental data compiled from a CB perspective is more commonly used in the scientific community (EEA, 2013). In addition, several other approaches have been proposed in the literature including: income-based responsibility; technology-adjusted responsibility; shared-responsibility and value added-based responsibility.

3.3.1 Production-Based Responsibility

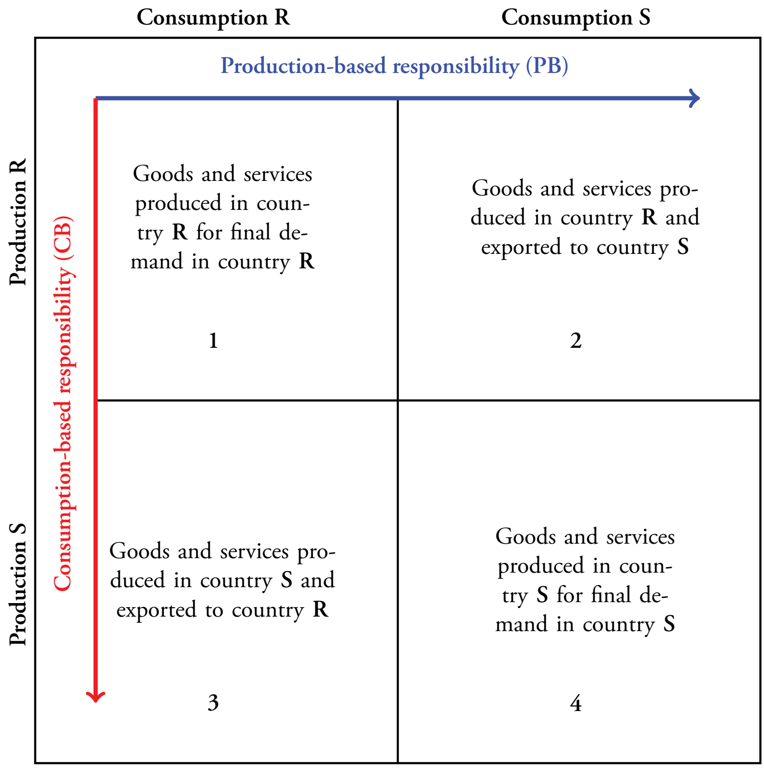
The production-based (PB) perspective accounts for the environmental impacts that result from the economic activities of a country's resident companies and private households (together known as 'resident units') in relation to their economic output (production), irrespective of the geographic location of where these activities take place (EEA, 2013). This is shown in Figure 7, where the producer's responsibility consists of goods and services produced and consumed in country R, plus the exports from country R to country S. One often-cited limitation of the PB approach is that it creates the possibility of carbon leakage through imports of goods and services from other countries (Peters, 2008).

The PB approach is similar to the territorial perspective in terms of magnitude, but differs in the allocation of activities associated with international transport and resident versus non-resident economic activity. The PB method includes the national and international transport of products performed by resident units (e.g. ships owned by companies residing in the country), whereas the territorial accounting method focuses on the physical location of impact and includes only transport within national borders (EEA, 2013).

3.3.2 Consumption-Based Responsibility

According to the consumption-based (CB) perspective (also known as consumer footprint or upstream), the consumer is held responsible for the environmental impacts that come from the production of goods and services. Under this principle, all environmental impacts occurring along the chains of production and distribution are allocated to the final consumer. This means that environmental impacts related to production of imports are taken into account but those related to production of exports are not included. The consumer's responsibility of country R as shown in

Figure 7: Production-Based (PB) vs. Consumption-Based (CB) Responsibility



Notes: Production-Based (PB) responsibility for country **R** is given by 1+2 and for country **S** by 4+3. Consumption-Based (PB) responsibility for country **R** is given by 1+3 and for country **S** by 4+2. Balance of Energy (or emissions) Embodied in Trade (BEET) for country **R** is given by (1+2)-(1+3) = 2-3 and for country **S** by (4+3)-(4+2) = 3-2.

Figure 7 consists of goods and services produced and consumed in country R, plus imports from country S for domestic and final consumption. The CB perspective removes territorial boundaries and takes into account international trade by considering the global impacts (Peters, 2008). However, a CB approach also has some drawbacks, one of which is more complex and data-intensive calculations, which require additional assumptions and thus increase uncertainty.

3.3.3 Other Allocation Approaches

The income-based approach (also known as downstream or supply-based responsibility) accounts for all the environmental impacts that where generated downstream along the supply chain due to the supply of primary factors of production (Lenzen and Murray, 2010; Marques et al., 2012). In this case, the environmental responsibility is assigned to the supplier of primary factors of production who benefits from environmental pressure due to receipt of a payment from the inputs supplied.

Kander et al. (2015) propose technology-adjusted consumption-based accounting (TCBA), which is defined as as TCBA = PB + Imports - Exports with a world average technology. Cleaner countries, when calculated with the CB approach, do not gain any credit for their low carbon technologies in their export sector but are burdened with all the responsibility for imports. Using TCBA allows for countries to be fully responsible for the level and composition of their consumption as well as the production technology in their exports. Domingos et al. (2016) note that PB and CB are attributional approaches that allocate environmental responsibility for the existing production systems. TCBA, on the other hand, is a consequential approach which models how the world would be different if agents' actions were to change (e.g. how emissions would differ if a country's exports did not exist).

In addition to the full responsibility approaches (PB, CB, income-based and TCBA) mentioned above, several shared-responsibility approaches have been proposed in the literature to overcome the shortcomings associated with consumption- and production-based approaches. Gallego and Lenzen (2005) and Lenzen et al. (2007) have argued that production and consumption accounting principles represent two extremes and suggest a shared responsibility between the producer and consumer. This approach allocates responsibility for production impacts amongst all agents including consumers, producers, workers and investors in a way that reflects their various contributions to the production process.

Recently, Piñero et al. (2018) proposed a value added-based approach which allocates environmental pressures occurring along an international supply chain to the participating sectors and countries according to the share of value added they generate within that specific supply chain. For some countries and sectors applying this method can significantly increase or decrease total environmental responsibility in comparison to the consumer or income responsibility.

4 Methodology

This section introduces the basic structure of an input-output table, followed by the explanation of environmental input-output analysis (EIOA) and structural decomposition analysis (SDA). This section relies heavily on the input-output analysis textbook by Miller and Blair (2009).

Table 2: Structure of a Single Region Input Output Table

		Intermediate demand			Final demand	Output
		Sector 1	Sector 2	Sector n		
Intermediate demand	Sector 1 Sector 2 Sector n	$\mathbf{Z}$			$\mathbf{Y}$	$\mathbf{x}$
Value Added		$(\mathbf{v})'$			GDP	
Total Input		$(\mathbf{x})'$				

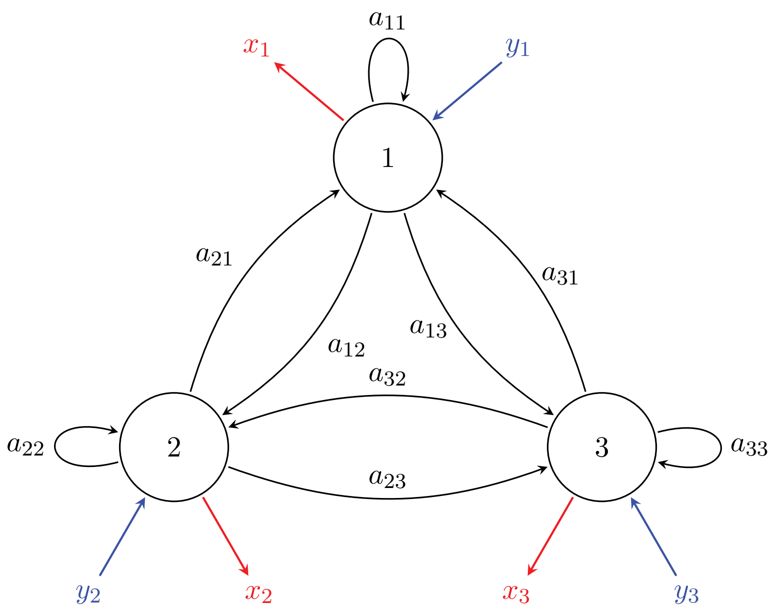
4.1 Single-Region Input-Output Table

The structure of a basic input-output table (IOT) for a single region is presented in Table 2. This input-output transactions table contains information on economic flows (in monetary terms) for a given economy within a particular year. The rows show the distribution of an industry's output throughout the economy. The columns show the composition of inputs required by a particular industry to produce the required output.

The area labelled *Intermediate demand* displays inter-industry exchanges of goods and services for intermediate use. For instance, sales from the 'iron and steel' sector to the 'manufacture of vehicles' sector. The part labelled *Final demand* records the sales by each industry to final demand categories, such as household consumption, governmental investments, and sales abroad (Exports). Final demand categories are often grouped into domestic final demand and foreign final demand. The row sum of intermediate and final demand transactions represents total *Output* for each industry.

The row labelled *Value Added*, accounts for the other inputs to production, such as labour (wages, salaries), government services (indirect taxes), capital (interest payments), land (rental payments), entrepreneurship (profit) and imports (purchases from industries outside the region). Total expenditure on intermediate and primary inputs of each productive sector is labelled *Input*. In an input-output table, the total value of output of each industry (row sum) is equal to its total expenditure on inputs (column sum), hence the term *input-output*.

Figure 8: Production and Interindustry Linkages



4.2 Input-Output Analysis

Input-Output analysis (IOA) is a name given to an analytical framework developed by Leontief (1936), in recognition of which he received a Memorial Nobel Prize in Economic Science in 1973.

The basic idea behind the IOA is that a national (or regional) economy can be divided into a number of sectors that are interlinked and whose relationship can be represented in a mathematical matrix (Miller and Blair, 2009). A schematic illustration of an input-output relationship for a three-sector economy is given in Figure 8. The sectors are labelled as 1, 2, 3 external demand for these sectors labelled as y_1, y_2, y_3 output denoted as x_1, x_2, x_3 and coefficients of requirements a_{ij} denotes the amount required by industry i per unit output of industry j. Given this information, IOA aims to determine the changes in output $\mathbf{x}$ given some external demand $\mathbf{y}$.

The IOA involves the use of three matrices: (i) a transaction matrix; (ii) a matrix of technical coefficients; (iii) a matrix of interdependence coefficients sometimes also referred to as Leontief or total impact coefficients. Each of these matrices and their main functions are described below.

4.2.1 Transaction Matrix

The fundamental information used in the IOA concerns the flow from each industrial or service sector considered as a producer, to each of the sectors, itself and others, considered as consumers. This basic information is essential for the development of the IO model and is contained in an input-output transaction table. An example of such table was presented in the previous section. The input-output table describes the flow of goods and services (in monetary terms) between all the individual sectors of the economy over a stated period. It has one row and one column for each sector of the economy. The rows of such table show the distribution of the producer's output throughout the economy, while the columns describe the composition of inputs necessary for a specific industry to produce its output.

Given that the national economy can be divided into *n* number of sectors, the total output (production) of sector *i* can be written as x_i and the total final demand for sector *i*'s product can be represented as y_i. Therefore the distribution of sector's *i* product to other sectors and final demand can be written as:

$$x_i = z_{i1} + z_{ij} + \cdots + z_{in} + y_i = \sum_{j=1}^{n} z_{ij} + y_i \tag{4}$$

where the z_{ij} term shows interindustry transactions (these are also known as intermediate demand, as shown in Table 2) by sector *i* to all sectors *j* and itself (when *j*=*i*) and y_i is the final demand for sector i.

With the *n* number of sectors in the economy each of the sectors will have an equation like (4) that identifies their output. In matrix form, this relationship can be summarised as:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nn} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \tag{5}$$

in compact form:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{y} \tag{6}$$

The *z*'s in the *j*th column represent the sales to *j* sector, or to put it differently it shows the purchases of sector j of various products from other sectors (e.g. to make a car we need rubber, steel, etc.). It is important to note that the producing sector also requires other inputs, for example labour and capital – these are termed as value added in sector j, similarly inputs for sector j that come from abroad are regarded as imports. Lower-case letters **y** and **x** corresponds to the vectors of final demand and total output respectively, and upper case letter **Z** represents the matrix of interindustry sales.

4.2.2 Technical Coefficients

The input-output transaction table provides a very detailed picture of the structure of the economy. However, in such a format, it is not useful for analytical analysis and thus has to be transformed into what is called a technical coefficient table.

The technical coefficients in input-output analysis show the total amount of product i (domestically produced and imported) used as input in the production of one monetary unit of industry j's output. The technical coefficient can be calculated by dividing input in a certain sector with the total output in that sector. For instance, if the x_j represents the total output of sector j and z_{ij} represents the value of sales from sector i to sector j then the technical coefficient (a_{ij}) can be derived as:

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{7}$$

A complete set of such coefficients for all sectors of an economy in the format of a rectangular table is called the technical coefficient matrix or the direct coefficient matrix. The technical coefficient matrix is most often presented with the capital letter **A**. In matrix algebra, it is obtained as:

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{in} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{in} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nn} \end{bmatrix} \begin{bmatrix} 1/x_1 & 0 & \cdots & 0 \\ 0 & 1/x_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1/x_n \end{bmatrix} \tag{8}$$

In compact form this can be written as:

$$\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1} \tag{9}$$

A 'hat' over **x** vector denotes a diagonal matrix with the elements of **x** vector on the main diagonal.

4.2.3 Leontief Coefficients

The technical coefficient matrix **A** described in the previous section reflects the direct effect of a change in final demand to change in the production of a certain sector. To estimate the indirect effect, one needs to obtain the so-called interdependence matrix which is also known as the total requirement matrix or Leontief matrix. The coefficients of this matrix measure the total (direct and indirect) effect and show how much production will be induced in all sectors by a final demand increase of one unit in a specific sector.

The paragraph below shows how the interdependence coefficients are derived in input-output framework. As shown in Equation 7, inter-industry relationships among sectors can be presented as $a_{ij} = z_{ij}/x_j$. This equation can be rearranged and rewritten as $a_{ij}x_j = z_{ij}$, which implies that the intermediate sales from sector *i* to sector j depends on the output in sector j (x_j) and technical coefficient (a_{ij}). Given this, we can rewrite Equation 4 in matrix form as :

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{10}$$

This equation shows that the level of output in any particular sector depends on the level of output in other sectors, input requirements of each sector and its own final demand. We can find final demand in each of these sectors, by bringing **x** terms to the left-hand side:

$$\mathbf{x} - \mathbf{A}\mathbf{x} = \mathbf{y} \tag{11}$$

Factoring out **x** gives:

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{y} \tag{12}$$

where **I** is the $n \times n$ identity matrix with the ones on the main diagonal and zeros elsewhere:

$$\mathbf{I} = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}, \text{so then } (\mathbf{I}-\mathbf{A}) = \begin{bmatrix} (1-a_{11}) & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & (1-a_{22}) & \cdots & -a_{in} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & (1-a_{nn}) \end{bmatrix}$$

The unique solution for Equation 12 can be found by using standard matrix algebra i.e. taking $(\mathbf{I}-\mathbf{A})$ to the other side of the equation:

$$\mathbf{x} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{13}$$

where $(\mathbf{I}-\mathbf{A})^{-1} = \mathbf{L} = [l_{ij}]$ is the *Leontief inverse* or the total requirements matrix. The coefficients of this matrix show the effect on production in sector i from a unit change in final demand in sector j ($\partial x_i/\partial f_j = l_{ij}$). The Leontief inverse gives the solution to the input-output system which allows the identification of the levels of output from all sectors of the economy required to achieve the specified level of final demand. The Leontief inverse is the fundamental part of the input-output analysis and will be the empirical cornerstone of this thesis. A more intuitive way to explain and express the Leontief inverse is using the power series approximation:

$$\mathbf{L} = (\mathbf{I}-\mathbf{A})^{-1} = (\mathbf{I}+\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots) \tag{14}$$

And applying the power series to Equation 13 yields:

$$\mathbf{x} = (\mathbf{I}-\mathbf{A})^{-1}\mathbf{y} = (\mathbf{I}+\mathbf{A}+\mathbf{A}^2+\mathbf{A}^3+\cdots)\mathbf{y} \tag{15}$$

This can be rewritten without parentheses as:

$$\mathbf{x} = \mathbf{I}\mathbf{y}+\mathbf{A}\mathbf{y}+\mathbf{A}^2\mathbf{y}+\mathbf{A}^3\mathbf{y}+\cdots = \underbrace{\mathbf{I}\mathbf{y}}_{\text{Initial round effect}} + \underbrace{\mathbf{A}\mathbf{y}}_{\text{1st round effect}} + \underbrace{\mathbf{A}(\mathbf{A}\mathbf{y})}_{\text{2nd round effect}} + \underbrace{\mathbf{A}(\mathbf{A}^2\mathbf{y})}_{\text{3rd round effect}} + \cdots \tag{16}$$

This expression describes the production needed throughout the whole supply chain in order to satisfy final demand **y**. The *Initial round* effect shows that to meet the final demand, one must produce **Iy**. However, the production of the initial final demand (**Iy**) generates a need for inputs to the production process which are given by **A** (production recipe). So, **Ay** is the *first round* of effect showing the production that occurs at this stage in order to produce $\mathbf{y}$. But the production of $\mathbf{Ay}$ itself generates a need for additional inputs. Similarly, as before post-multiplying $\mathbf{A}$ by $\mathbf{Ay}$, gives the *second round* of effect $\mathbf{A}(\mathbf{Ay})$ which expresses the production that occurs at this stage in order to produce $\mathbf{Ay}$. This procedure can continue indefinitely, but in many applications, it has been found that after seven or eight rounds, the terms multiplying $\mathbf{y}$ become insignificantly distinct from zero (Miller and Blair, 2009). The sum of these production rounds plus the quantity of $\mathbf{y}$ itself yields the gross output $\mathbf{x}$.

4.3 Environmentally Extended Input-Output Analysis

The input-output framework discussed so far is used for determining the total production needed in order to satisfy the final demand in a given country. To calculate the factor content (e.g. carbon emissions or energy) embodied in international trade, the traditional Leontief input-output model has to be extended and linked to the environmental accounts. The factor of interest in this study is energy use, however, the analytical framework could be applied to any factor associated with an inter-industry activity, e.g. carbon emissions, employment, water use or land use.

The first environmental extensions for the input-output model were developed in the late 1960s (Miller and Blair, 2009). Leontief (1970) had an interest in ecological economics and proposed one of the key methodological extensions to account for the environmental pollution that has later been applied and developed further by many researchers.

Furthermore, within the input-output framework, two methods are commonly used to calculate energy embodied in international trade (Miller and Blair, 2009): the single region input-output (SRIO) model and the multi-region input-output (MRIO) model. Both methods are based on different underlying assumptions and have different data requirements. A detailed review of these methods and their application to environmental studies can be found in Peters (2008). The main aspects of an environmentally extended SRIO and MRIO models are described below.

4.3.1 Single-Region Input-Output

The standard single-region input-output (SRIO) model in Equation 13 can be expressed in more detail to show a complete accounting of monetary flows in the economy as (United Nations, 1999):

$$\mathbf{x} = (\mathbf{I} - (\mathbf{A}^d + \mathbf{A}^m))^{-1}(\mathbf{y}^d + \mathbf{y}^e + \mathbf{y}^m - \mathbf{m}) \tag{17}$$

where $\mathbf{A}^d$ is the domestic input coefficient matrix, $\mathbf{A}^m$ is the coefficient matrix of imported intermediate demand, $\mathbf{y}^d$ is the vector of domestic final-demand products, $\mathbf{y}^e$ is the vector of final export demand, $\mathbf{y}^m$ is the vector of imported final demand products, $\mathbf{m}$ is the vector of total imports into the domestic economy which includes both industry demand ($\mathbf{A}^m\mathbf{x}$) and final demand ($\mathbf{y}^m$) i.e. $\mathbf{m} = \mathbf{A}^m\mathbf{x} + \mathbf{y}^m$. Subtraction of imports $\mathbf{m}$ implies that only the domestic final demand $\mathbf{y}^d$ and production of exports $\mathbf{y}^e$ will have an impact on domestic output $\mathbf{x}$.

When calculating factors embodied in trade, it might be convenient to make use of an artificial second region and set up the SRIO model as consisting of two regions (see e.g. Proops et al., 1993; Andrew et al., 2009; Serrano and Dietzenbacher, 2010). Changing the notation in Equation 17 as $\mathbf{A}^{11} = \mathbf{A}^d$ for the domestic input coefficients, $\mathbf{A}^{21} = \mathbf{A}^m$ for the import coefficients, $\mathbf{y}^{11} = \mathbf{y}^d$ for domestic final demand, $\mathbf{y}^{21} = \mathbf{y}^m$ for imports to region 1, $\mathbf{y}^{21} = \mathbf{y}^e$ for the exports, yields:

$$\begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{bmatrix} = \left[\mathbf{I} - \begin{bmatrix} \mathbf{A}^{11} & 0 \\ \mathbf{A}^{21} & \mathbf{A}^{11} + \mathbf{A}^{21} \end{bmatrix}\right]^{-1} \begin{pmatrix} \mathbf{y}^{11} + & \mathbf{y}^{12} \\ \mathbf{y}^{21} + & 0 \end{pmatrix} \tag{18}$$

where $\mathbf{x}^1$ gives the gross output in region 1, and $\mathbf{x}^2$ represents the output of an artificial region required to produce imports into the first region. In this case, an artificial region has no final consumption of domestic production (i.e. $\mathbf{y}^{22} = 0$) and exports from region 1 are not linked to imports to the second region (i.e. $\mathbf{A}^{12} = 0$). This assumption (i.e. $\mathbf{A}^{12} = 0$) reflects the fact that exports from country 1 are negligible compared with total output by an artificial rest of the world region. It is known as the *small country assumption* (see e.g. Proops et al. 1993). Another common assumption in the SRIO framework is that imports are produced with domestic technology. This assumption is often referred to as the *domestic technology assumption* (DTA). It implies that $\mathbf{A}^{11} + \mathbf{A}^{21} = \mathbf{A}^{12} + \mathbf{A}^{22}$ and as a result in Equation 18, $\mathbf{A}^{12} + \mathbf{A}^{22}$ is given by $\mathbf{A}^{11} + \mathbf{A}^{21}$. It is important to note that the technology is given by the structure of the inputs, no matter whether domestically produced or imported.

Given Equation 18, energy use incorporated as:

$$\begin{bmatrix} \mathbf{e}^{11} & \mathbf{e}^{12} \\ \mathbf{e}^{21} & \mathbf{e}^{22} \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{q}}^1 & 0 \\ 0 & \hat{\mathbf{q}}^2 \end{bmatrix} \left[\mathbf{I} - \begin{bmatrix} \mathbf{A}^{11} & 0 \\ \mathbf{A}^{21} & \mathbf{A}^{11} + \mathbf{A}^{21} \end{bmatrix}\right]^{-1} \begin{bmatrix} \mathbf{y}^{11} & \mathbf{y}^{12} \\ \mathbf{y}^{21} & 0 \end{bmatrix} \tag{19}$$

where $\mathbf{q}^1$ and $\mathbf{q}^2$ show energy use per unit of industry output, $\mathbf{e}^{11}$ is energy required to satisfy domestic final demand in country, $\mathbf{e}^{12}$ is energy required to produce exports from country 1 and $\mathbf{e}^{21}$ is energy required to produce imports for country 1. Here it is assumed that energy intensities are the same in both regions i.e. $\mathbf{q}^1 = \mathbf{q}^2$. This assumption can be partially relaxed by replacing

$\mathbf{q}^2$ with a world average or a representative country's energy intensities (Druckman and Jackson, 2009; Andrew et al., 2009). Druckman and Jackson (2009) describe this approach as a quasi-multi-regional input–output (QMRIO) model.

Producer-based (PB) responsibility (as shown in Figure 7) for region 1 is given by:

$$\mathbf{PB}^1 = \mathbf{e}^{11} + \mathbf{e}^{12}$$

and consumer-based (CB) responsibility by:

$$\mathbf{CB}^1 = \mathbf{e}^{11} + \mathbf{e}^{21}$$

4.3.2 Multi-Region Input-Output Analysis

Multi-region input-output (MRIO) analysis is not a new concept. Already in early the 1950s, Isard (1951) extended the classical Leontief model to account for regional analyses by formulating an inter-regional input-output (IRIO) model. Not long after this, the input-output community turned its attention to the world economy by developing international and multinational models (Leontief, 1974). Although the idea was developed much earlier, MRIO tables have become more widely used in the last two decades. This late start is often attributed to the data-hungry and computationally-intensive process of the construction of the MRIO table (Kanemoto and Murray, 2013). Today a practitioner can choose from several global multi-regional databases (GMRIO) such as WIOD (Dietzenbacher et al., 2013; Timmer et al., 2015, 2016), Eora (Lenzen et al., 2012, 2013) and EXIOBASE (Tukker et al., 2013; Wood et al., 2015; Stadler et al., 2018).

One of the main advantages of MRIO is that it overcomes the issues associated with the SRIO method by eliminating the domestic technology assumption. The MRIO approach distinguishes between imports that are directed towards final consumption and those that are directed towards intermediate consumption. Those imports that are directed towards intermediate consumption can be allocated to either the production of goods for domestic use or the production of exports. This unique MRIO structure allows the tracing and analysis of the supply chain between regions.

The environmentally extended multi-regional input-output (EMRIO) model can be defined as:

$$\mathbf{E} = \hat{\mathbf{q}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \hat{\mathbf{q}}\mathbf{L}\mathbf{Y} \tag{20}$$

All elements in the equation have the same meaning as in the SRIO model but they represent the global system instead of a single country (as is the case in the SRIO). Given k number of countries and n number of sectors, each element in equation 20 could be described by block matrices and vectors as:

$$\underset{kn\times k}{\mathbf{E}} = \begin{bmatrix} \mathbf{e}^{11} & \mathbf{e}^{12} & \cdots & \mathbf{e}^{1k} \\ \mathbf{e}^{21} & \mathbf{e}^{22} & \cdots & \mathbf{e}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{e}^{k1} & \mathbf{e}^{k2} & \cdots & \mathbf{e}^{kk} \end{bmatrix} \text{ and a block element } \underset{n\times 1}{\mathbf{e}^{rs}} = \begin{bmatrix} e_1^{rs} \\ e_2^{rs} \\ \vdots \\ e_n^{rs} \end{bmatrix}$$

where each element of this block e_i^{rs} contains energy flow from sector i in country r to country s, and $r = s$ denotes domestic energy use.

The global energy intensity vector can be written as:

$$\underset{1\times kn}{\mathbf{q}} = \begin{bmatrix} \mathbf{q}^1 & \mathbf{q}^2 & \cdots & \mathbf{q}^k \end{bmatrix} \text{ where a block element } \underset{1\times n}{\mathbf{q}^s} = \begin{bmatrix} q_1^s & q_2^s & \cdots & q_n^s \end{bmatrix}$$

contains energy intensity for country s and element q_i^s denotes energy intensity for sector i in country s.

Similarly, the Leontief inverse has the following form:

$$\underset{kn\times kn}{\mathbf{L}} = \begin{bmatrix} \mathbf{I}-\mathbf{A}^{11} & -\mathbf{A}^{12} & \cdots & -\mathbf{A}^{2k} \\ -\mathbf{A}^{21} & \mathbf{I}-\mathbf{A}^{22} & \cdots & -\mathbf{A}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{A}^{k1} & -\mathbf{A}^{k2} & \cdots & \mathbf{I}-\mathbf{A}^{kk} \end{bmatrix}^{-1} = \begin{bmatrix} \mathbf{L}^{11} & \mathbf{L}^{12} & \cdots & \mathbf{L}^{1k} \\ \mathbf{L}^{21} & \mathbf{L}^{22} & \cdots & \mathbf{L}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{L}^{k1} & \mathbf{L}^{k2} & \cdots & \mathbf{L}^{kk} \end{bmatrix}$$

And a block element:

$$\underset{n\times n}{\mathbf{L}^{rs}} = \begin{bmatrix} l_1^{rs} & l_{12}^{rs} & \cdots & l_{1n}^{rs} \\ l_{21}^{rs} & l_{22}^{rs} & \cdots & l_{2n}^{rs} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1}^{rs} & l_{n2}^{rs} & \cdots & l_{nn}^{rs} \end{bmatrix}$$

where l_{ij}^{rs} represents total output occurring in country r sector i due to the changes in final demand in country s sector j. Similarly, technical coefficient matrix $\underset{n\times n}{\mathbf{A}^{rs}}$ block element a_{ij}^{rs} describes the amount of input by sector i in country r required per unit of output of sector j in country s.

In the same way, the final demand matrix is given as:

$$\underset{kn\times k}{\mathbf{Y}} = \begin{bmatrix} \mathbf{y}^{11} & \mathbf{y}^{12} & \cdots & \mathbf{y}^{1k} \\ \mathbf{y}^{21} & \mathbf{y}^{22} & \cdots & \mathbf{y}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{y}^{k1} & \mathbf{y}^{k2} & \cdots & \mathbf{y}^{kk} \end{bmatrix} \text{ with a block element } \underset{n\times 1}{\mathbf{y}^{rs}} = \begin{bmatrix} y_1^{rs} \\ y_2^{rs} \\ \vdots \\ y_n^{rs} \end{bmatrix}$$

where y_i^{rs} denotes final demand for sector i in country r sold to final users in country s.

Equation 20 can be written in more detailed form as:

$$\begin{bmatrix} \mathbf{e}^{11} & \mathbf{e}^{12} & \cdots & \mathbf{e}^{1k} \\ \mathbf{e}^{21} & \mathbf{e}^{22} & \cdots & \mathbf{e}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{e}^{k1} & \mathbf{e}^{k2} & \cdots & \mathbf{e}^{kk} \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{q}}^{1} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \hat{\mathbf{q}}^{2} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \hat{\mathbf{q}}^{k} \end{bmatrix}$$
$$\begin{bmatrix} \mathbf{I}-\mathbf{A}^{11} & -\mathbf{A}^{12} & \cdots & -\mathbf{A}^{2k} \\ -\mathbf{A}^{21} & \mathbf{I}-\mathbf{A}^{22} & \cdots & -\mathbf{A}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{A}^{k1} & -\mathbf{A}^{k2} & \cdots & \mathbf{I}-\mathbf{A}^{kk} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{y}^{11} & \mathbf{y}^{12} & \cdots & \mathbf{y}^{1k} \\ \mathbf{y}^{21} & \mathbf{y}^{22} & \cdots & \mathbf{y}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{y}^{k1} & \mathbf{y}^{k2} & \cdots & \mathbf{y}^{kk} \end{bmatrix} \tag{21}$$

Energy embodied in the exports of country r is the sum of all row elements in matrix $\mathbf{E}$ except those on the diagonal $\mathbf{e}^{exp} = \sum_{s\neq r}^{k} \mathbf{e}^{rs}$. Energy embodied in imports is the sum of column elements except those on the diagonal $\mathbf{e}^{imp} = \sum_{r\neq s}^{k} \mathbf{e}^{sr}$. The diagonal elements in matrix $\mathbf{E}$ denote domestic energy use $\mathbf{e}^{dom} = \mathbf{e}^{rr}$. This information allows the derivation of other measures such as balance of energy (or other factor) embodied in trade (BEET), which is given by BEET $= \mathbf{i}'_n\mathbf{e}^{exp} - \mathbf{i}'_n\mathbf{e}^{imp}$, in this case $\mathbf{i}_n$ is a $1 \times n$ summation vector that aggregates $n \times 1$ vectors $\mathbf{e}^{exp}$ and $\mathbf{e}^{imp}$ to 1×1 scalars.

4.4 Structural Decomposition Analysis

When decomposition analysis makes use of the input-output model, it is called structural decomposition analysis (SDA) (Hoekstra and Van Den Bergh, 2002). The other main decomposition approach is index decomposition analysis (IDA) which uses sector-level or country-level data (Ang and Zhang, 2000).

Structural decomposition analysis (SDA) is a technique that utilises the fundamental input-output equation to break down changes over time (or space) in one variable (e.g. energy use) into various driving forces of change (e.g. energy intensity, level of final demand). Two basic SDA variants exist – an additive and a multiplicative one (Hoekstra and van der Bergh, 2003). Within energy and emissions studies the additive variant is most commonly used (Lenzen, 2016).

An example of a three factor decomposition for **e** based on equation 13 [2] is given as:

$$\triangle \mathbf{e} = \underbrace{\triangle \mathbf{qLY}}_{\substack{\text{Intensity}\\\text{effect}}} + \underbrace{\mathbf{q}\triangle \mathbf{LY}}_{\substack{\text{Technology}\\\text{effect}}} + \underbrace{\mathbf{qL}\triangle \mathbf{Y}}_{\substack{\text{Consumption}\\\text{effect}}} \tag{22}$$

The first factor $\triangle\mathbf{qLY}$ shows the effect of a change in **e** due to changes in the energy intensity, the second $\mathbf{q}\triangle\mathbf{LY}$ shows the effect of changes in the Leontief inverse, and $\mathbf{qL}\triangle\mathbf{Y}$ expresses the changes in the level of final demand. A more detailed discussion of the model is provided in the Appendix of Paper 2.

Resource use and pollutant emissions studies often rely on a six-factor decomposition of a form $e = \mathbf{qLuv}YP$ where **q** is a factor intensity per unit of output, **L** captures technological changes, **u** describes structure of final demand, **v** describes the destination share (e.g. household consumption, government consumption or exports), the scalar Y denotes per-capita final demand, and P is population (Lenzen, 2016).

In recent years the availability of global multi-regional databases enabled researchers to perform more detailed decompositions and account for various trade-related effects. Often this is done by decomposing **L** into trade and technology effects and final demand **Y** into equivalent trade structure and consumption mix effects (Oosterhaven and Van Der Linden, 1997; Arto and Dietzenbacher, 2014; Hoekstra et al., 2016). Such decomposition allows the evaluation of the effects of changes in trade structure and global value chains for the growth in energy use or carbon emissions (Arto and Dietzenbacher, 2014; Hoekstra et al., 2016; Kaltenegger et al., 2017). This type of decomposition is applied in Paper 2 to evaluate the importance of trade (and other factors) for changes in energy footprint.

[2] Note that here $\hat{\mathbf{q}}$ from Equation 13 is expressed as **q** (not diagonal) meaning that **e** is a row vector representing consumption-based energy use for each country in the MRIO system.

Table 3: Thesis Data Sources and Coverage

		Study period		
	Data Type	1970–1990	1995–2009	2000–2014
Paper 1	Input-output	Available	Available	
	Energy	Not Available	Available	
Paper 2	Input-output	Available	Available	
	Energy	Not Available	Available	
Paper 3	Input-output		Available	Available
	Energy		Available	Not Available
Paper 4	Input-output		Available	
	CO_2		Available	

Notes: Period 1970–1990 is represented by several benchmark years not complete time series.

5 Data

Most of the data for this thesis comes from three sources: (i) International Energy Agency (IEA); (ii) World Input-Output Database (WIOD) 2013 and 2016 releases; and (iii) OECD input-output database. The IEA database is the main source for energy data, WIOD for multi-region input-output tables and OECD for single-region input-output tables. Some of the data is available in the 'ready to use' format, while in some cases, it had to be compiled and prepared for the analysis. Table 3 illustrates which parts had to be compiled and which ones were available in 'ready to use' format.

5.1 Energy Data

The main source of energy and other energy-related data is the International Energy Agency (IEA). The latest IEA (2017) edition provides World Energy balances for 178 countries and regional aggregates for the period 1960-2015 (OECD countries and regions) and 1971-2015 (non-OECD countries and regions). For each year and country, energy balances cover 65 products and 85 flows. Table 4 illustrates a typical structure of the IEA energy balance matrix for a single country. For example, a flow entitled 'Transport' shows how much and what type of energy product (e.g. coal, oil, gas, etc.) is used for transport purposes in a given country during a specific year.

The energy data was used to create energy accounts for four countries (Denmark, France, the USA

Table 4: IEA energy balance structure

product → / flow ↓	Energy Product				
	product 1	product 2	...	product 65	Total
TPES					
Production	...	...	...	...	...
Imports	...	...	...	...	...
Exports	...	...	...	...	...
International marine bunkers	...	...	...	...	...
International aviation bunkers	...	...	...	...	...
Stock changes	...	...	...	...	...
Transformation processes					
...	...	...	...	...	...
Energy industry own use					
...	...	...	...	...	...
Total final consumption					
Industry					
...	...	...	...	...	...
Transport					
...	...	...	...	...	...
Other					
...	...	...	...	...	...
Non-energy use					

and the UK) from the OECD database and for all countries in the WIOD 2016 release. Such energy accounts were not needed for WIOD 2013 which is available with the environmental extensions that include energy accounts.

5.2 Input-Output Data

Input-output tables come from WIOD and OECD input-output databases. The WIOD database contains 2013 and 2016 data releases. The earlier WIOD 2013 release provides World Input-Output Tables (WIOT) and underlying data, covering 40 countries plus the 'rest of the world' region disaggregated into 35 sectors for the period 1995-2011 (Timmer et al., 2015). It also contains the environmental accounts including, energy use, CO_2 emissions, emissions to air, land use, material use and water use for the period from 1995 to 2009.

The WIOD 2016 release contains world input-output tables and underlying data, covering 43 coun-

Table 5: World Input-Output Table Structure and Size

			Intermediate demand ($\mathbf{Z}$)			Final demand ($\mathbf{Y}$)			Output ($\mathbf{x}$)
Country ↓ →			1	$\dots$	k	1	$\dots$	k	
Sector ↓→			1 $\dots$ n	$\dots$	1 $\dots$ n	1 $\dots$ p	$\dots$	1 $\dots$ p	
($\mathbf{Z}$)	1	1 $\vdots$ n	$\mathbf{Z}^{11}$	$\dots$	$\mathbf{Z}^{1k}$	$\mathbf{Y}^{11}$	$\dots$	$\mathbf{Y}^{1k}$	$\mathbf{x}^1$
	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
	k	1 $\vdots$ n	$\mathbf{Z}^{k1}$	$\dots$	$\mathbf{Z}^{kk}$	$\mathbf{Y}^{k1}$	$\dots$	$\mathbf{Y}^{kk}$	$\mathbf{x}^k$
$(\mathbf{v})'$			$(\mathbf{v}^1)'$	$\dots$	$(\mathbf{v}^k)'$				
$(\mathbf{x})'$			$(\mathbf{x}^1)'$	$\dots$	$(\mathbf{x}^k)'$				

tries plus the 'rest of the world' region disaggregated into 56 sectors for the period 2000-2014. As opposed to, the WIOD 2013 release, the latest WIOD 2016 version comes without the environmental extensions (Timmer et al., 2016). Paper 3 deals with the construction of energy accounts for the WIOD 2016 release. All transactions in WIOT are expressed in US dollars, and market exchange rates were used for currency conversions of original data from individual countries.

A structure of the WIOT is displayed in Table 5. The table consists of k countries and n sectors. In the WIOD 2013 release, $k = 41$ and $n = 35$ and in the WIOD 2016, $k = 44$ and $n = 56$. The size of the intermediate demand matrix is $kn \times kn$ for the WIOD2013 which results in a 1435×1435 and for the WIOD2016 a 2464×2464 matrix.

The final demand of an individual country is divided into p number of categories (in both databases $p = 5$): Final consumption expenditure by Households, Final consumption expenditure by non-profit organisations serving households, Final Consumption expenditure by Government, Gross fixed capital formation, Changes in inventories and valuables. The final demand matrix size is $kn \times kp$ for WIOD2013 which results in a 1435×205 and for WIOD 2016 a 2464×220 matrix. These final demands are often summed, so they represent an aggregate final demand of a given country yielding $nk \times k$ matrix. The size of the total output vector is $kn \times 1$.

The WIOD 2013 release comes with various environmental extensions. For this thesis, I used only

CO_2 emissions and energy use data. The structure of the environmental extensions is prepared in a way that matches the structure of WIOT. The extension matrix has a size $f \times kn$ where in the case of energy use $f = 27$ and denotes the type of fuel (e.g. oil, coal) and in the case of CO_2 $f = 28$ and denotes emissions by fuel type. The column sum gives the total use of specific factor (i.e. energy use or CO_2) by sector n in country k.

Single region input-output tables covering the period from circa 1970 to 1990 were obtained from the OECD database. The data from the OECD is available for 10 countries and for a limited number of years. Four countries, Denmark, France, the USA and the UK, were chosen for the analysis. This choice was mainly driven by data availability, but the countries were selected so that they represent a wide range of cases that differ in terms of trade involvement, energy systems and the size of the economy. For instance, the USA, the largest economy in the sample, is the least engaged in trade (trade/GDP), while Denmark, the smallest economy, is the most engaged in trade.

The OECD SRIO tables distinguish between 36 industrial sectors. The common industrial classification for the collection of the OECD input-output tables was designed to identify technology-intensive and/or trade-sensitive sectors, e.g. pharmaceuticals, computers, communication equipment, automobiles, aircraft, etc. As a result, the manufacturing sector is disaggregated more finely than the agriculture, mining and service sectors in the OECD IO (OECD, 2016). The IO tables expressed in 1980 constant prices consist of domestic, import and total flow matrices.

5.3 Data Limitations

This study involves several data limitations. The choice of countries in Paper 1 and Paper 2 is limited by data availability. The OECD Input-Output database contains SRIO tables for ten countries and five benchmark years. However, for some countries, for example, Italy, the data is available only for one benchmark year, while for other countries the benchmark years are different. The decision was made to select a set of countries that would be as similar as possible in terms of data coverage but would differ in terms of energy systems, the size of the economy and engagement in trade.

In Paper 2, 3 and 5 for the period 1995–2009 data was obtained from the WIOD 2013 database, but there also exist other global muti-region input-output databases that provide more detailed sector and country coverage, e.g. Eora, EXIOBASE3, GTAP. In general, the choice of the database depends on the research question and the type of evidence required. This thesis focuses on high-income countries and requires a database with detailed coverage of such countries. Furthermore, as noted by Owen (2015) to properly use the Eora database requires high-performance computing, while GTAP has a license fee. Also, EXIOBASE3 with the full-time series was made publicly available only in 2018. Given this WIOD database with its broad coverage of high-income countries, long-time series and free availability made it the most attractive option.

6 Summary of Papers and Main Results

Paper 1: Energy Use and Economic Growth in High-Income Countries: The Role of Trade 1970–2009

Long-term trends show that economic growth in high-income countries was closely linked with energy use until about 1970. The period after 1970 is marked by the decoupling of GDP per capita from energy use per capita. As explained in Section 3.1, this decoupling seen in high income countries can be a result of trade and production offshoring. The central aim of this paper is to examine how energy content embodied in trade changed over time and how it affects the decoupling relationship between economic activity (expressed in GDP per capita terms) and energy use per capita.

Two common ways to account for factor content embodied in trade are production-based accounting (PB) and consumption-based accounting (CB) principles. PB includes energy related to production of exports, while CB includes energy related to production for imports. Comparison of PB and CB indicators allow the evaluation of the proposition that decoupling has been achieved by production offshoring.

Energy content embodied in trade for Denmark, France, the UK and the USA during the period 1970–2009 was estimated using Single-region input-output (SRIO) and multi-region input-output (MRIO) techniques. The SRIO model was applied for the period from 1970 to 1990 (for this period MRIO data is not available) and the MRIO model for the period from 1995 to 2009. It is well known that SRIO analysis suffers from the domestic technology assumption (DTA). To partially relax this assumption, energy embodied in imports was calculated using a four-country average energy intensity.

For all countries except Denmark, consumption-based energy use is higher than production-based. For France and the USA, the two indicators follow similar trend while for the UK this connection is weaker. The story of decoupling does not change notably for France and the USA even after accounting for energy embodied in imports. For the UK, on the other hand, decoupling appears to be less pronounced in the CB case. From the PB perspective, energy use in the UK has declined in absolute terms, while from the consumption perspective it has increased but at a much lower rate than GDP. In general, the results suggest that taking into account energy embodied in imports shifts the energy use curve upwards but does not notably affect the decoupling trend.

Paper 2: Explaining Decoupling in High-income Countries: A Structural Decomposition Analysis of the Change in Energy Footprint from 1970 to 2009

Paper 2 is co-authored with Richard Wood. The author of this thesis was responsible for the concept, study design, structural decomposition analysis and led the practical aspects of the paper.

Paper 2 is a follow-up to the study presented in Paper 1 (which addressed the question how much energy is embodied in trade and how it evolved over time). Paper 2 asks why energy use from the consumption-based perspective changed the way it did. To address this question Paper 2 examines the main factors that contribute to the decoupling of consumption-based energy use (footprint) and economic growth in four high-income countries (Denmark, France, the UK and the USA). Specifically, we look at the changes in energy footprints due to changes in industrial energy efficiency, trade structure, production technology, mix and level of final demand and population. By analysing these factors, we can identify and understand the main driving forces behind the energy decoupling (from CB perspective) seen in the high-income countries. We look at how these factors change over time and assess whether the main reason for decoupling has been purely due to energy efficiency measures, changes in the structure of an economy (e.g. a move towards a service-based economy), or due to production offshoring.

We apply structural decomposition analysis (SDA) to quantify changes in energy footprint, into various driving forces of change. In particular, we are interested in quantifying the effect of changes in the trade structure of intermediate and final products. A positive (negative) trade structure effect indicates a shift in sourcing patterns towards countries with more (less) energy-intensive production technologies. If imports come from countries with exactly the same energy intensities, then the trade structure effect is zero.

The results demonstrate that the changes in energy footprint have been driven mainly by two countervailing forces: declines in energy intensity and increases in consumption per capita. The trade sourcing effect was negligible in the beginning of the study period but has grown in importance since 1995 and accounted for 6.9% (Denmark), 2.7% (France), 12.8% (UK) and 5.6% (USA) change in energy footprint over the period 1995–2009. These results imply that there has been a small substitution of more energy-efficient domestic production by foreign production of lower efficiency, but the effect size was relatively small compared with other effects.

Paper 3: Constructing Energy Accounts for WIOD 2016 Release

Paper 1 and Paper 2 cover a period from 1970 to 2009 but relatively little is known about the development of energy embodied in trade in the post-crisis years (2009–2014). This is mainly due to the lack of environmental accounting data covering those years. These issues are addressed in Paper 3 which aims to: (i) demonstrate how data from the International Energy Agency (IEA) can be used to construct energy accounts that match the WIOD 2016 sectoral classification; (ii) present detailed comparison of WIOD2016 and WIOD2013 energy accounts; (iii) analyse global production- (PB) and consumption-based (CB) energy use for the period 2000–2014 and (iv) create an interactive and user-friendly visualisation platform to enable the efficient and effective dissemination of results.

Energy data for the construction of energy accounts is obtained from the IEA database and the input-output data is obtained from the WIOD 2016 database. The two sources of data are combined to construct energy accounts that match the WIOD 2016 year, country and sector aggregation. The newly constructed energy accounts are calibrated to match WIOD 2013 energy accounts and then applied to calculate global energy use trends for the period 2000–2014. This is done using multi-regional input-output analysis.

The results for selected BRIC (Brazil, Russia, India and China) countries, China (separately from BRIC), EU28, and the USA indicate that from 2000 to 2014, production-based (PB) and consumption-based (CB) energy use has declined marginally in the EU28 and the USA, and has increased considerably in BRIC countries and China. Furthermore, the difference between PB and CB has contracted for the EU28 countries, the US and China since about 2008 indicating that the energy content in trade has become more balanced. In addition, country-specific results show that PB per capita has declined in 24 and CB in 29 out of 44 countries. In most cases, the PB and CB measures follow a similar trend, with a change in one being closely mirrored by the other. This implies that the decoupling seen in the PB case is often echoed by a similar change in the CB indicator.

Paper 4: Decoupling or Delusion? Measuring Emissions Displacement in Foreign Trade

In Paper 4 the author of this thesis assisted with the concept, study design, multi-region input-output data analysis and visualisations.

Paper 4 complements the previous papers that focus on energy use by providing an additional perspective on CO_2 emissions which are directly related to energy use. More specifically, this paper presents a method to detect structural carbon displacement in trade: the technology adjusted balance of emissions embodied in trade (TBEET). TBEET builds on existing ideas by separating out the effects of scale and composition of trade from the effects of different energy systems. This is achieved by imposing an assumption of identical world average technologies across countries. The TBEET measure is related to the pollution terms of trade (PTT) indicator proposed by Antweiler (1996) which measures the environmental gains or losses that a country sustains from engaging in international trade. The TBEET is essentially the same but in addition it includes the volume of trade effect.

The TBEET indicator is calculated for Sweden and the UK from 1995 to 2009, a period when both countries reported decreasing production-based emissions together with sustained economic growth. The results show that emissions imbalances between countries are lower than what conventional analysis of balance emissions embodied in trade might suggest. For Sweden, TBEET is positive throughout the studied period, implying that there is no net displacement of carbon emissions. This means that Swedish exports continue to contribute to avoiding more emissions abroad than that is generated by Swedish imports, even if this effect is declining and might switch sign in the near future. This can be interpreted as Sweden supplying carbon-intensive products to the world that are elsewhere produced with worse carbon efficiency. This is mainly because the monetary trade balance outweighs the negative effect of trade composition (specialisation) effect.

For the UK, TBEET indicates some net displacement of carbon emissions, but to a lesser extent than what the standard balance of emissions embodied (BEET) analysis suggests. This is expected because in TBEET we exclude the effect due to differences in technology between countries. For the UK, trade composition has a clearly negative impact and is the main driver of the increasingly negative TBEET throughout the period. The negative impact from trade specialisation is also increasing over time. The impact from trade balance is much weaker and varies over the period.

For both Sweden and the UK, the impact from trade composition has become more and more negative over the period. This could be due to a shift in the export structure towards less energy-heavy and carbon-demanding products, or a shift in the import structure towards more energy-heavy and carbon-demanding products, or both.

7 Discussion and Conclusions

The purpose of this dissertation is to help understand the role of trade in the relationship between energy use and economic growth in high income countries. The approach involves looking at the key factors affecting energy use, CO_2 emissions and economic growth from roughly 1970 to 2014. This research thus contributes methodologically and empirically to the energy use and economic growth literature by considering environmental impacts embodied in international trade.

The results presented in Paper 1 demonstrate that the content of energy embodied in trade is large, amounting to roughly 10-50% of total energy use. For large economies such as the USA the share is lower, and for small economies such as Denmark, the share of energy embodied in trade is higher. Furthermore, in around 1970, the content of energy embodied in imports and exports was roughly the same. Large imbalances started to appear since about 1990, mainly because the share of energy embodied in imports increased, while the share of energy embodied in exports remained virtually unchanged from 1970 to 2009. This coincides with the period of the second unbundling and rapid production fragmentation across countries, which began in the 1980s and accelerated in the 2000s (see e.g. Baldwin and Lopez-Gonzalez 2015 and Los et al. 2015). The imbalances continued to increase until the global financial crisis in 2008. Since then the difference between energy content in imports and exports has started to shrink. This reflects the deceleration of global trade since 2011 (Timmer et al., 2016).

The increasing share of energy embodied in trade poses a question as to whether the decoupling seen from the production perspective has been achieved by scaling down domestic production and importing goods and services from elsewhere. One way to test this proposition is to look at the consumption-based perspective which accounts for energy content embodied imports. Despite some spatial and temporal variations, the results indicate that the decoupling between energy use and economic growth seen from the production-based perspective is broadly resembled by the consumption-based indicator. This was shown in Paper 2 for the USA, France, and to a lesser extent the UK and also in Paper 3 where country-specific results show that between 2000 and 2014, PB per capita has declined in 24 and CB in 29 out of 44 countries. Most recent evidence (Quéré et al., 2019) shows similar results for CO_2 emissions. However, it should be stressed that: (i) the decoupling indicator is influenced by the choice of the base year, a different base year might affect the strength of the decoupling (e.g. relative or absolute); and (ii) throughout this dissertation energy use is often displayed on a per capita basis, and the aggregate energy use might be different if changes are driven by increase (decrease) in population.

It is critically important to understand the reasons for these changes over time. The decomposition results presented in Paper 2 and Paper 4 inform about the importance of factors that are driving changes in energy use (Paper 2) and CO_2 (Paper 4). The trade structure (or sourcing) effect was of particular interest. It measures the substitution effect of domestically produced goods for imported goods (or for inputs substituted from one country for those from another country). This can be estimated at the intermediate level (i.e. from where producers source their inputs) and final demand level (from where consumers buy). If producers and consumers shift to buying goods and services from countries with more (less) energy-intensive production technologies, energy use will increase (decrease). The effect is zero in a case where intermediate and final goods and services are produced with identical technologies. The results in Paper 2 demonstrate that the trade structure effect of both intermediate and final products is positive. It implies that changes in the sourcing patterns of the four countries under study (Denmark, France, the UK and the USA) contribute to an increase in energy footprint. The effect was negligible in the beginning of the study period (c1970–1990) but has grown in importance since 1995 and accelerated the growth of the energy footprint by roughly 0.5% per year (roughly 1/3 of the consumption per capita effect). This suggests that global energy requirements would have been slightly lower if the goods were produced domestically rather than imported. Several other studies have reported similar findings for CO_2 emissions. For instance, Hoekstra et al. (2016) shows that between 1995 and 2007, changes in sourcing patterns lowered production-based CO_2 emissions in high-wage countries by 0.5 Gt but raised emissions in low-wage and medium-wage countries by 1.5 Gt and 0.07 Gt, respectively, leading to a net increase in global CO_2 emissions of roughly 1 Gt. In a similar study Arto et al. (2014) reports similar findings highlighting that the trade structure effect (0.6 Gt) in comparison with other drivers such as level of consumption per capita (14 Gt) or change in technology (-8.4 Gt) had a very moderate effect on global emissions over time between 1995 and 2008.

Energy efficiency improvements have been a dominant source of energy savings for a long time. This is reflected in a falling energy intensity which was, by far, the strongest factor decelerating the growth of consumption-based energy use. On the demand side, increased consumption per capita was the most important driver, followed by the population effect. The IPAT equation (presented in section 2.2) suggests that demand for energy (or another impact) could be reduced in three ways: (i) by reducing population; (ii) by changing lifestyle (consumption); (iii) by keeping lifestyle the same, but reducing its energy intensity through 'efficiency' and 'technology' (MacKay, 2009). The increasing need for deep decarbonisation, and the central role that energy has in greenhouse gas emissions implies that either the supply side efficiencies must be radically increased, or more be done on the demand side to break the strong, consistent pull that increasing affluence has. With a large proportion of the global population looking to emulate the lifestyle choices of high-income countries, the link between affluence and energy demand is likely to become more important, not less. In contrast, energy use per capita in affluent nations has already reached a plateau and any upward trends are highly unlikely (Smil, 2011). Yet it is important to ensure the reduction of excessive energy use by utilising more efficient technologies. For example, average annual per capita energy use in the USA is about twice the average of the richest European economies (see Table 1 in Paper 1), but the standard of living is about the same. Considering the magnitude of the effort needed for any substantial reduction of emissions, it is important that not only renewables but all carbon-free energy sources are considered as viable substitutes for fossil fuels.

Energy content embodied in trade has grown over the past few decades. Arguably, from a global environmental perspective, it does not matter where the goods are produced, instead what matters is how much is consumed and how the goods and services are produced. Evidence presented in this dissertation suggests that changes in the trade structure of high-income countries contribute to an increase of global energy use, but compared with the consumption per capita, the trade structure effect is considerably smaller. Converging energy and carbon intensities across countries are likely to make the trade structure effect an even less important contributor to the changes in energy use and CO_2 emissions over time.

8 References

Akizu-Gardoki, O., Bueno, G., Wiedmann, T., Lopez-Guede, J. M., Arto, I., Hernandez, P., and Moran, D. (2018). Decoupling between human development and energy consumption within footprint accounts. *Journal of Cleaner Production*, 202:1145–1157.

Andrew, R., Peters, G. P., and Lennox, J. (2009). Approximation and Regional Aggregation in Multi-Regional Input–Output Analysis for National Carbon Footprint Accounting. *Economic Systems Research*, 21(3):311–335.

Ang, B. W. and Zhang, F. Q. (2000). A survey of index decomposition analysis in energy and environmental studies. *Energy*, 25(12):1149–1176.

Antweiler, W. (1996). The Pollution Terms of Trade. *Economic Systems Research*, 8(4):361–366.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C. S., Jansson, B.-O., Levin, S., Maler, K.-G., Perrings, C., and Pimentel, D. (1995). Economic Growth, Carrying Capacity, and the Environment. *Science*, 268(1):520–521.

Arto, I. and Dietzenbacher, E. (2014). Drivers of the Growth in Global Greenhouse Gas Emissions. *Environmental Science & Technology*, 48(5388-5394).

Arto, I., Rueda-Cantuche, J. M., and Peters, G. P. (2014). Comparing the GTAP-MRIO and WIOD databases for carbon footprint analysis. *Economic Systems Research*, 26(3):327–353.

Ayres, R. U. and Kneese, A. V. (1969). Production, Consumption, and Externalities. *The American Economic Review*, 59(3):282–297.

Bairoch, P. and Kozul, R. (1996). Globalization Myths: Some Historical Reflections On Integration, Industrialization And Growth In The World Economy. Technical report, UNCTAD Discussion Papers.

Baldwin, R. (2006). Globalisation: the great unbundling(s). *Economic Council of Finland*, 20(3).

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

Bolt, J., Inklaar, R., de Jong, H., and van Zanden, J. L. (2018). Rebasing 'Maddison': new income comparisons and the shape of long-run economic development. *GGDC Research Memorandum*, 174.

Burke, P. J. (2011). The National-Level Energy Ladder and its Carbon Implications. Technical report, Centre for Climate Economics & Policy, Crawford School of Economics and Government, The Australian National University, Canberra.

Chen, B., Yang, Q., Li, J., and Chen, G. (2017). Decoupling analysis on energy consumption, embodied GHG emissions and economic growth – The case study of Macao. *Renewable and Sustainable Energy Reviews*, 67:662–672.

Chertow, M. R. (2000). The IPAT Equation and Its Variants. *Journal of Industrial Ecology*, 4(4):13–29.

Cole, H. S. D., Freeman, C., Jahoda, M., Pavitt, K., of Sussex., U., and Unit., S. P. R. (1973). *Models of doom: a critique of The limits to growth*. Universe Books, New York.

Commoner, B., Ehrlich, P. R., and Holdren, J. P. (1972). Response. *Bulletin of the Atomic Scientists*, 28(5):17–56.

Cook, E. (1971). The Flow of Energy in an Industrial Society. *Scientific American*, 225(3):134–147.

Dasgupta, S., Laplante, B., Wang, H., and Wheeler, D. (2002). Confronting the Environmental Kuznets Curve. *The Journal of Economic Perspectives*, 16(1):147–168.

Davis, S. J. and Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences*, 107(12):5687–5692.

Diakoulaki, D. and Mandaraka, M. (2007). Decomposition analysis for assessing the progress in decoupling industrial growth from CO_2 emissions in the EU manufacturing sector.

Dicken, P. (1998). *Global Shift: Transforming the World Economy*. SAGE Publications, London, third edit edition.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., and De Vries, G. (2013). The Construction of World Input-Output Tables in the WIOD Project. *Economic Systems Research*, 25(1):71–98.

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

Druckman, A. and Jackson, T. (2009). The carbon footprint of UK households 1990–2004: A socio-economically disaggregated, quasi-multi-regional input-output model. *Ecological Economics*, 68(7):2066–2077.

EEA (2013). European Union CO_2 emissions: different accounting perspectives. Technical Report 20, European Environment Agency.

Ehrlich, P. (1968). *The population bomb*. Ballantine Books, New York.

Ehrlich, P. R. and Holdren, J. P. (1972). Critique. *Bulletin of the Atomic Scientists*, 28(5):16–27.

Federico, G. and Tena-Junguito, A. (2017). A tale of two globalizations: gains from trade and openness 1800–2010. *Review of World Economics*, 153(3):601–626.

Feenstra, R. C., Inklaar, R., Timmer, M. P., Aten, B., Atkeson, A., Basu, S., Deaton, A., Diewert, E., Heston, A., Jones, C., Rao, P., Rodríguez-Clare, A., and Végh, C. (2015). The Next Generation of the Penn World Table. *American Economic Review*, 105(10):3150–3182.

Fernihough, A. and O'Rourke, K. H. (2014). Coal and the European Industrial Revolution. Technical report, Univeristy of Oxford.

Findlay, R. and O'Rourke, K. H. (2007). *Power and plenty: trade, war, and the world economy in the second millennium*. Princeton University Press.

Fischer-Kowalski, M., Ren, Y., Moriguchi, Y., Crane, W., Krausmann, F., Eisenmenger, N., Giljum, S., Hennicke, P., Kemp, R., Romero Lankao, P., and Bella Siriban Manalang Jeff McNeely, A. (2011). Decoupling natural resource use and environmental impacts from economic growth. Technical report, UNEP, International Resource Panel.

Fouquet, R. (2009). A Brief History of Energy. In *International Handbook on the Economics of Energy*, chapter 1. Edward Elgar Publishing.

Gallego, B. and Lenzen, M. (2005). A consistent input-output formulation of shared producer and consumer responsibility. *Economic Systems Research*, 17(4):365–391.

Grossman, G. M. and Krueger, A. B. (1991). Environmental Impacts of a North American Free Trade Agreement. Technical report, NBER, Cambridge.

Grossman, G. M. and Krueger, A. B. (1995). Economic Growth and the Environment. *The Quarterly Journal of Economics*, 110(2):353–377.

Hoekstra, R., Michel, B., and Suh, S. (2016). The emission cost of international sourcing: using structural decomposition analysis to calculate the contribution of international sourcing to CO_2 – emission growth. *Economic Systems Research*, 28(2):151–167.

Hoekstra, R. and Van Den Bergh, J. C. J. M. (2002). Structural Decomposition Analysis of Physical Flows in the Economy. *Environmental and Resource Economics*, 23:357–378.

Hoekstra, R. and van der Bergh, J. J. C. J. M. (2003). Comparing structural and index decomposition analysis. *Energy Economics*, 25(1):39–64.

Hosier, R. (2004). Energy ladder in developing countries. *Encyclopedia of Energy*, 2:423:435.

Isard, W. (1951). Interregional and Regional Input-Output Analysis: A Model of a Space-Economy. *The Review of Economics and Statistics*, 33(4):318–328.

Jakob, M. and Marschinski, R. (2012). Interpreting trade-related CO_2 emission transfers. *Nature Climate Change*, 3(1):19–23.

Kaltenegger, O., Löschel, A., and Pothen, F. (2017). The Effect of Globalisation on Energy Footprints: Disentangling the Links of Global Value Chains. *Energy Economics*, 68:148–168.

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

Kander, A., Malanima, P., and Warde, P. (2013). *Power to the People*. Princeton University Press.

Kanemoto, K. and Murray, J. (2013). What is MRIO? MRIO benefits & limitations. In Murray, J. and Lenzen, M., editors, *The sustainability practitioner's guide to multi-regional inputoutput analysis*, chapter Chapter 1, pages 1–9.

Klasing, M. J. and Milionis, P. (2014). Quantifying the evolution of world trade, 1870-1949. *Journal of International Economics*, 92:185–197.

Lenzen, M. (2016). Structural analyses of energy use and carbon emissions-an overview. *Economic Systems Research*, 28(2):119–132.

Lenzen, M., Kanemoto, K., Moran, D., and Geschke, A. (2012). Mapping the Structure of the World Economy; Supporting Information. *Environmental Science & Technology*, 46(15):8374–8381.

Lenzen, M., Moran, D., Kanemoto, K., and Geschke, A. (2013). Building Eora: a Global Multi-Region Input-Output Database At High Country and Sector Resolution. *Economic Systems Research*, 25(1):20–49.

Lenzen, M. and Murray, J. (2010). Conceptualising environmental responsibility. *Ecological Economics*, 70(2):261–270.

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

Leontief, W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics*, 18(3):105–125.

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, 52(3):262–271.

Leontief, W. (1974). Structure of the World Economy: Outline of a Simple Input-Output Formulation. *The Swedish Journal of Economics*, 76(4):387–401.

Levinson, A. (1996). Environmental regulations and manufacturers' location choices: Evidence from the Census of Manufactures. *Journal of Public Economics*, 62:5—-29.

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

MacKay, D. (2009). *Sustainable Energy - without the hot air*. UIT, Cambridge, England.

Malthus, T. (1798). *An Essay on the Principle of Population*. London.

Marques, A., Rodrigues, J., Lenzen, M., and Domingos, T. (2012). Income-based environmental responsibility. *Ecological Economics*, 84:57–65.

Meadows, D. H., Meadows, D. L., William, R., and Behrens III, W. W. (1972). *The Limits to Growth*. Universe Books.

Miller, R. E. and Blair, P. D. (2009). *Input-output analysis : foundations and extensions*. Cambridge University Press.

Nordhaus, W. D. (1992). Lethal Model 2: The Limits to Growth Revisited. *Brookings Paper on Economic Activity*, 2(1–59).

OECD (2016). The OECD input-output database: Sources and methods. Technical report.

Oosterhaven, J. and Van Der Linden, J. A. (1997). European Technology, Trade and Income Changes for 1975-85: An Intercountry Input-Output Decomposition. *Economic Systems Research*, 9(4):393–412.

Owen, A. E. (2015). *Techniques for evaluating the differences in consumption-based accounts*. PhD thesis, The University of Leeds.

Peters, G. and Solli, C. (2010). *Global carbon footprints: Methods and import/export corrected results from the Nordic countries in global carbon footprint studies*, volume 1.

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

Peters, G. P. (2010). Policy Update: Managing carbon leakage. *Carbon Management*, 1(1):35–37.

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

Piñero, P., Bruckner, M., Wieland, H., Pongrácz, E., and Giljum, S. (2018). The raw material basis of global value chains: allocating environmental responsibility based on value generation. *Economic Systems Research*.

Pomeranz, K. (2000). *The great divergence : China, Europe, and the making of the modern world economy*. Princeton economic history of the Western world. Princeton University Press, Princeton, N.J. ; Oxford.

Proops, J. L. R., Faber, M., and Wagenhals, G. (1993). *Reducing CO_2 Emissions: A Comparative Input-Output Study for Germany and the UK.* Springer, Berlin.

Quéré, C. L., Korsbakken, J. I., Wilson, C., Tosun, J., Andrew, R., Andres, R. J., Canadell, J. G., Jordan, A., Peters, G. P., and van Vuuren, D. P. (2019). Drivers of declining CO_2 emissions in 18 developed economies. *Nature Climate Change 2019 9:3*, 9(3):213.

Reddy, A. K. N. and Goldemberg, J. (1990). Energy for the Developing World. *Scientific American*, 263(3):110–119.

Schurr, S. and Netschert, B. (1960). *Energy in the American Economy 1850-1975: An Economic Study of Its History and Prospects*. Johns Hopkins Press, Baltimore.

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

Smil, V. (2000). Energy in the Twentieth Century: Resources, Conversions, Costs, Uses, and Consequences. *Global Environmental Change*, 25:21–51.

Smil, V. (2011). Global Energy: The Latest Infatuations. *American Scientist*, 99(3):212.

Smil, V. (2013). *Making the Modern World: Materials and Dematerialization.* Wiley, Chichester, UK.

Smil, V. (2016). *Energy transitions: global and national perspectives*. ABC-CLIO, Santa Barbara, USA.

Solow, R. M. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics*, 70(1):65–94.

Solow, R. M. (1974). Intergenerational Equity and Exhaustible Resources. *The Review of Economic Studies*, 41:29.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A., and Tukker, A. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, 22(3):502–515.

Stern, D. I. (2004a). Economic Growth and Energy. *Encyclopedia of Energy*, 2:35–51.

Stern, D. I. (2004b). The Rise and Fall of the Environmental Kuznets Curve. *World Development*, 32(8):1419–1439.

Stern, D. I. (2010). The Role of Energy in Economic Growth Crawford School The Australian National University.

Tapio, P. (2005). Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. *Transport Policy*, pages 1–15.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23(3):575–605.

Timmer, M. P., Los, B., Stehrer, R., and de Vries, G. J. (2016). An Anatomy of the Global Trade Slowdown based on the WIOD 2016 Release.

Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J. M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., and Kuenen, J. (2013). Exiopol – Development and Illustrative Analyses of a Detailed Global Mr Ee Sut/Iot. *Economic Systems Research*, 25(1):50–70.

United Nations, . (1999). UN Handbook of input-output table compilation and analysis. Technical Report 74, United Nations.

Vehmas, J., Kaivo-oja, J., and Luukkanen, J. (2003). Global Trends of Linking Environmental Stress and Economic Growth.

Warde, P. (2007). Energy Consumption in England and Wales, 1560–2000. *Series on Energy Consumption*.

Wiedmann, T. and Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, 11(5):314–321.

Wiedmann, T., Lenzen, M., Turner, K., and Barrett, J. (2007). Examining the global environmental impact of regional consumption activities - Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecological Economics*, 61(1):15–26.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., and Alier, J. M. (2015). The material footprint of nations. *PNAS*, 112(20):6271–6276.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J. H., Merciai, S., and Tukker, A. (2015). Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. *Sustainability*, 7(1):138–163.

Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., and Tukker, A. (2018). Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. *Journal of Industrial Ecology*, 00(0):1–12.

Wrigley, E. A. (2006). The transition to an advanced organic economy: half a millennium of English agriculture. *The Economic History Review*, 59(3):435–480.

WTO (2013). Trends in International Trade. Technical report, World Trade Organization.

WTO (2017). World Trade Report: Trade, Technology and Jobs. Technical report, WTO.

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

Zhang, C., Chen, W.-Q., Liu, G., and Zhu, D.-J. (2017). Economic Growth and the Evolution of Material Cycles: An Analytical Framework Integrating Material Flow and Stock Indicators. *Ecological Economics*, 140:265–274.

Zhang, Y. (2012). Scale, Technique and Composition Effects in Trade-Related Carbon Emissions in China. *Environmental and Resource Economics*, 51(3):371–389.

Paper 1

Energy Use and Economic Growth in High-Income Countries: The Role of Trade 1970–2009

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Abstract

Long-term trends show that economic growth in developed countries has been closely linked with energy use until about 1970. The period after this is marked by a decoupling of GDP per capita from energy use per capita. This study investigates whether the apparent decoupling is a real phenomenon or a result of the separation of production and consumption activities. Single-region input-output (SRIO) and multi-region input-output (MRIO) techniques have been applied to analyse energy embodied in trade for Denmark, France, the UK and the USA during the period 1970–2009. The results of this study show that taking into account energy embodied in imports shifts the energy use curve upwards but does not affect the decoupling trend notably over the long term. In addition, the share of energy embodied in imports have increased while the share share of energy embodied in exports remained stable, as a result the gap between energy embodied in imports and exports have widened over time.

JEL Classification

C67, F18, N70, N74, Q43

Keywords

Multi-Region Input-Output Analysis, Single-Region Input-Output Analysis, Energy Embodied in Trade, Decoupling, Economic Growth, Trade, Footprint

1 Introduction

Historical evidence shows that the relationship between energy use and economic growth in developed countries was tightly coupled until about 1970 (as shown in Figure 2 on page 7). The period after this is marked by stabilisation in energy use per capita and economic growth without a proportional increase in energy use.

Several factors have been put forward to explain this change: (i) structural changes in composition of national output towards lighter manufacturing industries and services that, on average, used less energy per unit of output than the heavy industries that had been dominant in the past; (ii) technological change and significant improvements in thermal efficiency of energy conversion; (iii) changes in the composition of energy supply, in particular a relative increase of electricity inputs (electricity is a high-quality form of energy, thus less electricity is required to produce the same amount of output) and fluid fuels (petroleum and natural gas), which are in many ways more flexible than solid fuels in the uses to which they could be put into (Schurr, 1984; Smil, 1992; Meyers and Schipper, 1992; Kander et al., 2013).

Another element that has received less attention in explaining the change since the 1970s is energy embodied in traded goods. Trade entails the movement of goods produced in one country for consumption in another. This implies that a country can partially disconnect its domestic economic and energy systems as some goods can be produced in and imported from other countries. Grossman and Krueger (1995) discussed the issue of trade in relation to the Environmental Kuznets Curve (EKC)[1], noting that the downward sloping part of the EKC could arise because of the relocation of pollution intensive industries from one country to another. The authors conclude that while some 'environmental dumping' undoubtedly takes place, the volume of trade is too small to account for the reduced pollution that has been observed to accompany episodes of economic growth.

However, over the last few decades, the volume of trade has increased dramatically. Between 1970 and 2009, global trade grew by an average of 7% each year. Compared with the 1970s, in 2009 the value of trade was almost a factor of 10 higher for manufactured products, 2.3 higher for fuels and mining products and more than 3 times higher for agricultural products (WTO, 2013). The increasing integration of world markets has brought with it a disintegration of the production process in which the domestic production of goods and services are combined with those produced abroad (Feenstra, 1998).

Although the apparent decoupling of energy consumption from economic growth can be attributed

[1] Their study considers carbon emissions, but energy is arguably at the centre of it as fossil fuel combustion is the largest source of greenhouse gas emissions, accounting for about 80% of these.

to the structural change within a country and the use of more efficient technologies, it can also be affected by the fact that countries import more goods and services from other countries that may or may not be more resource- and energy-intensive. If the changes experienced on the production side are not accompanied by similar changes in the structure of consumption, then the apparent decoupling could be the result of production relocation from one country to another (Cole, 2004).

Many studies have quantified energy and carbon content embodied in international trade (see e.g. Wiedmann et al. 2007). Energy analyses emerged in the 1970s. Most of the early studies focused on determining how much energy is used in the production of goods and services (Wright, 1974; Bullard III et al., 1975; Proops, 1977; Costanza, 1984). Fieleke (1974) was among the first to look specifically at the energy content of US imports and exports in 1970. The study showed that the content of imports is more intensive than that of exports. Similar studies have followed, initially focusing on a single country and a specific year (Jacobsen, 2000; Machado et al., 2001; Liu et al., 2010), then on to various countries over specific years (Enevoldsen et al., 2007) and lately to global analyses of 10–20 year periods (Gasim, 2015; Lan et al., 2016) and longer (Kaltenegger et al., 2017). The results indicate that most industrialised countries are net importers of carbon emissions and energy while developing countries are net exporters. However, due to limited data availability for the period before 1990, little attention has been devoted to studying the changes associated with energy use and trade over a longer period.

This study seeks to bridge the gap by estimating the energy embodied in trade for the UK, USA, France and Denmark during the period c.1970–2009. The primary aim of this paper is to examine to what extent the change in energy consumption and apparent decoupling in high income countries can be attributed to international trade (i.e. energy embodied in imported goods). The scope of this problem warrants more detailed questions that target specific aspects studied in this paper, such as: (i) What shares of energy are linked to production for export and how much is embodied in imported goods? (ii) Do countries exhibit similar decoupling trends?

Energy use is directly tied to CO_2 emissions and climate change (because the combustion of fossil fuels is the primary cause of CO_2 emissions); thus, understanding the relationship between energy use and economic growth has significant policy implications. If the decline in energy consumption comes from increasing imports of energy-intensive goods and producing less of them domestically, then the observed pattern would not be replicable in other less developed countries. Furthermore, if developing countries follow the energy and carbon-intensive growth paths of industrialised countries, this is likely to aggravate existing environmental issues and become a major challenge for global sustainability (Grossman and Krueger, 1995; Haberl, 2006). However, if the gains come from technology, then policies encouraging technology transfer, economies of scale and learning by doing effects could be encouraged and replicated.

2 Background

2.1 Energy and Economic Growth

Long-term trends show that global economic output has been marching in lockstep with global energy use. Between 1900 and 2000, energy use increased about 17-fold (from 22 EJ to 380EJ), and gross output rose 16 fold (from 2 trillion to 32 trillion US dollars) (Smil, 2000, 2013). However, this trend is not universal: a closer look at the country level reveals different energy use patterns that vary between economies at different stages of development (Jakob et al., 2012). Energy intensities (total energy use per unit of GDP) rise during the early stages of industrialisation, peak, and then decline as economies mature and use energy more efficiently. Country-specific ascents and declines may have very different slopes, and peaks can be sharp or can appear as extended plateaus (Smil, 2000).

Differences in energy use and income per capita are often explained by decoupling and convergence hypotheses. The convergence hypothesis, taken from economic growth literature suggests that energy use per capita becomes more equal over time. Kander et al. (2013) list several stylised facts concerning energy use and growth for a set of today's developed countries over the past two centuries. One such fact is that in the 20th century energy intensity fell and converged across developed economies.

Declining and converging energy intensities among developed economies imply that there has been decoupling between energy use and growth. As shown in Figure 2 (on page 7), the first signs of a relative decoupling in industrialized countries occurred in the 1920s. Before World War I, the consumption of energy had been rising at the same or similar rate as GDP while after the war rose at a slower rate than GDP. This trend of relative decoupling continued until about the 1970s. At this point the historical relationship between energy use and economic growth was shattered by the two oil crises. The oil price shocks (1973–74 and 1978–80) were so profound that, between 1973 and 1986 there was no growth in US energy use while the economy grew by 30% (Goldemberg et al., 1985). Since then many oil-dependent economies have invested heavily in the search for alternative energy sources. Globally the share of oil in the energy mix declined from 46.2% in 1973 to 31.3% in 2014 (IEA, 2017).

The existing evidence suggests that economic growth does not have to be supported by the virtually identical expansion of energy use. Global energy intensity has declined by 34%, from 360 (kg of oil equivalent per 1000$ GDP; 1990 Intl$) in 1970 to 237 (kg of oil equivalent per 1000$ GDP; 1990 Intl$) in 2009. The energy intensities of the USA, UK, France and Denmark follow a similar trend, but the differences in energy intensities among equally rich countries remain large. For instance, the US energy intensity is almost twice as large as the UK intensity. In some cases even neighbouring countries with virtually identical GDP per capita can display large differences: for example, in 2009 the French economy was 25% more energy intensive than that of the UK (see Table 1).

Table 1: Energy, Growth, Trade and Population, 1970–2009

	1970	1975	1980	1985	1990	1995	2000	2005	2009
Denmark									
Population (10^6)	4.9	5.1	5.1	5.11	5.1	5.2	5.3	5.4	5.5
Energy p.c (10^3)	3.9	3.5	3.7	3.8	3.4	3.7	3.5	3.5	3.3
GDP p.c (10^3)	12.7	13.6	15.3	17.4	18.5	20.4	23.0	24.0	23.3
Trade (as % GDP)	58	60	66	72	67	69	83	89	89
Energy intensity	307.1	257.4	241.8	218.4	183.8	181.4	152.2	145.8	141.6
France									
Population (10^7)	5.2	5.4	5.5	5.7	5.9	6.0	6.1	6.3	6.5
Energy p.c (10^3)	2.9	3.0	3.5	3.6	3.8	4.0	4.1	4.3	3.9
GDP p.c (10^3)	11.4	12.9	14.8	15.5	17.6	18.3	20.4	21.5	21.2
Trade (as % GDP)	31	36	43	47	42	43	55	53	50
Energy intensity	254.4	232.6	236.5	232.3	215.9	218.6	201.0	200.0	184.0
United Kingdom									
Population (10^7)	5.8	5.6	5.6	5.7	5.7	5.8	5.9	6.0	6.2
Energy p.c (10^3)	3.7	3.6	3.5	3.6	3.6	3.7	3.8	3.7	3.1
GDP p.c (10^3)	10.7	11.8	12.9	14.2	16.4	17.6	21.1	23.8	23.5
Trade (as % GDP)	42	51	50	53	47	51	52	52	55
Energy intensity	345.8	305.1	271.3	253.5	219.5	210.2	180.1	155.5	131.9
United States									
Population (10^7)	20.5	21.6	22.7	23.8	25.0	26.6	28.2	29.6	30.8
Energy p.c (10^3)	7.6	7.7	7.9	7.5	7.7	7.8	8.1	7.8	7.1
GDP p.c (10^3)	15.0	16.3	18.6	20.1	23.2	24.6	28.7	30.8	29.9
Trade (as % GDP)	11	15	20	17	20	22	25	26	25
Energy intensity	506.7	472.4	424.7	373.1	331.9	317.1	282.2	253.2	237.5

Notes: Population and GDP (1990 Intl$) per capita (GDP p.c) from Bolt et al. (2018). Energy p.c – Energy per capita (kilograms of oil equivalent per person) and trade (imports + exports) as percentage of GDP from OECD (2018). Energy intensity – kilograms of oil equivalent per 1000$ GDP (1990 Intl$).

2.2 Country Context

This study covers four industrialised economies that are similar in terms of economic development but differ in terms of engagement in international trade, energy use and the size of the economy. Understanding the characteristics and energy use in these countries is critical to designing appropriate mitigation policies. Summary statistics for population, GDP per capita, trade (imports + exports as % of GDP), energy use per capita (kilograms of oil equivalent/per capita) and energy intensity, for the four countries are presented in Table 1. The UK and France are among the largest economies in the EU. Both countries have similar trade profiles. Imports and exports constituted 42% (UK) and 31% (France) of GDP in 1970 and about 50% in 2009. The level and trend of energy use differ among the four countries. In 1970, energy use in France (2900 kgoe/pc) was lower than in the UK (3700 kgoe/pc), but by 2009 it had increased in France to 3900 kgoe/pc and declined in the UK to 3100 kgoe/pc.

The USA is one of the world's largest economies and the largest trading nation in absolute terms. Trade accounted for 11% of GDP in 1970 and by 2009 it increased to 25% making the USA the fastest growing country in terms of trade but the least engaged in trade among the four countries in the sample. US energy use per capita decreased from 7600 kgoe in 1970 to 7100 kgoe in 2009. The USA exhibits the highest energy use per capita – about twice as large as the three other countries in the sample.

Denmark is a relatively small economy that is heavily involved in trade. The combined share of imports and exports expressed as a percentage of GDP increased from 58% in 1970 to 89% in 2009 (highest share in the sample). Furthermore, Denmark has one of the lowest energy intensities in the sample, despite economic growth, its energy use had declined by 15% from 3900 kgoe/pc in 1970 to 3300 kgoe/pc in 2009.

2.3 Direct vs. Indirect Energy

Direct energy can be either used in the economy as input in the production of goods and services or consumed by households and the public sector – for heating, transport and similar purposes (Östblom, 1982). Indirect energy embodied in non-energy products refers to the energy that is used to produce, package, transport and sell the things we buy and consume.

The division of direct vs. indirect energy is highly appropriate when considering the energy related to international trade. In a globalised world, production chains extend beyond a country's borders; thus, including energy embodied in traded goods is essential in calculating a country's total energy use. Without such adjustment, a country's energy use can look profoundly different making it easy to show a declining trend by importing more intermediate and finished consumption goods from abroad.

3 Method

This study uses input-output analysis (IO) developed by Leontief (1936). Within the input-output framework, two methods are commonly used to calculate the energy embodied in international trade (Miller and Blair, 2009): the single-region input-output (SRIO) model and the multi-region input-output (MRIO) model. Both methods are based on different underlying assumptions and have different data requirements (Peters, 2008).

The analysis in this paper is split into two parts. The first part (from 1970 to 1990) is based on the SRIO model. The SRIO model estimates the energy content embodied in trade by assuming that all other countries in the world have the same technological structure as the modelled country – i.e. that imported goods and services are produced with the same technology as the domestic technology in the same sector – hence this assumption is known as the *domestic technology assumption* (DTA). Alternatively, one could use country-specific energy intensities to estimate energy flows between countries. For example, energy embodied in imports from the USA should be calculated using US energy intensities. However, in the SRIO tables, the source of imports is not known, and thus it is not possible to use country-specific energy intensities. It has been suggested that when the actual source of imports is not known, one may use the energy intensity of a typical country of imports (e.g. the USA), a weighted average of the energy intensities of the main countries from which the goods are imported (Tolmasquim and Machado, 2003), or world-average intensities for imports (Andrew et al., 2009).

A sensitivity analysis using (i) the DTA assumption, (ii) the four country weighted average energy intensity, and (iii) the USA as a typical country of imports has been performed to give a sense of the potential under/over estimation of energy embodied in imports as compared with the MRIO model. The results displayed in Appendix Figure A.1 show that energy embodied in imports calculated under the DTA are lower for the UK, France and Denmark and little less for the USA. Energy embodied in imports would be underestimated using this assumption. The four country average produces the estimates that are most similar to the actual estimates of energy embodied in imports when calculated with a full MRIO model. Hence, for the period 1970–1990 the four country weighted average intensity is applied to calculate energy embodied in imports.

The second part of the analysis from 1995 to 2009, is based on the MRIO model. This method overcomes the issues associated with the SRIO DTA by using different technology factors for different countries. The MRIO method allows for more detailed and accurate estimation of energy embodied in imports and exports.

The basic idea behind the IO analysis is that a national (or regional) economy can be divided into a number of sectors that are interlinked and whose relationships can be represented in a mathematical matrix. Formally, the standard input-output model can be expressed as

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{1}$$

where $\mathbf{x}$ is the total output vector, $\mathbf{A}$ is the technical coefficient matrix, its element $[a_{ij}]$ reflects the proportion of inputs from sector i required to produce one unit of output in sector j, and $\mathbf{y}$ is a column vector of final demand. The above equation can be rewritten as:

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

where $(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{L}$ is known as the Leontief inverse or the total requirement matrix. Its element $[l_{ij}]$ shows the effect on production in sector i from a unit change in final demand in sector j (Leontief, 1936; Miller and Blair, 2009).

Equation 2 can be presented in more detail to show a complete accounting of monetary flows (United Nations, 1999) in the economy as :

$$\mathbf{x} = (\mathbf{I} - (\mathbf{A}^d + \mathbf{A}^m))^{-1}(\mathbf{y}^d + \mathbf{y}^e + \mathbf{y}^m - \mathbf{m}) \tag{3}$$

where $\mathbf{A}^d$ is the domestic input coefficient matrix, $\mathbf{A}^m$ is the coefficient matrix of imported intermediate demand, $\mathbf{y}^d$ is the vector of domestic final-demand products, $\mathbf{y}^e$ is the vector of final export demand, $\mathbf{y}^m$ is the vector of imported final demand products, and $\mathbf{m}$ is the vector of total imports into domestic economy, which includes both industry demand ($\mathbf{A}^m\mathbf{x}$) and final demand ($\mathbf{y}^m$) i.e. $\mathbf{m} = \mathbf{A}^m\mathbf{x} + \mathbf{y}^m$.

To calculate the energy content embodied in trade, the SRIO model was set up as consisting of two regions: region 1 (denoted with superscript '1') and an artificial rest of world region (denoted with '2') (see e.g. Andrew et al., 2009; Serrano and Dietzenbacher, 2010; Proops et al., 1993). Changing the notation in Equation 3 as $\mathbf{A}^{11} = \mathbf{A}^d$ for the domestic input coefficients, $\mathbf{A}^{21} = \mathbf{A}^m$ for the import coefficients, $\mathbf{y}^{11} = \mathbf{y}^d$ for domestic final demand, $\mathbf{y}^{21} = \mathbf{y}^m$ for imports to region 1, and $\mathbf{y}^{12} = \mathbf{y}^e$ for the exports yields:

$$\begin{bmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \end{bmatrix} = \left[\mathbf{I} - \begin{bmatrix} \mathbf{A}^{11} & 0 \\ \mathbf{A}^{21} & \mathbf{A}^{11} + \mathbf{A}^{21} \end{bmatrix}\right]^{-1} \begin{pmatrix} \mathbf{y}^{11} + & \mathbf{y}^{12} \\ \mathbf{y}^{21} + & 0 \end{pmatrix} \tag{4}$$

in this case an artificial region has no final consumption of domestic production (i.e. $\mathbf{y}^{22} = 0$), exports from region 1 are not linked to imports to the second region (i.e. $\mathbf{A}^{12} = 0$) and $\mathbf{x}^2$ represents the output of an artificial region required to produce imports into the first region. As noted above, a common assumption in the SRIO framework is that imports are produced with the domestic technology (DTA). This implies that $\mathbf{A}^{11} + \mathbf{A}^{21} = \mathbf{A}^{12} + \mathbf{A}^{22}$; as a result, $\mathbf{A}^{12} + \mathbf{A}^{22}$ is replaced by $\mathbf{A}^{11} + \mathbf{A}^{21}$. It is important to note that the technology is given by the structure of the inputs, no matter whether domestically produced or imported.

Energy use is included into Equation 4 as $\mathbf{E} = \hat{\mathbf{q}}\mathbf{L}\mathbf{Y}$; this can be expressed in more detailed form as:

$$\begin{bmatrix} \mathbf{e}^{11} & \mathbf{e}^{12} \\ \mathbf{e}^{21} & \mathbf{e}^{22} \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{q}}^1 & 0 \\ 0 & \hat{\mathbf{q}}^2 \end{bmatrix} \left[\mathbf{I} - \begin{bmatrix} \mathbf{A}^{11} & 0 \\ \mathbf{A}^{21} & \mathbf{A}^{11} + \mathbf{A}^{21} \end{bmatrix} \right]^{-1} \begin{bmatrix} \mathbf{y}^{11} & \mathbf{y}^{12} \\ \mathbf{y}^{21} & 0 \end{bmatrix} \tag{5}$$

where $\mathbf{q}^1$ and $\mathbf{q}^2$ shows energy use per unit of industrial output, $\mathbf{e}^{11}$ is the energy required to satisfy domestic final demand in region 1, $\mathbf{e}^{12}$ is the energy required to produce exports from region 1, and $\mathbf{e}^{21}$ is the energy required to produce imports for region 1. The DTA assumption also implies that energy intensities are the same in both regions, i.e. $\mathbf{q}^1 = \mathbf{q}^2$. The DTA assumption is partially relaxed here by replacing $\mathbf{q}^2$ with a weighted four country (Denmark, France, UK and USA) average energy intensities (Druckman and Jackson, 2009; Andrew et al., 2009).

In the SRIO model, production-based energy use (PB) for region 1 is obtained as:

$$PB^1 = \underbrace{\mathbf{i}'_n\mathbf{e}^{11}}_{\text{domestic}} + \underbrace{\mathbf{i}'_n\mathbf{e}^{12}}_{\text{EEX}} + \underbrace{h^1}_{\text{households}}$$

where $\mathbf{i}'_n$ is an n-element summation vector consisting of ones; $\mathbf{i}'\mathbf{e}^{11}$ is total energy use due to production of goods and services for domestic consumption in region 1; $\mathbf{i}'\mathbf{e}^{12}$ is energy embodied in exports (EEX); it shows the total energy use in country 1 required for the production of goods and services exported to region 2 (i.e. RoW); h^1 is the direct energy use by households in country 1.

Similarly consumption-based energy use (CB) for country 1 is given as:

$$CB^1 = \underbrace{\mathbf{i}'_n\mathbf{e}^{11}}_{\text{domestic}} + \underbrace{\mathbf{i}'_n\mathbf{e}^{21}}_{\text{EEM}} + \underbrace{h^1}_{\text{households}}$$

where $\mathbf{i}'\mathbf{e}^{21}$ is energy embodied in imports (EEM); it shows the total energy use in RoW that occurs due to the production of goods and services exported to country 1. Note that domestic and household elements are the same as in PB.

For the period 1995–2009, the energy extended multi-region input-output model is defined as:

$$\mathbf{E} = \widehat{\mathbf{q}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}$$

Given k countries (k=41) and n sectors (n=35), matrix **E** can be expressed in its partitioned form as:

$$\underset{kn\times k}{\mathbf{E}} = \begin{bmatrix} \mathbf{e}^{11} & \mathbf{e}^{12} & \cdots & \mathbf{e}^{1k} \\ \mathbf{e}^{21} & \mathbf{e}^{22} & \cdots & \mathbf{e}^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{e}^{k1} & \mathbf{e}^{k2} & \cdots & \mathbf{e}^{kk} \end{bmatrix} \text{ and a block element } \underset{n\times 1}{\mathbf{e}^{rs}} = \begin{bmatrix} e_1^{rs} \\ e_2^{rs} \\ \vdots \\ e_n^{rs} \end{bmatrix}$$

where each element of this block e_i^{rs} contains the energy flow from sector i in country r to country s ($r = s$ denotes domestic energy use).

Energy use from a production-based perspective can be expressed as:

$$PB^r = \underbrace{\mathbf{i}_n'\mathbf{e}^{rr}}_{\text{domestic}} + \underbrace{\mathbf{i}_n'(\sum_{s\neq r}^{k} \mathbf{e}^{rs})}_{\text{EEX}} + \underbrace{h^r}_{\text{households}}$$

and from consumption-based (PB) perspective as:

$$CB^r = \underbrace{\mathbf{i}_n'\mathbf{e}^{rr}}_{\text{domestic}} + \underbrace{\mathbf{i}_n'(\sum_{s\neq r}^{k} \mathbf{e}^{sr})}_{\text{EEM}} + \underbrace{h^r}_{\text{households}}$$

All elements (i.e. Domestic, EEX, EEM and households) have the same meaning as in the SRIO model, but in the MRIO model the EEX and EEM elements are summed over k-1 countries.

Given the above information, the balance of energy embodied in trade (BEET) for a given country can be calculated as:

$$BEET^r = PB^r - CB^r = EEX^r - EEM^r$$

BEET shows whether a country is a net importer or exporter of energy content embodied in trade.

4 Data

The World Input-Output Database (WIOD) is the main source of data for the period 1995–2009. The WIOD consists of series of multi-region input-output tables (MRIOT) and environmental/energy sub-databases, covering 35 industries and 41 countries/regions, including 27 EU and 13 other major advanced and emerging economies, plus a region called 'Rest of the World' (Timmer et al., 2015).

For the period from c.1970[2] to 1990 the data were extracted from two sources: IO tables from the OECD IO database (OECD, 2016) and energy balances from the IEA database (IEA, 2017). The OECD SRIO tables distinguish between 36 industrial sectors. However the data are only available for a limited number of countries and specific time periods. Due to data availability this study focuses on Denmark, France, the UK and the USA. These developed nations offer a range of cases with different trade patterns (for instance, the USA is less engaged in trade in relative terms than the UK and France) and energy systems.

The WIOD database offers ready to use harmonised MRIO tables and energy accounts with the same sectoral classification. The OECD IO tables and the IEA energy balances, however use different industrial classifications. Typically, the IEA sectors are more aggregated than the OECD IO sectors. In this study the connection between the physical IEA energy balances and the monetary SRIO tables follows the 'minimum information method' as explained by Genty et al. (2012).

4.1 Allocating IEA Data

The connection of the OECD IO tables and the IEA energy balances involves several steps. First is the direct allocation of energy to the industries where the OECD IO sectoral classification matches the IEA energy flow (one-to-one allocation). Second is the allocation of energy to the OECD IO sectors where the IEA classification do not have sufficient sectoral detail (one-to-many allocation). The splitting of the IEA energy flow to several sectors is performed according to the monetary structure of the energy-supplying sectors – *Petroleum and coal products* (sector 9) and *Electricity, gas and water* (sector 25) – from the OECD IO table. For instance, IEA energy flow for *Machinery* is split among five OECD IO sectors, based on their monetary expenditure of sector 9 and sector 25 products. The final step is to allocate energy use in road transport among all of the OECD IO sectors and households. This is done by using the information of monetary expenditure for sector

[2] The IO benchmark years differ among selected countries, thus a letter 'c' refers to the approximate period. For instance, c.1970 for the UK = 1968, and for the USA and France c.1970 = 1972. See Appendix Table A.5 for more details.

9 and sector 25 products. All linkages between the IEA energy flows and the OECD sectors are shown in Appendix Table A.6. Cells containing '1' represent a link between the IEA energy flow and the OECD sector while empty cells imply no link. The allocation procedure is explained in a formal way bellow.

Let **C** be an $f \times n$ binary concordance matrix representing the link between the IEA energy flow and the OECD sector as shown in Appendix Table A.6. Let **s** be an $n \times 1$ column vector containing the input (in monetary terms) from energy related sectors in the IO table: sector 9 and sector 25. For example, s_1 contains input to the sector *Agriculture, forestry and fishery* from *Petroleum and coal products* (sector 9) plus *Electricity, gas and water* (sector 25). The normalised mapping matrix **M** is then obtained as:

$$\mathbf{M} = (\widehat{\mathbf{sC}})^{-1}\mathbf{C}\hat{\mathbf{s}}$$

Matrix **M** corresponds to matrix **C** but instead of '1' it contains shares showing how much of each energy flow is allocated to a given sector. Next, let **E** be a $p \times f$ energy product by energy flow matrix (see Appendix Table A.3 for energy flow and Table A.4 for energy product details). Matrix **E** is modified as:

$$\underset{65\times5355}{\overline{\mathbf{E}}} = \left[(\hat{\mathbf{e}}^1)(\hat{\mathbf{e}}^2)\cdots(\hat{\mathbf{e}}^f)\right]$$

Matrix $\overline{\mathbf{E}}$ is obtained by diagonalising each of the f $(f = 85)$ IEA energy flows of size 65×1 and stacking them horizontally. Every row from matrix **M** (which shows the use of a given energy flow) is replicated p times ($p = 65$) to match the energy product dimension as:

$$\underset{5355\times37}{\overline{\mathbf{M}}} = \begin{bmatrix} (\mathbf{m}^1)'_{\times p} \\ (\mathbf{m}^2)'_{\times p} \\ \vdots \\ (\mathbf{m}^f)'_{\times p} \end{bmatrix}$$

Multiplying the two matrices yields:

$$\underset{65\times37}{\mathbf{Q}} = \overline{\mathbf{E}} \times \overline{\mathbf{M}}$$

where **Q** is the energy use matrix showing the use of the 65 energy products by the 36 OECD sectors plus households. The energy product dimension (65) has been further aggregated to obtain the total energy use as:

$$\mathbf{q} = \mathbf{i}'_p \mathbf{Q}$$

where $\mathbf{i}'_p$ is a p-element summation vector consisting of ones and $\mathbf{q}$ is a 1×37 total energy use vector corresponding to the sectoral classification of the OECD IO table plus households. For the input-output analysis, households are removed from vector $\mathbf{q}$ and kept in a scalar h.

Energy use in this study represents the so-called emission relevant energy use. It excludes energy commodities used for non-energy purposes (e.g. Bitumen used for road construction, Naphtha for plastics production) and energy commodities used as input for transformation (e.g. the coal that is transformed into coke and coke oven gas).

5 Results

The main results are summarised in Table 2. Domestic energy use (Domestic), energy embodied in exports (EEX), energy embodied in imports (EEM) and direct energy consumption by households are expressed on a per capita basis. Energy use from the production perspective (PB) is a sum of domestic energy use, energy embodied in exports and direct energy use by households. Energy use from the consumption perspective (CB) is the sum of domestic energy use, energy embodied in imports and direct energy use by households.

The share of energy embodied in exports and imports differs among countries. The UK and France have similar profiles in terms of EEX and EEM with about 20% of their total energy embodied in exports and between 20–50% in imported goods. The USA displays smaller shares, 5–9% of energy is embodied in exports and 7–22% in imports. Denmark, the smallest economy in the sample, has the highest shares of energy embodied in trade, with EEX accounting for 21–55% and EEM 21–49%.

Table 2: Energy Embodied in Trade, 1970–2009

	c.70	c.75	c.80	c.85	90	95	00	05	09
Denmark									
(1) Domestic	1.9	2.0	2.2	2.4	2.1	2.4	2.1	2.0	1.9
(2) EEX	0.9	0.9	1.1	1.1	1.3	2.0	2.6	3.4	3.7
(3) EEM	2.0	2.2	1.9	1.0	1.9	2.5	2.4	3.0	2.7
(4) Households	1.5	1.5	1.3	1.3	1.1	1.2	1.1	1.2	1.2
PB (1+2+4)	4.3	4.4	4.5	4.8	4.5	5.6	5.8	6.6	6.8
CB (1+3+4)	5.4	5.6	5.3	4.8	5.1	6.0	5.6	6.3	5.7
BEET (2-3)	-1.1	-1.2	-0.8	0.1	-0.6	-0.4	0.2	0.4	1.1
EEX/PB (%)	21	21	23	23	28	36	44	51	55
EEM/PB (%)	47	49	41	21	42	44	41	46	39
France									
(1) Domestic	2.5	2.4	2.4	2.3	2.6	2.8	2.9	3.1	3.0
(2) EEX	0.6	0.7	0.8	0.8	1.0	0.9	1.1	1.1	0.9
(3) EEM	0.9	1.0	1.2	0.6	1.4	1.3	1.6	1.8	1.7
(4) Households	0.5	0.7	0.7	1.0	1.0	1.0	1.1	1.1	1.1
PB (1+2+4)	3.6	3.8	3.9	4.1	4.6	4.6	4.9	5.2	4.9
CB (1+3+4)	3.9	4.1	4.4	3.9	5.0	5.1	5.5	6.0	5.8
BEET (2-3)	-0.2	-0.3	-0.5	0.3	-0.5	-0.5	-0.5	-0.8	-0.9
EEX/PB (%)	17	18	20	20	21	19	21	19	18
EEM/PB (%)	24	26	32	14	31	29	32	35	35
UK									
(1) Domestic	2.7	2.6	2.5	2.2	2.4	2.2	2.3	2.3	2.0
(2) EEX	0.9	0.9	1.0	0.9	0.9	0.8	0.8	0.9	0.8
(3) EEM	0.7	1.0	1.2	0.8	2.8	1.3	1.9	2.3	1.8
(4) Households	0.7	0.8	0.9	0.8	0.9	1.0	1.1	1.1	1.1
PB (1+2+4)	4.3	4.3	4.4	3.9	4.2	4.0	4.3	4.3	3.9
CB (1+3+4)	4.1	4.4	4.6	3.8	6.1	4.6	5.3	5.7	4.9
BEET (2-3)	0.1	0.0	-0.2	0.1	-1.9	-0.5	-1.0	-1.4	-1.0
EEX/PB (%)	20	22	24	23	22	19	20	20	20
EEM/PB (%)	17	22	27	21	67	32	43	52	46
USA									
(1) Domestic	6.9	7.1	6.3	6.4	6.5	6.4	7.0	6.9	6.3
(2) EEX	0.5	0.6	0.7	0.6	0.8	0.7	0.7	0.6	0.7
(3) EEM	0.6	0.8	0.8	0.9	1.1	1.1	1.7	2.0	1.6
(4) Households	1.8	1.7	1.5	1.4	1.7	1.3	1.5	1.7	1.7
PB (1+2+4)	9.1	9.4	8.4	8.4	9.0	8.4	9.2	9.2	8.7
CB (1+3+4)	9.3	9.7	8.5	8.8	9.3	8.8	10.2	10.6	9.6
BEET (2-3)	-0.2	-0.2	-0.1	-0.4	-0.3	-0.4	-1.0	-1.4	-0.9
EEX/PB (%)	5	7	8	7	9	8	8	7	8
EEM/PB (%)	7	9	9	11	12	13	18	22	18

Notes: EEX - Energy Embodied in Exports, EEM Energy Embodied in Imports, BEET - Balance of Energy Embodied in Trade. All numbers (except %) are expressed on a per capita (kilograms of oil equivalent per person) basis. See Appendix Table A.5 for an exact benchmark year (c.70, c.75, c.80, c.85) for each country.

The difference between EEX and EEM is reflected in the balance of energy embodied in trade (BEET). The balance is positive if EEX is greater than EEM and vice versa. With a few exceptions, most countries display negative BEET meaning that more energy is embodied in imports than exports. At the beginning of the period, the shares of EEX and EEM are quite similar which is reflected in a balanced BEET. Over time BEET deteriorates for most countries except Denmark, where BEET is positive implying that the country is a net exporter of energy. For France, UK and the USA, deteriorating BEET is driven by increasing EEM while EEX remains relatively stable.

A country may avoid using energy by importing goods from other countries. Accounting for energy embodied in imports affects the relationship between GDP and energy use in several ways. As shown in Figure 1 for the UK, USA and France the level of CB is higher, but the decoupling is still visible. For the UK, the absolute decoupling seen from the PB perspective disappears in the CB case. In contrast, for Denmark, CB energy use is higher than PB energy use.

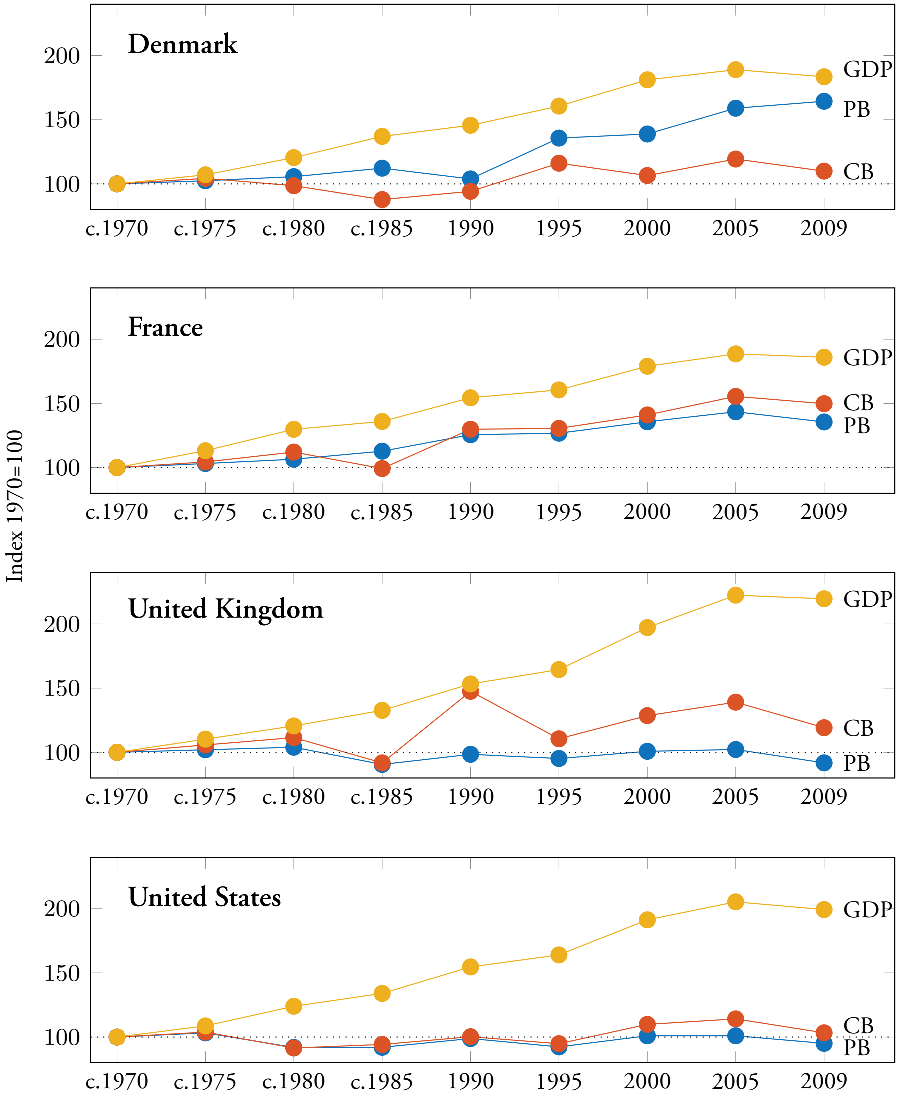
Furthermore, the variance of energy per capita declined over time, from a coefficient of variation (CV) of 0.48 in 1970 to 0.35 in 2009 for PB and from 0.44 to 0.32 for CB. The declining variance implies that countries are becoming more similar in terms of energy use per capita. For the USA and the UK, energy use per capita has declined from an initially high level while for Denmark and France it has increased from an initially low level.

Table 3: PB and CB Variance Between Countries, 1970–2009

	c.1970	c.1975	c.1980	c.1985	1990	1995	2000	2005	2009
CV (PB)	0.48	0.48	0.42	0.38	0.42	0.34	0.36	0.33	0.35
CV (CB)	0.44	0.42	0.38	0.36	0.35	0.31	0.36	0.32	0.32

Note: CV – Coefficient of Variation (= standard deviation/mean). PB – Production-based energy use. CB – Consumption-based energy use. See Appendix Table A.5 for an exact benchmark year (c.1970, c.1975, c.1980, c.1985).

Figure 1: Production- and Consumption-based Energy Use Per Capita vs. GDP Per Capita, 1970–2009



Notes: Production-based (PB) and Consumption-based (CB) energy use and GDP are on per capita basis. See Appendix Table A.5 for an exact benchmark year (c.1970, c.1975, c.1980, c.1985).

5.1 Energy Terms of Trade by Country

The trade imbalances strongly influence net balances of energy embodied in trade. The BEET measure does not show whether the imbalances have resulted from changes in the scale or the composition of trade. For instance, a negative net BEET may reflect a scale effect, i.e. total imports higher (in value) than total exports. A relevant question is whether the exports are becoming less energy intensive while imports more energy intensive. The overall energy intensity of imports and exports can be estimated by multiplying imports and exports by sector-specific energy intensities, aggregating them and dividing by total imports (m) and exports (e) as:

$$E^m = \frac{\sum_{i=1}^{n} q_i m_i}{\sum_{i=1}^{n} m_i} \qquad E^e = \frac{\sum_{i=1}^{n} q_i e_i}{\sum_{i=1}^{n} e_i}$$

where E^m and E^e are the energy intensity of imports and exports, respectively, q_i is the total (direct + indirect) energy intensity, and m_i and e_i are values of imports and exports, respectively, for sector i.

The results presented in Table 4 illustrate that the energy intensity of imports and exports have declined steadily in all countries over the period. On average, in 1970 one million dollar worth of exports embodied 52 TJ, of energy and in 2009 the same value of exports embodied 15 TJ and of energy. On the import side, the decline was about the same: from 61 TJ in 1970 to 24 TJ in 2009. Falling energy intensities are a sign of improvement implying that both imported and exported goods have become less energy intensive. In most cases, energy intensity of imports has been higher than that of exports. Further evidence also suggests that energy intensities of exports are more dispersed across countries than those of imports and that over time the differences between the countries have become larger (CV has increased).

Table 4: Energy Intensity of Exports and Imports

	Denmark		France		UK		USA		Mean		CV	
	E^e	E^m	E^e	E^m	E^e	E^m	E^e	E^m	E^e	E^m	E^e	E^m
c.1970	39	69	47	54	57	49	66	70	52	61	0.23	0.18
c.1975	30	57	38	50	51	52	55	59	43	54	0.27	0.07
c.1980	28	48	30	46	46	55	42	59	36	52	0.24	0.12
c.1985	44	42	60	43	57	50	52	62	53	49	0.14	0.19
1990	24	43	34	45	32	60	42	46	33	49	0.23	0.15
1995	17	24	16	26	15	26	24	34	18	28	0.23	0.16
2000	22	24	19	30	14	31	21	38	19	31	0.20	0.18
2005	19	19	14	25	11	27	18	38	15	27	0.24	0.28
2009	19	15	12	23	11	24	17	34	15	24	0.28	0.32

Notes: E^e - Energy intensity of exports, E^m - Energy intensity of imports. See Appendix Table A.5 for an exact benchmark year (c.1970, c.1975, c.1980, c.1985). Units – Tera Joules (TJ) per one million US dollars (1982$ for the period c1970–1990; 1995$ for the period 1995–2009).

Dividing energy intensity of exports by energy intensity of imports gives the energy terms of trade (ETT)[3]:

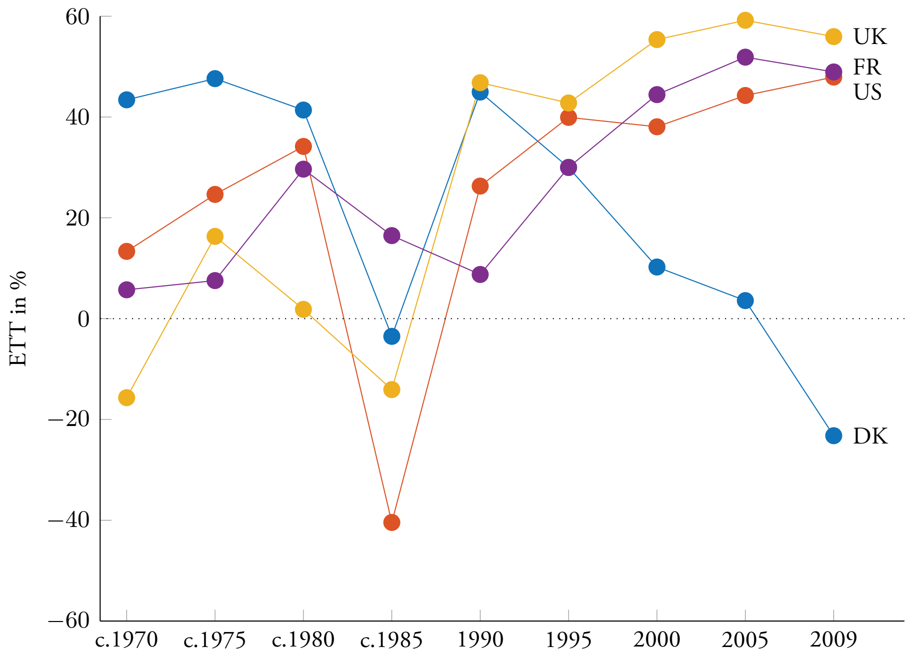
$$ETT = \left(1 - \frac{E^e}{E^m}\right) \times 100$$

The ratio measures by how much the energy content of $1 of exports is different from the energy content of $1 of imports (Antweiler, 1996). A country 'gains' in terms of energy from trade in relative terms whenever its imported goods have higher energy content than its exported goods (Muradian et al., 2002; Cole, 2004).

The ETT results for the selected countries are presented in Figure 2. Except for a few instances, most of the results are positive. This implies that imports were on average more energy intensive than exports. For most countries (except Denmark) ETT has improved over time – much more so during the second half of the study period. It is important to note that the observed differences in energy intensity of imports and exports can occur due to: (i) differences in the compositions of imports and exports, and (ii) differences in technology (energy use per unit of output) which was used to produce imports and exports.

[3]ETT is a modified version of the PTT from Antweiler (1996). It is modified in two ways: (i) the result is subtracted from 1, so the 'gains' are positive and the 'losses' are negative; (ii) it is expressed in percentage terms, not as an index.

Figure 2: Energy Terms of Trade (ETT)



Notes: EET– Energy Terms of Trade. See Appendix Table A.5 for an exact benchmark year (c.1970, c.1975, c.1980, c.1985).

5.2 Energy Embodied in Trade by Sector

The most important sectors in terms of energy embodied in exports (EEX) and imports (EEM) for the four country average is shown in table 5. The total share of energy embodied in the top 10 categories in 1970 and 2009 is about the same for EEX and EEM. However, the share of exports and imports in value terms differs substantially. For instance, the top 10 EEX categories in 1970 accounted for 71% of total energy embodied in exports and represented 59% of the total exports (in value terms) whereas in 2009 the top 10 EEX categories accounted for 79 % of total energy embodied in exports but represented only 40% of the total exports. This suggests that while global value chains have become more complex and fragmented, only a few products remain very energy intensive and contribute significantly towards EEX and EEM. For instance, in 2009 the sector *Electricity, Gas and Water Supply* accounted for about 27% of total energy embodied in EEX and 34% in EEM.

Table 5: The Top 10 Energy Embodied in Exports (EEX) and Energy Embodied in Imports (EEM) Sector Shares, 1970 vs. 2009, (Four Country Average)

			c.1970			
		EEX	Exports ($)		EEM	Imports ($)
1	Transport (29)	16 %	11 %	PetroCoal (9)	17 %	10 %
2	Food (3)	8 %	10 %	Mining (2)	14 %	20 %
3	Iron Steel (12)	8 %	3 %	Metals (14)	7 %	4 %
4	Chemicals (7)	8 %	6 %	IronSteel (12)	7 %	4 %
5	Machinery (15)	7 %	10 %	Transport (29)	6 %	3 %
6	PetroCoal (9)	6 %	4 %	Chemicals (7)	5 %	5 %
7	Vehicles (21)	6 %	7 %	RbrPlastic (10)	5 %	1 %
8	Metals (14)	4 %	2 %	MnfOther (24)	4 %	1 %
9	Agriculture (1)	4 %	5 %	Food (3)	4 %	7 %
10	ProGoods (23)	3 %	1%	Agriculture (1)	4 %	6 %
	Total	71 %	59 %		73 %	61 %
			2009			
1	ElecGas (17)	27 %	1 %	ElecGas (17)	34 %	2 %
2	WTrnsprt (24)	18 %	6 %	Metals (12)	8 %	3 %
3	Chemicals (9)	7 %	11 %	Chemicals (9)	8 %	6 %
4	AirTrnsprt (25)	6 %	2 %	Mining (2)	7 %	1 %
5	Metals (12)	5 %	4 %	PetroCoal (8)	6 %	7 %
6	PetroCoal (8)	5 %	3 %	AirTrnsprt (25)	4 %	1 %
7	Mining (2)	4 %	2 %	InTrnsprt (23)	4 %	1 %
8	InTrnsprt (23	3 %	2 %	RbrPlastic (10)	3 %	1 %
9	Agriculture (1)	3 %	2 %	PPP (7)	2 %	2 %
10	Food (3)	2 %	7 %	Agriculture (1)	2 %	2 %
	Total	79 %	40 %		78 %	27 %

Note: Energy embodied in Exports (EEX). Energy Embodied in Imports (EEM). Numbers in brackets refer to the full sector name given in Appendix Table A.1 for 1970 and Table A.2 for 2009. See Appendix Table A.5 for an exact benchmark year (c.1970).

6 Discussion and Conclusions

The apparent decoupling can be explained by different mechanisms. Some of these, such as structural and technological change, are well known and imply progress towards more sustainable growth. Others, such as energy embodied in traded goods, may distort the picture by creating the illusion of decoupling. This study investigates how the apparent decoupling trend seen from the production perspective (which includes energy related to production of exports) changes under the consumption perspective (which includes energy related to production of imports).

The findings show that energy embodied in imports affects the relationship between energy use and GDP by shifting the energy use (CB) curve upwards, but the impact is relatively small, and the decoupling remains virtually unchanged. This is true for all countries except Denmark, which is a net exporter of energy embodied in trade and exhibits an unusual (for a developed economy) trend of PB exceeding CB. One explanation for this is that a large share (about 10–20% during 1995–2009) of Danish exports comes from water transport services, the 3rd most energy-intensive sector of the country and about 12 times more intensive than the two other important export categories: *Chemicals and Chemical Products* and *Food, Beverages and Tobacco*. It is important to stress that in this study energy use includes international aviation and marine bunkers while in many official figures which rely on the territorial approach these are excluded or presented separately giving a different perspective on the same issue. For instance, in other cases (see e.g. NER, 2012) that do not include bunker fuels provide evidence of absolute decoupling for Denmark. However, the results presented in this study and other studies (Kaltenegger et al., 2017) that include bunker fuels show weak decoupling for Denmark (this was also the case in this study, see Figure 1).

Although CB follows a similar pattern to PB and exhibits a similar decoupling trend, this does not mean that the energy embodied in imports is negligible. In fact the opposite is true. The energy embodied in imports is higher than the energy embodied in exports and accounts for a significant share of total energy use (30–40% in France, Denmark and the UK; 10–20% in the US. Furthermore, it has been increasing in the USA and UK and has remained stable in France. At the same time energy embodied in exports remained virtually unchanged over the study period.

The energy intensities of imports and exports have declined steadily over time; the rate of decline was faster for exports. Furthermore, energy terms of trade (ETT) have 'improved' for all countries in the sample. This means that one dollar of imports embodied more energy than one dollar of exports. From an individual country perspective this might be seen as good because a country gains in terms of energy. However, from an environmental perspective this might be less desirable because more energy use is often associated with a greater environmental impact (emissions). Only in those cases where imports come from countries with cleaner energy systems would this make environmental sense.

Results at the industry level show that the 10 most intensive import and export categories have remained practically unchanged. Their contribution to the total EEX and EEM increased marginally from about 70% in 1970 to about 80% in 2009. In value terms the changes were more substantial. In 1970 the top 10 EEX and EEM categories accounted for roughly 60%-70%; by 2009 the contribution of the top 10 categories declined to 40% of exports and 27% of imports. This suggests that imports and exports have become more fragmented over time, and the majority of energy content embodied in trade is concentrated in a few product categories.

PB and CB indicators for three of the four countries in the sample follow a very similar trend: a decline or increase in one variable is echoed by a similar change in the other indicator. Akizu-Gardoki et al. (2018) in a study of 126 countries for the period from 2000 to 2014 identify six exemplary countries that have been able to maintain a continuous absolute decoupling trend between Human Development Index and energy footprint. France and the UK are two of these exemplary countries which are also considered in this study. While this study does not provide evidence of absolute decoupling it shows that countries such as the UK and USA are close to achieving absolute decoupling between GDP and energy footprint over a long time frame.

7 References

Akizu-Gardoki, O., Bueno, G., Wiedmann, T., Lopez-Guede, J. M., Arto, I., Hernandez, P., and Moran, D. (2018). Decoupling between human development and energy consumption within footprint accounts. *Journal of Cleaner Production*, 202:1145–1157.

Andrew, R., Peters, G. P., and Lennox, J. (2009). Approximation and Regional Aggregation in Multi-Regional Input–Output Analysis for National Carbon Footprint Accounting. *Economic Systems Research*, 21(3):311–335.

Antweiler, W. (1996). The Pollution Terms of Trade. *Economic Systems Research*, 8(4):361–366.

Bolt, J., Inklaar, R., de Jong, H., and van Zanden, J. L. (2018). Rebasing 'Maddison': new income comparisons and the shape of long-run economic development. *GGDC Research Memorandum*, 174.

Bullard III, C. W., Herendeen, R. A., Bullard, C. W., and Herendeen, R. A. (1975). The energy cost of goods and services. *Energy policy*, 3(4):268–278.

Cole, M. A. (2004). US environmental load displacement: Examining consumption, regulations and the role of NAFTA. *Ecological Economics*, 48(4):439–450.

Costanza, R. (1984). Embodies energy and economic value xn the united states economy: 1963, 1967. *Resources and Energy*, 6:129–163.

Druckman, A. and Jackson, T. (2009). The carbon footprint of UK households 1990–2004: A socio-economically disaggregated, quasi-multi-regional input-output model. *Ecological Economics*, 68(7):2066–2077.

Enevoldsen, M. K., Ryelund, A. V., and Andersen, M. S. (2007). Decoupling of industrial energy consumption and CO_2-emissions in energy-intensive industries in Scandinavia. *Energy Economics*, 29(4):665–692.

Feenstra, R. C. (1998). American Economic Association Integration of Trade and Disintegration of Production in the Global Economy. *The Journal of Economic Perspectives*, 12(4):31–50.

Fieleke, S. N. (1974). The Energy Content of U.S. Exports and Imports. *International Finance Discussion Papers*, 51.

Gasim, A. A. (2015). The embodied energy in trade: What role does specialization play? *Energy Policy*, 86(1):186–197.

Genty, A., Arto, I., and Neuwahl, F. (2012). Final Database of Environmental Satellite Accounts: Technical Report on Their Compilation. Technical report.

Goldemberg, J., Johansson, T. B., N Reddy, A. K., Jose Goldemberg, B., and Williams, R. H. (1985). Basic Needs and Much More with One Kilowatt per Capita. *Ambio*, 14(4/5):190–200.

Grossman, G. M. and Krueger, A. B. (1995). Economic Growth and the Environment. *The Quarterly Journal of Economics*, 110(2):353–377.

Haberl, H. (2006). The global socioeconomic energetic metabolism as a sustainability problem. *Energy*, 31(1):87–99.

IEA (2017). World Energy Balances 2017. Technical report, International Energy Agency.

Jacobsen, H. K. (2000). Energy Demand, Structural Change and Trade: A Decomposition Analysis of the Danish Manufacturing Industry. *Economic Systems Research*, 12(3):319–343.

Jakob, M., Haller, M., and Marschinski, R. (2012). Will history repeat itself? Economic convergence and convergence in energy use patterns. *Energy Economics*, 34(1):95–104.

Kaltenegger, O., Löschel, A., and Pothen, F. (2017). The Effect of Globalisation on Energy Footprints: Disentangling the Links of Global Value Chains. *Energy Economics*, 68:148–168.

Kander, A., Malanima, P., and Warde, P. (2013). *Power to the People*. Princeton University Press.

Lan, J., Malik, A., Lenzen, M., McBain, D., and Kanemoto, K. (2016). A structural decomposition analysis of global energy footprints. *Applied Energy*, 163:436–451.

Leontief, W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics*, 18(3):105–125.

Liu, H., Xi, Y., Guo, J., and Li, X. (2010). Energy embodied in the international trade of China: An energy input-output analysis. *Energy Policy*, 38(8):3957–3964.

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

Meyers, S. and Schipper, L. (1992). World energy use in the 1970s and 1980s: exploring the changes. *Annual Review of Energy and the Environment*, 17:463–505.

Miller, R. E. and Blair, P. D. (2009). *Input-output analysis : foundations and extensions*. Cambridge University Press.

Muradian, R., O'Connor, M., and Martinez-Alier, J. (2002). Embodied pollution in trade: estimating the 'environmental load displacement' of industrialised countries. *Ecological Economics*, 41(1):51–67.

NER (2012). Danish leadership in decoupling economic growth. *Nordic Energy Research*.

OECD (2016). The OECD input-output database: Sources and methods. Technical report.

OECD (2018). Data of OECD Countries. *Online Database [https://data.oecd.org]*.

Östblom, G. (1982). Energy use and structural changes. Factors behind the fall in Sweden's energy output ratio. *Energy Economics*, 4(1):21–28.

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

Proops, J. (1977). Input-output analysis and energy intensities: a comparison of some methodologies. *Applied Mathematical Modelling*, 1:181–186.

Proops, J. L. R., Faber, M., and Wagenhals, G. (1993). *Reducing CO_2 Emissions: A Comparative Input-Output Study for Germany and the UK*. Springer, Berlin.

Schurr, S. H. (1984). Energy use, Technological Change, and Productive Efficiency: An Economic-Historical Interpretation. *Annual Review of Energy*, 9(1):409–425.

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

Smil, V. (1992). Elusive links: energy, value, economic growth, and quality of life. *OPEC Rev.*, 1992:1.

Smil, V. (2000). Energy in the Twentieth Century: Resources, Conversions, Costs, Uses, and Consequences. *Global Environmental Change*, 25:21–51.

Smil, V. (2013). *Making the Modern World : Materials and Dematerialization*. Wiley, Chichester, UK.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23(3):575–605.

Tolmasquim, M. T. and Machado, G. (2003). Energy and Carbon Embodied in the International Trade of Brazil. *Mitigation and Adaptation Strategies for Global Change*, 8:139.

United Nations, . (1999). UN Handbook of input-output table compilation and analysis. Technical Report 74, United Nations.

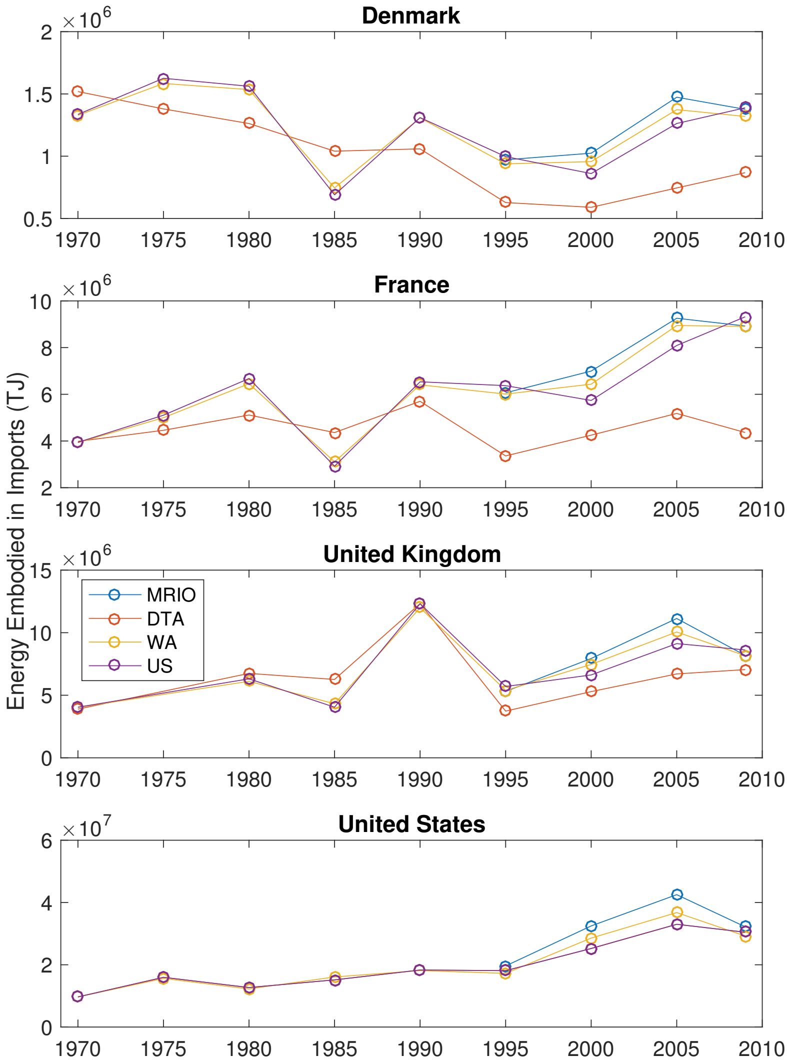
Wiedmann, T., Lenzen, M., Turner, K., and Barrett, J. (2007). Examining the global environmental impact of regional consumption activities - Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecological Economics*, 61(1):15–26.

Wright, D. J. (1974). Goods and services: an input-output analysis. *Energy Policy*, 2(4):307–315.

WTO (2013). Trends in International Trade. Technical report, World Trade Organization.

8 Appendix

Figure A.1: Energy Embodied in Imports (EEM) Based on Different Assumptions



Note: Energy embodied in imports calculated using: MRIO - actual energy intensities; DTA - energy intensities of importing country; World Average - world average energy intensities, US - United States energy intensities

Table A.1: OECD Database Sectoral Coverage

No	Name	Code
1	Agriculture, forestry & fishery	1
2	Mining and quarrying	2
3	Food, Beverages and Tobacco	31
4	Textiles, apparel & leather	32
5	Wood products & furniture	33
6	Paper, paper products & printing	34
7	Industrial chemicals	351+ 352+ 3522
8	Drugs & medicines	3522
9	Petroleum & coal products	353+ 354
10	Rubber & plastic products	355+ 356
11	Non-metallic mineral products	36
12	Iron & steel	371
13	Non-ferrous metals	372
14	Metal products	381
15	Non-electrical machinery	382- 3825
16	Office & computing machinery	3825
17	Electric apparatus, nec	383- 3832
18	Radio, TV & communication equipment	3832
19	Shipbuilding & repairing	3841
20	Other transport	3843+ 3844+ 3849
21	Motor vehicles	3843
22	Aircraft	3845
23	Professional goods	385
24	Other manufacturing	39
25	Electricity, gas & water	4
26	Construction	5
27	Wholesale & retail trade	61+ 62
28	Restaurants & hotels	63
29	Transport & storage	71
30	Communication	72
31	Finance & insurance	81+ 82
32	Real estate and business services	83
33	Community, social & personal services	9
34	Producers of government services	
35	Other producers	
36	Statistical discrepancy	

Notes: The International Standard Industrial Classification (ISIC) Rev.2 codes

Table A.2: World Input-Output Database Sectoral Coverage

No	Name	Code
1	Agriculture, Hunting, Forestry and Fishing	AtB
2	Mining and Quarrying	C
3	Food, Beverages and Tobacco	15t16
4	Textiles and Textile Products	17t18
5	Leather, Leather and Footwear	19
6	Wood and Products of Wood and Cork	20
7	Pulp, Paper, Paper , Printing and Publishing	21t22
8	Coke, Refined Petroleum and Nuclear Fuel	23
9	Chemicals and Chemical Products	24
10	Rubber and Plastics	25
11	Other Non-Metallic Mineral	26
12	Basic Metals and Fabricated Metal	27t28
13	Machinery, Nec	29
14	Electrical and Optical Equipment	30t33
15	Transport Equipment	34t35
16	Manufacturing, Nec; Recycling	36t37
17	Electricity, Gas and Water Supply	E
18	Construction	F
19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	50
20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	51
21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	52
22	Hotels and Restaurants	H
23	Inland Transport	60
24	Water Transport	61
25	Air Transport	62
26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	63
27	Post and Telecommunications	64
28	Financial Intermediation	J
29	Real Estate Activities	70
30	Renting of M&Eq and Other Business Activities	71t74
31	Public Admin and Defense; Compulsory Social Security	L
32	Education	M
33	Health and Social Work	N
34	Other Community, Social and Personal Services	O
35	Private Households with Employed Persons	P

Notes: The Statistical classification of economic activities in the European Community (NACE) codes.

Table A.3: IEA Energy Flows

No	Name	Code	No	Name	Code
1	Production	f1	44	Gas-to-liquids (GTL) plants	f44
2	Imports	f2	45	Own use in electricity, CHP and heat plants	f45
3	Exports	f3	46	Pumped storage plants	f46
4	International marine bunkers	f4	47	Nuclear industry	f47
5	International aviation bunkers	f5	48	Charcoal production plants	f48
6	Stock changes	f6	49	Non-specified (energy)	f49
7	Total primary energy supply	f7	50	Losses	f50
8	Transfers	f8	51	Total final consumption	f51
9	Statistical differences	f9	52	Industry	f52
10	Transformation processes	f10	53	Iron and steel	f53
11	Main activity producer electricity plants	f11	54	Chemical and petrochemical	f54
12	Autoproducer electricity plants	f12	55	Non-ferrous metals	f55
13	Main activity producer CHP plants	f13	56	Non-metallic minerals	f56
14	Autoproducer CHP plants	f14	57	Transport equipment	f57
15	Main activity producer heat plants	f15	58	Machinery	f58
16	Autoproducer heat plants	f16	59	Mining and quarrying	f59
17	Heat pumps	f17	60	Food and tobacco	f60
18	Electric boilers	f18	61	Paper, pulp and print	f61
19	Chemical heat for electricity production	f19	62	Wood and wood products	f62
20	Blast furnaces	f20	63	Construction	f63
21	Gas works	f21	64	Textile and leather	f64
22	Coke ovens	f22	65	Non-specified (industry)	f65
23	Patent fuel plants	f23	66	Transport	f66
24	BKB/peat briquette plants	f24	67	World aviation bunkers	f67
25	Oil refineries	f25	68	Domestic aviation	f68
26	Petrochemical plants	f26	69	Road	f69
27	Coal liquefaction plants	f27	70	Rail	f70
28	Gas-to-liquids (GTL) plants	f28	71	Pipeline transport	f71
29	For blended natural gas	f29	72	World marine bunkers	f72
30	Charcoal production plants	f30	73	Domestic navigation	f73
31	Non-specified (transformation)	f31	74	Non-specified (transport)	f74
32	Energy industry own use	f32	75	Other	f75
33	Coal mines	f33	76	Residential	f76
34	Oil and gas extraction	f34	77	Commercial and public services	f77
35	Blast furnaces	f35	78	Agriculture/forestry	f78
36	Gas works	f36	79	Fishing	f79
37	Gasification plants for biogases	f37	80	Non-specified (other)	f80
38	Coke ovens	f38	81	Non-energy use	f81
39	Patent fuel plants	f39	82	Non-energy use industry/transformation/energy	f82
40	BKB/peat briquette plants	f40	83	Memo: Non-energy use chemical/petrochemical	f83
41	Oil refineries	f41	84	Non-energy use in transport	f84
42	Coal liquefaction plants	f42	85	Non-energy use in other	f85
43	Liquefaction (LNG) / regasification plants	f43			

Table A.4: IEA energy products

No	Name	Code	No	Name	Code
1	Hard coal (if no detail)	p1	34	Other kerosene	p34
2	Brown coal (if no detail)	p2	35	Gas/diesel oil excl. biofuels	p35
3	Anthracite	p3	36	Fuel oil	p36
4	Coking coal	p4	37	Naphtha	p37
5	Other bituminous coal	p5	38	White spirit & SBP	p38
6	Sub-bituminous coal	p6	39	Lubricants	p39
7	Lignite	p7	40	Bitumen	p40
8	Patent fuel	p8	41	Paraffin waxes	p41
9	Coke oven coke	p9	42	Petroleum coke	p42
10	Gas coke	p10	43	Other oil products	p43
11	Coal tar	p11	44	Industrial waste	p44
12	BKB	p12	45	Municipal waste (renewable)	p45
13	Gas works gas	p13	46	Municipal waste (non-renewable)	p46
14	Coke oven gas	p14	47	Primary solid biofuels	p47
15	Blast furnace gas	p15	48	Biogases	p48
16	Other recovered gases	p16	49	Biogasoline	p49
17	Peat	p17	50	Biodiesels	p50
18	Peat products	p18	51	Other liquid biofuels	p51
19	Oil shale and oil sands	p19	52	Non-specified primary biofuels and waste	p52
20	Natural gas	p20	53	Charcoal	p53
21	Crude/NGL/feedstocks (if no detail)	p21	54	Elec/heat output from non-specified mnf gases	p54
22	Crude oil	p22	55	Heat output from non-specified combustible fuels	p55
23	Natural gas liquids	p23	56	Nuclear	p56
24	Refinery feedstocks	p24	57	Hydro	p57
25	Additives/blending components	p25	58	Geothermal	p58
26	Other hydrocarbons	p26	59	Solar photovoltaics	p59
27	Refinery gas	p27	60	Solar thermal	p60
28	Ethane	p28	61	Tide, wave and ocean	p61
29	Liquefied petroleum gases (LPG)	p29	62	Wind	p62
30	Motor gasoline excl. biofuels	p30	63	Other sources	p63
31	Aviation gasoline	p31	64	Electricity	p64
32	Gasoline type jet fuel	p32	65	Heat	p65
33	Kerosene type jet fuel excl. biofuels	p33			

Table A.5: Data Sources and Coverage

	Input Output Tables								
	c.1970	c.1975	c.1980	c.1985	1990	1995	2000	2005	2009
	OECD SRIO					*WIOD MRIO*			
UK	1968	n/a	1979	1984	1990	1995	2000	2005	2009
USA	1972	1977	1982	1985	1990	1995	2000	2005	2009
France	1972	1977	1982	1985	1990	1995	2000	2005	2009
Denmark	1972	1977	1982	1985	1990	1995	2000	2005	2009
	Energy Flows								
	c.1970	c.1975	c.1980	c.1985	1990	1995	2000	2005	2009
	International Energy Agency (IEA)					*WIOD Energy accounts*			
UK	1968	n/a	1979	1984	1990	1995	2000	2005	2009
USA	1972	1977	1982	1985	1990	1995	2000	2005	2009
France	1972	1977	1982	1985	1990	1995	2000	2005	2009
Denmark	1972	1977	1982	1985	1990	1995	2000	2005	2009

Notes: SRIO - Single Region Input Output; MRIO - Multi Region Input Output; WIOD - World Input Output Database. OECD – Organisation for Economic Co-operation and Development. n/a – not available, when providing the results for the UK c.1975 is taken as an average of (c.1970+c.1980)/2.

Table A.6: Concordance Between IEA Energy Flows (Row) and OECD Sectors (Column)

Sector No (full sector name is given in table A.1)

Energy flow (energy flow name is given in table A.3)

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	H
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f13																									1												
f14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1
f15																									1												
f16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1	1	1	1	1	1	1	1	1
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f85																																				1	

Paper 2

Explaining Decoupling in High-Income Countries: A Structural Decomposition Analysis of the Change in Energy Footprint from 1970 to 2009

Viktoras Kulionis and Richard Wood

Abstract

The absolute decoupling of energy use from economic growth is an interesting phenomenon observed in highly developed countries in recent decades. However, little is known about what has driven this decoupling, especially considering the possibility that it is at least partially due to increased trade. This study uses structural decomposition analysis to examine the main factors that contribute to changes of energy footprint in Denmark, the United Kingdom, France and the United States of America back to 1970. The results show that the changes in energy footprint have been driven mainly by two countervailing forces: declines in energy intensity and increases in consumption per capita. Trade sourcing effect was negligible in the beginning of the study period but has grown in importance since 1995 and accelerated the growth of energy footprint by roughly 0.5% per year. Whilst the electricity sector has clearly played the dominant role, the contribution of factor changes in services and manufacturing should not be overlooked.

JEL Classification

C67, N74, O13, P18, P28, Q43, Q56

Keywords

Structural Decomposition Analysis, International Trade, Energy Footprint, Input-Output Analysis

1 Introduction

The rate of growth of global primary energy use has been remarkably stable since 1850 (2.4%/year ± 0.08%) (Sorrell, 2015). However, since primary energy use (E) has grown more slowly than gross domestic product (GDP) (Y), there has been a steady decline in global energy intensity (E/Y). Declining energy intensity is a sign of decoupling, which comes in two forms: relative and absolute.

Relative decoupling occurs when energy use increases at a slower rate than output. It has been evident in England since the late nineteenth century (Warde, 2007), in the USA (Schurr and Netschert, 1960) and at an aggregate European level and globally since around 1970 (Kander et al., 2013; Smil, 2016) .

Absolute decoupling, on the other hand, refers to a situation in which energy use declines in absolute terms whilst output continues to grow. It is a much more recent phenomenon observed only in a few countries since about 1970. For example, in the UK and the USA, GDP per capita has increased at about 2% per year since this time, and over the same period energy use has declined at about 0.5% per year (see Figure 1).

There are a number of factors that affect the relationship between economic growth and energy use. On the demand side, changes in lifestyle and household incomes trigger shifts in consumption patterns. According to Engel's Law, as income rises, demand diversifies away from necessities (e.g. food) towards other goods and services. Shifts in consumption patterns and shifts in the composition of the economy are inter-dependent. On the supply side, firms of various industries aim to accommodate changes in final demand. Driven by competition and profit, firms innovate, enabling continuous increases in productivity and declining prices. This in turn stimulates further demand and allows firms/industries to grow in both relative (structural change) and absolute terms.

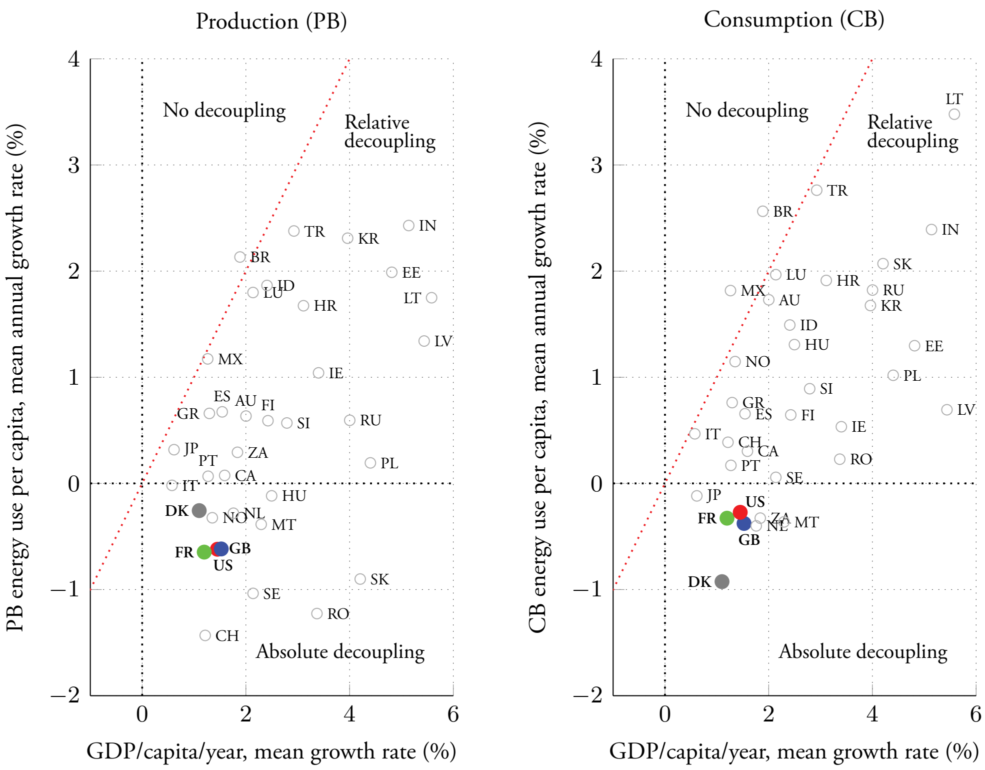
To date most of the energy-growth literature has focused on investigating energy use from the production-based (PB) perspective. PB takes into account energy used within the borders of the country including energy used for the production of goods and services that are exported to other countries. However, this approach does not take into account energy use associated with imported goods. An alternative consumption based (CB) approach, also known as a footprint, represents energy use associated with the consumption of goods and services and takes into account energy use needed to produce imported goods and services. The difference between the two accounting approaches centres on how they account for trade. Both methods have their own strengths and weaknesses, and which one is better depends on the question at hand (see Afionis et al., 2017, for detailed comparison of PB vs. CB).

International trade grew by an average of 7.2% per year between 1970 and 2008. Many studies have quantified the content of various environmental indicators embodied in trade. Recent results demonstrate that in 2011, 29% of the global energy use, 26% of global land use, 32% of materials, 26% of global water use and over 24% of global greenhouse gas (GHG) emissions are embodied in trade (Wood et al., 2018). Most indicators display relative decoupling at global scale with land use being the only indicator showing small absolute decoupling from both PB and CB perspectives (Wood et al., 2018).

Decoupling – and in particular absolute decoupling – is a highly desirable sustainability goal as it implies removal of the link between energy use and GDP. Since energy use accounts for two-thirds of GHG emissions IEA (2015) it also implies that economic growth can be achieved without an increase in emissions. Understanding the drivers behind national and sectoral dynamics of energy footprint and the interplay of structural changes and sectoral efficiency improvements has important policy implications. Knowing how these drivers have changed over time can help us understand how they are likely to evolve in the future. Linking the results with future projections on energy use (Schandl et al., 2016) can shed light on potential areas where the reduction of energy use can be achieved with minimal impacts on improvements in living standards.

Although absolute decoupling of energy use from economic growth is not visible on a global scale, there are individual countries that do show this trend (on per capita basis). The factors influencing the changing relationship between energy use and the economy are important for understanding the role energy plays in the economy, how that role has changed, and how it is likely to evolve in the future. Tracing how the connection between changes in energy use and changes in the economy has evolved requires identifying specific factors of change. In this study we examine the main factors that contribute to absolute decoupling of energy footprint and economic growth in four highly developed countries (Denmark, United Kingdom, France and the United States of America). We look at the changes in energy footprints due to changes in industrial energy efficiency, production technology, mix and level of final demand, population, and international trade. By analysing these factors, we can understand the main driving forces behind the energy decoupling seen in developed countries. We look at how these factors change over time and assess whether the main reasons for decoupling have been energy efficiency measures, changes in the structure of the economy (e.g. a move towards a service based economy), or offshoring of production activities. Whilst other cross-country energy SDA studies have been performed, this study is unique in its coverage of time: from the impact of the oil crisis in the 1970s, to the rapid growth in global trade in the 2000s. Furthermore, for the first time, we look specifically at the contribution of the substitution effect of trade – capturing the impact of different energy productivities in different regions of the world.

Figure 1: PB and CB Energy Use Per Capita vs GDP Per Capita, 1995-2011 (Average Yearly Change)



Notes: Data from Wood et al. (2018). Filled circles represent the countries considered in this study. Dotted red line separates decoupling and non-decoupling areas.

2 Background

A number of studies have attempted to explain the link between energy and GDP at the sectoral, national or international level. The latest survey lists a total of 101 journal papers on economy-wide SDA applied to energy and emissions between 2000 and 2015 (Wang et al., 2017). Initially a decomposition methodology was applied to study changes in industrial energy demand (Proops, 1984; OTA, 1990; Rose and Chen, 1991); later with the growing awareness of climate change, this was extended to greenhouse gas emissions and environmental analysis in general (Lenzen, 2016)

The increased interest in energy studies started with the first oil crisis in 1973/74 and the subsequent energy price rise. Researchers were interested in quantifying the impact on industrial energy use resulting from changes in the structure of an economy. Although detailed comparison of the empirical outcomes is difficult because the countries, periods, environmental issues and decomposition methods vary considerably between studies, it is possible to draw some general conclusions.

For most developed economies, the final demand level is the most important long-term determinant of increased energy use (Lenzen, 2016). Changes in technology through energy intensity (energy per unit of production) has generally been found to be the most important force for decline in aggregate energy use, especially during the years immediately after the oil crises of 1973 and 1979 (Ang and Zhang, 2000). Changes in the production structure as measured through input-output coefficients (A and L matrices, this effect is also treated as technological change) and the final demand mix effect (i.e. structural change) has been found to have a modest effect on reductions in energy use.

Evidence from recent energy footprint studies reinforce these findings and shows that affluence and population growth are driving energy footprints worldwide whilst energy intensity partially counteracts these effects (Lan et al., 2016; Kaltenegger et al., 2017). For the UK, Hardt et al. (2018) provide a decomposition that in addition to the above results captures a strong offshoring effect for the UK. Rather than using a structural decomposition approach to the analysis, they calculate an index showing the percentage of foreign output to global output required for UK demand. Here we extend this analysis by applying structural decomposition methods to look specifically at substitution both in the supply-chain (intermediate production), and by final consumers.

The vast majority of studies maintain that energy use grew at a slower pace since 1970s despite the significant increase in GDP. Many energy sector analysts attribute this decoupling to be a phenomenon of the 1970s; they claim that before 1973, energy and economic growth were coupled, and after 1973 they were decoupled (Mackillop, 1989). However, so-called relative decoupling has been evident in some countries since the beginning of the 19th century. For instance, for much of the half century between 1920 and 1970, US energy intensity was declining – at times at an even more rapid rate than during the period of high-energy prices ushered in by the 1973 oil embargo (Schurr, 1985). Energy economic history for the OECD countries appears different in the post-1973 period in the sense that there is a break in the long-term trend between energy and GDP. After 1973, energy consumption increased less than GDP in some countries and in others it remained stagnant or declined in absolute terms.

Decline of energy use in absolute terms signifies absolute decoupling, which is a highly desirable goal as it implies economic growth without an increasing use of energy resources. However, absolute decoupling is not a global phenomenon – so far it is has been evident only in a limited number of countries for instance the UK and USA. It is not clear yet whether there is a specific mechanism common among countries that have achieved absolute decoupling.

Several reasons have been advanced to explain this phenomenon, including: development of more energy efficient technology, and structural shifts in the economy away from more energy-intensive heavy industry (Rose and Chen, 1991).

Energy efficiency can also be improved by switching to more efficient fuels – often known as "climbing up the energy ladder". Cross-country comparisons reveal a positive correlation between economic growth and modern fuel uptake, suggesting that as a country progresses through the industrialisation process, its reliance on fuels such as natural gas increases and the importance of the less efficient and more polluting fuels such as coal decreases (Van Der Kroon et al., 2013).

Countries may improve their decoupling performance simply by importing production from other countries, making their energy consumption relatively low. One way to examine this proposition is to look at energy embodied in the consumption of goods and services (which includes energy related to production of imports, but excludes energy related to production of exports) rather than at the production activities in a country (which includes energy related to production of exports but excludes energy related to production of imports). Methodologically this means taking imports into account but excluding exports (Akizu-Gardoki et al., 2018).

3 Model and Data

3.1 Input-output Analysis

This study uses input-output analysis (IO) developed by Leontief (Leontief, 1936, 1970). Within the input-output framework, two methods are commonly used to calculate energy embodied in international trade (Miller and Blair, 2009). The single region input-output (SRIO) model and the multi-region input-output (MRIO) model. The standard Leontief IO model can be expressed as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{LY} \tag{1}$$

where $\mathbf{x}$ is the vector of output, $\mathbf{A}$ is the matrix of technical coefficients, $\mathbf{Y}$ is the vector of final demands and $(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{L}$ is the total requirement matrix representing interdependencies between industries.

For the period 1970–1990 we extended the SRIO model in Equation 1 to incorporate energy use as:

$$\mathbf{e} = \begin{bmatrix} \mathbf{q}^d & \mathbf{q}^{avrg} \end{bmatrix} \left[\mathbf{I} - \begin{bmatrix} \mathbf{A}^d & 0 \\ \mathbf{A}^m & \mathbf{A}^d + \mathbf{A}^m \end{bmatrix} \right]^{-1} \begin{bmatrix} \mathbf{y}^d \\ \mathbf{y}^m \end{bmatrix} \tag{2}$$

where **e** is the total energy requirements (i.e. CB) and **q** is the direct energy intensity vector representing energy use per unit of output for a given country, $\mathbf{A}^d$ and $\mathbf{A}^m$ are domestic and foreign technical coefficient matrices, $\mathbf{y}^d$ is domestic final demand and $\mathbf{y}^m$ is imports. The SRIO model assumes that imports are produced with the technology of the importing country (domestic technology assumption) and that the energy intensities are the same. To relax this assumption, we use a four country average energy intensity $\mathbf{q}^{avrq}$ to estimate energy embodied in imports. A similar approach has been used by Andrew et al. (2009) and Serrano and Dietzenbacher (2010).

For the period 1995–2009 we use the MRIO model and the energy footprint is computed as:

$$\mathbf{x} = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{qLY} \tag{3}$$

where **q**, **A**, **L**, and **Y** have the same meanings as above but represent a multi-regional input-output system; e.g. element a_{ij}^{rs} show how much (in value) input from sector i in country r is necessary to produce one unit of output in sector j in country s.

3.2 Structural Decomposition Analysis (SDA)

The central idea of Structural decomposition analysis (SDA) is that changes in energy use **E** within a certain period can be decomposed into various driving forces of change: energy intensity, level and structure of final demand, population, etc. (Hoekstra and Van Den Bergh, 2002). The general decomposition equation used here is given as:

$$\mathbf{e} = \mathbf{qLu}\hat{\mathbf{d}}\hat{\mathbf{p}} \tag{4}$$

Where final demand **Y** as described above is broken down into **u** the mix of final demand, **d** the level per capita of final demand, and **p** denotes population. In order to see the effects of trade on the changes of total energy footprint, we further decompose **A** into production structure (**H**) and trade structure effects (**T**) ($\mathbf{T} \otimes \mathbf{H}$ represents the Hadamard product or element by element multiplications) and factor **u** into equivalent product mix (**G**) and trade sourcing (**B**) effects as:

$$\mathbf{e} = \mathbf{q}(\mathbf{I} - \mathbf{T} \otimes \mathbf{H})^{-1}(\mathbf{B} \otimes \mathbf{G})\hat{\mathbf{d}}\hat{\mathbf{p}} \tag{5}$$

For a full appraisal of the approach, the reader is referred to Appendix. Given the total energy footprint at time 0 as $\mathbf{e}^0$ and at time 1 as $\mathbf{e}^1$, then the change in energy use $\triangle\mathbf{e} = \mathbf{e}^1 - \mathbf{e}^0$ can be decomposed into an exhaustive sum of the following factors:

$$\triangle\mathbf{e} = \triangle\mathbf{q} + \triangle\mathbf{T} + \triangle\mathbf{H} + \triangle\mathbf{B} + \triangle\mathbf{G} + \triangle\mathbf{d} + \triangle\mathbf{p} \tag{6}$$

where:

$\triangle\mathbf{q}$: the energy intensity (efficiency) effect, measures how falling or rising sectoral energy intensity affects consumption based energy use.

$\triangle\mathbf{T}$: the trade structure of intermediate inputs effect, measures how change in intermediate input shares affect energy use. It has positive effect if intermediate input structure shifts towards more energy-intensive countries.

$\triangle\mathbf{H}$: the overall production technology effect, measures changes in the technology of the economy irrespective of the source country.

$\triangle\mathbf{B}$: the final demand trade structure effect, measures the change in energy use due to changes in the composition of imports for final demand.

$\triangle\mathbf{G}$: the final demand mix effect, measures the change in energy use due to changes in the composition of final demand.

$\triangle\mathbf{d}$: the final demand level per capita effect, measures the change in energy use due to increasing or decreasing levels of final demand per capita (affluence).

$\triangle\mathbf{p}$: the population effect, measures the change in energy use due to changes in population.

As shown by Dietzenbacher and Los (1998), there is no unique way to decompose a change in one variable into the changes in its determinants. In the case of k components (here k=7) the number of equivalent decompositions amounts to $k!$. We use an average of the two so-called polar decomposition forms proposed by Dietzenbacher and Los (1998) to solve the non-uniqueness problem (see Appendix for more details).

3.3 Data

The World Input-Output Database (WIOD) is the main source of input-output and energy data for the period 1995–2009. The WIOD consist of series of multi-region input-output tables (MRIOT) and environmental/energy sub-databases, covering 35 industries and 41 countries/regions, including 27 EU and 13 other major advanced and emerging economies, plus a region called 'Rest of the World' (Timmer et al., 2015).

For the earlier period from c.1970 to 1990, the data were extracted from two sources: IO tables in 1980 (1982 for the USA) constant prices covering several benchmark years (see Appendix in Paper 1 for coverage detail) from the OECD IO database OECD (2016) and energy balances from IEA (2017). The OECD SRIO tables distinguish between 36 industrial sectors. The data are available for a limited number of years and specific countries. Given data availability, this study focuses on four countries Denmark, France, the United States (USA) and the United Kingdom (UK). These four countries are similar in terms of their income per capita but differ in terms of total GDP (the USA is the largest), engagement in trade (Denmark is the most engaged and the USA the least) and energy systems.

The WIOD database offers 'ready to use' harmonised MRIO tables and energy accounts with the same sectoral classification. The OECD IO tables and the IEA energy balances, however use different industrial classifications. Typically, the IEA sectors are more aggregated than the OECD IO sectors. The connection[1] of the physical IEA energy balances with the monetary OECD IO tables follows the 'minimum information method' as in the WIOD 2013 release (Genty et al., 2012). Two types of energy accounts are available in the WIOD database: emissions relevant energy use and gross energy use. For this analysis we utilise emissions relevant energy use.

4 Results

The results are presented in two parts: (i) for the period 1970–90 (SRIO model), and (ii) for the period 1995–2009 (MRIO model).

4.1 Period I c.1970–1990

Decomposition results for the period c.1970-1990 are presented in Table 1 and visualised in Figure 2. The results are presented as annualised percentage rates of change from the base year figure and total for the entire period. Average country results show that changes in energy efficiency of industrial production ($\triangle \mathbf{q}$) and changes in production structure ($\triangle \mathbf{H}$) have a negative impact on energy footprint. The effect of industrial structure ($\triangle \mathbf{H}$) was negative for all countries except the UK. Changes in the final demand structure ($\triangle \mathbf{G}$) resulted in a decline in energy footprint in most

[1]The procedure to allocate IEA energy sources among OECD sectors is explained in Paper 1 and Paper 3 of this thesis.

Table 1: Structural Decomposition Analysis Results by Country and Factor, c1970–1990 (in %)

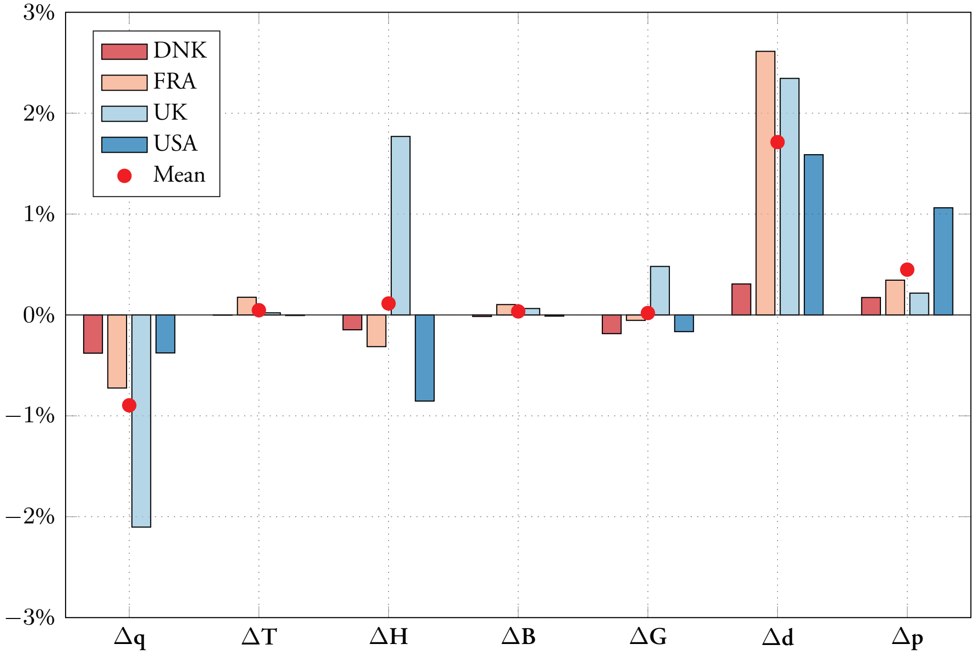
	q	T	H	B	G	d	p	E
DNK 72-77	0.5	0.1	-0.8	0.1	-0.1	1.1	0.4	1.3
DNK 77-80	-0.7	0.0	0.5	0.0	-0.9	-0.8	0.2	-1.7
DNK 80-85	-3.1	0.0	-0.6	0.0	0.2	1.4	0.0	-2.3
DNK 85-90	1.6	-0.1	0.3	-0.1	0.0	-0.4	0.1	1.4
DNK 72-90	-0.4	0.0	-0.2	0.0	-0.1	0.4	0.2	-0.2
DNK 72-90	**-7.4**	**0.0**	**-4.0**	**-0.2**	**-2.2**	**7.8**	**3.0**	**-3.0**
FRA 72-77	-1.7	0.0	-0.2	0.1	0.3	2.4	0.6	1.5
FRA 77-80	0.2	0.8	-0.8	0.2	-0.4	2.7	0.5	3.2
FRA 80-85	-4.4	0.0	-0.6	0.0	-0.1	2.3	0.6	-2.2
FRA 85-90	2.6	0.0	0.3	0.1	-0.1	3.7	-0.1	6.4
FRA 72-90	-1.0	0.1	-0.3	0.1	0.0	2.8	0.4	2.1
FRA 72-90	**-17.3**	**2.2**	**-5.2**	**1.8**	**-0.5**	**50.5**	**6.4**	**37.9**
UK 68-79	-3.2	0.1	0.9	0.1	0.3	2.9	0.2	1.2
UK 79-84	-1.2	-0.1	-1.0	0.1	-2.0	0.2	0.1	-3.9
UK 84-90	-1.9	0.1	5.0	0.0	2.7	3.7	0.4	10.0
UK 68-90	-2.4	0.0	1.6	0.1	0.4	2.5	0.2	2.4
UK 68-90	**-52.8**	**0.6**	**34.5**	**1.7**	**9.8**	**55.1**	**4.6**	**53.6**
USA 72-77	-0.2	0.0	0.0	0.0	-0.1	1.1	1.0	1.8
USA 77-82	-2.0	0.0	-0.1	0.0	-0.5	-0.1	0.7	-2.0
USA 82-85	0.0	0.0	-1.2	0.0	-0.2	2.6	1.6	2.6
USA 85-90	0.6	0.0	-2.3	0.0	0.1	3.0	1.1	2.5
USA 72-90	-0.5	0.0	-0.9	0.0	-0.2	1.5	1.0	1.1
USA 72-90	**-8.1**	**-0.1**	**-15.3**	**-0.2**	**-3.0**	**27.5**	**18.7**	**19.5**

Notes: Text in **bold** provides cummulitave change in energy footrpint for the entire period, all other results are presented as annual percentage change. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect, **E** – total change.

years (with few exceptions) but played a relatively minor role. Improvement in energy efficiency was the strongest negative factor, accounting for -7.4% to -52.8% decrease in energy footprint. If all other components had remained constant (i.e., $\triangle\mathbf{T} = 0$, $\triangle\mathbf{H} = 0$, $\triangle\mathbf{B} = 0$, $\triangle\mathbf{G} = 0$, $\triangle\mathbf{d}$, $\triangle\mathbf{p}$), this decrease would represent how the energy footprint would have changed over time due to improvement in energy efficiency ($\triangle\mathbf{q}$).

In contrast, changes in consumption per capita ($\triangle\mathbf{d}$) and population ($\triangle\mathbf{p}$) had positive effects on energy footprint. The final demand level per capita was the strongest component in this group accounting for between 7.8% and 55% of the total change in energy footprint. This reflects an increasing level of spending (people demanding more things), which, everything else being equal, leads to an increase in energy requirements. The population effect was the strongest in the US

Figure 2: SDA by Country and Factor, c.1970–1990 (Average for the Period)



Notes: **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** the production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population change effect.

(+18.7%).

To a large extent the effect of spending is offset by improvements in energy efficiency and to some extent by the production recipe. Broadly this can be treated as technological change (the **H** effect is interpretable as a technological effect of changes in the intermediate input structure, and the intensity effect **q** assesses the effect of change in the sector level use of the indicator per unit output). These two effects show that the methods and processes used to produce a set level and mix of output had changed so they required less energy. The trade structure effect – i.e. the sum of trade in intermediated products **T** and final **B** – had a positive forcing effect on energy use in France (4%) and the UK (10.4%) and low negative effect in Denmark (-0.2%) and the USA (-0.3%).

Table 2: Structural Decomposition Analysis Results by Country and Factor, 1995–2009 (in %)

	q	T	H	B	G	d	p	E
DNK 95-00	-2.3	-0.2	-0.4	0.2	-0.2	1.6	0.4	-0.8
DNK 00-05	-1.5	0.6	1.0	0.5	-0.3	1.5	0.3	2.1
DNK 05-09	-0.7	0.0	-0.9	0.3	-1.3	-0.7	0.5	-2.8
DNK 95-09	-1.5	0.1	-0.1	0.3	-0.6	0.8	0.4	-0.5
DNK 95-09	**-21.4**	**2.1**	**-0.8**	**4.8**	**-7.5**	**12.9**	**5.6**	**-4.3**
FRA 95-00	3.9	-0.1	-1.9	0.2	-3.0	2.6	0.5	2.2
FRA 00-05	-2.3	0.3	1.3	0.3	0.3	1.2	0.8	2.0
FRA 05-09	-2.3	-0.1	-0.2	-0.1	0.4	0.4	0.7	-1.2
FRA 95-09	-0.2	0.0	-0.2	0.2	-0.8	1.4	0.7	1.0
FRA 95-09	**-1.1**	**0.4**	**-3.3**	**2.3**	**-11.9**	**20.6**	**9.4**	**16.5**
UK 95-00	-2.1	0.4	0.7	0.3	-0.3	3.8	0.3	3.1
UK 00-05	-1.7	0.7	-0.2	0.8	-0.3	2.8	0.6	2.8
UK 05-09	-1.2	0.2	-1.4	0.2	-0.7	-1.3	0.9	-3.2
UK 95-09	-1.7	0.4	-0.3	0.4	-0.5	1.8	0.6	0.9
UK 95-09	**-23.7**	**6.3**	**-3.1**	**6.5**	**-6.1**	**28.2**	**8.5**	**16.6**
USA 95-00	-2.6	0.2	0.9	0.1	-0.3	3.6	1.2	3.1
USA 00-05	0.5	0.3	-2.1	0.3	-0.7	2.3	1.1	1.6
USA 05-09	-0.6	0.2	-1.7	0.1	-0.3	-0.9	1.1	-2.0
USA 95-09	-0.9	0.2	-1.0	0.2	-0.5	1.7	1.2	0.9
USA 95-09	**-13.3**	**3.2**	**-12.6**	**2.4**	**-6.7**	**25.9**	**16.2**	**15.2**

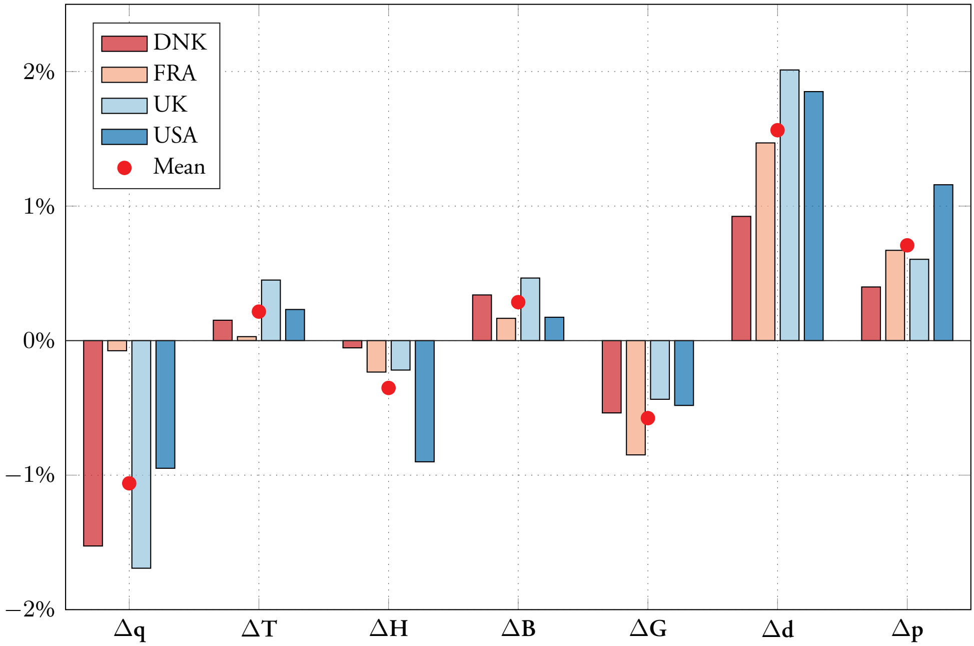
Notes: Text in **bold** provides cummulitave change in energy footrpint for the entire period, all other results are presented as annual percentage change. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** – production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population effect, **E** – total change.

4.2 Period II 1995–2009

Decomposition results for the period from 1995 to 2009 and its sub-periods are presented in Table 2, and Figure 3 shows the contribution of **q**, **T**, **H**, **B**, **G**, **d**, and **p** over the period for each country.

From the sub-period decomposition, we can see that the contribution of different factors varies from year to year in terms of size and sign. Change in energy intensity ($\triangle\mathbf{q}$) had mainly negative effects on energy footprint in all countries. For Denmark this effect was -21.4%, France -1.1%, the UK -23.7%, and the USA -13.3% over the entire period. Changes in the production structure (**H**) had negative but considerably smaller impacts in most countries except the USA (-12.6%). Most of the negative effect is outweighed by the changes in the final demand per capita and population. For Denmark final demand effect accounted for 12.9% for France 20.6% for the UK 28.2% and for the USA 25.9% increase in energy footprint. This counterbalancing between energy intensity and the level of final demand resembles what has been observed in the earlier period.

Figure 3: SDA by Country and Factor, 1995–2009 (Average for the Period)



Notes: **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** the production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population change effect.

The changes in the trade structure of intermediate **T** and final products **B** had mainly positive albeit very low effects. The positive effect implies that imported intermediate and final goods had shifted to countries where the production of the same goods and services required more energy. This effect would be equal to zero if imports of intermediate and final goods were produced with identical technologies in all countries.

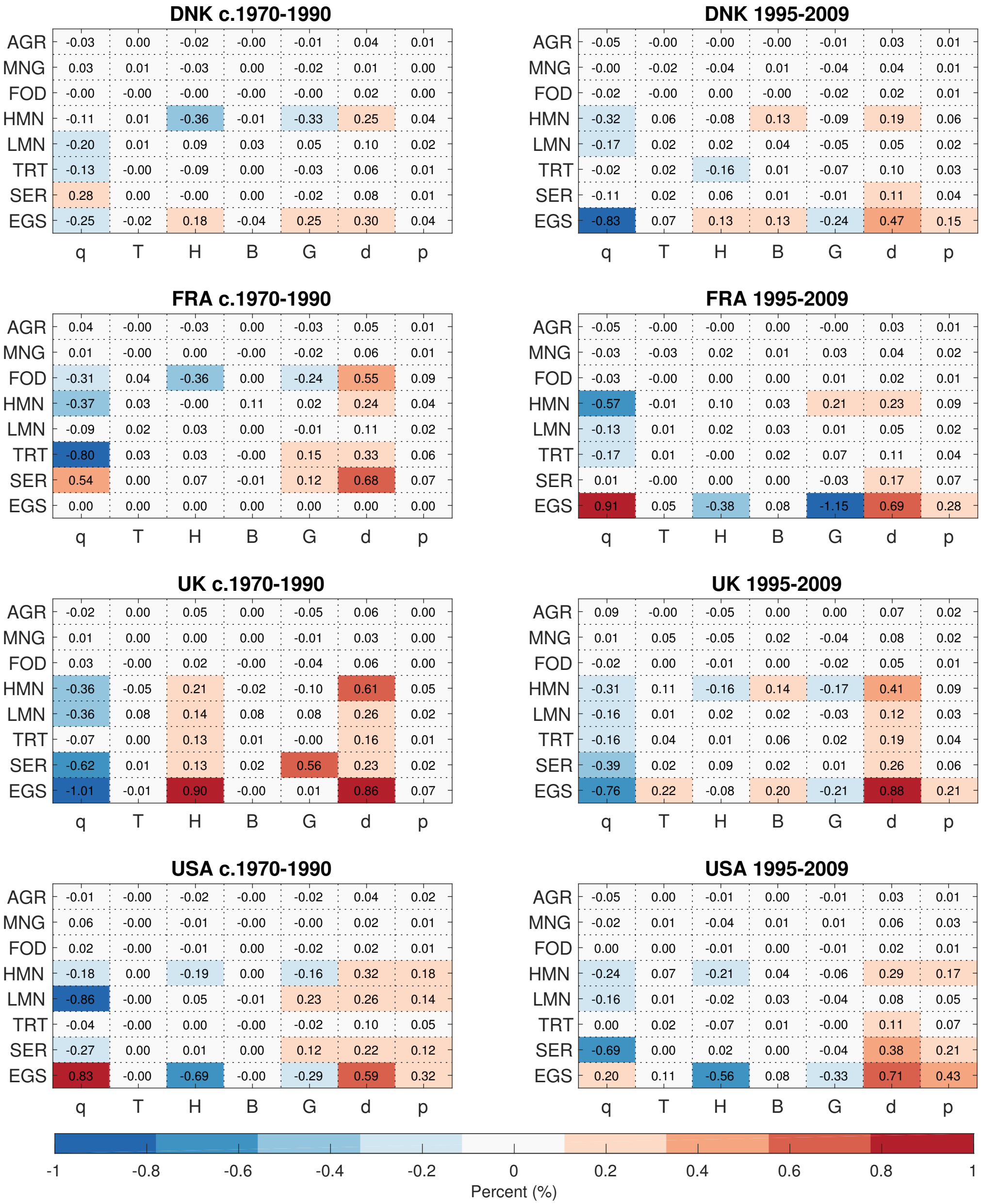
4.3 Products Groups

To make the results more informative, we aggregated the sectoral decomposition results into eight broad categories following similar aggregation classification as in Andrew and Peters (2013) (see Appendix for details). This exercise allows to see which sectors contribute the most to the increase and decrease of energy footprint.

Yearly average sectoral decomposition results for each factor, all countries and both time periods are presented in Figure 4. The results show that the effects are not uniform across sectors. For instance, the energy intensity effect in Denmark c1970–1990 is positive in energy-intensive manufacturing (*HMN*) and services (*SER*) but negative in all other sectors. This implies that energy demands to produce one unit of output in *HMN* and *SER* have increased over time.

Most of the changes in energy footprint are concentrated in energy-intensive manufacturing *(HMN),* non-energy-intensive manufacturing *(LMN),* services *(SER),* transport *(TRT),* and electricity and gas supply *(EGS*). Agriculture *(AGR),* mining *(MNG)* and food *(FOD)* are less important contributors to the changes in energy footprint. It is important to note that the low effect in some industries might occur simply due to the lack of change over time which does not necessarily imply a lack of energy use. For example, as shown in Voigt et al. (2014), mining (MNG) accounted on average for 2.3% of global energy use (6th highest share out of 35 sectors) during 1995–2007, but its average energy intensity has changed very little over the same time span.

Figure 4: SDA by Sector and Factor for the Periods c.1970–1990 and 1995–2009 (yearly change in %)



Notes: AGR – Agriculture; MNG – Mining; FOD – Food; HMN – Energy-intensive manufacturing, LMN – Non-energy-intensive manufacturing; TRT – Transport services; SER – Services; EGS – Electricity and gas supply. **q** – energy intensity effect, **T** – intermediate demand trade structure effect, **H** the production technology effect, **B** – final demand trade structure effect, **G** – consumption mix effect, **d** – affluence effect, **p** – population change effect.

5 Discussion and Conclusions

Economic growth was associated with an increasing use of energy in the developed economies until about the 1970s. Since then the level of energy has remained virtually unchanged or increased at a very low rate in industrialised countries. The main aim of this study is to examine how the energy footprint has changed since the 1970s and which factors where driving the change.

We have looked at the total energy requirements of final demand of a country (a so-called 'energy footprint' approach) in order to capture potential effects of production displacement to foreign regions. We decomposed and compared the energy footprint for Denmark, France, the UK and the USA during the period from c.1970 to 2009. Our analysis shows that the countries bear many similarities, but only Denmark displayed an absolute decline in energy footprint. In the other countries, energy footprint has increased by roughly 2% per year during the earlier sub period (c.1970–1990) and 1% during the second sub period (1995–2009).

On the supply side, we looked at three factors energy intensity, technological change and trade in intermediate goods. Energy intensity, which is a measure of the energy required to produce one unit of output, has been the main driving force for the decline in energy footprint. During both sub-periods it had a decreasing effect on overall energy footprints. Certain industries can be pointed to for achieving the largest gains. Whilst the efficiency improvements in the electricity sector have in general been the largest, perhaps more surprising is the significant role service industries have had in lowering aggregate energy use by efficiency improvements. The contributions of efficiencies in the service industry to lowering energy demand is similar to that of the manufacturing industry (Figure 4), and have often not been offset by increased demand to the same extent.

Across the economy, however, the net decrease attributable to the improvements of energy use on the supply side was offset by growth in the overall level of demand. As the household and other final demand categories demand more goods and services, this triggers an increase in energy use. During the earlier period these factors increased overall energy footprints by roughly 2%, and from 1995 to 2009 they increased footprints by roughly 1.5% per year. This effect was accentuated further by changes in population. Increased aggregate demand has the largest impact on electricity and manufactured goods (Figure 4).

The final demand structure effect (**G**) represents changes in lifestyle and consumption patterns. This effect was stronger during the second sub-period (1995–2009) and accounted for roughly -0.5% a year on average across countries. Hence, whilst overall demand has grown, the lower elasticities of basic goods like electricity mean that a lower percentage of demand goes to these sectors. As such, the evidence confirms that countries are in general shifting their final demand towards goods and services that are less energy-intensive on average.

Changes in the trade of intermediate (**T**) and final products (**B**) accelerated the growth of the global energy footprint by roughly 0.5% per year. Such results imply that there has been a small substitution of more energy efficient domestic production by, foreign production of lower efficiency. Despite several minor yearly differences, the general pattern of what is driving energy footprint up and what works in the opposite direction seems to be similar across countries.

Energy efficiency improvements have been a dominant source of energy savings for a long time, and this is likely to continue into the future. In the past, it was electricity that freed factory design from restrictions associated with steam and water power. Information technologies have played an important role since the 1970s by allowing more precise and controlled production processes. One could speculate that the adoption and diffusion of artificial intelligence will play a similarly important role going forward – for instance, by allowing producers to manage energy output generated from multiple sources to match social, spatial and temporal variations in demand in real-time (Wolfe, 2017). However, with the central role that the current energy system has in producing greenhouse gas emissions, it is clearly one of the main focuses for policies to achieve deep decarbonisation. Our results imply that either these supply side efficiencies must be radically increased, or much more needs to be done on the demand side to break the strong, consistent pull that increasing affluence has. With the majority of the global population looking to emulate the lifestyle choices that these developed countries have, the link between affluence and energy demand is likely to become more important, not less.

6 References

Afionis, S., Sakai, M., Scott, K., Barrett, J., and Gouldson, A. (2017). Consumption-based carbon accounting: does it have a future? *Wiley Interdisciplinary Reviews: Climate Change*, 8(1):1—-19.

Akizu-Gardoki, O., Bueno, G., Wiedmann, T., Lopez-Guede, J. M., Arto, I., Hernandez, P., and Moran, D. (2018). Decoupling between human development and energy consumption within footprint accounts. *Journal of Cleaner Production*, 202:1145–1157.

Andrew, R., Peters, G. P., and Lennox, J. (2009). Approximation and Regional Aggregation in Multi-Regional Input–Output Analysis for National Carbon Footprint Accounting. *Economic Systems Research*, 21(3):311–335.

Andrew, R. M. and Peters, G. P. (2013). A Multi-Region Input-Output Table Based on the Global Trade Analysis Project Database (GTAP-MRIO). *Economic Systems Research*, 25(1):37–41.

Ang, B. W. and Zhang, F. Q. (2000). A survey of index decomposition analysis in energy and environmental studies. *Energy*, 25(12):1149–1176.

Arto, I. and Dietzenbacher, E. (2014). Drivers of the Growth in Global Greenhouse Gas Emissions. *Environmental Science & Technology*, 48(5388-5394).

Dietzenbacher, E. and Los, B. (1998). Structural decomposition techniques: sense and sensitivity. *Economic Systems Research*, 10(4):307–324.

Genty, A., Arto, I., and Neuwahl, F. (2012). Final Database of Environmental Satellite Accounts: Technical Report on Their Compilation. Technical report.

Hardt, L., Owen, A., Brockway, P., Heun, M. K., Barrett, J., Taylor, P. G., and Foxon, T. J. (2018). Untangling the drivers of energy reduction in the UK productive sectors: Efficiency or offshoring? *Applied Energy*, 223(December 2017):124–133.

Hoekstra, R., Michel, B., and Suh, S. (2016). The emission cost of international sourcing: using structural decomposition analysis to calculate the contribution of international sourcing to CO2-emission growth. *Economic Systems Research*, 28(2):151–167.

Hoekstra, R. and Van Den Bergh, J. C. J. M. (2002). Structural Decomposition Analysis of Physical Flows in the Economy. *Environmental and Resource Economics*, 23:357–378.

Hoekstra, R. and van der Bergh, J. J. C. J. M. (2003). Comparing structural and index decomposition analysis. *Energy Economics*, 25(1):39–64.

IEA (2015). Energy Climate and Change. Technical report, International Energy Agency: World Energy Outlook Special Report.

IEA (2017). World Energy Balances 2017. Technical report, International Energy Agency.

Kaltenegger, O., Löschel, A., and Pothen, F. (2017). The Effect of Globalisation on Energy Footprints: Disentangling the Links of Global Value Chains. *Energy Economics*, 68:148–168.

Kander, A., Malanima, P., and Warde, P. (2013). *Power to the People*. Princeton University Press.

Lan, J., Malik, A., Lenzen, M., McBain, D., and Kanemoto, K. (2016). A structural decomposition analysis of global energy footprints. *Applied Energy*, 163:436–451.

Lenzen, M. (2016). Structural analyses of energy use and carbon emissions-an overview. *Economic Systems Research*, 28(2):119–132.

Leontief, W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics*, 18(3):105–125.

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, 52(3):262–271.

Mackillop, A. (1989). Decoupling-recoupling and oil shock. *Energy Policy*, pages 311–322.

Miller, R. E. and Blair, P. D. (2009). *Input-output analysis : foundations and extensions*. Cambridge University Press.

OECD (2016). The OECD input-output database: Sources and methods. Technical report.

Oosterhaven, J. and Van Der Linden, J. A. (1997). European Technology, Trade and Income Changes for 1975-85: An Intercountry Input-Output Decomposition. *Economic Systems Research*, 9(4):393–412.

OTA (1990). Energy Use and the U.S. Economy. *U.S. Congress, Office of Technology Assessment*, OTA-BP-E-5.

Proops, J. L. R. (1984). Modelling the energy-output ratio. *Energy Economics*, 6(1):47–51.

Rose, A. and Chen, C. Y. (1991). Sources of change in energy use in the A structural decomposition analysis. *Resources and Energy*, 13:1–21.

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., and Owen, A. (2016). Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. *Journal of Cleaner Production*, 132:45–56.

Schurr, S. (1985). Productive Efficiency and Energy Use. *Annals of Operations Research*, 2:229–238.

Schurr, S. and Netschert, B. (1960). *Energy in the American Economy 1850-1975: An Economic Study of Its History and Prospects*. Johns Hopkins Press, Baltimore.

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

Smil, V. (2016). *Energy transitions: global and national perspectives*. ABC-CLIO, Santa Barbara, USA.

Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews*, 47:74–82.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23(3):575–605.

Van Der Kroon, B., Brouwer, R., and Van Beukering, P. J. H. (2013). The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. *Renewable and Sustainable Energy Reviews*, 20(1):504–513.

Voigt, S., De Cian, E., Schymura, M., and Verdolini, E. (2014). Energy intensity developments in 40 major economies: Structural change or technology improvement? *Energy Economics*, 41:47–62.

Wang, H., Ang, B. W., and Su, B. (2017). Assessing drivers of economy-wide energy use and emissions: IDA versus SDA. *Energy Policy*, 107(1):585–599.

Warde, P. (2007). Energy Consumption in England and Wales, 1560-2000. *Series on Energy Consumption*.

Wolfe, F. (2017). How Artificial Intelligence Will Revolutionize the Energy Industry.

Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., and Tukker, A. (2018). Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. *Journal of Industrial Ecology*, 00(0):1–12.

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

7 Appendix

Input-output Framework and Structural Decomposition Analysis

Multi-regional Input-Output Framework

Structural decomposition analysis uses the input–output model and data to quantify a change in variables such as total output, value added, labor demand as well as change in physical flows such as energy use, CO_2 emissions and various other pollutants and resources (Hoekstra and Van Den Bergh, 2002; Hoekstra and van der Bergh, 2003). Bellow we present the structure of the standard environmentally extend multi region input (EEMRIO) output model and explain the SDA procedure. Note that for the period from c1970 to 1990 we use the single region input output model, but it has been set as consisting of two regions ($k = 2$) which allowed the use of a same decomposition procedure.

The standard environmentally extended MRIO model can be expressed in a compact form as:

$$\mathbf{e} = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{qLY} \tag{7}$$

Where **e** is the consumption-based (CB) energy use (also known as energy footprint), **q** is the energy intensity (energy use per unit of output). **L** is the Leontief inverse, its elements show direct and indirect requirements per unit of final demand. **Y** is the final demand.

Given k number of countries (labelled r, s) and n number of sectors (labelled i, j) each element in equation 7 can be described by block matrices and vectors. Global consumption based energy use is given as:

$$\underset{1\times k}{\mathbf{e}} = \left[e^1 \cdots e^s \cdots e^k\right]$$

where e^s contains consumption based energy use in country i. Global energy intensity is given as:

$$\underset{1\times kn}{\mathbf{q}} = \left[\mathbf{q}^1 \cdots \mathbf{q}^s \cdots \mathbf{q}^k\right] \text{ and } \underset{1\times n}{\mathbf{q}^s} = \left[q_1^s \cdots q_j^s \cdots q_n^s\right]$$

where q_j^s shows energy use per unit of output in sector j country s. The Leontief inverse is given as:

$$\underset{kn\times kn}{\mathbf{L}} = \begin{bmatrix} \mathbf{L}^{11} & \cdots & \mathbf{L}^{1s} & \cdots & \mathbf{L}^{1k} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{L}^{r1} & \cdots & \mathbf{L}^{rs} & \cdots & \mathbf{L}^{rk} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{L}^{k1} & \cdots & \mathbf{L}^{ks} & \cdots & \mathbf{L}^{kk} \end{bmatrix} \text{ and } \underset{n\times n}{\mathbf{L}^{rs}} = \begin{bmatrix} l_{11}^{rs} & \cdots & l_{1j}^{rs} & \cdots & l_{1n}^{rs} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ l_{i1}^{rs} & \cdots & l_{ij}^{rs} & \cdots & l_{in}^{rs} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ l_{n1}^{rs} & \cdots & l_{nj}^{rs} & \cdots & l_{nn}^{rs} \end{bmatrix}$$

where l_{ij}^{rs} indicates the amount of output that needs to be produced in industry i in country r to satisfy one unit of final demand for product j from country s. Global The final demands can be written as:

$$\underset{kn\times k}{\mathbf{Y}} = \begin{bmatrix} \mathbf{y}^{11} & \cdots & \mathbf{y}^{1s} & \cdots & \mathbf{y}^{1k} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{y}^{r1} & \cdots & \mathbf{y}^{rs} & \cdots & \mathbf{y}^{rk} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{y}^{k1} & \cdots & \mathbf{y}^{ks} & \cdots & \mathbf{y}^{kk} \end{bmatrix} \text{ and } \underset{n\times 1}{\mathbf{y}^{rs}} = \begin{bmatrix} y_1^{rs} \\ \vdots \\ y_i^{rs} \\ \vdots \\ y_n^{rs} \end{bmatrix}$$

where y_i^{rs} denotes final demand for sector i in country r sold to final users in country s.

Trade in Intermediate Inputs and Final Demand

L and **Y** matrices are desegregated further to isolate the trade effect. Broadly the trade effect can be split into the intermediate trade effect (e.g. manufacturer in country r buys input into production from a supplier in country s) and trade for final consumption effect (a consumer in country r purchases a car from country s). The intermediate trade structure effect is obtained by splitting the **A** matrix from the Leontief inverse $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ into two components $\mathbf{A} = \mathbf{T} \otimes \mathbf{H}$ (the symbol $\otimes$ stands for the Hadamard product element-wise multiplication). In a partitioned formed each component can be expressed as:

$$\underset{kn\times kn}{\mathbf{T}} = \begin{bmatrix} \mathbf{T}^{11} & \cdots & \mathbf{T}^{1s} & \cdots & \mathbf{T}^{1k} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \mathbf{T}^{r1} & \cdots & \mathbf{T}^{rs} & \cdots & \mathbf{T}^{rk} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \mathbf{T}^{k1} & \cdots & \mathbf{T}^{ks} & \cdots & \mathbf{T}^{kk} \end{bmatrix} \text{ and } \underset{n\times n}{\mathbf{T}^{rs}} = \begin{bmatrix} t_{11}^{rs} & \cdots & t_{1j}^{rs} & \cdots & t_{1n}^{rs} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ t_{i1}^{rs} & \cdots & t_{ij}^{rs} & \cdots & t_{in}^{rs} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ t_{n1}^{rs} & \cdots & t_{nj}^{rs} & \cdots & t_{nn}^{rs} \end{bmatrix}$$

where t_{ij}^{rs} indicates the share of intermediate input from industry i in country r supplied to country s for j sector ($r = s$ reflects the share of domestic inputs and $r \neq s$ reflects imports). Next, the $\mathbf{H}$ matrix is given as:

$$\underset{kn\times kn}{\mathbf{H}} = \begin{bmatrix} \mathbf{H}^{1} & \cdots & \mathbf{H}^{s} & \cdots & \mathbf{H}^{k} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \mathbf{H}^{1} & \cdots & \mathbf{H}^{s} & \cdots & \mathbf{H}^{k} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \mathbf{H}^{1} & \cdots & \mathbf{H}^{s} & \cdots & \mathbf{H}^{k} \end{bmatrix} \text{ and } \underset{n\times n}{\mathbf{H}^{s}} = \begin{bmatrix} h_{11}^{s} & \cdots & h_{1j}^{s} & \cdots & h_{1n}^{k} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ h_{i1}^{s} & \cdots & h_{ij}^{s} & \cdots & h_{in}^{k} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ h_{n1}^{s} & \cdots & h_{nj}^{s} & \cdots & h_{nn}^{k} \end{bmatrix}$$

where h_{ij}^{s} indicates the total amount of output of industry i (irrespective of the country of origin i.e. r) input per unit of output of industry j in country s. The full $\mathbf{H}$ matrix is obtained by stacking identical $\mathbf{H}^s$ matrices k times. The final demand matrix $\mathbf{Y}$ is split into four components $\mathbf{Y} = (\mathbf{B} \otimes \mathbf{G})\hat{\mathbf{d}}\hat{\mathbf{p}}$. In a partitioned formed trade coefficient matrix can be expressed as:

$$\underset{kn\times k}{\mathbf{B}} = \begin{bmatrix} \mathbf{b}^{11} & \cdots & \mathbf{b}^{1s} & \cdots & \mathbf{b}^{1k} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \mathbf{b}^{r1} & \cdots & \mathbf{b}^{rs} & \cdots & \mathbf{b}^{rk} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \mathbf{b}^{k1} & \cdots & \mathbf{b}^{ks} & \cdots & \mathbf{b}^{kk} \end{bmatrix} \text{ and } \underset{n\times 1}{\mathbf{b}^{rs}} = \begin{bmatrix} b_{1}^{rs} \\ \vdots \\ b_{i}^{rs} \\ \vdots \\ b_{n}^{rs} \end{bmatrix}$$

where b_i^{rs} indicates the share of final demand for industry i in country s supplied by country r ($r = s$ reflects the share of domestic supply and $r \neq s$ reflects imports). The structure of final demand is given as:

$$\underset{kn\times k}{\mathbf{G}} = \begin{bmatrix} \mathbf{g}^1 & \cdots & \mathbf{g}^s & \cdots & \mathbf{g}^k \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{g}^1 & \cdots & \mathbf{g}^s & \cdots & \mathbf{g}^k \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{g}^1 & \cdots & \mathbf{g}^s & \cdots & \mathbf{g}^k \end{bmatrix} \text{ and } \underset{n\times 1}{\mathbf{g}^s} = \begin{bmatrix} g_1^s \\ \vdots \\ g_i^s \\ \vdots \\ g_n^s \end{bmatrix}$$

where g_i^s indicates consumption of industry i (irrespective of the country of origin) as a share of total final demand in country s. Total final demand per capita is given as:

$$\underset{k\times k}{\hat{\mathbf{d}}} = \begin{bmatrix} d^1 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ 0 & \cdots & d^r & \cdots & 0 \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & d^k \end{bmatrix}$$

where d^r indicates final demand per capita in country r. Population is given as:

$$\underset{k\times k}{\hat{\mathbf{p}}} = \begin{bmatrix} p^1 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ 0 & \cdots & p^r & \cdots & 0 \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & p^k \end{bmatrix}$$

where p^r indicates population in country r.

Structural Decomposition Analysis

The SDA procedure undertaken in this study builds on previous research (Oosterhaven and Van Der Linden, 1997; Xu and Dietzenbacher, 2014; Arto and Dietzenbacher, 2014; Hoekstra et al., 2016).

Given the total energy footprint at point in time 0 ($t = 0$) as $\mathbf{e}^0$ and point in time 1 ($t = 1$) as $\mathbf{e}^1$, then the change in energy footprint $\triangle\mathbf{e} = \mathbf{e}^1 - \mathbf{e}^0$ can be decomposed into an exhaustive sum of the following factors:

$$\underbrace{\triangle\mathbf{e}}_{\substack{\text{Energy}\\\text{footprint}}} = \underbrace{\triangle\mathbf{q}}_{\substack{\text{Energy}\\\text{intensity}}} + \underbrace{\triangle\mathbf{T}}_{\substack{\text{Intermediate}\\\text{trade structure}}} + \underbrace{\triangle\mathbf{H}}_{\substack{\text{Production}\\\text{technology}}} + \underbrace{\triangle\mathbf{B}}_{\substack{\text{Final demand}\\\text{trade structure}}} + \underbrace{\triangle\mathbf{G}}_{\substack{\text{Consumption}\\\text{mix}}} + \underbrace{\triangle\mathbf{d}}_{\substack{\text{Consumption}\\\text{per capita}}} + \underbrace{\triangle\mathbf{p}}_{\text{Population}} \tag{8}$$

A well-known issue in the SDA literature is the non-uniqueness of the decomposition. Dietzenbacher and Los (1998) addressed this issue and recommend using the average of the *k*! (where *k* stands for number of components) different complete decompositions. They also showed that the average of all *k*! is closely approximated by the average of two so-called polar forms. The average of the two polar decompositions (indicated by the subscript a and b) is given by $\triangle\mathbf{e} = \mathbf{e}^1 - \mathbf{e}^0 = (\mathbf{e}_a + \mathbf{e}_b)/2$. Furthermore, as noted in Arto and Dietzenbacher (2014) the MRIO data need to be deflated to avoid price biases that occur from the use of tables in currents prices [2]. This is achieved by using MRIO tables in current prices for the period $t = 0$ and tables in previous year's prices for period $t = 1$. The final decomposition equation can be expressed as:

$$\triangle\mathbf{e} = \frac{1}{2}(\triangle\mathbf{q})\mathbf{L}_1(\mathbf{B}_1 \otimes \mathbf{G}_1)\hat{\mathbf{d}}_1\hat{\mathbf{p}}_1 + \frac{1}{2}(\triangle\mathbf{q})\mathbf{L}_0(\mathbf{B}_0 \otimes \mathbf{G}_0)\hat{\mathbf{d}}_0\hat{\mathbf{p}}_0 \tag{9}$$
$$+\frac{1}{4}\mathbf{q}_0\mathbf{L}_0(\triangle\mathbf{T}) \otimes (\mathbf{H}_0 + \mathbf{H}_1)\mathbf{L}_1(\mathbf{B}_1 \otimes \mathbf{G}_1)\hat{\mathbf{d}}_1\hat{\mathbf{p}}_1 \tag{10}$$
$$+\frac{1}{4}\mathbf{q}_1\mathbf{L}_1(\triangle\mathbf{T}) \otimes (\mathbf{H}_0 + \mathbf{H}_1)\mathbf{L}_0(\mathbf{B}_0 \otimes \mathbf{G}_0)\hat{\mathbf{d}}_0\hat{\mathbf{p}}_0 \tag{11}$$
$$+\frac{1}{4}\mathbf{q}_0\mathbf{L}_0(\mathbf{T}_0 + \mathbf{T}_1) \otimes (\triangle\mathbf{H})\mathbf{L}_1(\mathbf{B}_1 \otimes \mathbf{G}_1)\hat{\mathbf{d}}_1\hat{\mathbf{p}}_1 \tag{12}$$
$$+\frac{1}{4}\mathbf{q}_1\mathbf{L}_1(\mathbf{T}_0 + \mathbf{T}_1) \otimes (\triangle\mathbf{H})\mathbf{L}_0(\mathbf{B}_0 \otimes \mathbf{G}_0)\hat{\mathbf{d}}_0\hat{\mathbf{p}}_0 \tag{13}$$
$$+\frac{1}{2}\mathbf{q}_0\mathbf{L}_0(\triangle\mathbf{B} \otimes \mathbf{G}_1)\hat{\mathbf{d}}_1\hat{\mathbf{p}}_1 + \frac{1}{2}\mathbf{q}_1\mathbf{L}_1(\triangle\mathbf{B} \otimes \mathbf{G}_0)\hat{\mathbf{d}}_0\hat{\mathbf{p}}_0 \tag{14}$$
$$+\frac{1}{2}\mathbf{q}_0\mathbf{L}_0(\mathbf{B}_0 \otimes \triangle\mathbf{G})\hat{\mathbf{d}}_1\hat{\mathbf{p}}_1 + \frac{1}{2}\mathbf{q}_1\mathbf{L}_1(\mathbf{B}_1 \otimes \triangle\mathbf{G})\hat{\mathbf{d}}_0\hat{\mathbf{p}}_0 \tag{15}$$
$$+\frac{1}{2}\mathbf{q}_0\mathbf{L}_0(\mathbf{B}_0 \otimes \mathbf{G}_0)(\triangle\hat{\mathbf{d}})\hat{\mathbf{p}}_1 + \frac{1}{2}\mathbf{q}_1\mathbf{L}_1(\mathbf{B}_1 \otimes \mathbf{G}_1)(\triangle\hat{\mathbf{d}})\hat{\mathbf{p}}_0 \tag{16}$$
$$+\frac{1}{2}\mathbf{q}_0\mathbf{L}_0(\mathbf{B}_0 \otimes \mathbf{G}_0)\hat{\mathbf{d}}_0(\triangle\hat{\mathbf{p}}) + \frac{1}{2}\mathbf{q}_1\mathbf{L}_1(\mathbf{B}_1 \otimes \mathbf{G}_1)\hat{\mathbf{d}}_1(\triangle\hat{\mathbf{p}}) \tag{17}$$

where, the effect of $\triangle\mathbf{q}$ is given by equation 9, the effect of $\triangle\mathbf{T}$ by 10 and 11, the effect of $\triangle\mathbf{H}$ by 12 and 13, the effect of $\triangle\mathbf{B}$ by 14, the effect of $\triangle\mathbf{G}$ by 15, the effect of $\triangle\mathbf{d}$ by 16 and the effect of $\triangle\mathbf{p}$ by 17.

[2] This is not applicable for the period from c1970 to 1990 for which we use SRIO tables in constant prices

Note that in order to estimate the impact of $\triangle\mathbf{T}$ and $\triangle\mathbf{H}$, requires $\triangle\mathbf{L}$ to be expressed in terms of $\triangle\mathbf{A}$. As shown in (Miller and Blair, 2009) this can be achieved as:

$$\triangle\mathbf{L} = \mathbf{L}_0(\triangle\mathbf{A})\mathbf{L}_1 = \mathbf{L}_1(\triangle\mathbf{A})\mathbf{L}_0 \tag{18}$$

In the decomposition the impact of $\triangle\mathbf{L}$ is given by:

$$\triangle\mathbf{L} = \frac{1}{2}\mathbf{q}_0(\triangle\mathbf{L})(\mathbf{B}_1 \otimes \mathbf{G}_1)\hat{\mathbf{d}}_1\hat{\mathbf{p}}_1 + \frac{1}{2}\mathbf{q}_1(\triangle\mathbf{L})(\mathbf{B}_0 \otimes \mathbf{G}_0)\hat{\mathbf{d}}_0\hat{\mathbf{p}}_0 \tag{19}$$

Replacing $\triangle\mathbf{L}$ with $\mathbf{L}_0(\triangle\mathbf{A})\mathbf{L}_1$ and $\mathbf{L}_1(\triangle\mathbf{A})\mathbf{L}_0$ yields:

$$\triangle\mathbf{L} = \frac{1}{2}\mathbf{q}_0\mathbf{L}_0(\triangle\mathbf{A})\mathbf{L}_1(\mathbf{B}_1 \otimes \mathbf{G}_1)\hat{\mathbf{d}}_1\hat{\mathbf{p}}_1 + \frac{1}{2}\mathbf{q}_1\mathbf{L}_0(\triangle\mathbf{A})\mathbf{L}_1(\mathbf{B}_0 \otimes \mathbf{G}_0)\hat{\mathbf{d}}_0\hat{\mathbf{p}}_0 \tag{20}$$

The effect of $\triangle\mathbf{A}$ can be replaced by $\triangle\mathbf{T}$ and $\triangle\mathbf{H}$ as:

$$\triangle\mathbf{A} = \frac{1}{2}(\triangle\mathbf{T}) \otimes (\mathbf{H}_1 + \mathbf{H}_0) + \frac{1}{2}(\triangle\mathbf{H}) \otimes (\mathbf{T}_1 + \mathbf{T}_0) \tag{21}$$

substituting $\triangle\mathbf{A}$ into equation 20 gives the effect of $\triangle\mathbf{T}$ by 10 and 11 and the effect of $\triangle\mathbf{H}$ by 12 and 13.

Table A.1: OECD Sectoral Coverage and Aggregation

No	Name	Code	Sector	No
1	Agriculture	AGR	Agriculture, forestry & fishery	1
2	Mining	MNG	Mining and quarrying	2
3	Food	FOD	Food, Beverages and Tobacco	3
4	Energy-intensive manufacturing	HMN	Paper, paper products & printing	6
			Industrial chemicals	7
			Drugs & medicines	8
			Petroleum & coal products	9
			Rubber & plastic products	10
			Non-metallic mineral products	11
			Iron & steel	12
			Non-ferrous metals	13
5	Non-energy-intensive manufacturing	LMN	Textiles, apparel & leather	4
			Wood products & furniture	5
			Metal products	14
			Non-electrical machinery	15
			Office & computing machinery	16
			Electric apparatus, nec	17
			Radio, TV & communication equipment	18
			Shipbuilding & repairing	19
			Other transport	20
			Motor vehicles	21
			Aircraft	22
			Professional goods	23
			Other manufacturing	24
6	Transport	TRT	Transport & storage	29
7	Services	SER	Construction	26
			Wholesale & retail trade	27
			Restaurants & hotels	28
			Communication	30
			Finance & insurance	31
			Real estate and business services	32
			Community, social & personal services	33
			Producers of government services	34
			Other producers	35
			Statistical discrepancy	36
8	Electricity and gas	EGS	Electricity, gas & water	25

Table A.2: WIOD Sectoral Coverage and Aggregation

No	Name	Code	Sector	No
1	Agriculture	AGR	Agriculture, Hunting, Forestry and Fishing	1
2	Mining	MNG	Mining and Quarrying	2
3	Food	FOD	Food, Beverages and Tobacco	3
4	Energy-intensive manufacturing	HMN	Pulp, Paper, Paper , Printing and Publishing	7
			Coke, Refined Petroleum and Nuclear Fuel	8
			Chemicals and Chemical Products	9
			Rubber and Plastics	10
			Other Non-Metallic Mineral	11
			Basic Metals and Fabricated Metal	12
5	Non-energy-intensive manufacturing	LMN	Textiles and Textile Products	4
			Leather, Leather and Footwear	5
			Wood and Products of Wood and Cork	6
			Machinery, Nec	13
			Electrical and Optical Equipment	14
			Transport Equipment	15
			Manufacturing, Nec; Recycling	16
6	Transport	TRT	Inland Transport	23
			Water Transport	24
			Air Transport	25
			Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies	26
7	Services	SER	Construction	18
			Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel	19
			Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	20
			Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	21
			Hotels and Restaurants	22
			Post and Telecommunications	27
			Financial Intermediation	28
			Real Estate Activities	29
			Renting of M&Eq and Other Business Activities	30
			Public Admin and Defense; Compulsory Social Security	31
			Education	32
			Health and Social Work	33
			Other Community, Social and Personal Services	34
			Private Households with Employed Persons	35
8	Electricity and gas	EGS	Electricity, Gas and Water Supply	17

Paper 3

Constructing Energy Accounts for WIOD 2016 Release

Viktoras Kulionis

Abstract

Most of today's products and services are made in global supply chains. As a result, the consumption of goods and services in one country is associated with various environmental pressures all over the world due to international trade. Advances in global multi-region input-output models have allowed researchers to draw detailed, international supply-chain connections between production and consumptions activities and associated environmental impacts. Due to limited data availability, there is little evidence about the more recent trends in global energy use from a consumption-based perspective (i.e. footprint). In order to expand the analytical potential of the existing WIOD 2016 dataset to a wider range of research themes, this paper constructs energy accounts and presents global energy use trends for the period 2000–2014. The results for selected countries/regions indicate that from 2000 to 2014 production-based (PB) and consumption-based (CB) energy use has declined marginally in the EU28 and the USA, and has increased considerably in BRIC countries and China. Furthermore, the difference between PB and CB has contracted for EU28, US and China since about 2008 indicating the energy content in trade has become more balanced.

JEL Classification

C67, C80, C82, P18, P28, Q56

Keywords

Energy Accounts, Satellite Accounts, Environmental Extensions, Input-output Analysis, Energy Embodied in Trade

1 Introduction

Addressing the problem of climate change has moved high up on government agendas across the world. Effective strategies to reduce country-specific impacts require accurate and reliable environmental statistics. Such statistics should not only account for environmental pressures occurring within the borders of a country but should also allow environmental pressures embodied in imports and exports to be considered.

This issue is of particular importance given that most of today's products and services are no longer produced within a single country and are made in global supply chains (Baldwin, 2011; Timmer et al., 2014; Los et al., 2015). This means that countries import intermediate goods and raw materials, to which they add one or more layers of value and sell the product either for final consumption or to another producer who adds the next value layer (Tukker and Dietzenbacher, 2013). At each of these steps environmental pressure is generated in the form of emissions, waste or natural resource use.

Normally environmental impacts are calculated following a production-based (PB) approach. This method assigns the responsibility of a specific factor (e.g. energy or CO_2) to the country where the impact occurs. Following significant growth in the volume of trade and increasing production fragmentation, however, many scholars have begun to discuss appropriate ways to measure the responsibility for environmental impacts and to assess the effects of trade on the environment (Tukker and Dietzenbacher, 2013; Wiedmann and Lenzen, 2018; Piñero et al., 2018).

One way to account for the factor content embodied in trade is to use the consumption-based (CB) approach. Significant attention has been devoted to the use of consumption-based accounting principles (also referred to as 'footprint') in the past few decades (Davis and Caldeira, 2010; Peters et al., 2011). Multi-regional input-output (MRIO) analysis has proven to be an essential tool for this task and the availability of global multi-regional input-output (GMRIO) databases has enabled researchers to draw detailed, global supply-chain connections between the production and consumption of goods and services.

Recent evidence suggests that for developed countries environmental impacts embodied in imports are generally higher than in exports and for developing countries the opposite is true – that is environmental impacts embodied in exports are higher than in imports (Wiedmann and Lenzen, 2018). Furthermore, between 1995–2011, the share of total global environmental impacts embodied in trade increased from 20% to 29% for energy use and from 19% to 24% for GHG emissions (Wood et al., 2018).

While MRIO models are a powerful tool for analysing environmental impacts of countries, their data and computational requirements are often cited as barriers to timely, detailed and robust studies (Andrew et al., 2009). A review of the main global MRIO initiatives indicate that there are seven global MRIO databases (Owen, 2015). Three of these databases (Eora, WIOD 2013 release, EXIOBASE3) come with consistent time series and with the environmental satellite accounts that allow various environmental analyses over time (e.g. estimation of carbon or energy footprints). However, comparisons have shown that MRIO databases yield diverging results (Moran and Wood, 2014). These disagreements are often attributed to different classifications and levels of aggregation, differences in assembly and reconciliation techniques, and due to the use of different data sources (Geschke et al., 2014). In general, each MRIO database suffers from one or several errors (Wood et al., 2015). Inomata and Owen (2014) note that this should not be seen as problematic because MRIO databases are built with different target audiences and applications in mind, and more emphasis should be placed on understanding the uncertainty in MRIO outcomes. Consistency and robustness of environmental indicators is a key concern for policy-makers (Moran and Wood, 2014). Hence, the availability of several MRIO databases with environmental extensions is necessary for comparing environmental indicators between different databases and for evaluating the robustness across results. This is of particular importance for the period after 2009, for which MRIO database coverage is very limited.

Furthermore, Dietzenbacher et al. (2013) emphasise that a useful database for analysing economic, social and environmental issues should take into account three aspects: (i) be global, (ii) cover changes over time, and (iii) include socioeconomic and environmental indicators. The WIOD database released in 2016 satisfies (i) and (ii) but (iii) only partially because it does not contain environmental extensions. To improve this aspect and expand the analytical potential of the existing WIOD 2016 database to a wider range of research themes, this paper focuses on constructing energy accounts that match WIOD 2016 country, year and industry classifications.

In more detail, this study aims to: (i) demonstrate how data from the International Energy Agency (IEA) can be used to construct energy accounts that match the WIOD 2016 sector, year and country classification, (ii) present detailed comparison of WIOD2016 and WIOD2013 energy accounts, (iii) analyse global production- (PB) and consumption-based (CB) energy use for the period 2000–2014 and (iv) create an interactive and user-friendly visualisation platform to enable efficient and effective dissemination of results.

2 Data

2.1 Energy Data

Data for this study comes from two sources: (*i*) International Agency (IEA) and (*ii*) World Input-Output Database (WIOD). IEA (2017) is the main source of energy data. The latest IEA 2017 edition provides World Energy balances for 178 countries and regional aggregates over the period 1960–2015 (OECD countries and regions) and 1971–2015 (non-OECD countries and regions). For each year and country, the energy balances cover 65 products and 85 flows. For example, the flow *iron and steel* contains data on which and how much energy product (e.g. coal, oil, other) the *iron and steel* industry used during a specific year. A data extract from the IEA has the following dimensions:

$$\text{Year} \times \text{country} \times \text{flow} \times \text{product} = 14 \times 43 \times 65 \times 85$$

It covers a 14 year period from 2000 to 2014, and contains data for 43 countries, 65 energy products and 85 flows.

2.2 MRIO Data

Multi-regional input-output tables (MRIOT) come from WIOD, which contains the WIOD 2013 release (WIOD13 hereafter) and the WIOD 2016 release (WIOD16 hereafter). The WIOD13 version is a system of MRIO tables and socioeconomic and environmental accounts (Genty et al., 2012; Timmer et al., 2015, 2016). It covers 35 industries and 41 countries/regions, including 27 EU and 13 other major advanced and emerging economies, plus the Rest of the World (RoW) region over the period 1995–2011; environmental accounts cover the period 1995–2009.

A more recent WIOD16 database provides data for 56 industries and 44 countries (28 EU, 15 other major countries and RoW region) for the period from 2000 to 2014 (see Appendix Table A.1 and Table A.2). It also provides socioeconomic accounts from 2000 to 2014, but does not provide environmental accounts.

The two databases overlap over the period from 2000 to 2009. This allows comparison of WIOD16 energy use estimates with the WIOD13 version to get a sense of accuracy of the WIO16 estimates. The aim is to provide estimates that closely resemble those in WIOD13 so that the two databases could be linked to study the changes in energy use over an extended period: 1995-2014. This is a novel contribution of this paper and could serve the scientific community in many ways.

3 Methodology

This section outlines the allocation procedure of the 83 flows and 66 energy products from the IEA energy balances with the WIOD16 56 sectors and one final demand category: *households*. The allocation procedure builds on previous studies by Genty et al. (2012), Wood et al. (2015), Wiebe and Yamano (2016) and Owen et al. (2017). The procedure to construct energy accounts starting from energy balances involves a series of steps. Each step is explained below with examples.

3.1 IEA Allocation Procedure

Step 1: Extraction of Energy Use Data from IEA

The IEA energy balances show the supply and use of energy products by industries and final use categories as in Table 1. This data allows us to construct two energy extension vectors: one showing energy use by industry and another showing energy supply of different energy products (e.g. coal) by the source sector (e.g., Mining). The two vectors are equivalent in size (energy supply = energy use), but the allocation to industry sectors is different. Among the existing databases GTAP and WIOD provide energy use vectors, Eora provides energy-supply vectors, and EXIOBASE is the only database to provide both energy vectors (Owen et al., 2017). There is little information on the difference between the two vectors, and the choice of which energy extension vector to use largely depends on the question at hand. Owen et al. (2017) show that both energy extensions produce very similar estimates of the overall energy footprint for the UK. However, at a more detailed level, the results address different issues. For instance, the energy-supply vector reveals how dependent the UK is on its domestic energy supply, an issue that is of the utmost importance for energy security policy. On the other hand, the energy use vector allows for the attribution of actual energy use to industry sectors, which enables a better understanding of sectoral efficiency gains.

In order to be consistent with WIOD13 energy accounts, this study focuses on the construction of the energy use vector. The very first step in deriving energy use accounts from the IEA energy balances is to separate the use and the supply of energy products. Energy use consists of: the total final consumption (Industry + transport + Other + Non-energy use); the aviation and marine bunkers (with a changed algebraic sign); the energy sector's own use (with a changed algebraic sign); and transformation processes/losses (with a changed algebraic sign).

Table 1: IEA Energy Balances, Exemplified with Data for Germany 2014 (Mtoe)

Flow \ Product	**Energy Product**				
	product 1	product 2	...	product 65	Total
TPES					**306**
Production	...	...	...	...	120
Imports	...	...	...	...	246
Exports	...	...	...	...	-49
International marine bunkers	...	...	...	...	-2
International aviation bunkers	...	...	...	...	-8
Stock changes	...	...	...	...	0.3
Transfers					0.7
Statistical differences					0.3
Transformation processes					-74
...	...	...	...	...	
Energy industry own use					**-16**
...	...	...	...	...	...
Total final consumption					**216**
Industry					55
...	...	...	...	...	...
Transport					55
...	...	...	...	...	...
Other					84
...	...	...	...	...	...
Non-energy use					22

Step 2: Establishing a Correspondence Link between WIOD and IEA

The next step is to establish a correspondence key linking energy balance items and WIOD16 industries plus households. An example of a binary correspondence matrix is displayed in Table 2. A value of 0 implies no link and 1 represents a link between the IEA flow and WIOD sector(s). The columns containing only one entry represent one-to-one allocation: for example, column *flow 2* is allocated to WIOD16 *sector 56*. The IEA flows that contain multiple entries of 1 represent one-to-many allocation. For instance, the IEA *flow 1* is allocated to WIOD16 *sector 1* and *sector 2*, while *flow 85* is split among all WIOD sectors + households.

Table 2: An Example of a Binary Concordance Matrix

		IEA energy flow			
		flow 1	flow 2	...	flow 85
WIOD16 (56 sectors + households)	sector 1	1	0	...	1
	sector 2	1	0	...	1
	...	...	...	...	...
	sector 56	0	1	...	1
	households	0	0	...	1

Step 3: Generating a Splitting Key

While one-to-one allocation is a straightforward task, one-to-many allocation requires disaggregation of a specific IEA flow among several WIOD16 sectors. The splitting key for this task is the total input in monetary terms from two WIOD16 energy related sectors: *coke and refined petroleum products* (*sector 10*) and *Electricity, gas, steam and air conditioning supply* (*sector 24*). An example of a splitting key with arbitrary numbers is shown in Table 3. For instance, the splitting key to allocate IEA *flow 1* among WIOD16 *sector 1* and *sector 2* is $\begin{bmatrix} 12/16 & 4/16 \end{bmatrix} = \begin{bmatrix} 0.75 & 0.25 \end{bmatrix}$. This means that 75% of IEA energy *flow 1* is allocated to *sector 1* and 25% to *sector 2*.

Table 3: An Example of a Splitting Key Vector (Arbitrary Numbers)

		WIOD16 ($)				
		sector 1	sector 2	...	sector 56	household
Coke and refined petroleum products	sector 10	5	1	...	1	3
Electricity, gas, steam and air conditioning supply	sector 24	7	3	...	0	11
Total	(s10+s24)	**12**	**4**	**...**	**1**	**14**

Step 4: Creating a Mapping Matrix

The information from Table 2 and Table 3 can be expressed in matrix form as:

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad \mathbf{a} = \begin{bmatrix} 12 & 4 & 1 & 14 \end{bmatrix}$$

Using this information we can obtain a normalised mapping matrix **M** corresponding to matrix **C** (see Liang et al., 2013; Fry, 2017), but instead of binary information it contains allocation shares. In a formal way this is achieved as:

$$\mathbf{M} = \hat{\mathbf{a}}\mathbf{C}\widehat{(\mathbf{a}\mathbf{C})}^{-1} \tag{1}$$

The resulting matrix **M** in more detailed form:

$$\mathbf{M} = \begin{bmatrix} 0.75 & 0 & 0.39 \\ 0.25 & 0 & 0.13 \\ 0 & 1 & 0.03 \\ 0 & 0 & 0.45 \end{bmatrix}$$

Mapping matrix **M** shows the allocation of IEA flow (given in columns) among WIOD16 sectors plus households (given in rows). For instance, values in the first column show that 75% of IEA energy *flow 1* is allocated to *sector 1* and 25% to *sector 2*.

Step 5: Allocation of IEA Energy Use to WIOD16

In step 5 we combine information obtained in Step 1 with matrix **M** from Step 4.

First, let **V** be a $p \times f$ matrix showing the use of 65 energy products by 85 energy flows as explained in Step 1. Matrix **V** is modified further by diagonalising the 66×1 vectors corresponding to each IEA energy flow and stacking them horizontally. This yields:

$$\underset{66\times5610}{\overline{\mathbf{V}}} = \left[(\hat{\mathbf{v}}^1)(\hat{\mathbf{v}}^2)\cdots(\hat{\mathbf{v}}^f)\right]$$

where block element **v** shows the energy use of 65 different energy products by a given energy flow.

Matrix **M** is modified by transposing and replicating each of its columns p times ($p = 66$); this yields:

$$\underset{5610\times57}{\overline{\mathbf{M}}} = \begin{bmatrix} (\mathbf{m}^1)'_{\times p} \\ (\mathbf{m}^2)'_{\times p} \\ \vdots \\ (\mathbf{m}^f)'_{\times p} \end{bmatrix}$$

where block element **m** contains allocation shares, which show how a given energy product should be allocated among WIOD16 sectors.

Multiplying the two matrices yields:

$$\underset{66\times 57}{\mathbf{E}} = \overline{\mathbf{V}} \times \overline{\mathbf{M}}$$

where **E** is the energy use matrix showing the use of the 65 energy products by the 56 WIOD16 sectors plus households. The energy product dimension (65) has been further aggregated to match the WIOD13 classification of 27 energy products (see Appendix for energy product detail). The dimensions of the final energy matrix are 27×57 and it corresponds to the sectoral classification of the WIOD16 plus households. The above steps were repeated for all WIOD16 countries except Rest of the World (RoW). For RoW, energy use was estimated by taking IEA World energy use and subtracting all energy use by WIOD16 countries.

The procedure presented in Step 5 can be exemplified using arbitrary data. An additional piece of information required for the example is energy balance data **V**. An example of energy balance data is given in Table 4; it displays the use of energy *product 1* and *product 56* by three energy flows.

Table 4: Simplified IEA Energy Balance Table, (Arbitrary Numbers)

		IEA product		
		product 1	...	product 65
IEA flow	flow 1	100	...	20
	flow 2	4	...	2
	...	...	...	...
	flow 85	15	...	1

Information from Table 4 can be presented in a matrix form as:

$$\mathbf{V} = \begin{bmatrix} 100 & 20 \\ 4 & 2 \\ 15 & 3 \end{bmatrix}$$

and in a modified version:

$$\overline{\mathbf{V}} = \begin{bmatrix} 100 & 0 & 4 & 0 & 15 & 0 \\ 0 & 20 & 0 & 2 & 0 & 3 \end{bmatrix}$$

Matrix $\mathbf{M}$ from Step 4 is modified by transposing and replicating each of its columns twice (because there are two products) as:

$$\overline{\mathbf{M}} = \begin{bmatrix} 0.75 & 0.25 & 0 & 0 \\ 0.75 & 0.25 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0.39 & 0.13 & 0.03 & 0.45 \\ 0.39 & 0.13 & 0.03 & 0.45 \end{bmatrix}$$

Multiplying $\overline{\mathbf{V}}$ by $\overline{\mathbf{M}}$ yields:

$$\mathbf{E} = \overline{\mathbf{V}} \times \overline{\mathbf{M}} = \begin{bmatrix} 81 & 27 & 4 & 7 \\ 16 & 5 & 2 & 1 \end{bmatrix}$$

Elements in the first row display the use of energy *product 1* by four WIOD16 sectors, and the second row gives the use of *product 2*. The sum of row elements in matrix $\mathbf{E}$ is equal to the sum of column elements in matrix $\mathbf{V}$.

Step 6: Accuracy

In step 6, the accuracy of WIOD16 energy use estimates was evaluated by measuring the difference in total energy use between WIOD13 and WIOD16. Steen-Olsen et al. (2014) have used a similar approach to estimate MRIO aggregation error. The relative error ε between WIOD13 and WIOD16 is defined as:

$$\varepsilon_t^r = \frac{E^r_{W16,t} - E^{r,t}_{W13,t}}{E^r_{W13,t}}$$

where $E^r_{W13,t}$ and $E^r_{W16,t}$ are the total energy use for year t and country r in $W13$ (WIOD13) and $W16$ (WIOD16), respectively.

Step 7: Calibration

In a final step 7, WIOD16 estimates are calibrated to match WIOD13 for the period 2000-2009 where the two databases overlap. It is important to note that while sectoral detail does not match between the two databases, energy product detail is the same: i.e. in WIOD13, energy use for a single country is given by a 35×27 energy matrix and in WIOD16 by a 56×27 matrix; hence the total energy use by energy product is given by 1×27 vector. The calibration is performed in two steps. First, total energy use by product for year t and country r in $W16$ (WIOD16) is divided by total product use in $W16$ (WIOD13) as:

$$\alpha_t^r = (\mathbf{E}_{W16,t}^r \mathbf{i}_s) \oslash (\mathbf{E}_{W13,t}^r \mathbf{i}_s)$$

where $\mathbf{E}_{W16,t}^r$ is a 27×56 WIOD16 energy use matrix, $\mathbf{E}_{W13,t}^r$ is a 27×35 WIOD13 energy use matrix, α is 27×1 vector that shows over/under estimation of a particular energy product, $\mathbf{i}$ is a summation vector of ones (for WIOD16 $s = 56$; for WIOD13 $s = 35$) and sign $\oslash$ denotes element-by-element division. The second step involves adjusting WIOD16 energy accounts as follows:

$$\overline{\mathbf{E}}_{W16,t}^r = \widehat{\alpha} \mathbf{E}_{W16,t}^r$$

where $\overline{\mathbf{E}}_{W16,t}^r$ is a 27×56 adjusted WIOD16 energy use matrix that closely matches energy use by product in WIOD13. It is assumed that under/over estimation of a particular energy product is equally distributed among all sectors. For instance, if coal use in WIOD16 is found to be underestimated by 2% then for every industry that uses coal, its consumption is raised by 2%.

The calibration strategy was applied for the years where the two datasets overlap, i.e. 2000–2009. For the period 2010–2014 an additional step was required to calibrate the estimates. It involved extrapolation of under/over estimation data from previous years using a five-year moving average. The same procedure was applied to calibrate energy use by households.

In order to show the scale of adjustments between the two databases, the results are provided for energy use before and after the calibration. However, the energy CB calculations are performed only using the calibrated data.

3.2 Production- and Consumption-Based Energy Use

In this section, a standard environmentally extended Leontief model is applied to calculate PB and CB energy use for WIOD13 and WIOD16. Given k countries and n sectors, the basic Leontief model can be expressed as:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{LY} \tag{2}$$

where $\mathbf{x}$ is a $kn \times 1$ vector of output, $\mathbf{A}$ is a $kn \times kn$ matrix of technical coefficients, $\mathbf{Y}$ is a $kn \times k$ matrix of final demands and $(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{L}$ is a $kn \times kn$ total requirement matrix representing interdependencies between industries (Miller and Blair, 2009).

Given a $1 \times kn$ total energy use vector $\mathbf{e}$, the MRIO model in equation 2 is extended to incorporate energy use as:

$$\mathbf{E} = \mathbf{U}\hat{\mathbf{q}}\mathbf{LY} \tag{3}$$

where $\mathbf{q} = \mathbf{e}\hat{\mathbf{x}}^{-1}$ is the direct energy intensity vector representing energy use per unit of output, $\mathbf{E}$ is a $k \times k$ energy use matrix that displays energy flows between countries and $\mathbf{U}$ is a $k \times kn$ aggregation matrix that collapses the country-by-product dimension (kn) to a country dimension (k).

The production-based (PB) energy use for all countries is given as:

$$\mathbf{e}_{PB} = \mathbf{E}\mathbf{i}_k$$

and the consumption-based (CB) energy requirements are given as:

$$\mathbf{e}_{CB} = \mathbf{i}_k'\mathbf{E}$$

where $\mathbf{i}_k$ is a summation vector of ones of dimension k.

4 Results

This section provides the results for three types of energy use: (i) WIOD 2013 energy use labelled as WIOD13, (ii) WIOD 2016 energy use before calibration labelled as WIOD16BC, and (iii) WIOD 2016 energy use after calibration labelled as WIOD16AC (see Step 6 and 7 in the methodology section for details). Energy accounts before calibration (WIOD16BC) are provided in order to give a sense of the inaccuracies that occur when IEA energy balances are allocated directly to WIOD16 industries and households. In this case, for some countries there might be differences in production-based energy use between WIOD13 and WIOD16BC. Energy accounts after calibration (WIOD16AC) adjusts for these differences, meaning that there should be little or no difference in production-based energy use between WIOD13 and WIOD16AC. Any existing differences (if there are any) in consumption-based energy use between WIOD13 an WIOD16AC can be attributed to differences in MRIO table structure (e.g. WIOD13 has lower country and sector coverage than WIOD16).

In addition, according to Wiedmann et al. (2011), effective and efficient dissemination of results is vital to exploiting the full potential of MRIO analysis in sustainability research. It is suggested that this can be achieved by visualising data and creating user-friendly platforms, enabling an efficient exchange of data and knowledge transfer. Following this suggestion, energy use accounts that match WIOD16 country, year and industry classification were made publicly available online (see Kulionis, 2019). Furthermore, production- and consumption-based energy use results were visualised and can be viewed using an interactive visualisation tool at `factor-flow.herokuapp.com`.

4.1 Initial IEA Allocation Results

The comparison between WIOD16BC and WIOD13 energy use estimates for selected years and the average for the period 2000–2009 are presented in Table 5. The results indicate that for most countries WIOD16BC and WIOD13 results vary between 1 and 4%, and in most cases the difference is positive: for the world total, the results are higher on average by 4.1% implying that WIOD16BC energy use estimates are on average higher than WIOD13. However, there are also some exceptions, e.g. Denmark, the Netherlands and Germany.

For Denmark, Malta, Belgium and Luxembourg, the estimates display greater discrepancies and vary between 10-20%. For Denmark and Luxembourg, the results are underestimated and for Malta and Belgium overestimated. For China and Austria, WIOD16BC, energy use estimates are on average 7–9% higher than WIOD13. For these countries, the results are less accurate (assuming WIOD13 is a correct measure) than for the rest of the sample, but they are precise (i.e. over/underestimation is similar over the years).

Switzerland, Croatia and Norway were not included in the WIOD13 release, and therefore it was not possible to present the estimation error for these countries.

4.2 Production- and Consumption-based Energy Use

Data from three energy accounts WIOD13, WIOD16BC, WIOD16AC have been applied to calculate PB and CB energy use for the period 2000 to 2014 (1995–2009 for WIOD13). To show annual variations between different estimates, the results are displayed for four selected countries

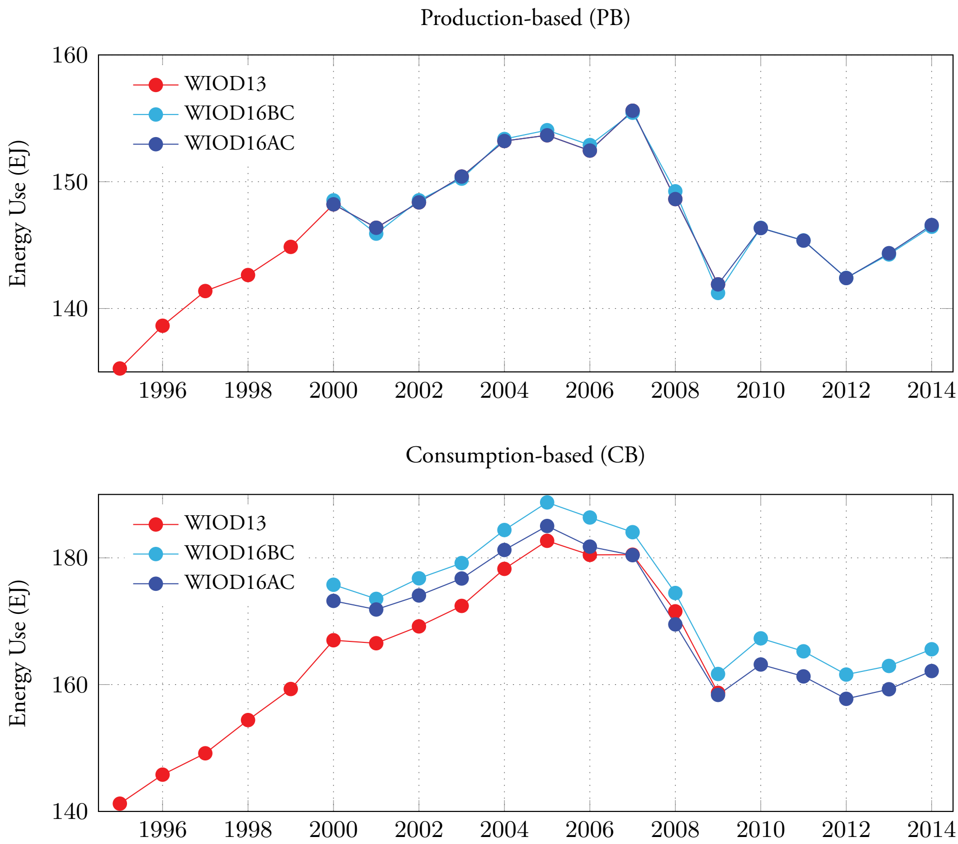
Table 5: Relative Estimation Error Between WIOD16BC and WIOD13, (Selected Years)

	2000 $\varepsilon_{00}(\%)$	2005 $\varepsilon_{05}(\%)$	2009 $\varepsilon_{09}(\%)$	2000-2009 $\lvert\varepsilon_{00-09}\rvert\ (\%)$
Denmark	-11.0	-19.9	-23.2	18.8
Malta	14.4	8.2	29.3	14.7
Belgium	9.1	13.1	10.7	13.8
Luxembourg	-10.4	-9.2	-18.5	11.3
China	7.3	10.1	8.6	9.1
Austria	7.7	9.1	7.0	8.3
Slovakia	4.9	5.9	5.6	5.4
Rest of World	3.4	4.4	5.6	4.5
Spain	5.0	4.2	4.4	4.4
Finland	5.5	5.0	3.3	4.4
Netherlands	-6.4	-4.3	-1.0	3.9
Taiwan	-1.9	-3.2	-5.4	3.3
Brazil	3.2	3.0	2.7	3.2
Ireland	1.2	-2.8	-8.8	3.2
Romania	1.8	4.4	2.1	3.1
Czech Republic	3.0	2.9	2.5	3.0
Greece	5.5	-2.9	-2.3	2.8
Bulgaria	2.9	2.8	1.3	2.6
Latvia	-1.4	-1.7	5.3	2.2
Cyprus	1.2	3.1	-1.4	1.9
Russia	2.1	1.7	1.1	1.7
Poland	1.6	1.6	1.5	1.6
Sweden	2.0	1.2	1.7	1.6
Estonia	-2.6	-1.2	-0.1	1.4
France	1.6	1.4	1.1	1.4
Portugal	1.7	1.0	1.2	1.4
Great Britain	1.0	1.1	1.2	1.3
Italy	0.3	1.7	1.9	1.3
Canada	0.6	1.5	1.6	1.2
Hungary	0.7	1.4	0.8	1.2
Australia	0.4	-1.6	1.8	1.1
Germany	-0.2	-0.9	-1.0	1.0
Mexico	-0.6	-0.1	0.5	1.0
Indonesia	0.2	-0.4	0.5	0.9
India	-0.9	-0.2	1.0	0.7
South Korea	0.9	0.6	-0.4	0.7
Lithuania	0.1	1.1	1.5	0.7
Japan	-0.3	-0.5	-1.0	0.6
Slovenia	0.2	0.1	1.7	0.4
Turkey	-0.1	-0.1	-1.0	0.4
United States	0.2	0.3	-0.5	0.2
Switzerland	n/a	n/a	n/a	n/a
Croatia	n/a	n/a	n/a	n/a
Norway	n/a	n/a	n/a	n/a
World Total	2.7	4.5	5.1	4.1

(China, Germany, Japan and the USA) in Figures 1, 2, 3 and 4. The two databases overlap from 2000 to 2009, so this period can be used to study the differences between WIOD13 , WIOD16BC and WIOD16AC. It is important to note that the PB indicator for WIODAC and WIOD13 is the same (or very close) due to calibration but CB can differ, for example, due to a greater sectoral and country detail.

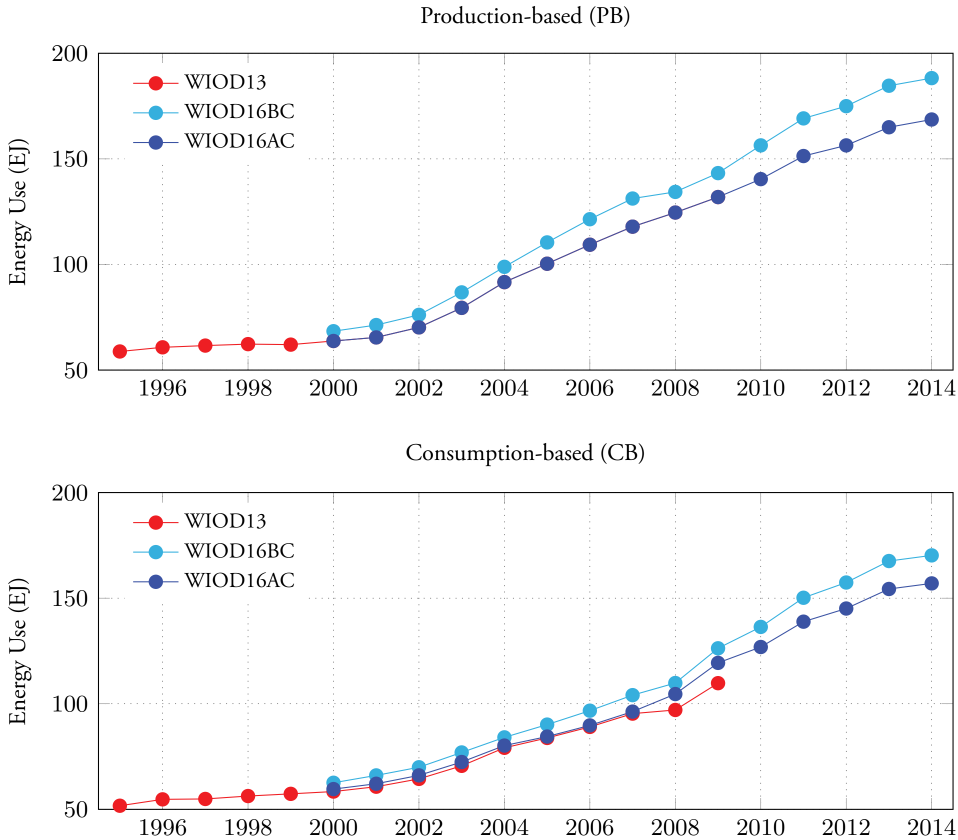
Figure 1 displays CB and PB results for the USA. PB results are virtually the same when calculated using WIOD13, WIOD16BC and WIOD16AC. On the other hand, CB results are larger when using WIOD16BC especially during the period 2000-2006. There is no difference between WIOD16BC and WIOD16AC for the PB indicator. The CB energy use estimates are highest with WIOD16BC and quite similar in size for WIOD13 and WIOD16AC (at least after 2006). Finally, we can also see that energy use has stabilised in the USA after 2008 for both PB and CB indicators.

Figure 1: PB and CB Energy Use for the USA, WIOD13 vs. WIOD16BC vs. WIOD16AC



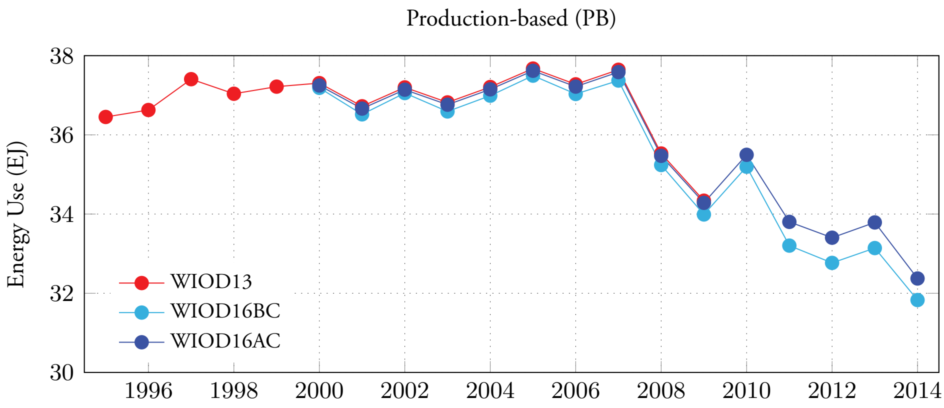
The same indicators are displayed for China in Figure 2. Here, we can see that WIOD16BC results are higher for both PB and CB measures, but they follow the same trend as WIOD13. The results for the period after 2009 show that energy use in China continues to increase. WIOD16AC results show that with calibrated data the CB measure is almost identical to WIOD13.

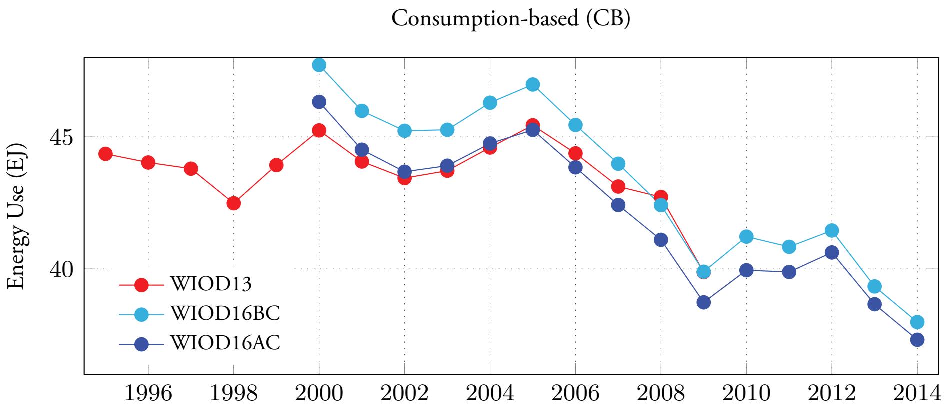
Figure 2: PB and CB Energy Use for China, WIOD13 vs. WIOD16BC vs. WIOD16AC



The results for Japan are displayed in Figure 3. In general, the results for Japan are similar to those of the USA. PB energy use is virtually the same in all three cases. In contrast, CB energy use is higher when calculated with WIOD16BC than with WIOD13 or WIOD16AC. Furthermore, WIOD16AC closely follows WIOD13 for the CB indicator until 2005 after this WIOD16AC is lower than WIOD13. PB has been declining from 2009, and CB has been on a declining trend since 2005.

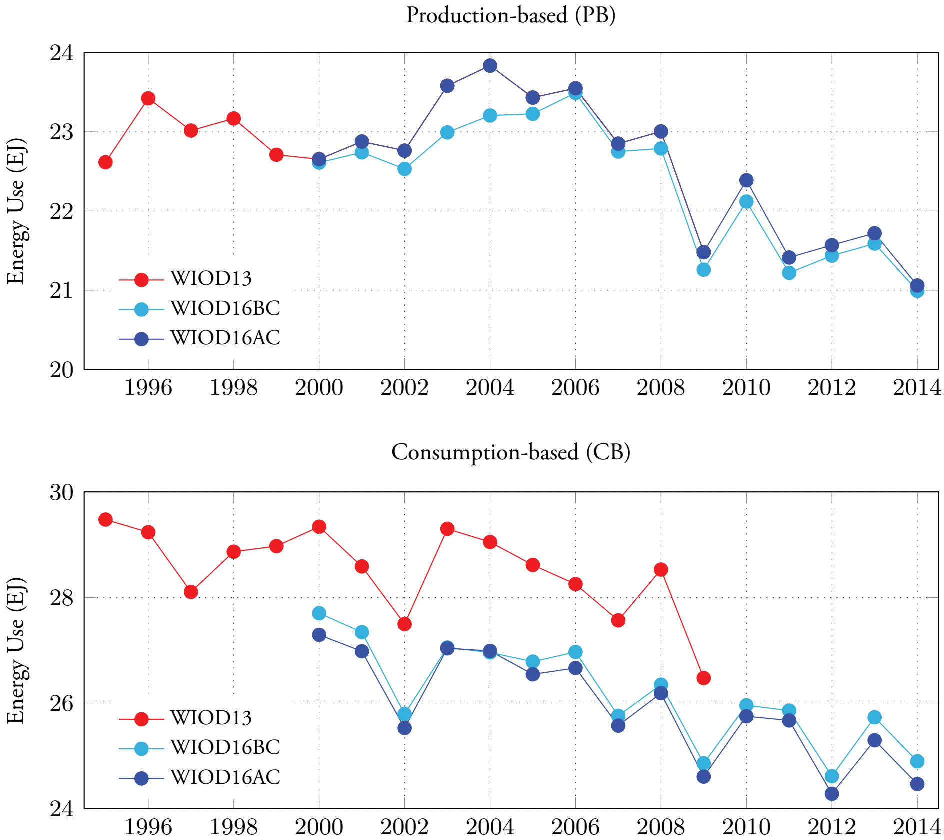
Figure 3: PB and CB Energy Use for Japan, WIOD13 vs. WIOD16BC vs. WIOD16AC





The results for Germany displayed in Figure 4 show a slightly different story. PB estimates are very similar according to WIOD13, WIOD16BC and WIOD16AC. However, CB results are different in the sense that WIOD16BC and WIOD16AC are closely linked and display lower values than WIOD13, which is opposite to the deviations seen in the case of the USA and Japan.

Figure 4: PB and CB Energy Use for Germany, WIOD13 vs. WIOD16BC vs. WIOD16AC



4.3 Differences Between WIOD13 and WIOD16AC Energy Footprint

As noted earlier, the production-based (PB) energy use has been adjusted to be the same between WIOD13 and WIOD16AC. However, the differences for consumption-based (CB) energy can occur due to different industry (56 sectors in WIOD16 vs. 35 sectors WIOD13) and country (44 countries in WIOD16 vs. 41 countries in WIOD13) aggregations. To show the scale of these variations, the differences between WIOD13 and WIOD16AC CB energy use for all countries over the period 2000–2009 are shown in Figure 5. The results are sorted from the highest positive difference to the lowest.

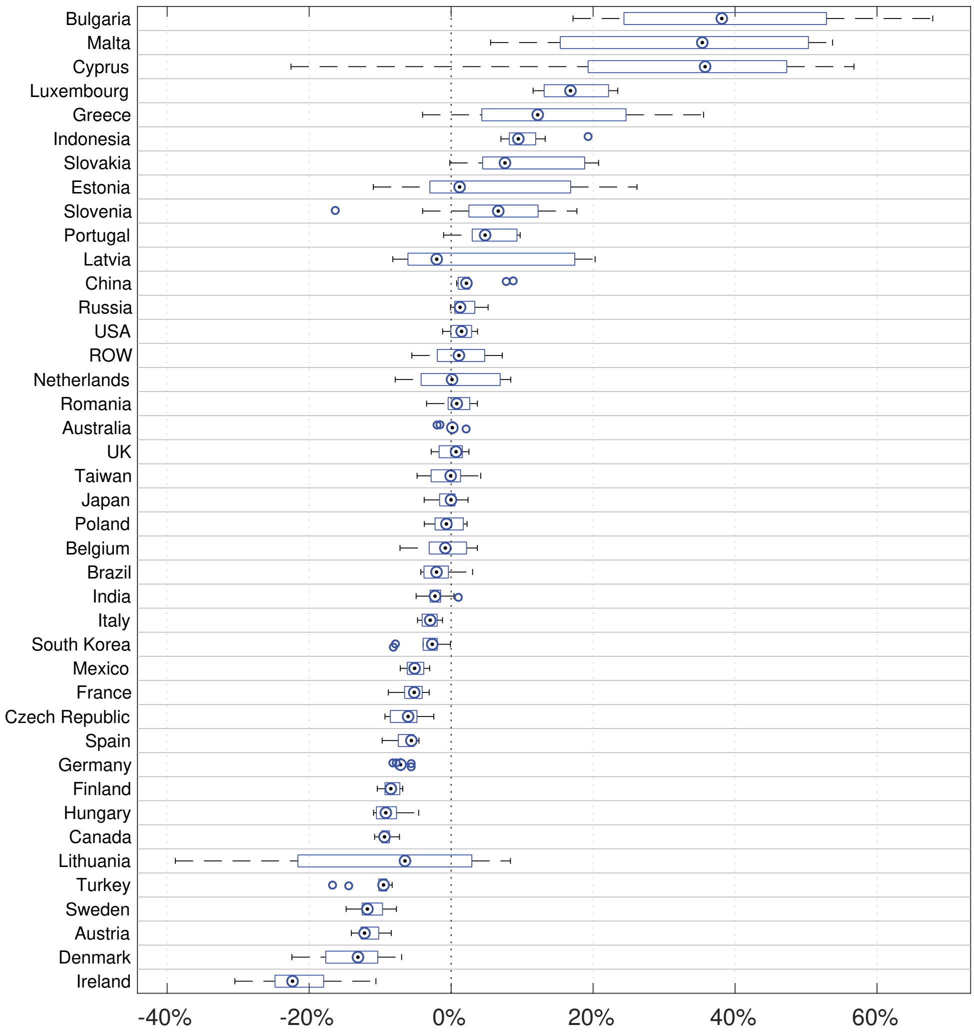
For countries at the top of the graph, CB results are higher when calculated using WIOD16AC; and for countries at the bottom of the graph, the CB results are lower. Bulgaria, Malta and Cyprus are outliers in this sample. WIOD16AC CB energy use is on average 30-40% higher than in WIOD13. These countries also display a high degree of variation (0–55%) in the results. This implies that in some years the results are quite similar, while in others they differ substantially. A high degree of variation in the results is also visible for Greece, Slovakia, Estonia, Slovenia, Latvia and Lithuania. For China, Russia, and the USA CB estimates are on average 1.5-3% higher and do not vary much over the years.

Another set of countries including the Netherlands, Romania, Australia, the UK, Taiwan, Japan and Poland do not show significant differences between different databases. The results for these countries are within ±1%.

The remaining countries at the bottom part of Figure 5 display CB results that are lower when calculated using WIOD16AC. For most countries, the estimates vary between 0 and 10%. A few notable exceptions are Sweden, Austria, Denmark and Ireland. For these countries, WIOD16AC CB estimates are more than 10% lower compared to WIOD13. The majority of the countries with lower CB estimates are EU countries.

The differences between the two databases could be due to several reasons. First, more detailed sectoral classification (from 35 to 56) can lead to lower estimates if disaggregated sectors (in WIOD16AC) have different energy intensities and imports occur predominantly from a sector with a lower intensity. Second, a more detailed country classification can lead to the same outcome if imports come from a country with lower energy intensities than the Rest of the World (RoW) aggregate. Finally, the differences in how IO tables and Energy accounts have been compiled also play a role.

Figure 5: Difference Between WIOD13 and WIO16AC Energy Footprint (CB), 2000–2009



4.3.1 Global Energy Use Trends 2000-2014

CB and PB energy use on per capita basis for the years 2000 vs. 2014 and the change (in %) over the period 2000-2014 are presented in Table 6 for all countries covered by WIOD16. The results for both PB and CB show substantial variations across countries.

Table 6: PB vs. CB Energy Use Per Capita, 2000 and 2014 (in GJ)

	PB			CB		
	2000	2014	△%	2000	2014	△%
Australia	333	335	0.4	342	455	33.0
Austria	224	230	2.7	302	296	-1.9
Belgium	429	354	-17.5	413	345	-16.6
Bulgaria	151	168	11.1	167	142	-15.1
Brazil	75	97	29.6	82	107	30.5
Canada	556	527	-5.3	430	484	12.4
Switzerland	221	196	-11.2	372	337	-9.3
China	51	123	143.6	47	115	143.0
Cyprus	178	102	-42.8	194	233	20.2
Czech Republic	241	246	1.8	218	212	-2.6
Germany	276	260	-5.6	332	302	-8.9
Denmark	309	267	-13.5	337	313	-7.2
Spain	210	185	-11.7	233	188	-19.3
Estonia	201	276	37.3	287	277	-3.5
Finland	443	437	-1.4	396	381	-3.8
France	279	225	-19.5	313	274	-12.4
Great Britain	260	184	-29.1	324	269	-17.0
Greece	216	217	0.5	349	223	-36.0
Croatia	142	125	-11.7	147	135	-8.6
Hungary	158	156	-1.3	162	145	-10.4
Indonesia	43	48	13.3	40	61	51.8
India	25	40	61.0	24	36	52.4
Ireland	221	170	-22.7	272	246	-9.4
Italy	221	167	-24.6	284	198	-30.4
Japan	294	257	-12.6	365	295	-19.2
South Korea	328	407	24.0	278	318	14.6
Lithuania	173	229	32.2	236	218	-7.9
Luxembourg	398	367	-7.6	675	639	-5.3
Latvia	90	115	27.6	170	184	8.2
Mexico	101	97	-4.5	116	109	-5.7
Malta	150	181	20.2	407	236	-42.1
Netherlands	478	440	-8.0	332	281	-15.4
Norway	508	449	-11.6	426	470	10.3
Poland	149	161	8.2	156	159	2.0
Portugal	171	160	-6.4	231	174	-24.4
Romania	107	107	0.6	94	117	24.7
Russia	297	366	23.2	176	272	54.3
Slovakia	216	196	-9.2	215	202	-6.2
Slovenia	169	164	-2.8	295	236	-20.2
Sweden	420	368	-12.4	391	356	-9.0
Turkey	76	95	25.1	95	116	22.5
Taiwan	289	343	18.6	287	238	-17.1
United States	525	461	-12.2	614	510	-16.8
Rest of World	65	71	8.6	53	67	28.2

Developed economies, in general, have higher PB and CB than developing countries. The USA, Canada and many European countries have PB and CB of more than 350 GJ/per capita. In contrast, India has about ten times lower PB and CB, accounting for roughly 35 GJ/per capita. China had the highest PB and CB growth in the sample – both measures increased by 143% between 2000 and 2014 – but the levels in 2014 are still less than half of the values for developed countries.

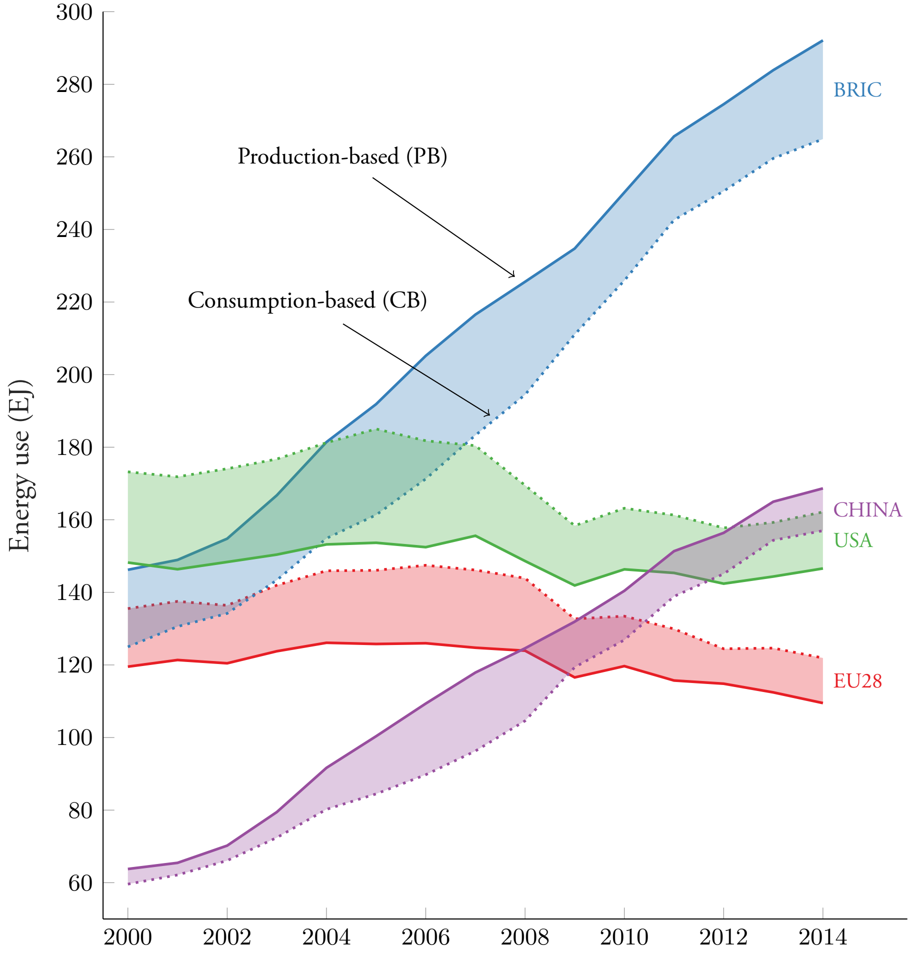
Figure 6 displays PB (solid line) and CB (dashed line) results over the period 2000-2014 for selected countries and regions. The area between the two lines represents net import (net export) of energy embodied in trade (aka BEET). The solid line being above the dashed line implies that a country/region is a net importer of energy, and the dashed line being above the solid one implies that a country is a net exporter of energy.

The BRIC countries and China are net exporters of energy. More energy is embodied in exports of goods and services than in imports. For the USA and the EU28, the result is the opposite. Furthermore, BRIC and China display an increasing PB and CB trend, while the USA and the EU28 show stable or declining trend (especially for the EU28).

The difference between PB and CB (the shaded area between the two lines) has contracted for EU28, the USA and China since about 2008. This implies that the energy content in trade has become more balanced over time. This study does not investigate the exact reason why this has happened, but this could be due to: changes in the volume of trade (e.g. EU28 imports or exports less than before); due to changes in technology (e.g. a basket of EU28 imports has become less energy intensive because exporting countries have improved their energy technology); or due to changes in the structure of trade (e.g. a basket of EU28 imports has shifted towards less energy intensive goods).

It is also apparent that PB and CB are closely correlated. An increase or decline in one measure is followed by a similar change in the other. For instance, CB for BRIC in 2012 was about the same as PB for BRIC in 2010. For the EU28 and the USA, these changes are less visible because the rate of change in the two measures is much slower.

Figure 6: PB and CB Energy Use for Selected Countries/Regions, 2000–2014



Notes: Solid line denotes Production-based (PB) and dotted line shows Consumption-based (CB) energy use.

5 Discussion and Conclusions

The aim of this paper is to construct energy accounts for the WIOD 2016 release and present the main trends in global energy use for 2000–2014 with a particular focus on the period after 2009, for which research on energy footprints is lacking.

The newly constructed WIOD16BC energy accounts are compared with the existing WIOD13 energy accounts for the period 2000–2009, the period for which the two databases overlap. This exercise shows the accuracy of the extended WIOD16BC energy accounts. The results show that the difference between WIOD16BC and WIOD13 energy accounts for most countries (34 out of 41) are within a 4% range. The differences are mainly due to the allocation procedure. Generally, such differences are in line with known differences between MRIO results within the IO community (Moran and Wood, 2014).

To ensure that the two databases are comparable, WIOD16BC energy accounts were calibrated to match WIOD13. Calibrated WIOD16AC energy accounts show the same PB energy use as WIOD13. However, as shown in Figure 5 CB results differ across countries. For most countries, the differences are within 5% but in some extreme cases, the differences range from -20% to +40 %. The negative difference shows by how much CB is underestimated and the positive result shows how much it is overestimated.

The exact source of these differences is not known, but a few possible explanations can be put forward. First, the differences can occur due to different sectoral and spatial aggregation. WIOD13 is more aggregated than WIOD16 both in terms of country and sector detail. The prevailing view is that the finer the level of sector disaggregation, the more accurate the results. Su and Ang (2010) use a single-country model to investigate emissions embodied in the exports of China and Singapore. They suggest that around 40 sector aggregation is sufficient to capture the majority of CO_2 emissions embodied in production. Bouwmeester and Oosterhaven (2013) show that for CO_2 emissions, aggregation errors are on average 2.3% when sectoral detail is reduced from 129 to 59 sectors and about 3.4 % when sectoral detail is reduced from 59 to 10 sectors. The spatial aggregation error is on average 1.4% when aggregating from 43 to 5 regions and 2.4% when aggregating from 5 to 2 regions. However, in most cases results differ strongly across countries, suggesting that a uniform prescription for the level of sectoral and spatial detail is not possible. Interestingly, the countries that show the largest aggregation error in the Bouwmeester and Oosterhaven (2013) study, also appear as having the most significant differences between CB estimates (see Figure 5) in this study (e.g. the Baltic countries, Cyprus, Luxembourg, Malta, Greece).

Second, the differences can occur due to different accounting conventions. The WIOD13 MRIO tables adhere to the 1993 version of System of National Accounts (SNA), and the WIOD16 release adheres to the 2008 version of SNA. The SNA 2008 version involves two major changes in the recording of international trade statistics. The first concerns changes to goods sent abroad for processing and the second to merchanting (Van De Ven, 2015). In the 1993 SNA, goods sent abroad for processing and then returned to the country from where they were dispatched are treated as undergoing an effective change of ownership and recorded as imports and exports (Timmer et al., 2016). The 2008 SNA version records transactions on the basis of a change of (economic) ownership, which means that goods processed in one country on behalf of another are not recorded as imports and exports even if they physically crossed the borders. These changes have significant consequences for the input-output tables and environmental analysis. Quantitatively, this leads to lower intermediate consumption, output, import and export estimates. For some countries, the reductions can be quite substantial (Aspden, 2008). Van Rossum et al. (2014)show that for the Netherlands, changing from SNA 1993 to SNA 2008 led to an -8.4% lower estimates for emissions embodied in imports and a +12.4% increase in the emission-trade balance. The authors conclude that new SNA 2008 concepts undermine the potential of the environmental input-output analysis.

Intensification of international trade and increasing production fragmentation over the last few decades has made countries more dependent on one another's supply of resources. As shown in Figure 6 the energy content embodied in trade remains high: PA and CB measures are highly correlated. This has important implications for the debate on the decoupling of energy use from economic growth. A prevailing hypothesis suggests that the decoupling seen from the PB perspective might be a result of production outsourcing. One way to test this hypothesis is to look at the CB energy use, which includes energy embodied in imports and deducts energy embodied in exports. Figure 6 shows that the PB and CB measures follow a similar trend, and a change in one is closely mirrored by the other. This implies that the decoupling seen in the PB case is also reflected in the CB measure. That is, PB and CB measures will have a similar shape of the so-called Environmental Kuznets curve, but the peak point will differ. The CB will peak at a higher point when CB > PB – this was the case for the USA and EU28 in Figure 6. Similarly, PB will peak higher when PB>CB – this was the case for BRIC and China as shown in Figure 6.

However, important questions remain. Why energy use changed the way it did? And how CO_2 emissions developed over the same period? Addressing these questions requires further analysis. First, to understand the driving forces of change in global energy use patterns requires structural decomposition analysis. This question has already been partially (only for renewable energy use) addressed by Dietzenbacher et al. (2019) using the dataset constructed in this study. Addressing the second question requires the construction of CO_2 satellite accounts. This type of accounts can be constructed by utilising WIOD16AC energy fuel information and applying appropriate CO_2 emissions factors. However, this task was beyond the scope of this study and remain subject to future research.

6 References

Andrew, R., Peters, G. P., and Lennox, J. (2009). Approximation and Regional Aggregation in Multi-Regional Input–Output Analysis for National Carbon Footprint Accounting. *Economic Systems Research*, 21(3):311–335.

Aspden, C. (2008). The Revision of the 1993 System of National Accounts – what does it change? *Economic & Labour Market Review*, 2(2):42—-47.

Baldwin, R. (2011). Trade and Industrialisation After Globalisation's 2nd Unbundling: How Building and Joining a Supply Chain are Different and Why It Matters.

Bouwmeester, M. C. and Oosterhaven, J. (2013). Specification and Aggregation Errors in Environmentally Extended Input-Output Models. *Environmental and Resource Economics*, 56(3):307–335.

Davis, S. J. and Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences*, 107(12):5687–5692.

Dietzenbacher, E., Kulionis, V., and Capurro, F. (2019). Measuring the Effects of Energy Transition: A Structural Decomposition Analysis of the Change in Renewable Energy Use between 2000 and 2014. *Unpublished Manuscript*.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., and De Vries, G. (2013). The Construction of World Input-Output Tables in the WIOD Project. *Economic Systems Research*, 25(1):71–98.

Fry, J. R. (2017). *Tracing waste, material and carbon flows using input-output models*. PhD thesis, University of Sydney.

Genty, A., Arto, I., and Neuwahl, F. (2012). Final Database of Environmental Satellite Accounts: Technical Report on Their Compilation. Technical report.

Geschke, A., Wood, R., Kanemoto, K., Lenzen, M., and Moran, D. (2014). Investigating alternative approaches to harmonise multi-regional input-output data. *Economic Systems Research*, 26(3):354–385.

IEA (2017). World Energy Balances 2017. Technical report, International Energy Agency.

Inomata, S. and Owen, A. (2014). Comparative evaluation of MRIO databases. *Economic Systems Research*, 26(3):239–244.

Kulionis, V. (2019). Energy accounts for the World Input Output Database (WIOD) 2016 release. Figshare.com, [online] https://doi.org/10.6084/m9.figshare.7551032.v2.

Liang, S., Liu, Z., Crawford-Brown, D., Wang, Y., and Xu, M. (2013). Decoupling Analysis and Socioeconomic Drivers of Environmental Pressure in China. *Environmental Science & Technology*, 48(1):1103–1113.

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

Miller, R. E. and Blair, P. D. (2009). *Input-output analysis : foundations and extensions*. Cambridge University Press.

Moran, D. and Wood, R. (2014). Convergence between the Eora, WIOD, EXIOBASE, and OpenEU's consumption-based carbon accounts. *Economic Systems Research*, 26(3):245–261.

Owen, A., Brockway, P., Brand-Correa, L., Bunse, L., Sakai, M., and Barrett, J. (2017). Energy consumption-based accounts: A comparison of results using different energy extension vectors. *Applied Energy*, 190:464–473.

Owen, A. E. (2015). *Techniques for evaluating the differences in consumption-based accounts*. PhD thesis, The University of Leeds.

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

Piñero, P., Bruckner, M., Wieland, H., Pongrácz, E., and Giljum, S. (2018). The raw material basis of global value chains: allocating environmental responsibility based on value generation. *Economic Systems Research*.

Steen-Olsen, K., Owen, A., Hertwich, E. G., and Lenzen, M. (2014). Effects of sector aggregation on CO_2 multipliers in multiregional input-output analyses. *Economic Systems Research*, 26(3):284–302.

Su, B. and Ang, B. (2010). Input-output analysis of CO_2 emissions embodied in trade: The effects of spatial aggregation. *Ecological Economics*, 70(1):10–18.

Timmer, M. P., Azeez Erumban, A., Los, B., Stehrer, R., and de Vries, G. J. (2014). Slicing Up Global Value Chains. *Journal of Economic Perspectives*, 28(2):99–118.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23(3):575–605.

Timmer, M. P., Los, B., Stehrer, R., and De Vries, G. J. (2016). An Anatomy of the Global Trade Slowdown based on the WIOD 2016 Release.

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

Van De Ven, P. (2015). New standards for compiling national accounts: what's the impact on GDP and other macro-economic indicators? Technical report, OECD STATISTICS BRIEF.

Van Rossum, M., Delahaye, R., Edens, B., Schenau, S., Hoekstra, R., and Zult, D. (2014). Do the new SNA 2008 concepts undermine Environmental Input Output Analysis. In *Conference paper 22nd International Input-Output Conference, 14-18 July 2014, Lisbon*, pages 14–18.

Wiebe, K. S. and Yamano, N. (2016). Estimating CO_2 Emissions Embodied in Final Demand and Trade Using the OECD ICIO 2015: Methodology and Results.

Wiedmann, T. and Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, 11(5):314–321.

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., and Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input-output analysis. *Ecological Economics*, 70(11):1937–1945.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J. H., Merciai, S., and Tukker, A. (2015). Global sustainability accounting-developing EXIOBASE for multi-regional footprint analysis. *Sustainability*, 7(1):138–163.

Wood, R., Stadler, K., Simas, M., Bulavskaya, T., Giljum, S., Lutter, S., and Tukker, A. (2018). Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. *Journal of Industrial Ecology*, 00(0):1–12.

7 Appendix

Table A.1: World Input-Output Database 2016 Country Coverage

No	Name	Code
1	Australia	AUS
2	Austria	AUT
3	Belgium	BEL
4	Bulgaria	BGR
5	Brazil	BRA
6	Canada	CAN
7	Switzerland	CHE
8	People's Republic of China	CHN
9	Cyprus	CYP
10	Czech Republic	CZE
11	Germany	DEU
12	Denmark	DNK
13	Spain	ESP
14	Estonia	EST
15	Finland	FIN
16	France	FRA
17	United Kingdom	GBR
18	Greece	GRC
19	Croatia	HRV
20	Hungary	HUN
21	Indonesia	IDN
22	India	IND
23	Ireland	IRL
24	Italy	ITA
25	Japan	JPN
26	Republic of Korea	KOR
27	Lithuania	LTU
28	Luxembourg	LUX
29	Latvia	LVA
30	Mexico	MEX
31	Malta	MLT
32	Netherlands	NLD
33	Norway	NOR
34	Poland	POL
35	Portugal	PRT
36	Romania	ROU
37	Russian Federation	RUS
38	Slovakia	SVK
39	Slovenia	SVN
40	Sweden	SWE
41	Turkey	TUR
42	Taiwan	TWN
43	United States	USA
44	Rest of World	ROW

Table A.2: World Input-Output Database 2016 Sectoral Coverage

No	Name	Code
1	Crop and animal production, hunting and related service activities	A01
2	Forestry and logging	A02
3	Fishing and aquaculture	A03
4	Mining and quarrying	B
5	Manufacture of food products, beverages and tobacco products	C10-C12
6	Manufacture of textiles, wearing apparel and leather products	C13-C15
7	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	C16
8	Manufacture of paper and paper products	C17
9	Printing and reproduction of recorded media	C18
10	Manufacture of coke and refined petroleum products	C19
11	Manufacture of chemicals and chemical products	C20
12	Manufacture of basic pharmaceutical products and pharmaceutical preparations	C21
13	Manufacture of rubber and plastic products	C22
14	Manufacture of other non-metallic mineral products	C23
15	Manufacture of basic metals	C24
16	Manufacture of fabricated metal products, except machinery and equipment	C25
17	Manufacture of computer, electronic and optical products	C26
18	Manufacture of electrical equipment	C27
19	Manufacture of machinery and equipment n.e.c.	C28
20	Manufacture of motor vehicles, trailers and semi-trailers	C29
21	Manufacture of other transport equipment	C30
22	Manufacture of furniture; other manufacturing	C31_C32
23	Repair and installation of machinery and equipment	C33
24	Electricity, gas, steam and air conditioning supply	D35
25	Water collection, treatment and supply	E36
26	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	E37-E39
27	Construction	F
28	Wholesale and retail trade and repair of motor vehicles and motorcycles	G45
29	Wholesale trade, except of motor vehicles and motorcycles	G46
30	Retail trade, except of motor vehicles and motorcycles	G47
31	Land transport and transport via pipelines	H49
32	Water transport	H50
33	Air transport	H51
34	Warehousing and support activities for transportation	H52
35	Postal and courier activities	H53
36	Accommodation and food service activities	I
37	Publishing activities	J58
38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	J59_J60
39	Telecommunications	J61
40	Computer programming, consultancy and related activities; information service activities	J62_J63
41	Financial service activities, except insurance and pension funding	K64
42	Insurance, reinsurance and pension funding, except compulsory social security	K65
43	Activities auxiliary to financial services and insurance activities	K66
44	Real estate activities	L68
45	Legal and accounting activities; activities of head offices; management consultancy activities	M69_M70
46	Architectural and engineering activities; technical testing and analysis	M71
47	Scientific research and development	M72
48	Advertising and market research	M73
49	Other professional, scientific and technical activities; veterinary activities	M74_M75
50	Administrative and support service activities	N
51	Public administration and defence; compulsory social security	O84
52	Education	P85
53	Human health and social work activities	Q
54	Other service activities	R_S
55	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	T
56	Activities of extraterritorial organizations and bodies	U
57	Households	HH

Table A.3: IEA and WIOD2016 Energy Product Correspondence

No	WIOD16 energy	IEA energy Product
1	HCOAL	Anthracite; Coking coal; Other bituminous coal; Sub-bituminous coal; Patent fuel
2	BCOAL	Lignite; Coal tar; BKB; Peat; Peat products; Oil shale and oil sands
3	COKE	Coke oven coke; Gas coke
4	CRUDE	Crude oil; Natural gas liquids; Refinery feedstocks; Additives/blending components; Other hydrocarbons
5	DIESEL	Gas/diesel oil excl. biofuels
6	GASOLINE	Motor gasoline excl. biofuels
7	JETFUEL	Aviation gasoline; Gasoline type jet fuel; Kerosene type jet fuel excl. biofuels
8	LFO	Light Fuel oil
9	HFO	Fuel oil
10	NAPHTA	Naphtha
11	OTHPETRO	Refinery gas; Ethane; Liquefied petroleum gases (LPG); Other kerosene; White spirit & SBP; Lubricants; Bitumen; Paraffin waxes; Petroleum coke; Other oil products
12	NATGAS	Natural gas
13	OTHGAS	Gas works gas; Coke oven gas; Blast furnace gas; Other recovered gases
14	WASTE	Industrial waste; Municipal waste (renewable); Municipal waste (non-renewable)
15	BIOGASOL	Biogasoline; Other liquid biofuels
16	BIODIESEL	Biodiesels
17	BIOGAS	Biogases
18	OTHRENEW	Primary solid biofuels; Charcoal
19	ELECTR	Electricity
20	HEATPROD	Elec/heat output from non-specified manufactured gases; Heat output from non-specified combustible fuels; Heat
21	NUCLEAR	Nuclear
22	HYDRO	Hydro
23	GEOTHERM	Geothermal
24	SOLAR	Solar photovoltaics; Solar thermal
25	WIND	Wind
26	OTHSOURC	Tide, wave and ocean; Other sources
27	LOSS	

Paper 4

Decoupling or Delusion? Measuring Emissions Displacement in Foreign Trade

Jiborn, M., Kander, A., Kulionis, V., Nielsen, H., and Moran, D. (2018) Decoupling or delusion? Measuring emissions displacement in foreign trade, *Global Environmental Change*, 49:27–34

Abstract

In a world where climate goals are global but action remains firmly in the hands of states, reliable methods are needed to ensure that emissions reductions on a national level are not offset by carbon leakage. Appropriate indicators are needed to help policy makers set accurate targets for the carbon balance of their foreign trade and monitor the development of trade in a meaningful way. This paper proposes a new displacement indicator – the technology adjusted balance of emissions embodied in trade – that improves on existing ideas by separating out the effects of scale and composition of trade from the effects of different technologies and energy systems. The new indicator is calculated for Swedish and UK trade from 1995 to 2009, a period when both countries have reported decreasing territorial emissions together with sustained economic growth. One key finding is that, for both countries, outsourcing of emissions is less serious than what conventional analysis of emissions embodied in trade suggests. For Sweden, the technology adjusted balance of emissions embodied in trade is positive throughout the studied period, implying that its exports reduce emissions abroad more than what is generated by its imports. However, we also find that both countries have changed the composition of their imports and exports during this period: imports have become more carbon intensive and, exports less so, compared to the world economy at large.

Keywords

Carbon Accounting, Carbon Footprints, Carbon Leakage, Decoupling, Emissions Displacement, Emissions Embodied in Trade, Global Climate Policy, Input-output Analysis, Index Decomposition

1 Introduction

Over the last few decades several industrialized countries, among them the UK and Sweden, have reported substantial reductions in territorial carbon emissions in combination with sustained economic growth. This has been interpreted as a successful decoupling of economic growth from carbon emissions (Andersson and Lövin, 2015; Evans, 2015; Aden, 2016).

Many studies, however, (Barrett et al., 2013; Davis and Caldeira, 2010; Peters et al., 2011; Li and Hewitt, 2008; Peters and Hertwich, 2008; Wiedmann et al., 2010) have shown that industrialized countries, including the UK and Sweden, are large net importers of carbon emissions embodied in traded goods. It has been suggested that the observed reductions of territorial emissions are largely the result of displacement rather than examples of real decoupling (Davis and Caldeira, 2010; Aichele and Felbermayr, 2015; Peters et al., 2012; Baiocchi and Minx, 2010).

To determine to what extent emissions reductions are due to actual decoupling and to what extent they result from displacement we need a reliable method for analyzing carbon transfers in international trade flows. In this paper, we argue that established methods fail to distinguish properly between different drivers of imbalances in flows of embodied emissions and are therefore potentially misleading. We propose a new method that is better suited to the task. We calculate the indicator for two representative countries to shed new light on the decoupling versus displacement controversy.

The issue is important for many reasons. If countries can meet their emissions targets by outsourcing carbon intensive production this may seriously undermine the efficiency of global climate policy. Conversely, widespread suspicion that national climate mitigation efforts are offset by carbon leakage may undermine the legitimacy of ambitious climate policies.

Spotting carbon leakage has been one motivation behind the development of consumption based carbon accounting methods in recent years (Davis and Caldeira, 2010). But the fact that a country is a net importer of emissions embodied in trade is not by itself evidence of emissions displacement.

Emissions displacement means that a country's foreign trade contributes to: (i) reduced domestic emissions, and (ii) increased emissions abroad, compared to a no-trade scenario with the same domestic and foreign consumption.

If a country's domestic production, and hence its export, is dominated by light (i.e. low carbon intensity) industry while heavy (i.e. high carbon intensity) industrial goods are imported, this will cause a net increase in direct emissions abroad and a net decrease in domestic emissions, compared to a no trade scenario with the same consumption pattern, and it can therefore be characterized as emissions displacement.

Net embodied imports or exports can also result from general differences in the carbon intensity of production between trading partners that do not contribute to increased emissions abroad. If a country has a more carbon-efficient production or energy system than its trading partners, even an exchange of exactly identical bundles of goods will result in a deficit in emissions embodied in trade (Jakob and Marschinski, 2012).

Kander et al. (2015) show that this latter case holds even if the more carbon-efficient country specializes in more energy intensive goods than what it imports. The exchange thereby results in a net reduction of the trading partner's as well as total global emissions. Clearly, it would be misleading to characterize this type of international exchange as emissions displacement.

To correctly identify emissions displacement, we must separate the effects of scale and composition of exports versus imports from the effects of general differences in carbon intensity between trading partners. Structural decomposition analysis provides a useful tool for this purpose (Copeland and Scott Taylor, 1994; Pan et al., 2008; Xu et al., 2011; Xu and Dietzenbacher, 2014; Zhang, 2012). Jakob and Marschinski (2012) identify four determinants of the flow of embodied emissions in international trade: (i) trade balance; (ii) trade specialization; (iii) average energy intensity of production in the entire economy, compared to that of trading partners; and (iv) average carbon intensity of energy in the entire economy, compared to that of trading partners.

We will argue, however, that decomposing the balance of emissions embodied in trade in this way is not sufficient to solve the problem. This has to do with the definition of trade specialization. On the export side, specialization is defined as the ratio between the carbon intensity of exports and the carbon intensity of the domestic economy at large. On the import side, it is the ratio between the carbon intensity of the imported goods and the carbon intensity of the world economy minus the importing country.

This definition of trade specialization corresponds to standard usage in international trade theory, and would be unproblematic in the present context if the relative differences in carbon intensity between sectors were the same for all countries, and if export constituted the same share of each country's economy. But clearly this is not always the case. As a result, exchange of identical goods between two countries may technically be considered as trade specialization, given that the carbon intensity of the traded goods, relative to the rest of the exporting country's economy, differs. But clearly such exchange does not contribute to increased emissions in any of the two countries, and hence does not amount to emissions displacement.

For example, Sweden has a very carbon efficient energy system compared to the world average. But

10 per cent of domestic emissions and 20 per cent of emissions embodied in Swedish exports are not energy related but result from industrial processes, particularly in the steel and cement industries. In the steel industry, the major source of carbon emissions is the use of coke as a reduction agent in the production of pig iron from iron ore. The same reduction process is standard in steel industries all over the world, but due to Sweden's low carbon energy system, process related emissions make up a much larger share of total carbon emissions in the Swedish steel industry. As a result, even if the absolute carbon intensity in the Swedish steel industry is lower than the world average, its relative carbon intensity compared to the Swedish economy at large is substantially higher than the corresponding relative carbon intensity of the average steel industry compared to the world economy.

An exchange of identical steel products between Sweden and the world market will therefore be considered as Swedish trade specialization in carbon intensive goods on the export side and less carbon intensive goods on the import side. But such exchange of identical goods will not, of course, affect carbon emissions neither in Sweden nor outside. Trade specialization in this sense, therefore, is not a reliable indicator of carbon displacement.

To avoid this problem, and cancel out noise stemming from general differences in carbon efficiency between countries, we propose an analysis where relative carbon intensities of exports and imports are standardized by using the world average carbon intensity for each sector (Kander et al., 2015; Domingos et al., 2016; Kander et al., 2016), and both imports and exports are compared with the carbon intensity of the world economy. In this way, any imbalances in trade related emissions can be attributed to either scale or composition of exports and imports.

This can provide policy makers with options for setting targets for the carbon balance of their foreign trade, and to be able to monitor the development of trade related emissions transfers in a meaningful way.

The technology adjustment suggested here could be seen as a correlate to factor adjustments that have been proposed in international trade theory in order to align theoretical predictions on factor content of trade with empirical observations in the presence of differences in factor productivity between countries (Davis and Weinstein, 2001; Choi and Krishna, 2004; Reimer, 2006; Maskus and Nishioka, 2009; Trefler and Zhu, 2010; Jakob and Marschinski, 2012).

In our context, the 'factor content' – carbon emissions – is an external cost and the idea is not primarily to test trade theoretical hypotheses. The adjustment suggested here serves instead to align national carbon accounting with effects on global emissions, in order to provide better feedback for policy makers.

To test the method, we apply it to Sweden and the UK. The reason for focusing on these two countries is that they have been put forward in the debate as examples of countries that have successfully decoupled economic growth from carbon emissions, providing evidence that a transition to a low carbon economy can be achieved without large economic sacrifice. For example, the Swedish government has claimed that the Swedish case "provides strong evidence that decoupling GDP growth from CO_2 emissions is possible" (Andersson and Lövin, 2015).

Sweden and the UK are similar in many respects, but there are also important differences in energy mix, production technologies and export composition, suggesting that a comparison between them may both shed light on the general decoupling/displacement controversy and generate relevant insights into how these differences affect displacement effects.

Table 1 shows that, regarding carbon intensity of energy and energy intensity, the UK is very similar to the average European Union country, whereas Sweden has a much more energy intensive economy, more similar to the world average than to other European countries. At the same time the carbon intensity of the Swedish energy mix is less than half of that of the UK, the EU or the world average.

Trade also makes up a very large share of the Swedish economy, compared to the UK, the EU or the world at large, and since a large proportion of Swedish export is in energy heavy basic industrial products such as steel and forestry, differences in carbon intensity of energy could have a great impact on the carbon balance in trade.

Table 1: Summary of Trade, Energy and Carbon Statistics for the UK, Sweden, EU and World

	Trade (% of GDP)	CO_2 intensity (kg per kg of oil equivalent)	Energy intensity (MJ/$2011 PPP GDP)	Electricity sources		
				oil, gas and coal (% of total)	hydroelectric (% of total)	nuclear (% of total)
Sweden						
1995	70	1.10	7.69	5	46	47
2000	82	1.04	6.10	3	54	39
2005	85	1.00	5.81	2	46	46
2009	83	0.95	5.01	3	48	38
UK						
1995	51	2.49	5.48	71	1	27
2000	52	2.43	4.82	74	1	23
2005	52	2.44	4.19	74	1	21
2009	55	2.41	3.67	74	1	19
EU						
1995	56	2.40	5.40	54	12	32
2000	69	2.31	4.81	54	12	31
2005	70	2.25	4.60	55	10	30
2009	68	2.17	4.13	53	11	28
World						
1995	44	2.48	7.18	62	19	18
2000	51	2.46	6.49	64	17	17
2005	56	2.51	6.19	66	16	15
2009	52	2.55	5.78	67	16	13

Data Source: `data.worldbank.org`

2 Methods

2.1 Environmentally Extended Input-Output Framework

The study is conducted within the framework of environmentally extended input-output analysis. Data on trade flows and carbon emissions intensities in different production sectors and countries were retrieved from the World Input Output Database, WIOD (Dietzenbacher et al., 2013; Timmer et al., 2015), which contains detailed information on 41 countries (collectively covering about 95% of global GDP) divided into 35 sectors, including 27 EU and 13 other major economies, plus an aggregated 'rest of world' region.

WIOD is one of several MRIO databases available to input-output researchers. Other databases include the Eora, GTAP-MRIO, OECD-Tiva and EXIOBASE. We choose to use WIOD as it offers a complete set of global input-output tables and environmental satellite accounts at homogenous sectoral classification, which is critical for our analysis in order to estimate the world average technology over a long term.

Each of these databases has its own set of strengths and weaknesses. For example, the full EORA has a much higher sector resolution and extends further in time, but the sector partitioning is not homogenous, and therefore does not support comparisons with world average. The homogenous version of Eora, on the other hand, contains only 26 sectors. EXIOBASE also has higher sector resolution than WIOD, but has been published only for one year. There is a more recent release of WIOD, which covers the period 2000–2014, but as yet it does not contain environmental accounts that are needed for our purpose. The 2013 release of WIOD, which we have used, strikes a balance between sector resolution, homogeneity and time extension, which makes it suitable for the current purpose.

Emissions in traded goods are traced through the value chain, from producer to final consumer, using IO analysis developed by Leontief (1936). The standard MRIO model can be expressed as:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{F} \tag{1}$$

where, $\mathbf{x}$ is the vector of total output, $\mathbf{A}$ is the matrix of technical coefficient, $\mathbf{F}$ is the final consumption vector. Solving the above equation for $\mathbf{x}$ gives:

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

where $(\mathbf{I} - \mathbf{A})^{-1} = L$ is known as the Leontief inverse or the total requirement matrix. Its elements capture direct and indirect effects from a unit change in final demand.

Emissions embodied in trade are obtained by pre-multiplying the above equation with the carbon intensity vector, as follows:

$$\mathbf{C} = \hat{\mathbf{e}}\mathbf{L}\mathbf{F} \tag{3}$$

In more detail:

$$
\begin{bmatrix} \mathbf{c}_{11} & \cdots & \mathbf{c}_{1j} \\ \vdots & \ddots & \vdots \\ \mathbf{c}_{i1} & \cdots & \mathbf{c}_{ij} \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{e}}_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \hat{\mathbf{e}}_i \end{bmatrix} \begin{bmatrix} \mathbf{l}_{11} & \cdots & \mathbf{l}_{1j} \\ \vdots & \ddots & \vdots \\ \mathbf{l}_{i1} & \cdots & \mathbf{l}_{ij} \end{bmatrix} \begin{bmatrix} \mathbf{f}_{11} & \cdots & \mathbf{f}_{1j} \\ \vdots & \ddots & \vdots \\ \mathbf{f}_{i1} & \cdots & \mathbf{f}_{ij} \end{bmatrix} \tag{4}
$$

Where **e** is the vector of direct carbon intensities (CO_2 emissions per unit of output) for each sector and the '^' operator denotes diagonalization. The pollution matrix **C** represents emissions associated with the production of goods and services in country i to satisfy final demand in country j. Diagonal elements (i.e. $i = j$) of the **C** matrix represents domestic pollution (d) due to domestic consumption $\mathbf{c}_i^d = \mathbf{c}_{ii}$.

Energy embodied in exports, CEX_i and imports CM_i of country i can be calculated as follows:

$$
CEX_i = \sum_{j \neq i}^{n} \mathbf{c}_{ij} \tag{5}
$$

$$
CM_i = \sum_{j \neq i}^{n} \mathbf{c}_{ji} \tag{6}
$$

In the standard model, a country's balance of emissions embodied in trade (BEET), is calculated as the difference between the carbon missions embodied in its exports CEX_i, and in its imports CM_i.

$$
BEET_i = CEX_i - CM_i \tag{7}
$$

Emissions embodied in exports are all direct emissions that have occurred within the country's borders as the result of production of goods that are finally consumed somewhere else. Likewise, emissions embodied in import are all direct emissions that have occurred outside the country's borders as the result of production of goods that are finally consumed in the country.

2.2 Adjusting for Technology Differences

As we argue in the introduction, the standard concept of BEET is not suitable for analyses of emissions displacement and carbon leakage. We therefore propose an alternative indicator, where irrelevant effects of general differences in energy systems and production technologies between countries have been cancelled out, to illuminate what is really interesting: specialization in heavy or light imports and exports and monetary balance of trade. We call this a technology-adjusted balance of emissions embodied in trade (TBEET).

The basic idea of TBEET is to standardize the relative carbon intensities for similar or identical products on the import and the export side by using the average carbon intensity on the world market for each sector. This will avoid spurious effects on the balance from similar goods being imported and exported. Admittedly, also a SRIO (single-region IO table), with domestic technology assumption for imports and exports, would in principle have achieved the same goal, but the additional benefit of using world average technology is that the cardinal ranking of export and import groups in terms of carbon intensity will be correct on the world scale, and also the construct will be additive. It will also be scale invariant, i.e. it will not matter if we study the sum of nations within EU or the EU as one unit of analysis, the results will be the same.

Let subscript s denote sector s and let $o_{i,s}$ be the total output of sector s in i. The carbon intensity $e_{i,s}$ is defined as:

$$e_{i,s} = \frac{c_{i,s}}{o_{i,s}} \tag{8}$$

The world average carbon intensity e_s^{WA} can be defined as:

$$e_s^{WA} = \frac{\sum_i^n c_{i,s}}{\sum_i^n o_{i,s}} \tag{9}$$

The technology-adjusted emissions embodied in exports, which we will label CEX_i^{WA}, are defined as the emissions that i's exports would have caused if the same products had been produced with world average technology:

$$CEX_i^{WA} = \sum_{j \neq i}^{n} \mathbf{c}_{ij}^{WA} \tag{10}$$

Similarly:

$$CM_i^{WA} = \sum_{j \neq i}^{n} \mathbf{c}_{ji}^{WA} \tag{11}$$

c_{ij}^{WA} is calculated in the same way as c_{ij}, except that country specific carbon intensities e_i are replaced by world average (WA) carbon intensities e_i^{WA}, this gives $\mathbf{C}^{WA} = \widehat{\mathbf{e}^{WA}}\mathbf{Lf}$.

2.3 Decomposition

We use the additive form of the refined Laspeyres index method (RLIM) to calculate the contributions of scale and composition of exports and imports to a country's technology adjusted balance of emissions embodied in trade, TBEET. Although the additive refined Laspeyres index decomposition is not as commonly used as the logarithmic mean Divisia index method (LMDI), both methods have been widely used in decomposition studies and have the advantage of not leaving any unexplained residual term (Sun, 1998; Sun and Ang, 2000).

Jakob and Marschinski (2012) use a similar method to decompose the standard BEET, into four different drivers: (i) trade balance; (ii) trade specialization; (iii) average energy intensity of production in the entire economy, compared to that of trading partners; (iv) average carbon intensity of energy in the entire economy, compared to that of trading partners.

Since the effects of differences in energy intensity of production and carbon intensity of energy are cancelled out in our model, only the first two factors remain in our analysis. Moreover, trade specialization is given a slightly different definition in our analysis, and as we show in Section 3.2, the empirical results differ fundamentally from those of Jakob and Marschinski (2012). In their analysis, export specialization is defined as the ratio between the carbon intensity of a country's export and the average carbon intensity of its entire domestic economy:

$$sp_i = \frac{\left(\frac{CEX_i}{EX_i}\right)}{\left(\frac{C_i}{GDP_i}\right)} \tag{12}$$

If this ratio is >1, the country specializes in exporting products that are relatively carbon intensive compared to the rest of the domestic economy.

This definition of trade specialization corresponds to standard usage in international trade theory but, as we argued in the introduction, may provide misleading results when used as a tool for analyzing carbon displacement.

In our analysis, the carbon intensity of exports as well as imports is calculated on the assumption that it was produced with world average carbon intensities for each sector, and these intensities are then divided by the carbon intensity of the world economy at large:

$$sp_i^{WA} = \frac{\left(\frac{CEX_i^{WA}}{EX_i}\right)}{\left(\frac{C_w}{GDP_w}\right)} \tag{13}$$

If this ratio is >1, the country specializes in exporting products that are relatively carbon intensive compared to the world economy.

The final decomposition into two factors – specialization, $\triangle C_i^{sp}$, and trade balance, $\triangle C_i^{TB}$– can then be written as:

$$\triangle C_i^{sp} = \left(\frac{CEX_i^{WA}}{EX_i} - \frac{CM_i^{WA}}{M_i}\right) \times M_i + \frac{1}{2} \times \left(\frac{CEX_i^{WA}}{EX_i} - \frac{CM_i^{WA}}{M_i}\right) \times (EX_i - M_i) \quad (14)$$

$$\triangle C_i^{TB} = \frac{CM_i^{WA}}{M_i} \times (EX_i - M_i) + \frac{1}{2} \times \left(\frac{CEX_i^{WA}}{EX_i} - \frac{CM_i^{WA}}{M_i}\right) \times (EX_i - M_i) \quad (15)$$

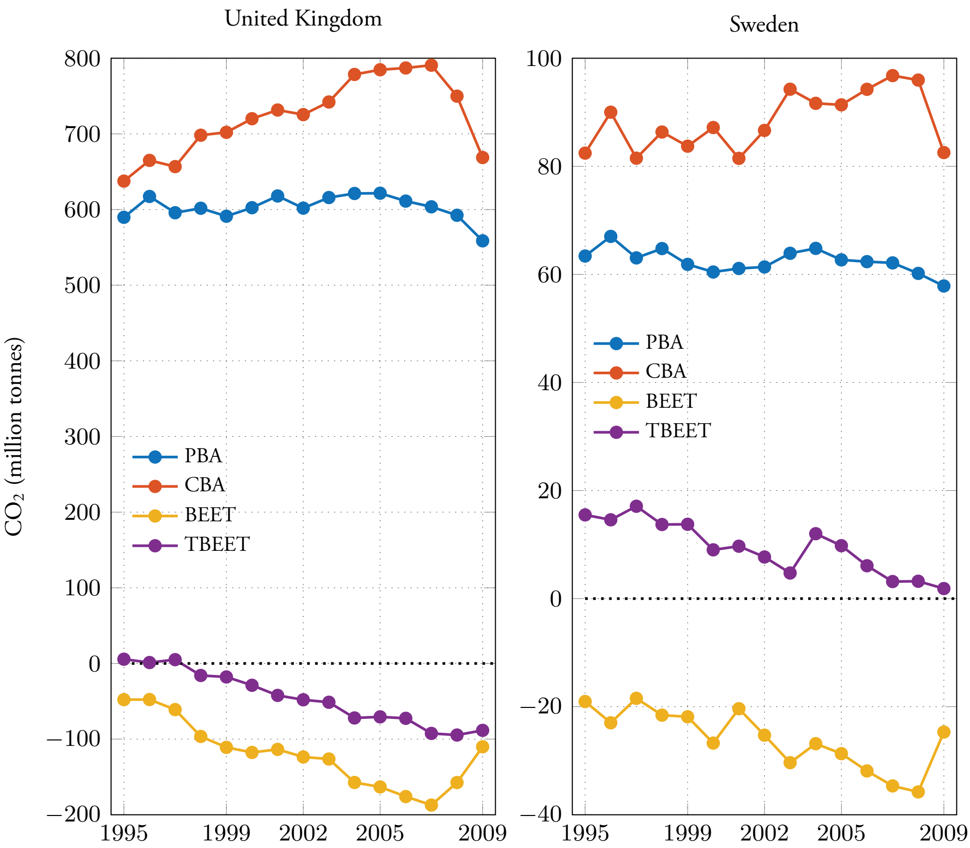
For purposes of comparison with previous results, our analysis will also include a four-factor decomposition of the standard BEET for the UK and Sweden, using the same method as Jakob and Marschinski (2012), but applied to the WIOD data.

3 Results

3.1 Development of Emissions for the UK and Sweden

Figure 1 presents production-based (PBA), and consumption-based (CBA) emissions for the UK and Sweden from 1995 to 2009. The balance of emissions embodied in trade (BEET) is equal to the difference between PBA and CBA. A negative BEET indicates net import of embodied emissions. As Figure 1 shows this is the case for the UK as well as for Sweden.

Figure 1: Swedish and UK Emissions and Emissions in Trade, 1995–2009



Notes: PBA – production based account. CBA – consumption based account. BEET – balance of emissions embodied in trade. TBEET – technology adjusted balance of emissions embodied in trade.

Figure 1 also outlines the development in the technology adjusted TBEET measure to illustrate how it differs from the traditional BEET measure.

For the UK, TBEET and BEET are both negative since 1998, but TBEET somewhat less so than BEET. This indicates a stable result with both methods, suggesting that Britain has specialized in importing more heavy goods and exporting more light products.

For Sweden, TBEET is positive in contrast to BEET that is negative throughout the whole period. But a worrying sign for policy makers is that the positive carbon balance of trade for Sweden is diminishing over time. What has happened after 2009 is not possible to say without more recent MRIO data, but a fair suspicion is that the negative trend for TBEET has continued, changing Sweden into a net displacer of carbon emissions through its international trade patterns.

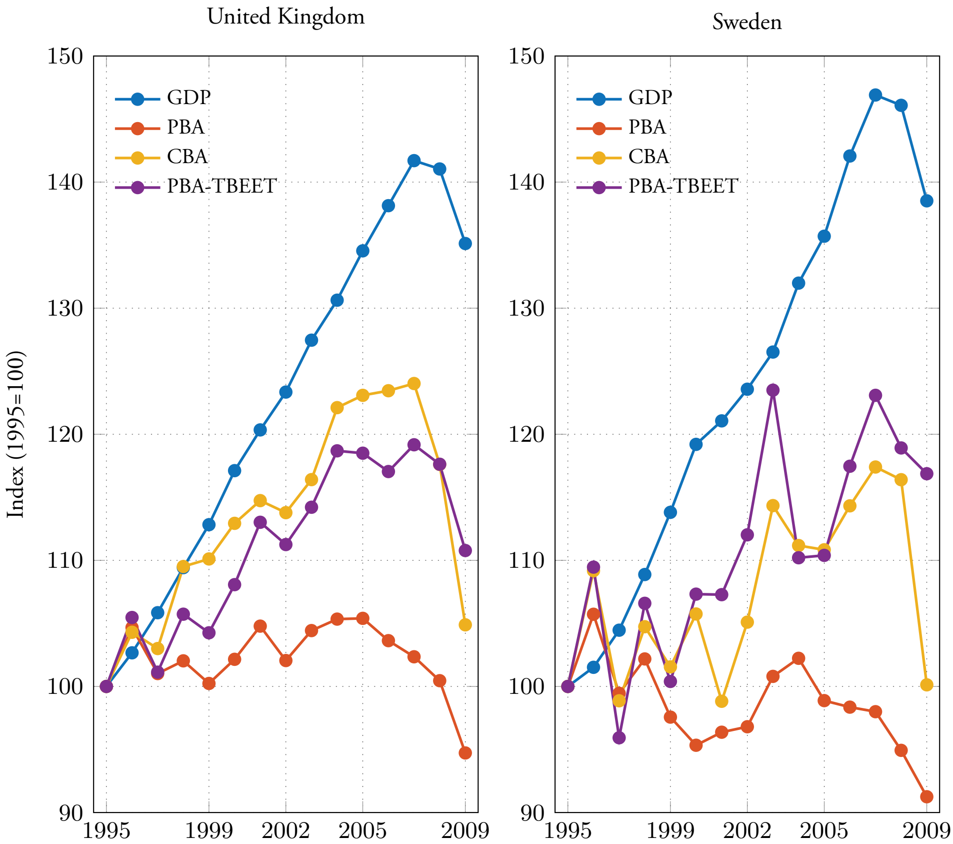
For Sweden, the BEET corresponds to 25 to 40 per cent of total emissions. The magnitude of the TBEET is smaller, corresponding to less than 25 per cent throughout the period. For the UK, the BEET corresponds to 10 to 25 percent of total emissions, whereas the TBEET is smaller than the BEET for all years except 2009, and never exceeds 15 per cent of total emissions.

For both countries, the change in TBEET over the period exceeds the decrease in production-based emissions. This clearly shows that changes in TBEET can have significant impact on emission trends.

It also implies that Swedish and UK claims to have managed to decouple economic growth from carbon emissions growth must be toned down. It is common to distinguish between absolute and relative decoupling, the former signifying an absolute reduction of emissions together with GDP growth, the latter a slower growth rate in emissions than in GDP, leading do decreasing carbon intensity of the economy albeit no reduction of absolute emissions.

Based on official records of production-based carbon emissions, both the UK and Sweden claim to show absolute decoupling. If the production-based emissions trend is adjusted for changes in TBEET, however, this is not correct.

Figure 2: Indices of GDP, Production-based (PBA), Consumption-based (CBA) and Production-based Emissions Adjusted for Displacement (PBA-TBEET) for the UK and Sweden, (Base Year 1995 = 100)



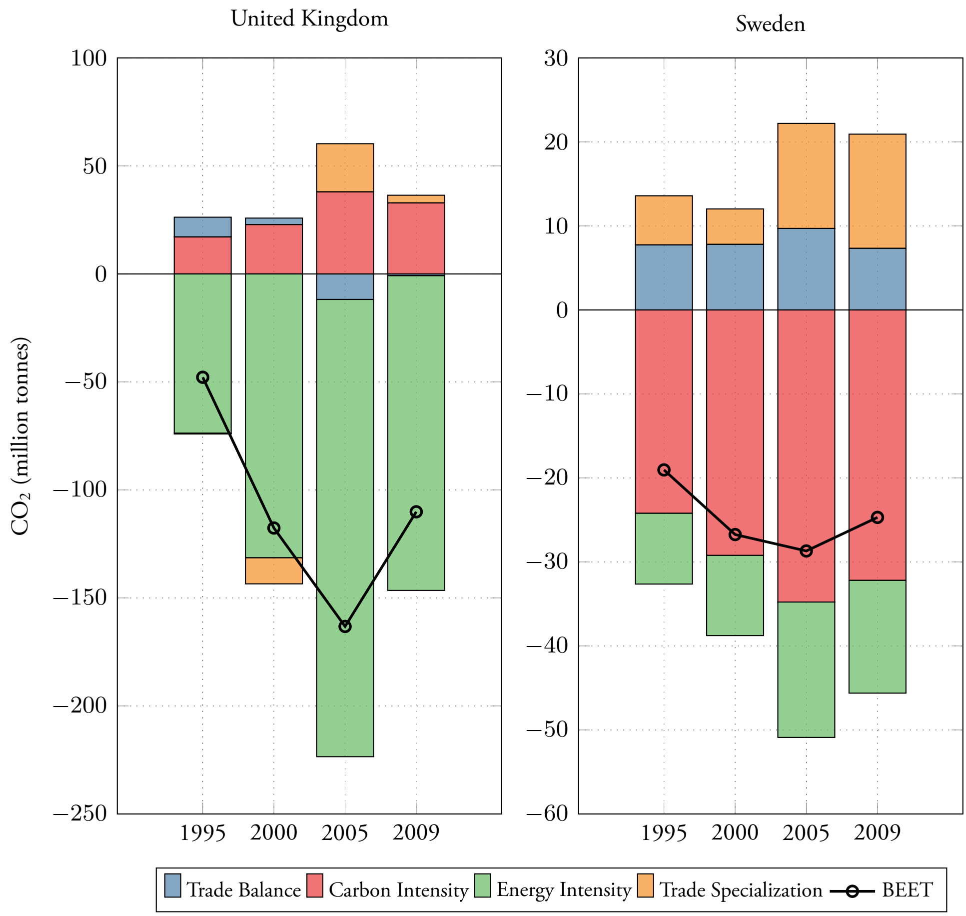
Notes: PBA – production based account. CBA – consumption based account. BEET – balance of emissions embodied in trade. TBEET – technology adjusted balance of emissions embodied in trade.

Figure 2 shows the development of GDP, production-based emissions (PBA) and PBA adjusted for displacement (PBA-TBEET) for the UK and Sweden, using 1995 as base year with index 100. As can be seen, both countries show relative decoupling, but none of them have decoupled economic growth from carbon emissions in the absolute sense.

3.2 Decomposition

For purposes of comparison, we first apply the four-factor decomposition analysis proposed by Jakob and Marschinski (2012) to the BEET of UK and Sweden. Figure 3 shows the contribution of the four different factors to the BEET for the UK and Sweden.

Figure 3: Decomposition of the BEET for the UK and Sweden Into Monetary Trade Balance, Carbon Intensity of Energy, Energy Intensity of Economy and Trade Specialization Effects



According to figure 3 it appears that the negative BEET for Sweden is driven entirely by the low energy intensity of the economy (compared to its trading partners) and the low carbon intensity of energy. Trade balance and specialization work in the opposite direction. The positive contribution of trade specialization has increased over the period, so it appears that reduced domestic emissions have been achieved together with an increased specialization towards carbon intensive exports and less carbon intensive imports. We will soon show, however, that this image changes drastically with the TBEET indicator proposed in this paper.

For the UK, the analysis suggests that the bulk of the negative British BEET is driven by energy intensity of the economy (the UK being more energy efficient than its trading partners). Trade balance and trade specialization exhibit no clear pattern.

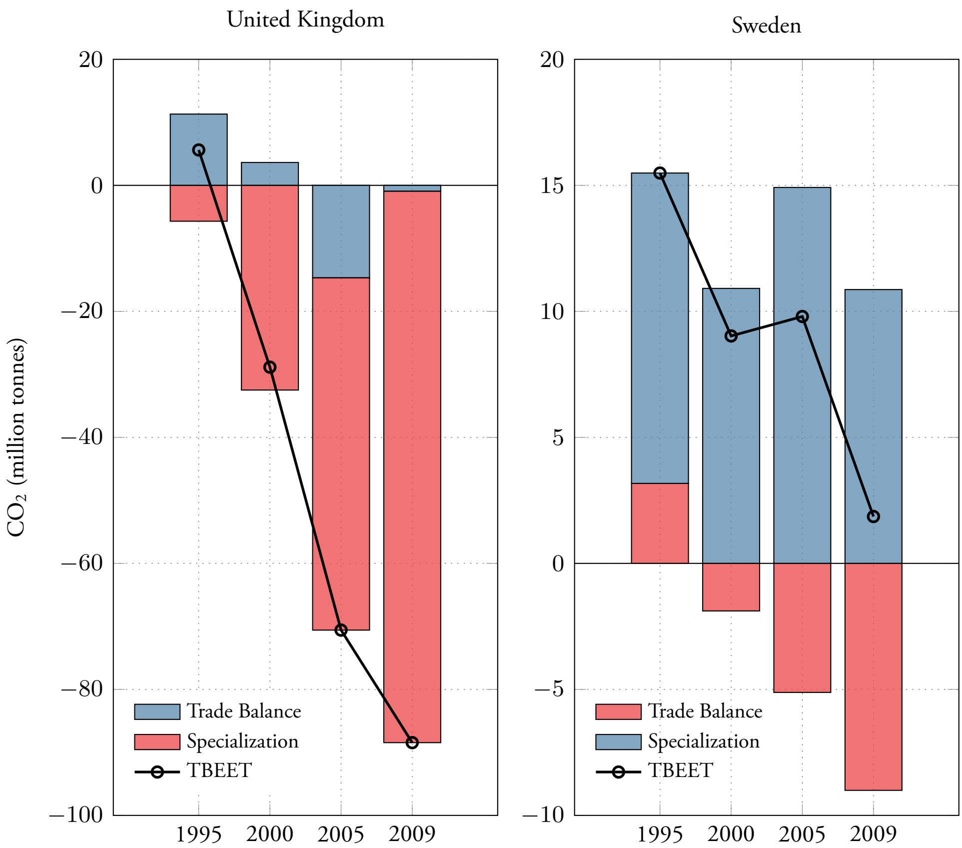
Thus, a structural decomposition analysis of the UK and Swedish BEET does not support the displacement hypothesis for any of the countries.

However, as our further analysis will show, this result is largely an effect of the standard definition of specialization, where exchange of identical products can be diagnosed as trade specialization if the relative carbon intensity of similar sectors, compared to the average carbon intensity of the whole domestic economy, vary between countries.

In our further analysis, we have therefore standardized the relative carbon intensities of each sector in export and import, by calculating carbon intensity on the assumption that all traded goods were produced with world average carbon intensity for the relevant sector, and comparing with the carbon intensity of the global economy.

The resulting technology adjusted balance of emissions embodied in trade, TBEET, can then be decomposed into only two drivers: trade balance and specialization. The result for the UK and Sweden is given in Figure 4.

Figure 4: Decomposition of the TBEET for the UK and Sweden into Monetary Trade Balance and Trade Specialization Effects



For the UK, trade specialization has a clearly negative impact and is the main driver of the increasingly negative TBEET throughout the period. The negative impact from trade specialization is also increasing over time. The impact from trade balance is much weaker and varies over the period.

This indicates that the UK is indeed outsourcing carbon emissions by importing more carbon intensive goods than it exports, and that the outsourcing of emissions is growing steadily throughout the period.

This contrasts with the conclusions suggested by the previous four-factor decomposition of the standard BEET, where the impact from British trade specialization was more ambiguous.

The contrast is even sharper in the Swedish case. For Sweden, the impact of trade specialization appeared to be positive throughout the period in the decomposition of the standard BEET. When differences in technology are completely adjusted for, the impact of specialization shows to be negative, and increasingly so over the period. Only for the first few years it is still positive, indicating that since 2002 the Swedish trade has turned from specializing in export of heavy industrial (carbon intensive) goods to importing more carbon intensive products than it exports. However, the impact from monetary trade balance outweighs the negative effect of trade specialization. The fact that Swedish TBEET remained slightly positive in 2009 is explained by a consistent positive monetary trade balance.

For both Sweden and the UK, the impact from trade specialization has thus become more and more negative over the period. This could be due to a shift in the export structure towards less energy heavy and carbon demanding products, or a shift in the import structure towards more energy heavy and carbon demanding products, or both.

Figure 5: Impact from Trade Structure for the United Kingdom and Sweden

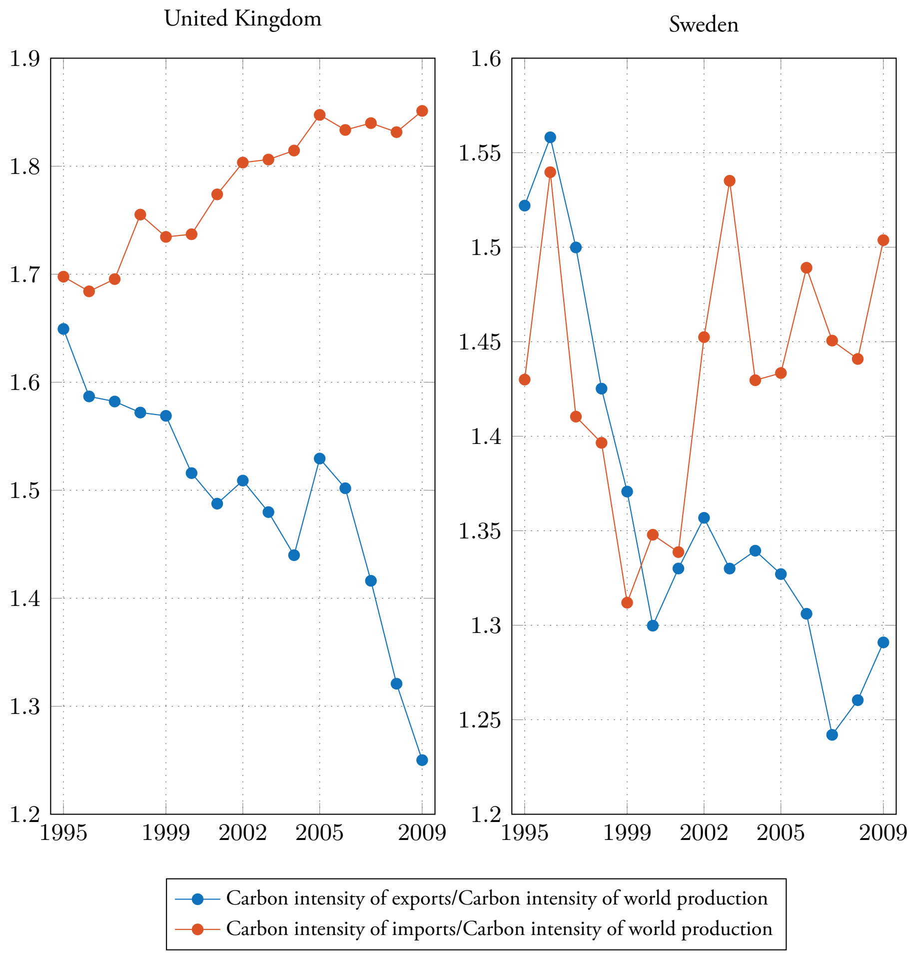


Figure 5 shows the development of the impact from trade specialization divided between imports and exports for the UK and Sweden. The analysis shows that for both countries the export structure has become less carbon intensive and the import structure more carbon intensive, although the trend is much more pronounced for the UK. This supports the conclusion that both countries have reduced domestic emissions, at least partly, by reorienting domestic production structure towards less carbon intensive goods and imports towards more carbon intensive goods.

4 Discussion

Our analysis shows that the proposed TBEET provides new and more reliable results regarding emissions displacement in international trade flows than standard balance of emissions embodied in trade.

One key observation is that, for both countries studied, outsourcing of emissions is less serious than what conventional analysis of emissions embodied in trade suggests. For Sweden, TBEET is even positive throughout the studied period, implying that there is no net displacement of carbon emissions. This means Swedish exports continue to contribute to avoiding more emissions abroad than what is caused by Swedish imports, even if this effect is declining and might switch sign in the near future (or perhaps already has, given that the most recent data are from 2009). This can be interpreted as Sweden supplying heavy products to the world that are elsewhere produced with worse carbon efficiency. For the UK, TBEET indicates some net displacement of carbon emissions, but to a lesser extent than what standard BEET analysis suggests.

Results in this study also reveal, however, that at least part of the observed reductions of production-based emissions in the UK and Sweden over the period 1995 to 2009 were offset by changes in the structure of foreign trade, which can be characterized as increased displacement. This is due to changes in the composition of imports as well as exports. The structure of imports is substantially more carbon intensive than exports for both countries at the end of the period, even when global technology differences of different commodity groups have been taken into account, and the gap is increasing.

Since our analysis covers only two nations, a limited time period and not all greenhouse gases, we cannot exclude the possibility of some real decoupling taking place in other developed economies, and certainly it does not prove that decoupling is impossible, but the analysis as such does not support the claim that absolute decoupling has taken place in the UK and Sweden in this period.

In our analysis, outsourcing of emissions can be attributed to either general trade imbalances or to the composition of export and import portfolios, or both. In the long run, however, trade imbalances also affect investment patterns: a country with a long-term trade surplus will over time invest more abroad than foreign investments within its borders. In current consumption based accounting no distinction is made between consumption and investments, so emissions related to foreign investments are accounted for as domestic consumption. This is an accounting principle that could be disputed. One possible area for future development of carbon accounting, which might contribute to a deeper understanding of how trade affects global emissions, would therefore be to develop models that separate between consumption and investments and take into account patterns of foreign investments.

It should be noted that displacement is not always bad for the global climate. If countries with more carbon intensive energy and production technologies than the world average specialize in less heavy industrial exports and instead import those commodities, this will be good for the climate. The ideal is not that all countries should have carbon neutral foreign trade. Rather, from the perspective of globally climate efficient distribution of production, each country should specialize according to comparative carbon advantages (Antweiler et al., 2001; Atkinson et al., 2011; Su and Thomson, 2016). That is, countries that are better endowed with for example renewable energy resources should focus on producing and exporting energy demanding goods – and hence show a positive TBEET – whereas countries with less renewable energy resources should focus on producing less energy demanding goods – and may therefore show a negative TBEET.

It is worrying, however, that countries like Sweden, with good access to hydropower and wind, and energy efficient production, and the UK, with energy efficient production, appear to be increasingly displacing carbon intensive production to countries that are less well-endowed in these respects. Also, for any country, it is clearly the case that any gains in domestic carbon efficiency can be lost if there is a parallel change of structure in export and import that increases displacement.

We suggest that the method of analysis proposed in this paper could serve as a useful complement to other climate policy monitoring instruments, and provide decision makers with valuable information about the global efficiency of domestic climate mitigation efforts.

After the Paris agreement, nations are faced with the challenge of living up to mitigation commitments stated in their Nationally Determined Contributions (NDCs). To this date 161 countries have submitted NDCs or Intended NDC's (INDCs). Most developed countries have submitted absolute targets for domestic emissions reductions, but some large rapidly emerging economies – most notably China and India – have submitted targets that are relative to their GDP growth, thereby allowing for increased domestic emissions in absolute terms. This mix of absolute and relative targets is probably a necessity for the agreement to be politically viable, but it also means that decision makers in countries with absolute commitments must ensure that national efforts are not offset by structural outsourcing to countries with only relative commitments.

For countries with carbon efficient energy mix and energy intensive export industries, an effective policy for reducing global emissions needs to strike a fine balance between incentivizing carbon efficiency and preserving competitiveness in those heavy industries. For such countries, policies that result in a shift to lighter production will be identified as effective from a pure CBA as well as a pure PBA perspective. The TBEET analysis shows that the real effect on global emissions might well be negative.

To avoid such counterproductive effects, national policy instruments such as carbon taxes, cap-and-trade systems and border tax adjustments should be designed to take relative carbon efficiency – as compared to similar production in other countries – into account.

5 References

Aden, N. (2016). The Roads to Decoupling: 21 Countries Are Reducing Carbon Emissions While Growing GDP.

Aichele, R. and Felbermayr, G. (2015). Kyoto and Carbon Leakage: An Empirical Analysis of the Carbon Content of Bilateral Trade. *Review of Economics and Statistics*, 97(1):104–115.

Andersson, M. and Lövin, I. (2015). Sweden: Decoupling GDP growth from CO_2 emissions is possible. The World Bank, [online at: blogs.worldbank.org].

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

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

Baiocchi, G. and Minx, J. C. (2010). Understanding Changes in the UK's CO_2 Emissions: A Global Perspective. *Environmental Science & Technology*, 44(4):1177–1184.

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

Choi, Y.-S. and Krishna, P. (2004). The Factor Content of Bilateral Trade: An Empirical Test. *Journal of Political Economy*, 112(4):887–914.

Copeland, B. R. and Scott Taylor, M. (1994). North-South Trade and the Environment. *The Quarterly Journal of Economics*, 109(3):755–787.

Davis, D. R. and Weinstein, D. E. (2001). An Account of Global Factor Trade. *American Economic Review*, 91(5):1423–1453.

Davis, S. J. and Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences*, 107(12):5687–5692.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., and De Vries, G. (2013). The Construction of World Input-Output Tables in the WIOD Project. *Economic Systems Research*, 25(1):71–98.

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

Evans, S. (2015). Analysis: UK carbon emissions fell 9% in 2014. Carbon Brief, [online at: carbonbrief.org].

Jakob, M. and Marschinski, R. (2012). Interpreting trade-related CO_2 emission transfers. *Nature Climate Change*, 3(1):19–23.

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

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

Leontief, W. (1936). Quantitative Input and Output Relations in the Economic Systems of the United States. *The Review of Economics and Statistics*, 18(3):105–125.

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

Maskus, K. E. and Nishioka, S. (2009). Development-related biases in factor productivities and the HOV model of trade. *Canadian Journal of Economics*, 42(2):519–553.

Pan, J., Phillips, J., and Chen, Y. (2008). China's balance of emissions embodied in trade: approaches to measurement and allocating international responsibility. *Oxford Review of Economic Policy*, 24(2):354–376.

Peters, G. P., Davis, S. J., and Andrew, R. (2012). A synthesis of carbon in international trade. *Biogeosciences*, 9(8):3247–3276.

Peters, G. P. and Hertwich, E. G. (2008). CO_2 Embodied in International Trade with Implications for Global Climate Policy. *Environmental Science & Technology*, 42(5):1401–1407.

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

Reimer, J. J. (2006). Global production sharing and trade in the services of factors. *Journal of International Economics*, 68(2):384–408.

Su, B. and Thomson, E. (2016). China's carbon emissions embodied in (normal and processing) exports and their driving forces, 2006-2012. *Energy Economics*, 59:414–422.

Sun, J. (1998). Changes in energy consumption and energy intensity: A complete decomposition model. *Energy Economics*, 20(1):85–100.

Sun, J. and Ang, B. (2000). Some properties of an exact energy decomposition model. *Energy*, 25(12):1177–1188.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23(3):575–605.

Trefler, D. and Zhu, S. C. (2010). The structure of factor content predictions. *Journal of International Economics*, 82(2):195–207.

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

Xu, M., Li, R., Crittenden, J. C., and Chen, Y. (2011). CO_2 emissions embodied in China's exports from 2002 to 2008: A structural decomposition analysis. *Energy Policy*, 39(11):7381–7388.

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

Zhang, Y. (2012). Scale, Technique and Composition Effects in Trade-Related Carbon Emissions in China. *Environmental and Resource Economics*, 51(3):371–389.

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