A Structural Decomposition Analysis of Global and National Energy Intensity Trends

Daniel Croner and Ivan Frankovic***

ABSTRACT

This paper analyses recent energy intensity trends for 40 major economies using a structural decomposition analysis. Our focus lies on the question whether improvements in energy intensity were caused by structural change towards a greener economy or by technological improvements. We account for intersectoral trade by using the World Input-Output database and adjust sectoral energy use via the environmentally extended input-output analysis. We find strong differences between consumption and production-based energy consumption across sectors, particularly in the construction and electricity industry. Using the three factor Logarithmic Mean Divisia Index method, our decomposition analysis shows that recent energy intensity reductions were mostly driven by technological advances. Structural changes within countries played only a minor role, whereas international trade by itself even increased global energy intensity. Compared to a previous study only using production-based sectoral energy data, we find structural effects on energy intensity reductions to be systematically weaker under consumption-based data.

Keywords: Energy Intensity, Logarithmic mean Divisia Index Decomposition, WIOD Database, Leontief Inverse

https://doi.org/10.5547/01956574.39.2.dcro

1. INTRODUCTION

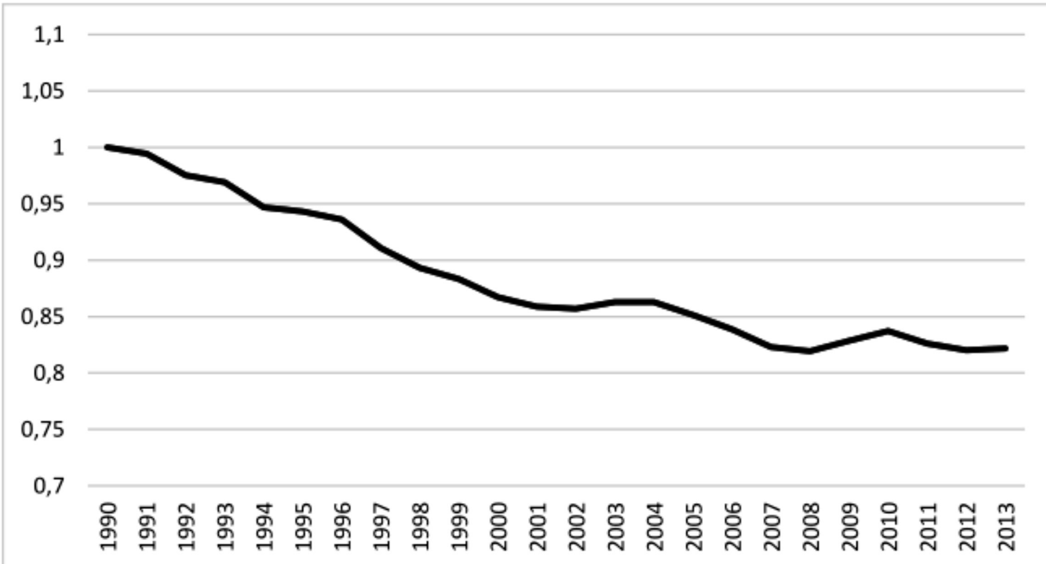
In the last decades, climate change caused by anthropogenic emissions of green house gases, particularly CO_2, has become a major concern for the world community. To a large extent, CO_2 emissions are caused by the global energy use. While ever increasing living standards lead to continuously rising energy consumption, it has also been an inevitable ingredient for economic growth, see e.g. Ayres et al. (2013). However, in order to meet the 2 degree Celsius target of the Copenhagen Accord 2009 and to avoid the possibly catastrophic consequences of even stronger global warming, countries have to reduce their carbon emissions significantly, see Chappe (2015). This requires, as we argue further below, also a substantial reduction of energy consumption. Considering the increasing energy demand that, so far, has come along with economic growth, such climate change targets and continued growth seem to be an insuperable contradiction. Nevertheless, a large body of literature on green growth suggests a way to harmonize both goals, and thus, to achieve a sustainable path of economic growth.[1]

1. For a discussion and introduction to green growth, see Bowen and Fankhaus (2011). Furthermore, OECD (2013) provides an overview of green growth policies.

* Corresponding author. University of Vienna, Faculty of Business, Economics and Statistics.) E-mail: daniel.croner@univie.ac.at.

** Wittgenstein Centre (IIASA, VID/ÖAW, WU) and Vienna Institute of Demography.

Figure 1: Development of energy intensity (ratio of global energy use to world GDP) since 1990 (base year)



Following the literature on green growth, there are at least two ways to achieve economic growth and simultaneously limit global warming. First, policy can aim at decoupling energy consumption from CO_2 emissions via the use of renewable energy. This approach has, however, so far failed on a global scale and has its limits even when taking into account future technological improvements, see Wirl and Yegorov (2015). Second, one can attempt to decouple economic growth from energy consumption and, hence, reduce the energy intensity (the ratio of energy use to output). Over the course of the last decades, the global energy intensity has been constantly decreasing (see Figure 1),[2] giving rise to some scope for this second path of green growth.

In our paper we investigate three different pathways of how the energy intensity of an economy can be reduced. First, technological progress can render production more efficient with respect to energy use. Second, the production of relatively energy-intensive goods and services can be outsourced to other countries. This approach, however, only decreases the domestic energy intensity but not necessarily global energy intensity.[3] Third, structural change within a country towards sectors with a relatively low energy use per unit of output can lower the energy intensity of the economy. In this paper we want to shed light on the question, to which extent changes in these three factors explain the decreasing global energy intensity. We do so by following an empirical approach exploiting the World Input-Output Database (WIOD), providing information about intersectoral trade within and across countries alongside with WIOD environmental accounts which entail data on sector-specific energy use. However, we adjust energy use as provided in the WIOD with respect to intersectoral trade using the environmentally extended input-output analysis (EEIOA).

2. The data in Figure 1 stems from the World Bank Indicators "GDP at market prices (constant 2010 USD)" and "Energy use (kg of oil equivalent)", available at *http://data.worldbank.org/indicator*.

3. In fact, trade can increase global energy intensity, if production is outsourced to countries with a higher energy use per output. This problematic aspect of international trade has been called Carbon Leakage in the context of CO_2 emissions. Peters et al. (2011) study the extent of international Carbon Leakage. Jakob and Marschinski (2013) discuss the implications of Carbon Leakage with respect to trade policies.

This enables us to determine the magnitude of energy use that a sector ultimately causes through its final demand by also considering energy consumption embodied in trade. We analyze the role of changes of structural shifts within economies and the world using the consumption-based approach and apply the Logarithmic Mean Divisia Index (LMDI), as proposed by Ang and Choi (1997). Additionally, we contrast our results to a decomposition using production-based energy consumption.

Our work is most importantly related to Voigt et al. (2014) who investigate to which extent energy intensity developments have been due to structural and technological change, based on an analysis of WIOD environmental accounts.[4] They find that, while structural change has played an important role in explaining energy efficiency trends in some countries, in particular in the U.S., global energy intensity has improved largely due to technological advancements. The study does not, however, adjust for energy use embodied in trade by using trade information from the WIOD and, thus, only considers the production-based perspective. Consequently, Voigt et al. (2014), solely implement an index decomposition analysis (IDA). In contrast, this paper employs a structural decomposition analysis (SDA) and uses information on intersectoral trade relationships.[5] By employing the LMDI method within a SDA framework, we are following an approach that was only recently established as traditionally LMDI is used in the context of IDAs (see Su and Ang (2012)). For example, Wachsmann et al. (2009) apply an SDA to energy use in Brazil using national input-output tables. Furthermore, Wood (2009) conducts a structural decomposition of greenhouse gas emissions in the Australian economy. Both studies use an additive LMDI decomposition method, while we resort to a multiplicative version of the LMDI to obtain a better comparability of our results to Voigt et. al (2014). An emerging literature applies the SDA to WIOD data, but differs to this paper with respect to the used decomposition method and the focus of analysis. For example, Zhong (2016) applies an averaging technique of perfect decomposition methods[6] to study emission and energy use trends. Xu and Dietzenbacher (2014) analyze global emission trends instead of energy use by employing an SDA using the WIOD. Finally, Peters et al. (2011) study CO_2 emissions embodied in trade and focus on a country-level analysis and on identifying the extent of carbon leakage. To our knowledge, a structural decomposition analysis on global energy intensity trends using the LMDI method has not been conducted yet.

More generally our analysis is based on the growing literature of structural change. A recent article from Mulder (2015) highlights the importance of structural effects in manufacturing sectors for OECD countries in the period from 1980 to 2005. He focuses particularly on the reasons of cross-country differences in energy intensity and finds that structural change is a diverging force. Metcalf (2008) investigates energy intensity trends on U.S. national and state level. At the national level he finds that roughly 75% of the reduction in energy intensity between 1970 and 2003 can be attributed to the technology effect. He also estimates that per capita income and energy prices have a significant impact on the energy efficiency within a sector but do not influence the structural composition of the economy considerably. Huntington (2010) uses a less aggregated sector structure of the U.S. economy for the period 1997 to 2006. His results indicate a much stronger structural effect: Almost 40% of energy intensity reduction are due to structural shifts. Cole et. al (2005) even find, that the technology effect within a sector led to an increase of CO_2 intensity in four European countries between 1990 and 1998. On the other hand Sun (1999) investigates CO_2 intensity trends in

4. We are able to completely reproduce the results of Voigt et al. (2014) and use them for comparison of our findings further below.

5. See Hoekstra et al. (2003) as well as Su and Ang (2012) for a discussion and comparison of IDA and SDA studies.

6. See Su and Ang (2012) for a discussion of differences with respect to the LMDI method.

the OECD countries for a long time series between 1960 and 1995 and finds that increasing energy efficiency is a main driver for declining CO_2 intensity.

Our results show that energy intensity in a number of sectors change dramatically, if we consider consumption-based data (in particularly for the construction and electricity sector). Nonetheless, the global decomposition results exhibit qualitatively similar trends as under production-based data. We find, however, that structural effects are systematically overestimated when using production-based energy data. Moreover, our analysis shows that technological improvements within the sectors are the most important factors of decreasing global energy intensity and that these primarily occurred during the times of increasing oil prices from 2004 to 2008, while structural changes within countries only modestly contributed to falling energy intensities. International trade even led to an increasing global energy intensity, indicating that production was outsourced to relatively more energy-intensive regions. On a country level, we find that the structural effect is strongly overestimated in a range of countries when using production-based data, particularly in Japan and Turkey. Our result for the U.S. indicates that the structural effect accounts for about 32% of the energy intensity decline. This result is in line with Huntington (2010), but strongly contrasts with Voigt et al. (2014) who find that structural change explains almost 80% of energy intensity decline in the U.S. between 1995 and 2007.[7] Our result, that structural change seems to be a weaker driving force of reductions in the energy intensity than previously assumed, has rather positive implications for environmental policy. As Huntington (2010) notes, such policy is more likely to have an effect on within sector efficiency than on the structural composition of the economy as the latter is often determined by other forces not easily to be influenced by policy-makers. Thus, a strong importance of technological factors in energy efficiency trends creates a possibly large role of policy interventions.

The remainder of the paper is structured as follows: In the following section the data as well as the EEIOA are introduced in detail, followed by a comparison of consumption- and production-based energy use in Section 3. Section 4 and 5 introduce the decomposition algorithm and present the main results of this study before Section 6 concludes.

2. DATA AND METHODS

Our analysis is based on the World Input-Output Database (WIOD), a public database providing time-series (covering the period from 1995 to 2011) of intersectoral input-output tables for 40 countries including a model estimation of the rest of the world. It features 35 standardized sectors, that can be further aggregated into agriculture, construction, manufacturing, electricity, transport, and service industry. The 40 countries covered in the database entail 27 member states of the European Union[8], the BRIC nations as well as other major economies such as the U.S., Canada, Australia and Japan. Together, these nations comprised more than 80 % of the world GDP in 2009.

The WIOD has been widely used in trade economics. Data from various national sources have been harmonized in order to enable comparability of data across countries. Moreover, the accompanying WIOD previous-year-prices dataset provides information on price developments on

7. The rather large difference between the result of Voigt et al. (2014) and Huntington (2010) is quite surprising considering the large overlap in the considered time period. While Huntington uses the North American Industry Classification System (NAICS) rather than the NACE classifcation applied in Voigt et al. (2014), this should nevertheless not produce such strongly differing results. As Huntington (2010) is employing the more refined NAICS sectoral structure, he should, if at all, be able to detect a stronger structural change.

8. As the WIOD was released in 2012, Croatia as the 28th member state is not included.

sectoral level, enabling us to deflate each sector independently instead of using aggregate national price deflators which lack important information on the heterogeneity of inflation in each sector.

In addition to the input-output tables, the WIOD is accompanied by environmental satellite accounts providing information about sector-specific gross energy use in terajoule (TJ), that encompasses the total energy requirements in the industry. Importantly, energy use only includes energy consumed in the production process of a given sector, while ignoring indirect energy consumption through trade of goods and services with other sectors.[9] We only use data on energy use from production and do not include household energy consumption as our main focus lies on structural effects and technology improvements within sectors.[10]

As international supply chains have been integrated to an increasing extent during the last decades (see Timmer et al. (2014)), it is necessary to account for energy transfers embodied in intersectoral and international trade to obtain a realistic picture of the energy use of a given sector. As an example, we consider the construction sector. In the WIOD environmental accounts, the energy use of the construction sector would be comprised mostly of electricity and fossil fuel consumption by vehicles and machinery deployed in construction works. While this direct energy demand by the construction sector is certainly not negligible, one would grossly underestimate the extent of energy consumption that is required for the final demand this sector is supplying if only this direct energy demand is considered. Obviously, the construction sector is heavily dependent on inputs from other sectors, such as materials from the mining and quarrying sector as well as the wood sector. Moreover, it requires heavy machinery, vehicles, and technical equipment from various manufacturing subsectors. Conversely, the output produced by the construction sector does not only satisfy final demand but also intermediate demand by other sectors. Consider as an example the manufacturing or service sector that require factories and office space for their production processes.

In our globalized economies, the interdependencies between sectors within and between countries through trade are highly developed, such that tracking indirect energy use for each sector would be a very cumbersome, if not impossible task. However, Wassily Leontief has developed a convenient method to calculate direct and indirect inputs required in the production processes of sectors, the Input-Output Analysis.[11] Moreover, he extended this method to study material and pollution flows across sectors in his seminal paper "Environmental Repercussions and the Economic Structure" (Leontief, 1970), laying the groundwork for what was later called the environmentally extended input-output analysis. This method allows us to determine the total energy use of a sector, based not only on its direct but also on the indirect energy consumption. The method translates production-based sectoral energy use as given in the WIOD environmental accounts, denoted by the vector e, into consumption-based energy use ($\tilde{e}$) and is described by

$$\tilde{e} = c(I - A)^{-1}\hat{y}, \tag{1}$$

where $\hat{y}$ is the diagonal matrix of the consumption vector y, x is industry-specific output, $c = e \oslash x$ is the energy coefficient, which indicates how much energy is needed for one unit of output ($\oslash$ denotes element-wise division) and A is the matrix of technological coefficients carrying information on

9. The WIOD and its accompanying environmental accounts are freely available at http://www.wiod.org. While this paper provides a short introduction on the use of input-output tables, detailed information on the database is provided in Timmer et al. (2015). Extensive documentation about the construction of the WIOD is compiled in Dietzenbacher et al. (2013). A technical report on the environmental accounts is provided by Genty (2012).

10. Here, we follow Xu and Dietzenbacher (2014) who took a similar approach in their analysis of global CO_2 emissions trends.

11. Leontief (1936) introduced the Input-Output Analysis for the first time.

Table 1: Summarized Country and Sector Statistic

Year	Mean	Std.dev	Min	Max	Mean	Std.dev	Min	Max
	Production Based Energy Use - Country Statistic				**Production Based Energy Use - Sector Statistic**			
1995	1.25e+07	2.48e+07	60551.79	1.21e+08	1.46e+07	3.46e+07	11011.24	1.62e+08
2002	1.40e+07	2.77e+07	67056.23	1.32e+08	1.64e+07	3.97e+07	12362.28	1.81e+08
2009	1.61e+07	3.22e+07	65405.9	1.35e+08	1.88e+07	4.53e+07	0	2.00e+08
	Consumption Based Energy Use - Country Statistic				**Consumption Based Energy Use - Sector Statistic**			
1995	1.25e+07	2.44e+07	80958.86	1.23e+08	1.46e+07	1.56e+07	38843.94	6.41e+07
2002	1.40e+07	2.76e+07	89722.68	1.42e+08	1.64e+07	1.79e+07	28062.52	7.39e+07
2009	1.61e+07	3.15e+07	89200.38	1.30e+08	1.88e+07	2.27e+07	10872.13	1.10e+08

the intersectoral trade structure.[12] Energy use is, hence, merely reallocated across sectors according to trade flows such that double-counting is avoided. In Croner and Frankovic (2016), we provide an extensive introduction to the EEIOA and its application to the WIOD-Tables as employed here. Moreover we therein provide a two sector, two country example of how production-based sectoral energy use is transformed into consumption-based accounting.

3. CONSUMPTION- VS. PRODUCTION-BASED ENERGY USE

This section compares energy use data from the WIOD environmental accounts (production-based energy use) with the measure of trade-adjusted energy consumption introduced in the previous section (consumption-based energy use). Table 1 provides summarized country and sector statistics for three selected years, where energy use is reported in terajoule. Consumption-based accounting reduces the variance across countries and, in particular, across sectors. We analyse general differences between consumption and production-based energy use for the year 2007 on an aggregated national and sectoral level. Lastly, we examine time trends of these differences across countries and sectors.

3.1 Country-level analysis

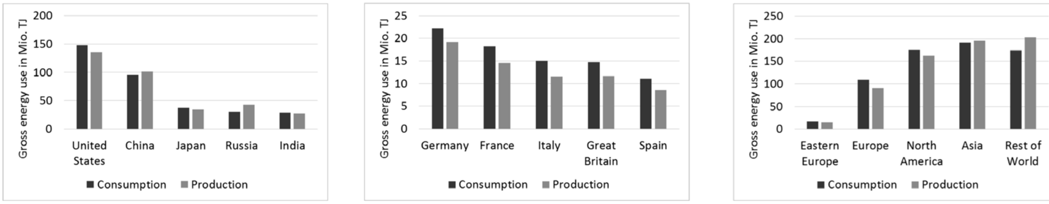
We begin with a country-level analysis where sectoral energy consumption is aggregated nationally. Figure 2 shows the world largest energy users consisting of the USA, China, Japan, Russia, and India in the year 2007.[13] In the U.S., consumption-based energy use exceeds the production-based value provided in the WIOD environmental accounts by 8.5 %. Hence, final consumption in the U.S. is associated with a larger energy consumption than required for the production of total output in the USA. While, to our knowledge, this result has not yet been established in the context of energy consumption, Peters et al. (2010) have shown that the USA is a net-importer of CO_2 emission considering the carbon-intensity of internationally traded goods and services. Considering that energy use and CO_2 emissions are highly correlated; i.e., high energy use in a given sector implies large CO_2 emissions[14], our results are consistent with these findings.

12. This model is based on direct impact coefficients, that is the energy used in a sector is associated with the monetary value flow from each sectors to the other sectors. It is well know that this approach has some important drawbacks because changes in physical energy flows might not correspondent with monetary flows. For instance the price of the intermediate inputs from the electricity sector might change due to service improvements where as the physical energy flow is not changing. This case might not be complete captured by the sectoral deflation. However, given the data availability it still seems the most accurate assumption.

13. We use the year 2007 as the last year before the global crisis after which large declines in international trade created an exception to the overall pattern of strong adjustment effects.

14. This correlation, of course, depends on the mix of energy sources used in the production.

Figure 2: Consumption and production-based gross energy use in 2007 in various world regions and countries



China, the second largest energy user in the world, exhibits the exact opposite pattern. Here, consumption-based energy use lies below the production-based value, a difference of 6.7 %. To a large part, the results of the USA and China reflect the trade patterns in each country; while the U.S. runs a large trade deficit, China is net exporter of goods and services.[15] In fact, across the 40 countries national trade deficits are strongly and negatively correlated with net energy imports.[16] In other words, the larger the net imports of goods in services in a given country are, the larger are the net imports of energy across our sample of 40 countries. Nonetheless, this pattern does not hold for all countries. For example, Japan, which exhibits a trade surplus, shows a relatively higher consumption-based energy use. Apparently, Japan's imports are heavily energy-intensive relative to its exports. In the case of Russia we observe the largest differences of consumption to production-based energy use, namely by 40.9 %. This is due to the rather energy-intensive exports in Russia, dominated by petroleum and gas production as well as the mineral resource industry. Interestingly, Russia's consumption-based energy use lies below Japan's while in terms of production-based energy consumption they would be ranked in the opposite way. Lastly, India is a net-importer of energy, a likely consequence of its trade deficit.

Figure 2 also shows energy use among the five largest European economies, consisting of Germany, France, Italy, Great Britain and Spain, in the year 2007. Considering that the latter four countries were running a trade deficit in 2007, it is not surprising that their consumption-based energy use exceeds the production-based values. The degree to which energy is implicitly imported through trade is remarkably stable across countries: In these countries, consumption-based exceeds production-based energy use by about 20%-23%. In contrast to this similarity across large European economies, Germany shows a different pattern. Despite its immense trade surplus (approx 5% of GDP in 2007), Germany nevertheless exhibits net energy imports. This indicates that the outputs produced in Germany for the use in foreign industries are distinctly less energy-intensive than those goods and services that are imported from foreign sources. However, and due to the large trade surplus, Germany's consumption-production gap in energy use amounts to only 13.7 % in 2007 and thus is considerably lower than in the other considered European countries.

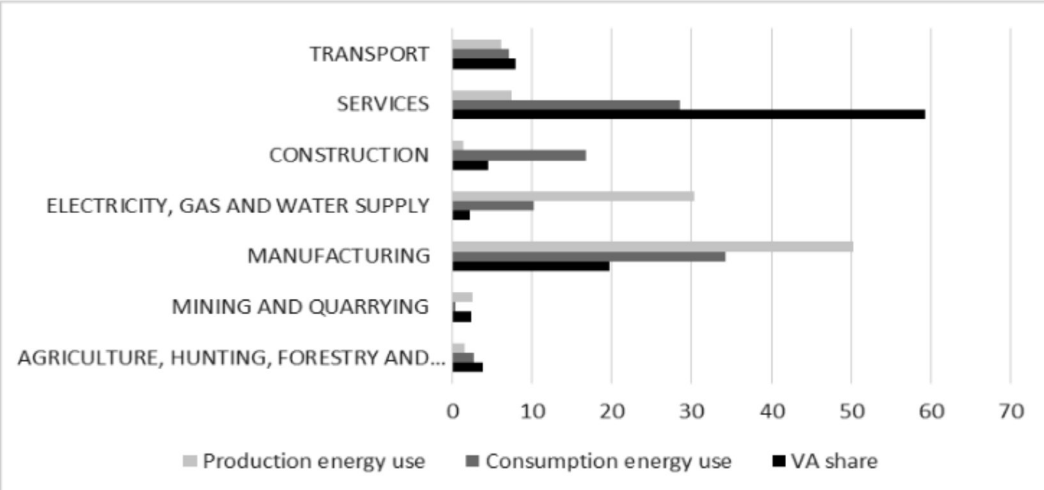
The far-right plot in figure 2 depicts consumption and production-based energy consumption in world regions.[17] Most interestingly, the Asian region is almost net-neutral with respect to trade-related energy imports and exports.

15. Here and in the following, data on trade patterns for 2007 is based on the indicator "Net trade in goods and services (BoP, current U.S.$)" from The World Bank (2016).

16. The correlation coefficient is -0.62.

17. Eastern Europe = Bulgaria, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia, Slovenia; Europe = Austria, Belgium, Cyprus, Germany, Denmark, Spain, Finland, France, Great Britain, Greece, Ireland, Italy, Luxembourg, Malta, Netherlands, Portugal, Sweden; North America = Canada, Mexiko, USA; Asia = China, India, Indonesia, Japan, Korea, Taiwan.

Figure 3: Gross energy use and value added shares in 2007 of 7 sectors aggregated to a global level



3.2 Sector-level analysis

We now focus on seven sectors[18] aggregated to a global level for the year 2007. Figure 3 shows consumption and production-based energy use share of the global energy consumption together with information on the industry-specific value added share of the world's GDP. This allows us to compare the energy use of a given sector relative to its market size. Due to their dominance, we focus on the service as well as on the manufacturing sector. While the former contributes nearly 60 % of the world GDP, it is responsible for only 8 % to the total energy use. In contrast, the manufacturing sector, with a market share of approximately 20 %, is responsible for about 50 % of global energy use. However, when considering the extent of energy use associated with the final demand that these sectors ultimately satisfy as measured by consumption-based energy use, this strong difference in sector-specific energy use narrows dramatically. From this consumption-based perspective, the service sector requires close to 30 % of world energy use, whereas the share of the manufacturing industry shrinks to about 35 %. The adjustment of energy use towards the service sector can be explained by its strong reliance on inputs from other sectors, whereas manufactures deliver a larger share of their outputs for the use of other sectors rather than for final demand.

The electricity, gas, and water supply sector as well as the mining and quarrying industry show a similar pattern as the manufacturers, being predominantly producers of intermediate inputs into other sectors. The construction industry, on the other side, exhibits a qualitatively similar adjustment as the service industry. Notably, it shows the strongest reallocation of energy use across all sectors which indicates a strong reliance on energy-intensive inputs from other sectors.

3.3 Time trends

So far, we have focused only on the differences between production and consumption-based energy use for the year 2007. In this section, however, we analyze time trends in these differences

18. In order to make the analysis more concise, we have aggregated the 35 sectors into seven more broadly defined sectors in this section. In the subsequent sections of the paper the more detailed sector disaggregation is used again.

Figure 4: Energy use trends in the USA (left) and China, base=1995

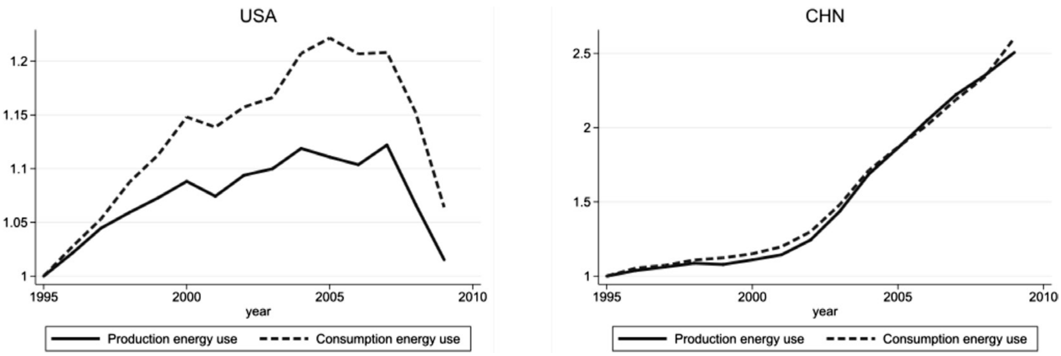
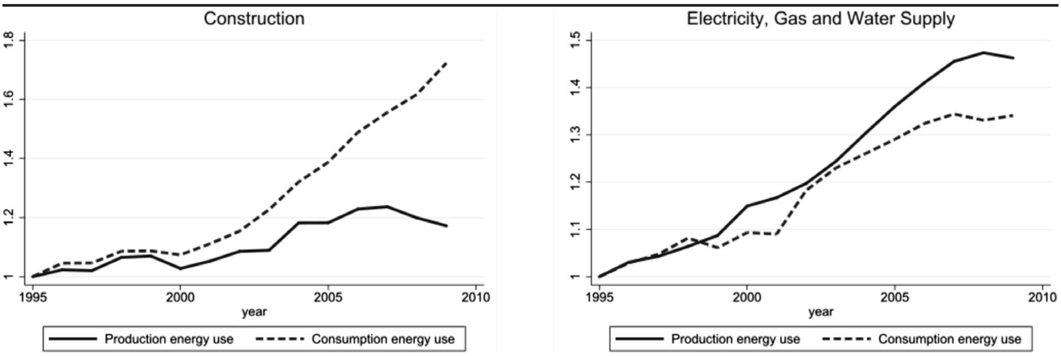


Figure 5: Energy use trends in the construction (left) and electricity, gas and water supply sector, base = 1995



across selected countries and global sectors. First we refer to Figure 4, that displays energy use trends for USA and China over the period from 1995 to 2009 with 1995 as the baseline.[19] Independent from the measure we apply, we observe an increase of energy use in the U.S. until the Great Recession in 2008 and a subsequent strong reduction. The gap between consumption and production-based energy consumption was widening until the recession and only declined slightly due to the slump in trade caused by the recession.[20] By contrast, China exhibits increases in energy use throughout the whole time period. The gap between consumption and production-based energy use was initially narrowing and later on remained fairly stable.

We extend the same time trend analysis on the global construction and energy sector. Figure 5 shows the evolution of consumption and production-based energy use (in each case relative to the level in 1995) for both sectors. We observe, that the difference between both measures has considerably increased over the considered time period. This becomes most evident when looking at the construction sector, which exhibits relatively stable production energy use since the mid 2000s but dramatically increasing consumption-based energy use in the same period. The rising integration of global supply chains, see Timmer et al. (2014) has, thus, likely resulted in larger transfer of energy embodied in trade.

19. While this is not shown in Figure 4, it is important to know how large the absolute levels of consumption and production-based energy use were in each country: In the U.S., consumption-based energy use exceeded the energy use in production in all years. In China, however, more energy was used in production than was associated with the country's consumption throughout the whole time-horizon that we consider.

20. See "Trade (% of GDP)" indicator for the U.S. and the world in The World Bank (2016)

4. DECOMPOSITION

Our main focus in this paper lies on the question whether structural, trade or technological factors drive the overall trend of global and national energy intensity.[21] First, we clarify these terms: "Structural effects" denote sectoral shifts within a country whereas trade effects denote structural changes between countries. "Technological effects" represent any changes within a specific sector such as those relating to production technology and processes or intrasectoral market share shifts between companies. Using this definition, note that technological effects encompass a broad range of factors. Anything that influences the ratio of energy input to consumption within a sector is captured herein. For example, if a manufacturer employs modern machinery instead of workers, it might lead to an increase of the energy intensity within a sector as the machine requires electricity to produce the same amount of output for final consumption. Moreover, consumption shifts from less energy efficient firms to more energy efficient firms that occur within one single sector would fall into the category of technological effects.

For decomposing the trend in energy intensity into the effects of trade, sectoral shifts within a country and technology, we use the Log-Mean Divisia Method II (LMDI II) introduced by Ang and Choi (1997). This method has the advantage that it leaves no residual term and therefore completely decomposes the trends in its components. Its original version is applied as a two factor decomposition method for specific countries.[22]

In order to obtain results on a global level we additionally use the three factor LMDI II introduced by Voigt et al. (2014) and apply it to our consumption-based energy use data to separate the effect of technological improvement as well as structural change within and between countries. But first we introduce the two factor LMDI II which decomposes the trend of energy intensity into technological improvements and structural change between sectors within a country.

4.1 Two factor LMDI II

The energy intensity of a country is defined as the sum of energy use of all its economic sectors divided by the sum of the overall final consumption levels of these sectors[23]. Hence we can write energy intensity as:

$$I_{j,t} = \sum_i \frac{E_{i,j,t}}{C_{j,t}} = \sum_i \frac{C_{i,j,t}}{C_{j,t}} \frac{E_{i,j,t}}{C_{i,j,t}} = \sum_i S_{i,j,t} I_{i,j,t} \tag{2}$$

where $t \in (1995, 2009)$ is the time period, $i = 1,...,35$ is the sector index, $j = 1,...,40$ indicates the country, $E_{i,j,t}$ is the energy use of sector i in economy j, $E_{j,t} = \sum_i E_{i,j,t}$ is the energy use of economy j, $C_{i,j,t}$ is final consumption of sector i in economy j, $C_{j,t} = \sum_i C_{i,j,t}$ is the consumption of the whole

21. Contrary to Voigt et al. (2014) we define global (national) energy intensity as the ratio of global (national) energy use to global (national) consumption when using the consumption-based energy use. Equivalently, sectoral energy intensity is defined as the ratio of sectoral consumption-based energy use to its consumption level. In view of an appropriate measure of sectoral responsibility of energy consumption, it is, however, important how much energy is needed for final consumption rather than for total output. The production-based measure, thus, overestimates the advances in energy intensity reductions as it also attributes increases in intermediate inputs as contributors to a lower energy intensity where the consumption-based approach only considers energy use relative to consumption.

22. The more recent method LMDI I proposed by Ang and Lui (2001) would have the additional advantage of consistency in aggregation which allows for consistent estimation of sub-groups. However, we do not apply further analysis of sub-groups in this paper. The focus of this article is rather to compare our results with Voigt et al. (2014) who used production-based data. For this reason we resort to the LMDI II method in this paper.

23. All foreign consumption of domestic produced goods is included.

economy, $S_{i,j,t} = \frac{C_{i,j,t}}{C_{j,t}}$ is the consumption share of sector i in total consumption of the country, $I_{i,j,t} = \frac{E_{i,j,t}}{C_{i,j,t}}$ is the energy intensity of sector i in economy j and $I_{j,t} = \frac{E_{j,t}}{C_{j,t}}$ is total energy intensity of economy j. Note that in the definition by Voigt et al. (2014) energy use is divided by gross output rather than consumption to obtain the energy intensity. In the subsequent sections we juxtapose results of the decomposition of the consumption and production-based energy use, where the former method is using the approach by Voigt et al. (2014) and the latter the approach presented here. As proven in Ang and Choi (1997), changes in energy intensity between period t and t+1 can be expressed as

$$D_{Tot,j,t+1} = \frac{I_{j,t+1}}{I_{j,t}} = D_{Str,j,t+1} D_{Int,j,t+1}. \tag{3}$$

The components are

$$D_{Str,j,t+1} = \exp\left[\sum_i \frac{L(\omega_{i,j,t+1}, \omega_{i,j,t})}{\sum_i L(\omega_{i,j,t+1}, \omega_{i,j,t})} \ln\left(\frac{S_{i,j,t+1}}{S_{i,j,t}}\right)\right] \tag{4}$$

$$D_{Int,j,t+1} = \exp\left[\sum_i \frac{L(\omega_{i,j,t+1}, \omega_{i,j,t})}{\sum_i L(\omega_{i,j,t+1}, \omega_{i,j,t})} \ln\left(\frac{I_{i,j,t+1}}{I_{i,j,t}}\right)\right] \tag{5}$$

where

$$L(\omega_{i,j,t+1}, \omega_{i,j,t}) = \frac{\omega_{i,j,t+1} - \omega_{i,j,t}}{\ln\left(\frac{\omega_{i,j,t+1}}{\omega_{i,j,t}}\right)} \tag{6}$$

and

$$\omega_{i,j,t} = \frac{E_{i,j,t}}{E_{j,t}} \tag{7}$$

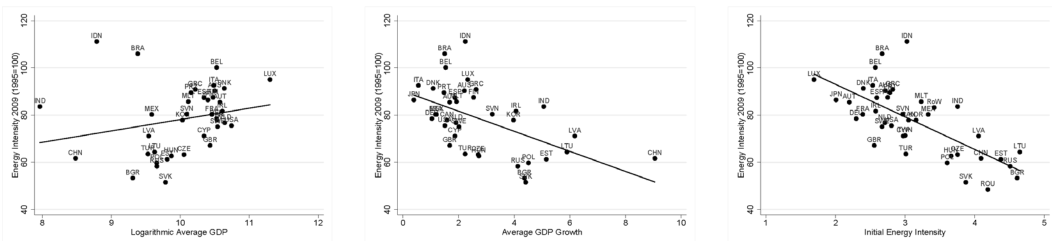
is the share of energy use from a specific sector in the overall energy use of the economy in a country. $L(\omega_{i,j,t+1}, \omega_{i,j,t})$ is a logarithmic weight function for country j which is normalized in (4) and (5) by dividing it through the sum of each country's weight function. $D_{Str,j,t+1}$ describes how much structural change within a country contributes to the change in overall energy intensity between period t and t+1. The higher the share of a sector is, the higher is its weight for total energy intensity. $D_{Int,j,t+1}$ shows to which extent technological improvements in a sector contribute to the change in overall energy intensity between t and $t+1$ (with "Int" standing for sectoral energy intensity). The lower $I_{i,j,t}$ is, the more efficient is the use of energy in a particular sector. While it is evident that D_{Tot} denotes the total change in energy intensity between two periods, the values of D_{Str} and D_{Int} can be interpreted counter-factually: D_{Str} represents the change in energy intensity caused by structural changes within the economy if technology had remained constant throughout the considered period. Conversely, D_{Int} denotes the change in energy intensity associated with technological progress if sectoral market shares had stayed unchanged.

In order to obtain a decomposed time series from 1995 to 2009 the results are chained as in Ang and Lui (2007). All indices are set to 1 for the baseline year 1995. The chained factors indicate the percentage change of each factor as compared to 1995.

Table 2: Summarized Country Statistic

Year	Mean	Std. dev	Min	Max
Total				
1995	1	0	1	1
2002	.878323	.1148429	.6547465	1.247.129
2009	.7755952	.145933	.4846849	1.111.699
Structural Effect				
1995	1	0	1	1
2002	.9713212	.0821956	.6606359	1.197.197
2009	.941888	.0876902	.650878	1.105.566
Technological Effect				
1995	1	0	1	1
2002	.9058169	.0997229	.6566586	1.112.162
2009	.8258537	.1454902	.4648073	1.128.145

Figure 6: Relationship between energy intensity improvement and GDP per capita (left), average GDP growth (center) and initial energy intensity (right)



5. RESULTS

In this section, we present the results of the decomposition of consumption-based energy use data. First we focus on the decomposition results on a country level and discuss patterns in efficiency gains across countries. Second, we analyze and decompose global energy intensity trends. Finally, we juxtapose the difference in decomposition results between consumption and production-based data.

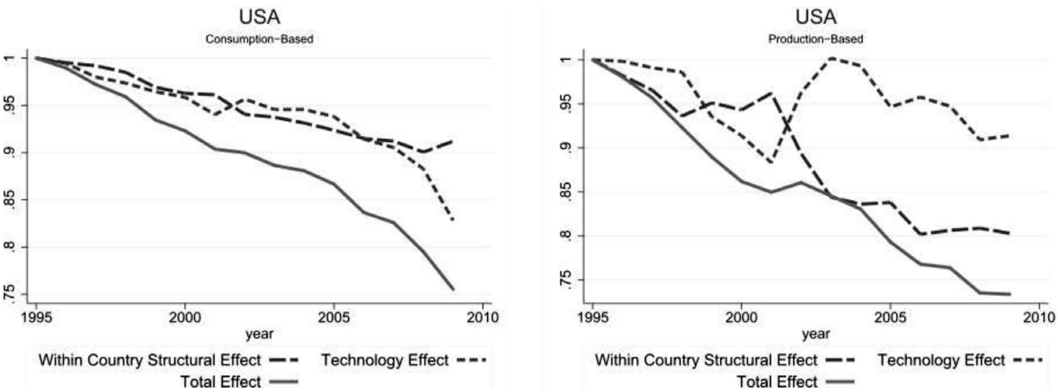
5.1 Decomposition on a country level

The country level results are summarized in Table 2. We see that the average energy intensity across the 40 considered countries in 2009 is about 77.6% of the intensity in 1995. The structural component is associated with a decline in energy intensity of about 5.8% and the technological effect of about 17.4% in 2009 compared to 1995. We identify strong technological improvements of up to 54% in some countries. The structural effect is generally weaker than the technological effect, which was especially strong in the years from 2004 to 2008, most likely driven by the increasing oil and energy prices during that time.

Figure 6 shows three scatter plots that depict the relationship between energy intensity improvements (y-axis) and GDP per capita, GDP growth as well as initial energy intensity (on the x-axis) across the 40 countries and the period 1995-2009 considered in the WIOD. The first graph shows that less developed countries tend to have more success in reducing energy intensity than countries with a higher development status, measured by the average GDP per capita (PPP).[24]

24. Here we use GDP per capita (PPP) in constant 2011 international Dollar from the World Bank (2016)

Figure 7: Decomposition trends for the USA



Hence, poorer countries exhibit on average higher relative gains in energy efficiency. In fact, this association is driven by the technological effect on energy efficiency that were most pronounced in poorer countries. By contrast, structural changes tended to be stronger in richer countries.[25]. Moreover, average GDP growth appears to be correlated with efficiency gains (center graph). Economies that grew at higher rates also exhibited large efficiency gains. Again, the association is shaped by the technological component, while the impact of structural changes seem to be independent of GDP growth. Finally and as shown in the right plot, countries with larger initial energy intensities also tended to improve their energy efficiency much stronger as seen in the graph at the right of Figure 6. Hence, we observe a global convergence of energy-intensities in the considered period.

In the following, we highlight the results of some selected countries of interest, namely USA, India, China, Japan and Turkey. Our choice of the USA and China is motivated by their large share in global energy consumption. The structure of the Indian economy has an increasing impact on global energy use as well. In addition we discuss decomposition results of Japan and Turkey because the differences to production-based data are most pronounced for these countries. In the Appendix A1, we provide the results for all nations. Figure 7 shows the development of energy use in the USA with consumption-based energy data (left graph) and production-based energy data (right graph). While the trends in energy intensity are quite similar, we can observe a dramatic difference in the contribution of structural and technological effects on overall energy intensity. For production-based data we see, starting at 2002, a strong trend towards the structural effect, contributing by about 80% to the overall energy intensity decline. In contrast, the consumption-based approach suggests a much weaker structural effect, being only responsible for about 32% of the total reduction in energy intensity.

We observe no differences across the production-based and consumption-based approach for China and India in the decomposition. Both approaches indicate that the structural effect played almost no role.[26] Therefore we just depict the consumption-based decomposition for this countries. In both countries, the structural effect was even resulting in a more energy-intensive economy during some years.

25. See Appendix A2 for a decomposition of energy efficiency gains in a structural and technological component and their relationship to GDP per capita, GDP growth and initial energy intensity.

26. This result might seem surprising considering the strong structural transformations in these countries during this time interval. However, by having a closer look at the data we find that sectors with increasing share of overall domestic consumption have similar energy intensity than sectors which where declining in their consumption share.

Figure 8: Decomposition trends for India and China

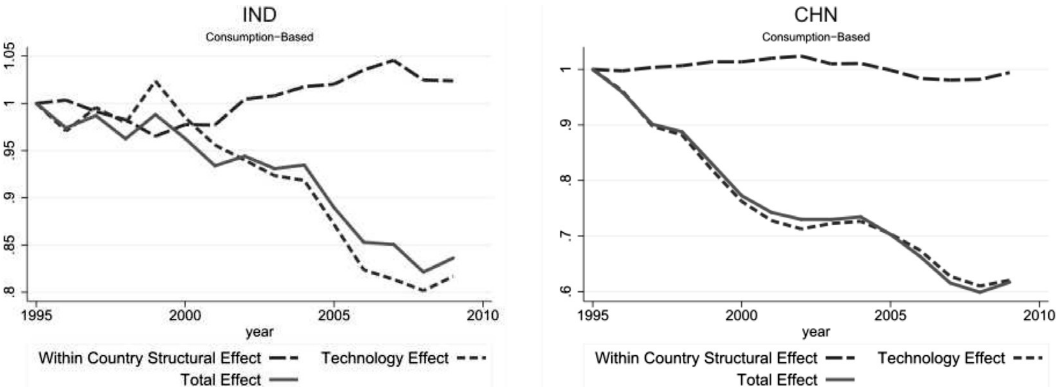
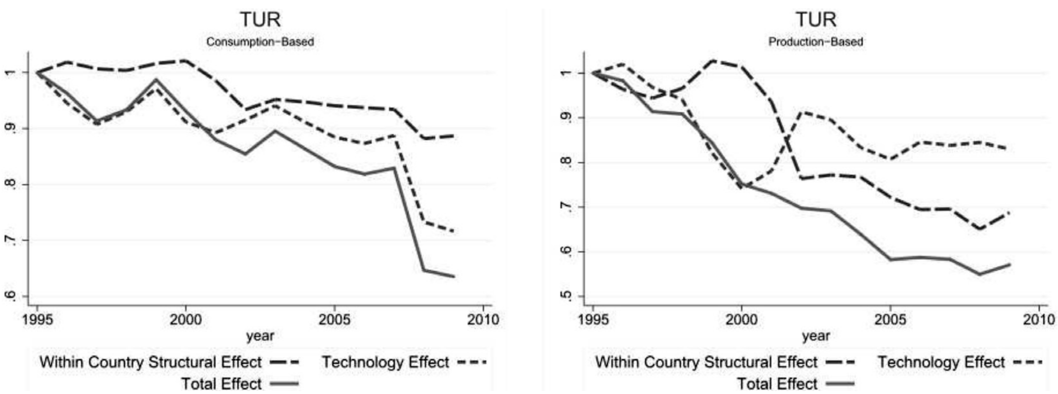


Figure 9: Decomposition trends for Turkey



The outcome for Turkey shows strong differences, in particular for the last two years of the time period considered. When decomposing production-based data, the technological effect is underestimated by about 10% while the structural effect appears to be strongly exaggerated. Note that the time trend of the total effect also differs across consumption and production-based data. This gap reflects the higher energy consumption of Turkey compared to its production-based energy use.

In Japan, structural changes seem responsible for all improvements in national energy efficiency under production-based energy consumption data, while the pattern dramatically changes if we look at consumption-based data. These differences are an indicator of the importance of an environmental extended input-output analysis in evaluating energy intensity trends.

5.2 Decomposition on a global level

In addition to the two factors considered in the country analysis, we also have to account for a third factor on a global level, namely the structural effect between countries, also called the trade effect. It is a well known concern that industrial countries, by tightening their environmental laws, create incentives for heavily polluting industries to move to less-regulated countries.[27] We

27. See e.g. Babiker (2005)

Figure 10: Decomposition trends for Japan

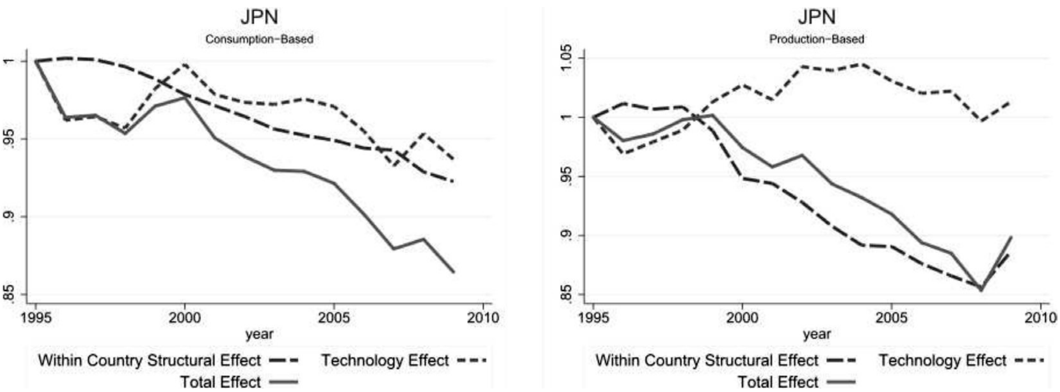
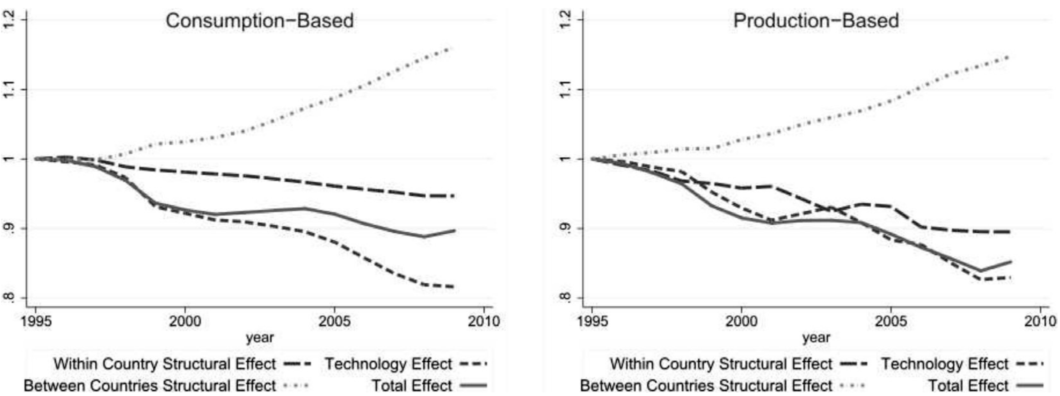


Figure 11: Global Decomposition Results



therefore decompose the global energy intensity trend into a technological effect, structural effect within a country and a structural effect between countries (trade effect). We apply a three factor decomposition analysis, described by Voigt et al. (2014).[28]

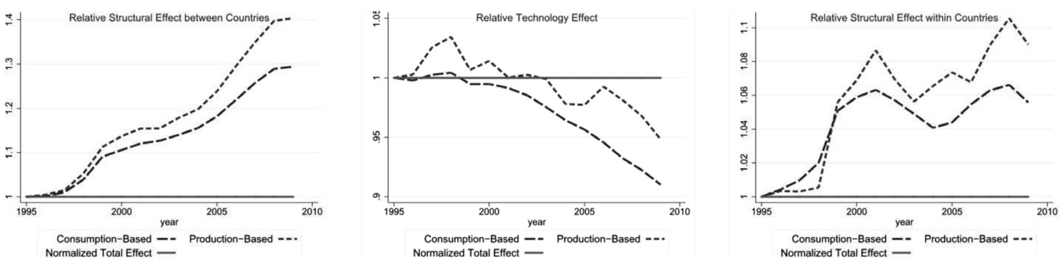
On a global scale, consumption and production-based results show similar patterns. It is evident in both approaches that the trade effect between countries, illustrated by the orange line in Figure 11, is associated with an increasing global energy intensity. This implies, that if everything else had remained unchanged, the shifts in the global trade structure from 1995 to 2009 would have driven up the global energy intensity by about 15%. As Voigt et al. (2014) note, this was due to the shift of the global economy towards countries like China and India that have relatively high energy intensities.

Both approaches imply that the structural effect within a country, shown by the blue line in Figure 11, lead to a reduction of global energy intensities.

Both approaches also have in common that the technology effect was the main driving force for energy efficiency gains. In particular we can see by examining the red line in Figure 11, that the increasing energy prices between 2004 and 2008 coincided with a strong global improvement due to technology.

28. This method is also explained in the Appendix of Croner and Frankovic (2016).

Figure 12: Comparison of Decomposition Results



To highlight some differences in results of both approaches we calculate the structural and technological effects relative to the total efficiency gains.[29] Figure 12 depicts the relative contribution of trade, between country and within country structural effect relative to normalized total effects for both approaches.

The trade effect appears to be weaker over the considered period using consumption-based data as can be inferred from the left hand graph of Figure 12. The overestimation of the trade effect under production-based data is due to the missing reallocation of energy embodied in trade away from energy-intensive countries such as China and India. In fact, a significant part of energy use in these countries is linked to final demand in less energy-intensive countries, see Section 3. Thus, the global shift in energy use is less pronounced when considering consumption-based rather than production-based energy use.

In addition, production-based data overestimate the importance of structural effect within a country, as seen in the second graph in Figure 12. We thus observe, once again, that, when energy-embodied trade is accounted for, structural changes appear to have a weaker effect on the global energy intensity.

The overestimation of structural effects using production-based data necessarily results in an underestimation of the technology effect. The contribution of the technology effect trend on overall energy intensity trends is almost double in the case of consumption-based data.

6. CONCLUSION

The fundamental question posed in the green growth literature is whether it is possible to reconcile economic growth with environmental sustainability. This question hinges most importantly on the feasibility of decreasing the emission of greenhouse gases and the exploitation of natural resources in global production processes. Apart from the utilization of renewable energy, widespread and significant reductions in energy intensities can contribute to achieving sustainable growth in the future. This can not only be achieved by technological but also by structural changes. Moreover, international trade can affect the global energy intensity. In this paper, we have attempted to shed some light on the importance of these three factors by analyzing recent developments in global and national energy intensities.

Our key contribution lies in the utilization of the World Input-Output database in combination with the accompanying environmental accounts to arrive at a consumption-based measure of energy use on a sectoral level. In contrast to Voigt et al. (2014), we are thus able to take into account the energy use of intermediate goods that contribute to the satisfaction of sectoral final demand.

29. We have to calculate the relative contributions because the total levels of energy intensity are different. This is due to the use of consumption data for measuring energy intensity in the consumption-based approach.

Only by doing so can we meaningfully study the ultimate effect of changes in consumption patterns on national or global energy intensities.

We find large effects of energy use adjustments according to the EEIOA. In particular, the energy use associated with final demand in the construction and service sector exceeds by far the energy consumption in their production processes. This indicates a strong reliance on energy-intensive inputs from other sectors. Conversely, the manufacturing industry as well as the electricity, water and gas sector that, to a large degree, deliver intermediate inputs to other sectors, show lower energy use when consumption-based for energy embodied in trade. Overall, we find that the global energy intensity from 1995 to 2009 was declining, predominantly due to more efficient technology used within sectors than due to a structural change in the economy. Nevertheless, structural change within countries played a sizable role in the reduction of energy consumption. Furthermore, our analysis shows that international trade by itself led to a higher energy intensity level. This is likely a result of outsourcing production processes to countries with lower levels of energy intensities.

Decomposing consumption and production-based energy use reveals that the role of structural change is systematically overestimated in previous studies. This is because, after adjusting sectoral energy use according to intersectoral trade, changes in structural composition, both within and between countries, appear to have a smaller impact on global energy intensities. Nevertheless, also the production-based decomposition identifies technological change as the main driver of reducing energy intensity. However, this qualitative similarity on a global level does not hold for each country. For instance, we show that, in some countries, like USA, Japan and Turkey, the technological effect is strongly underestimated. While structural change seems to be the driving factor of energy intensity reductions using production-based data, technology plays the dominant role using consumption-based energy use. Hence, our adjusted measure of energy use indicates that these countries are not exceptions from the general global pattern in which the main force of increasing energy efficiency is technological progress.

Our analysis implies that green growth policy has to take into account the adjustment of sectoral data in order to obtain a correct picture of what can be considered a “green” or “dirty” sector. This is particularly relevant for the theoretical literature on directed technical change and the environment that usually features such a stylized distinction between industries.[30] The interdependencies of sectors through trade of intermediate goods might even give rise to doubts whether such a classification of sectors can be meaningfully applied. More importantly for policy-makers is the fact that technological advances seem to play the largest role in the energy intensity trends. Given that environmental policy mostly affects within-sector efficiency and structural change itself is rather difficult to influence (Huntington (2010)), such policy is likely able to play a strong role in achieving efficiency goals.

There are several ways to build on this emerging literature analyzing environmental impacts of global production processes based on WIOD and its accompanying environmental accounts. First, past global trends have shown little evidence of a strong structural break towards relatively cleaner sectors. China has become the largest energy consumer in 2010 and is, therefore, of particular importance for future global energy intensities. In fact, China itself practically did not experience any effect from structural change, and its energy intensity decrease is explained completely by technological progress. More recent literature argues, however, that energy intensity gains in China during the 2010s might be mostly driven by structural change (see Jos et al. (2015)). Thus, it would be an interesting and important field for future research, once the data are available, to analyze whether there is a potential for structural transformation of economies beyond the magni-

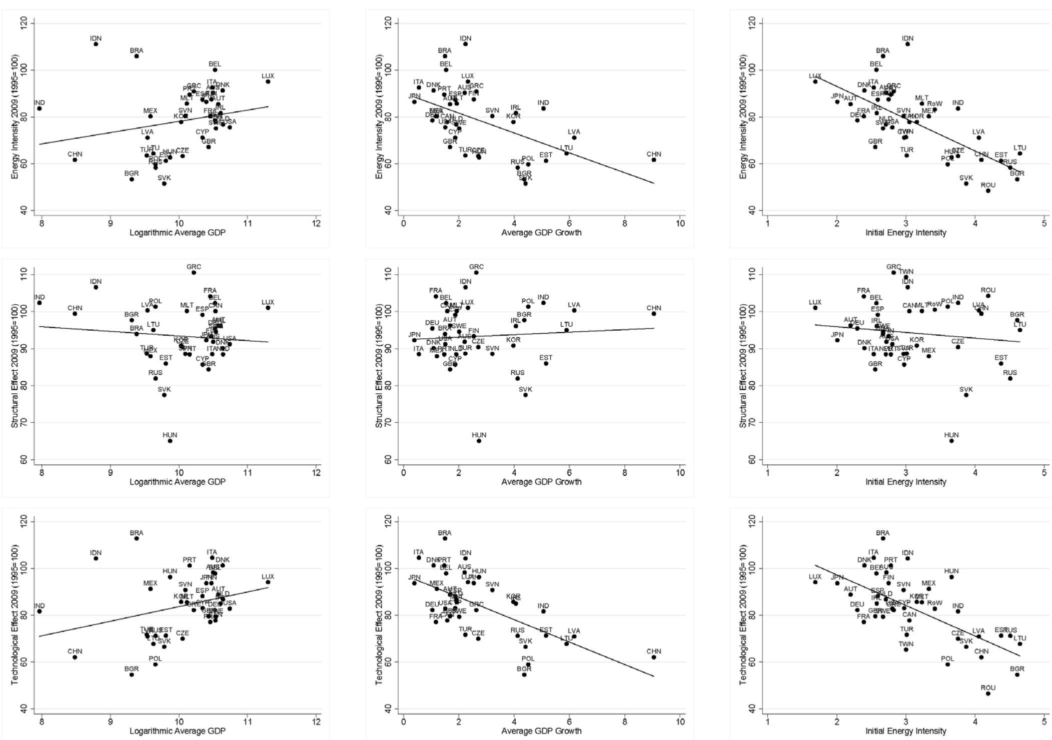
30. See e.g. Acemoglu et al. (2012)

tude shown in this paper for the period up to 2009.[31] Second, this work and numerous other papers have documented the large extent of emissions and energy embodied in international trade. In fact, we show that increasing outsourcing of energy-intensive production has by itself increased global energy intensities. Thus, an analysis of the effects of carbon border taxation on overall global energy and emission intensities poses another important further research challenge. Finally, technological improvements were identified as the main driver of decreasing energy intensities. WIOD accounts can be used to identify sectors and countries that would benefit most strongly from technology transfers and those that can provide the technology to do so. Considering the large differences in sectoral energy-intensities across countries, there is certainly scope for global energy intensity reductions through technology-transfers to less efficient countries. Following this reasoning, it would be an interesting field of future research to go more deeply into the details of technology change, e.g. the effect of energy prices or policies on global energy efficiency.

7. APPENDIX

In Figure 13, we present scatter plots of the relationship between the average GDP, average GDP growth and initial energy intensity and the overall energy intensity change (first row), the structural component of this change (second row) and technology component (third row). Furthermore, we provide consumption-based decomposition results for all countries not displayed in the main part of this paper.

Figure 13: Regression of Energy Intensity, Structural Effect and Technological Effect



31. Su and Ang (2012) point out that the construction of input-output tables are rather time-intensive such that there is a large time lag between publication and data used.

Table 3: Decomposition Results for the period 1995-2007 in percent with baseline year 1995 = 100

Country	Country Abbr.	Structural Effect	Technology Effect	Total	Country	Country Abbr.	Structural Effect	Technology Effect	Total
Australia	AUS	90	107	96	Italiy	ITA	92	99	92
Austria	AUT	95	79	75	Japan	JPN	93	91	84
Belgium	BEL	96	99	95	Korea	KOR	83	76	64
Bulgaria	BGR	113	43	48	Lithuenia	LTU	83	82	67
Brasilia	BRA	98	109	107	Luxembourg	LUX	78	105	82
Canada	CAN	96	85	81	Latvia	LVA	96	70	67
China	CHN	100	51	51	Mexico	MEX	86	94	81
Cyprus	CYP	88	64	56	Malta	MLT	111	74	82
Czech Rep.	CZE	78	80	62	Netherlands	NLD	89	87	77
Germany	DEU	100	74	74	Poland	POL	93	66	62
Denmark	DNK	91	91	82	Portugal	PRT	89	95	85
Spain	ESP	101	91	92	Romenia	ROU	88	65	57
Estonia	EST	68	81	55	Russia	RUS	93	62	58
Finland	FIN	90	85	77	Rest of World	RoW	102	75	77
France	FRA	93	87	81	Slovakia	SVK	66	89	59
UK	GBR	86	86	74	Slovenia	SVN	89	83	74
Greece	GRC	97	99	97	Sweden	SWE	91	83	75
Hungary	HUN	57	102	58	Turkey	TUR	86	80	69
Indonesia	IDN	104	101	104	Taiwan	TWN	100	52	52
India	IND	102	82	84	United States	USA	87	95	82
Ireland	IRL	89	82	73					

ACKNOWLEDGMENTS

We are grateful to Alexia Fürnkranz-Prskawetz, Michael Kuhn, Bernhard Mahlberg, Hanspeter Wieland and Franz Wirl for helpful discussions and comments. The responsibility for any errors lies entirely with us.

REFERENCES

Acemoglu, D., P. Aghion, L. Bursztyn and D. Hemous (2012). "The Environment and Directed Technical Change," *American Economic Review* 102(1): 131–166. https://doi.org/10.1257/aer.102.1.131.

Ang, B.W. and K.H. Choi (1997). "Decomposition of Aggregate Energy and Gas Emission Intensities for Industry: A Refined Divisia Index Method," *The Energy Journal* 18(3): 59–73. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol18-No3-3.

Ang, B.W. and N. Lui (2001). "A New Energy Decomposition Method: Perfect in Decomposition and Consistent in Aggregation," *Energy* 26: 537–548. https://doi.org/10.1016/S0360-5442(01)00022-6.

Ang, B.W. and N. Lui (2007). "Energy Decomposition Analysis: IEA Model versus other Methods," *Energy Economics* 35: 1426–1432. https://doi.org/10.1016/j.enpol.2006.04.020.

Ayres, R. U., J.C.J.M. van den Bergh, D. Lindenberger, and B. Warr (2013). "The Underestimated Contribution of Energy to Economic Growth," *Structural Change and Economic Dynamics* 27: 79–88. https://doi.org/10.1016/j.strueco.2013.07.004.

Babiker, M.H. (2005). "Climate Change Policy, Market Structure, and Carbon Leakage," *Journal of International Economics* 65: 421–445. https://doi.org/10.1016/j.jinteco.2004.01.003.

Bowen, A. and S. Fankhauser (2011). "The Green Growth Narrative: Paradigm Shift or Just Spin," *Global Environmental Change* 21(4): 1157–1159. https://doi.org/10.1016/j.gloenvcha.2011.07.007.

Buera, F. and J. Kaboski (2012). "The Rise of the Service Economy," *American Economic Review* 102(6): 2540–2569. https://doi.org/10.1257/aer.102.6.2540.

Chappe, R. (2015). "The Legal Framework of Global Environment Governance on Climate Change: A Critical Survey." *The Oxford Handbook of the Macroeconomics of Global Warming* 603–638.

Cole, M. A., J.R. Elliott and K. Shimamoto (2005). "A Note on Trends in European Industrial Pollution Intensities: A Divisia Index Approach." *The Energy Journal* 26(3): 61–73. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol26-No3-3.

Croner, D. and I. Frankovic (2016). "A Structural Decomposition Analysis of Global and National Energy Intensity Trend," *TU Vienna Working Paper* 8.

Dietzenbacher, E., B. Los, R. Stehrer, Timmer, M. and G.J. de Vries (2013). "An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production," *Review of International Economics* 23(3): 575–605.

Eichengreen, B. and P. Guptay (2013). "The Two Waves of Service Sector Growth," *Oxford Economic Papers* 65: 96–123. https://doi.org/10.1093/oep/gpr059.

Gently, A. (2012). "Final Database of Environmental Satellite Accounts: Technical Reports on their Compilation," *WIOD Deliverable 4.6*. http://www.wiod.org/new_site/database/eas.htm

Hoekstra, R. and J.J.C.J.M. van den Bergh (2003). "Comparing Structural and Index Decomposition Analysis," *The Energy Journal* 18(3): 59–73. https://doi.org/10.1016/S0140-9883(02)00059-2.

Huntingtion, H. G. (2010). *"Structural Change and U.S. Energy Use: Recent Patterns." The Energy Journal* 31(3): 25–40.

Jakob, M., R. Marschinski (2013). "Interpreting Trade-Related CO_2 Emission Transfers." *Nature Climate Change* 3: 19–23. https://doi.org/10.1038/nclimate1630.

Jos, O.G.J., G. Janssens-Maenhout, M. Muntean and J.A.H.W. Peters (2015). "Trends in Global CO2 Emissions: 2015 Report." *PBL Netherlands Environmental Assessment Agency* 1803.

Leontief, W.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. https://doi.org/10.2307/1927837.

Leontief, W.W. (1970). "Environmental Repercussions and the Economic Structure: An Input-Output Approach," *The Review of Economics and Statistics* 52(3): 262–271. https://doi.org/10.2307/1926294.

Metcalf, G. E. (2008). "An Empirical Analysis of Energy Intensity and Its Determinants at the State Level." *The Energy Journal* 29(3): 1–26. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol29-No3-1.

Miller, R.E. (2009). "Input-Output Analysis," *Cambridge University Press*. https://doi.org/10.1017/CBO9780511626982.

Mulder, P. (2009). "International Specialization, Sector Structure and the Evolution of Manufacturing Energy Intensity in OECD Countries." *The Energy Journal* 36(3): 111–136.

OECD (2013). "What have we learned from attempts to introduce green-growht policies?" *OECD Green Growth Papers*.

Peters, G.P., J.C. Minx, C.L. Weber and O. Edenhofer (2011). "Growth in emission transfers via international trade from 1990 to 2008." *Proceedings of the National Academy of Science of the United States of America* 108(1): 8903–8908. https://doi.org/10.1073/pnas.1006388108.

Su, B. and B.W. Ang (2012). "Structural decomposition analysis applied to energy and emissions: Some methodological developments," *Energy Economics* 34(1): 177–188. https://doi.org/10.1016/j.eneco.2011.10.009.

Sun, J.W. (1999). "Decomposition of Aggregate CO_2 Emissions in the OECD: 1960-1995." *The Energy Journal* 20(3): 147–155. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol20-No3-7.

The World Bank (2016). "World Development Indicators," *The World Bank* Washington D.C.. http://data.worldbank.org/indicator

Timmer, M., A.A. Erumban, B. Los, R. Stehrer and G.J. de Vries (2014). "Slicing Up Global Value Chains," *Journal of Economic Perspectives* 28(2): 99–118. https://doi.org/10.1257/jep.28.2.99.

Timmer, M., E. Dietzenbacher, B. Los, R. Stehrer and G.J. de Vries (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. https://doi.org/10.1111/roie.12178.

Voigt, S., E. D. Cian, M. Schymura, and E. Verdolini, (2014). "Energy intensity developments in 40 major economies: Structural change or technology improvement?" *Energy Economics* 41: 47–62. https://doi.org/10.1016/j.eneco.2013.10.015.

Wachsmann, U., R. Wood, M. Lenzen and R. Schaeffer (2009). "Structural Decomposition of Energy Use in Brazil from 1970 to 1996." *Applied Energy* 86(4): 578–587. https://doi.org/10.1016/j.apenergy.2008.08.003.

Wirl, F. and Y. Yegorov (2015). "Renewable Energy: Models, Implications and Prospects." *The Oxford Handbook of the Macroeconomics of Global Warming* 349–375.

Wood, R. (2009). "Structural Decomposition Analysis of Australia's Greenhouse Gas Emissions." *Energy Policy* 37(11): 4943–4948. https://doi.org/10.1016/j.enpol.2009.06.060.

Xu, Y. and E. Dietzenbacher (2014). "A Structural Decomposition analysis of the emissions embodied in trade." *Ecological Economics* 101: 10–20. https://doi.org/10.1016/j.ecolecon.2014.02.015.

Zhong, S. (2016). "Energy Consumption, Energy Intensity and Economic Development between 1995 and 2009: A Structural Decomposition Approach." *UNU-MERIT Working Paper*