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Forin, S., Radebach, A., Steckel, J. C., & Ward, H. (2018). The effect of industry delocalization on global energy use: A global sectoral perspective. Energy Economics, 70, 233–243. https://doi.org/10.1016/j.eneco.2017.12.031

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1. Introduction

In order to achieve ambitious climate change mitigation targets as formulated in the Paris Agreement (UNFCCC, 2015), emission reductions will be necessary across all sectors of the global economy. While a first best climate policy, i.e. putting a uniform, global price on carbon would ensure that improvement potentials in economic sectors are realized in the most cost-efficient way (Weitzman, 2014), it is rather unlikely to unfold in the near future (Cramton et al., 2017; Edenhofer et al., 2015; MacKay et al., 2015).

Differing ambition levels of unilateral climate policies are feared to induce competitiveness[1] losses for implementing regions (Branger and Quirion, 2015, 2014; Carbone and Rivers, 2017) and carbon leakage (see e.g., Jakob et al. 2014) through different channels (Carbone and Rivers, 2017; Dechezleprêtre and Sato, 2017). *Inter alia*, energy- and emission intensive trade exposed industries (EITE) (Carbone and Rivers, 2017), such as steel or aluminum could see large increases in relative production prices (Alexeeva-Talebi et al., 2012; Böhringer et al., 2012), and hence re- or delocalize to regions that have less ambitious regulations and less efficient production technologies in place. Thus, a higher price of emission-intensive goods in one region could inter alia lead to increased imports from non-regulated regions (Markusen 1975, Siebert 1979), an

[1] Identifying a good proxy for competitiveness is challenging (Jaffe et al., 1995). Depending on underlying studies, inter alia output, exports, employment profitability or market share have been applied (Carbone and Rivers, 2017).

effect that potentially supports *pollution havens* (Cole et al., 2006; Dietzenbacher and Mukhopadhyay, 2007; Eskeland and Harrison, 2003).

As no natural counterfactual to policies exists, and effects, which are difficult to isolate, are likely heterogeneous across countries, it is difficult to explicitly evaluate policy impacts (Dechezleprêtre and Sato, 2017). Reviewing the Computable General Equilibrium (CGE) modelling literature on impacts of unilateral climate policy, Carbone and Rivers (2017) find evidence for resulting negative effects on output, exports and employment as well as carbon leakage. Nevertheless, it has been argued that depending on the rate of technological spillover and the additional technological development caused by environmental regulations, the effects of (carbon) leakage could be more than offset (Gerlagh and Kuik, 2014). Literature also acknowledged that depending on relocation barriers, domestic effects might be more relevant than effects between countries (Dechezleprêtre and Sato, 2017). For instance, the US clean air act had no impact on the cement industry, i.e. relocation of production capacities, but contributed to large health benefits (Dechezleprêtre and Sato, 2017). In the same vein, the introduction of EU ETS has not led to measurable effects for the overall economy (Dechezleprêtre and Sato, 2017). In specific cases, environmental legislation can also increase firm profits, as Branger and Quirion (2015) show for the European cement industry. Nevertheless, considering the findings of Carbone and Rivers (2017), it is conceivable that unilateral climate policy can negatively affect EITE-sectors and hence be relevant for delocalization of production capacities.

Thus far, delocalization effects have mainly been explored at aggregated economic level. Voigt et al. (2014) and Löschel et al. (2015) have decomposed the structural component of energy intensity changes into a *between*- and a *within*-country structural effect. Both studies show that while a shift towards a less energy intensive economic structure is at work in most countries, the delocalization of production (between-country structural effect) partly compensates for this development. Although drivers of changes in emissions have been investigated at sectoral level, see e.g. Branger and Quirion (2015), and predictions have been made using CGE modelling

(Carbone and Rivers, 2017), an empirical investigation of sector-specific delocalization effects is currently missing.

In this study we aim to close this gap. We apply an advanced Logarithmic Mean Divisa Index (LMDI) decomposition methodology (Ang and Wang, 2015) to decompose energy use into value added, technological progress[2] and delocalization along sectoral lines of the economy. Our analysis is based on data from the Global Trade Analysis Project (GTAP), for the years 2001, 2004, 2007 and 2011 (Dimaranan, 2006; Narayanan et al., 2015) (details in Section 2), which allows to track changes over time. We consider 57 different sectors and up to 140 regions, which we transfer into a multi-regional input-output table (Andrew and Peters, 2013). We are interested in how delocalization effected the energy consumption of global sectors. Here, we understand delocalization as a relative shift of production capacities between countries for single sectors. We assume that if production technologies in two country were different and a relative shift in production capacities occurred, the global average technology and consequently the sectoral energy consumption changed. Our analysis uses these changes and gives indirect evidence when and in which sectors delocalization occurred.

We find that the increases of value added have consistently driven energy use at the sectoral level, while technological change has continuously led to decreases in energy use in the decade 2001-2011. We find evidence for ongoing sectoral delocalization. For most sectors, delocalization increases sectoral energy use by 1-6% per year. Delocalization effects have increased sharply in manufacturing industries that consume more than 50% of the global energy after 2004.

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[2] We use the energy intensity improvement rate to approximate technological progress. We use energy use per value added (VAD). Production chains are increasingly globalizing and fragmenting (Baldwin and Martin, 1999; Koopman et al., 2014; Timmer et al., 2014). It is hence important to adequately measure the contribution of single production steps. In contrast to output, VAD allows to reflect the significance and efficiency of a production step, i.e. how much additional value is generated from the inputs.

Subsequently, technological progress rates within manufacturing sectors have declined (2007-2011).

The remainder of our paper is structured as follows. Section 2 introduces the data and the methodological foundations of the decomposition analysis. Section 3 provides the results for different sectoral aggregation levels. Section 4 discusses the results and concludes.

2 Data and Methodology

This section develops a framework that allows identifying delocalization between countries at sectoral level. In contrast to former studies, which have focused on energy intensity in countries or regions, we consider *sectoral value added* and its distribution, which is decisive considering total energy use-driven GHG emissions. We decompose sectoral energy intensity changes into *delocalization* and *technology* components, envisaging the delocalization component as being the structural effect within sectors and between countries.

2.1 Data

For our analysis we use the Global Trade Analysis Project (GTAP) Data Base. The GTAP Data Base can be converted into a multi-regional input-output table (Peters et al., 2011), which allows to calculate sectoral value-added. In contrast to other multi-regional input-output datasets, such as Eora (Lenzen et al., 2013) and WIOD (Timmer et al., 2015), there are no annual releases of the GTAP Data Base. However, it does provide relatively high sectoral and regional resolutions (homogeneous across regions) (Tukker and Dietzenbacher, 2013), which are crucial for investigating delocalization effects, along with data on energy use. Table 1 shows the specifications of the different GTAP Data Base releases used in this analysis. The four years of data available generate three time windows for our analysis: 2001 to 2004, 2004 to 2007 and 2007 to 2011. Wherever the regional resolution differs within a time window, the higher resolved version is aggregated into the lower resolved one (see Appendix). Each separate year in GTAP is the reference year for the monetary value (Aguiar et al., 2016). Hence, we apply price deflator factors provided by the Worldbank (Worldbank, 2017) to adjust all monetary values to 2011 USD.

Year	2001	2004	2007	2011
GTAP Data Base version	6	9		
Documentation	Dimaranan (2006)	Narayanan et al. (2015)		
number of regions	87	140		
number of sectors	57			

Table 1: Overview of different GTAP versions used for each year, including their respective numbers of sectors and regions.

2.2 Factorizing sectoral energy intensity changes with Index Decomposition Analysis

In order to analyze the impact of delocalization on sectoral energy usage trends, we take the perspective of global production sectors, adapting and modifying the decomposition methodology by Ang and Wang (2015). Let S denote the set of considered sectors and R the set of considered regions in a dataset. With EU_s^t we denote energy usage in the global sector $s \in S$ at time t; $EU_{s,r}^t$ refers to the energy usage of sector s in region $r \in R$ at time t. With Y_s^t we denote the value-added of the global sector s at time t, while $Y_{s,r}^t$ refers to the value-added of sector s in region r at time t. EU_s^t can thus be decomposed in the following way:

$$
\begin{aligned}
EU_s^t &= \sum_r \frac{Y_{s,r}^t}{Y_s^t} \cdot \frac{EU_{s,r}^t}{Y_{s,r}^t} \cdot Y_s^t \\
&= \sum_r L_{s,r}^t \cdot T_{s,r}^t \cdot Y_s^t .
\end{aligned} \tag{1}
$$

The first component of the right side of equation (1), $L_{s,r}^t = \frac{Y_{s,r}^t}{Y_s^t}$ is the share of the global value-added of sector s that is created in region r at time t. This factor is novel to energy usage decomposition studies as it analyses the effect of shifts in the location of production within a global sector on energy usage. In the following we call factor L the localization factor, the change in localization will be denoted as delocalization. The second term $T_{s,r}^{t}=\frac{EU_{s,r}^{t}}{Y_{s,r}^{t}}$ is the sectoral energy intensity of sector s in region r at time t. We call this term T the technology factor. The third term Y refers to the economic size of the global sector, as it considers total value added.

2.3 Calculating the effects on energy usage change: Log Mean Divisia Index method

The factorization of energy use, as in equation (1), represents a static perspective at a given point in time. Our approach aims to derive the temporal variation of sectoral value added, energy efficiency developments and production locations. To comply with this dynamic approach, we apply the additive Logarithmic Mean Divisia Index method (LMDI) to equation (1) (Ang and Wang, 2015).

We use the logarithmic weight function according to Ang and Wang (2015):

$$\ell(x,y)=(x-y)/ln(\frac{x}{y}). \quad (2)$$

We obtain - analogously to Ang and Wang (2015) and Ang (2015) - the global changes in energy usage which are assigned to the factors L, T and V between two points in time t_0 and t_1:

$$\Delta^{t_0,t_1}EU_s(\mathrm{L})=\sum_r \ell(EU_{s,r}^{t_1},EU_{s,r}^{t_0})\cdot ln\left(\frac{L_{s,r}^{t_1}}{L_{s,r}^{t_0}}\right) \quad (3)$$

$$\Delta^{t_0,t_1}EU_s(\mathrm{T})=\sum_r \ell(EU_{s,r}^{t_1},EU_{s,r}^{t_0})\cdot ln\left(\frac{T_{s,r}^{t_1}}{T_{s,r}^{t_0}}\right) \quad (4)$$

$$\Delta^{t_0,t_1}EU_s(\mathrm{Y})=\sum_r \ell(EU_{s,r}^{t_1},EU_{s,r}^{t_0})\cdot ln\left(\frac{Y_{s}^{t_1}}{Y_{s}^{t_0}}\right). \quad (5)$$

The total of these three contributions give the overall absolute change in energy use of the global sector *s* between time t_0 and t_1

$$\Delta^{t_0,t_1} EU_s = EU_s^{t_1} - EU_s^{t_0} = \Delta^{t_0,t_1} EU_s(\mathrm{L}) + \Delta^{t_0,t_1} EU_s(\mathrm{T}) + \Delta^{t_0,t_1} EU_s(\mathrm{Y}). \quad (6)$$

Outcomes of Equations (3) to (5) can be positive or negative. The following results are possible:

i) $\Delta^{t_0,t_1} EU_s(\mathrm{L}) < 0$ means that delocalization contributed to a decrease in global energy usage, i.e. a shift towards more efficient regions, while

ii) $\Delta^{t_0,t_1} EU_s(\mathrm{L}) > 0$ shows that the delocalization factor between t_0 and t_1 contributed to increases in global energy usage, i.e. a shift towards less efficient regions.

iii) $\Delta^{t_0,t_1} EU_s(T) < 0$ means that the technology factor contributed to a decrease in global energy usage, i.e. the global sector became more energy efficient, while

iv) $\Delta^{t_0,t_1} EU_s(T) > 0$ shows that the technology factor between t_0 and t_1 contributed to increases in global energy usage.

v) $\Delta^{t_0,t_1} EU_s(\mathrm{Y}) < 0$ means that sectoral decline contributed to a decrease in global energy usage, while

vi) $\Delta^{t_0,t_1} EU_s(\mathrm{Y}) > 0$ means that sectoral growth lead to increases in energy usage.

To avoid misinterpretation, it is important to note that the relative delocalization effect described by a change in the localization factor L is not equivalent to the usual meaning of delocalization. In fact, the data used in this paper do not allow the tracking of displacement of single organizations at micro level. What we observe are changes in the proportion of regional production of the global sector s and its relationship to the sectoral energy usage. Put another way, the localization factor indicates whether production shares of a sector s has moved, between t_0 and t_1, to more (or less) energy-intensive countries.

3 Results

In this section we first introduce selected stylized facts and major trends. We then continue with detailed results of our sectoral decomposition, which was introduced in detail in Section 2.

3.1 Stylized facts and major trends

Looking at aggregated energy use patterns across the globe, we observe a major shift of regional weights, see Figure 1. Aggregated energy consumption between 2001 and 2011 almost doubled in East Asia, replacing North America as the world's largest energy consuming region[3].

In fast growing developing countries energy consumption has grown disproportionally in every macro sector[4], see Figure 2. When assessing the proportion of regional consumption by macro sector, the share of consumption in "Heavy-", and "Light Manufacturing", "Utilities and Construction", "Transport and Communication" "Textiles and Wearing Apparel" and "Processed Food" in Asia has significantly increased. For all other macro sectors, shares remain relatively constant. In contrast, EU25 and North American countries have demonstrated declining energy usage shares in some macro sectors.

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[3] See Appendix table A3 for an overview of regions and countries.

[4] Note that we separate between aggregated "macro" sectors and "micro" sectors that are further disaggregated. Table A2 gives a full list of sectors and how they are aggregated into "macro" sectors.

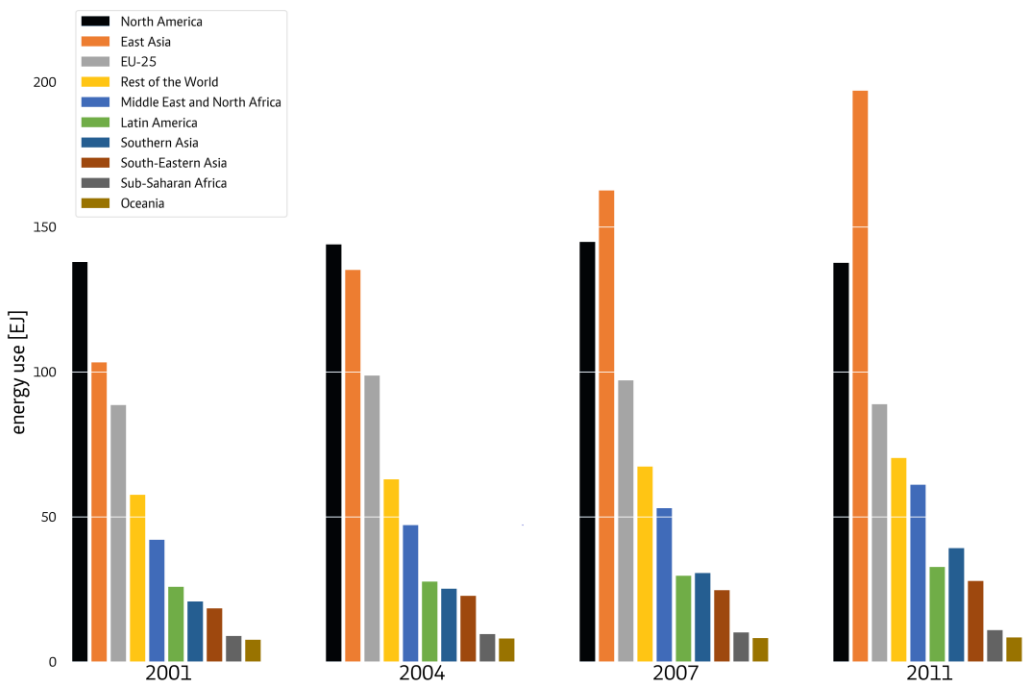
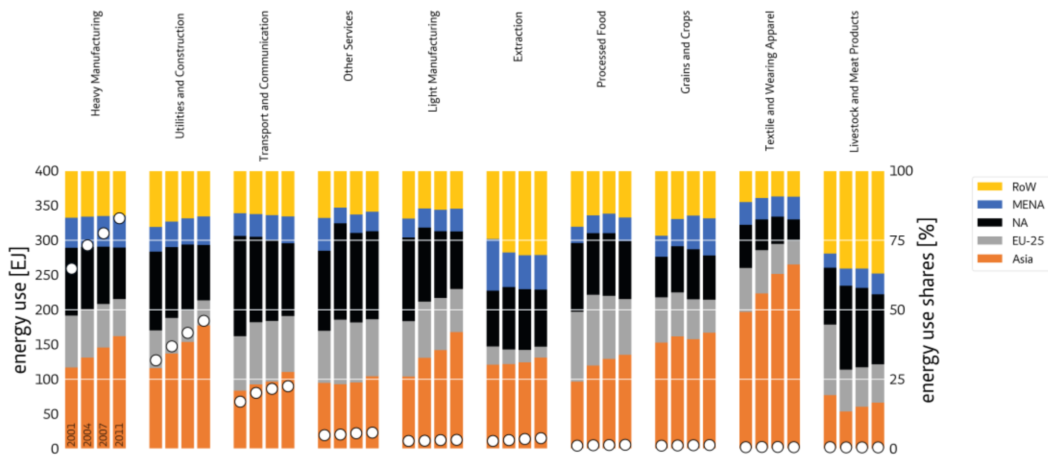


Figure 1: Primary energy usage of different world regions in Exajoules for 2001-2011.

Looking at growth in sectoral energy consumption, “Heavy Manufacturing”, “Utilities and Construction” and “Transport and Communication”, which are together responsible for almost 90% of global energy consumption, grew by 28%, 44.5% and 32.5% respectively, for the period 2001-2011. These values compare to a total growth rate of 31.9% across all sectors. The only sectors to witness a slight energy use reduction in this time period are “Textile and Wearing Apparel” and “Lifestock and Meat Products”, which are the macro sectors with the lowest energy usage. The energy use in the remaining macro sectors has increased.



Year	2001	2004	2007	2011
Total Energy Use [EJ]	**511.4**	**581.3**	**628.5**	**674.3**
Heavy Manufacturing	**259.3**	**292.8**	**310.1**	**331.9**
Utilities and Construction	**127.4**	**147.6**	**167.1**	**184.1**
Transport and Communication	**67.9**	**80.5**	**86.4**	**90.2**
Other Services	**19.7**	**20.8**	**22.4**	**23.4**
Light Manufacturing	**11.6**	**11.7**	**12.5**	**12.9**
Extraction	**11.5**	**12.7**	**14.2**	**15.5**
Processed Food	**4.6**	**5.4**	**5.5**	**5.9**
Grains and Crops	**4.5**	**5.0**	**5.3**	**5.6**
Textile and Wearing Apparel	**2.6**	**2.7**	**2.7**	**2.6**
Livestock and Meat Products	**2.5**	**2.1**	**2.2**	**2.3**

Figure 2: Total energy use in EJ (circles, left axis) and regional shares (bars, right axis) per region and sector for 2001, 2004, 2007 and 2011, respectively (RoW = Rest of the World, MENA = Middle East and Northern Africa, NA = North America, EU-25 = European Union of 25 members, see table A4 in the Appendix for more detail). Table shows sectoral energy use in EJ for different years.

3.2 Decomposition

In order to understand the energy consumption patterns observed, we apply the decomposition technique described in Section 2. Results are summarized in Figure 3.

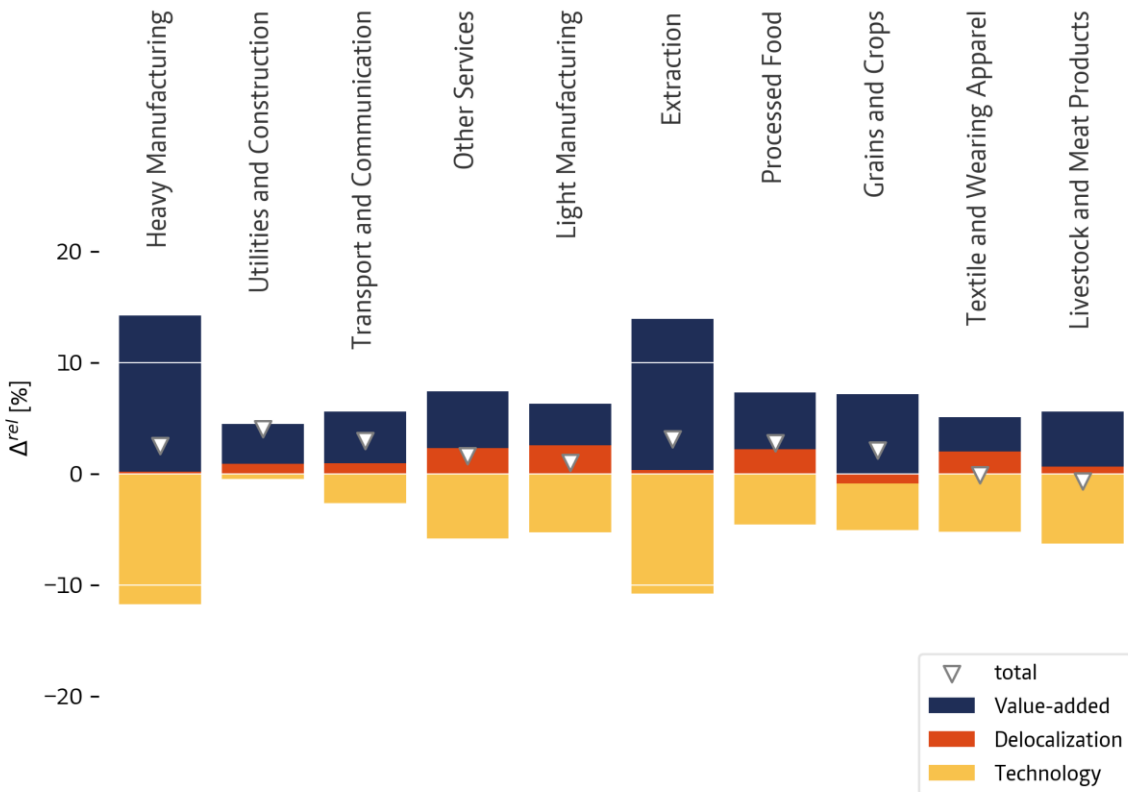


Figure 3: Average annual contributions to changes in energy usage of macro sectors by the technology, delocalization and sectoral value added factors for the period 2001-2011.

For all macro sectors, growth in the sectoral value added factor contributed to increases in energy usage. On average, its effect on energy use was 3-7% per year. The largest average contributions (10-15%) were observed in the "Heavy Manufacturing" and "Extraction" sectors. The increase in the latter could be a side effect of increases in the former, as extracted resources are relevant inputs for "Heavy Manufacturing". In contrast, technological improvements have constantly led to decreasing energy consumption, almost equating to the increases from value added contributions. For the entire period, delocalization has shown to have smaller impacts (<5%). Only one sector, "Grains and Crops", saw decreases in energy consumption due to delocalization. In contrast, two of the three most important energy consuming macro sectors, "Utilities and Construction" and "Transport and Communication" witnessed a growth in delocalization-driven energy use. As both macro sectors largely reflect infrastructure, the observed delocalization could be driven by large (necessary) investments to build-up and improve infrastructure in China, India and other Asian economies (Schäfer, 2005; Steckel et al., 2013; Steinberger et al., 2010), which is already provided in OECD countries.

Investigating delocalization for macro sectors in more detail, i.e. considering all periods separately, reveals a different picture, see Figure 4.

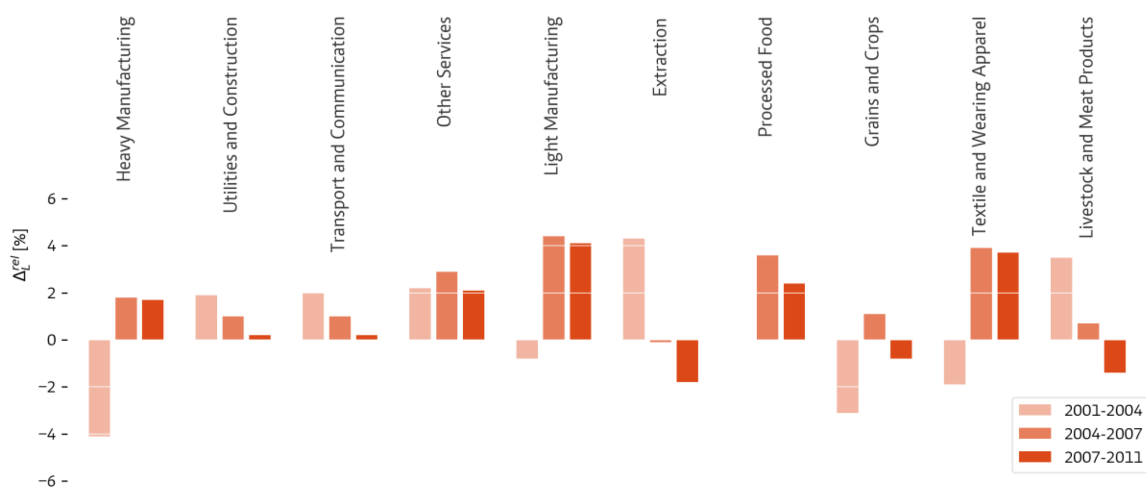


Figure 4: Delocalization effects at macro level. Annual percentage changes in energy intensities of macro sectors caused by delocalization.[5]

"Utilities and Construction", "Other services" and "Transport and Communication" are the only sectors that had a one-directional contribution and hence confirm the aggregated results when

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[5] Effects for macro sectors are derived by summing the effects of micro sectors.

looking at separate periods. Nevertheless, the former two reveal a decreasing delocalization rate. For all other sectors, there are significant variations in contributions of delocalization, with five sectors experiencing a reverse in the trend. The positive effect of delocalization on energy intensities of “Livestock and Meat Products” and “Extraction” in 2001-2004 reversed in the subsequent periods. The opposite is true for “Heavy Manufacturing”, “Light Manufacturing” and “Textiles and Wearing Apparel”, which recently (after 2004) witnessed relevant relative production shift to less energy efficient production locations[6]. Such effects have been indicated by observed structural changes in economies (Voigt et al., 2014) and the decline in US manufacturing (Acemoglu et al., 2016). They might be inter alia related to an increasing competitiveness of Asian economies in manufacturing sectors (McMillan et al., 2014; Rodrik, 2015).

Assessing contributions of change in technology at a more detailed level by increasing the temporal resolution, see Figure 5, shows a rather constant cross-sectoral contribution of energy efficiency improvements to the decrease in energy use.

[6] The energy-intensive trade-exposed sectors (EITE) include glass, steel, metals, pulp and paper, aluminum and chemicals (ACEEE, 2017). Hence, EITE sectors subsets part of “Heavy Manufacturing” and “Light Manufacturing”.

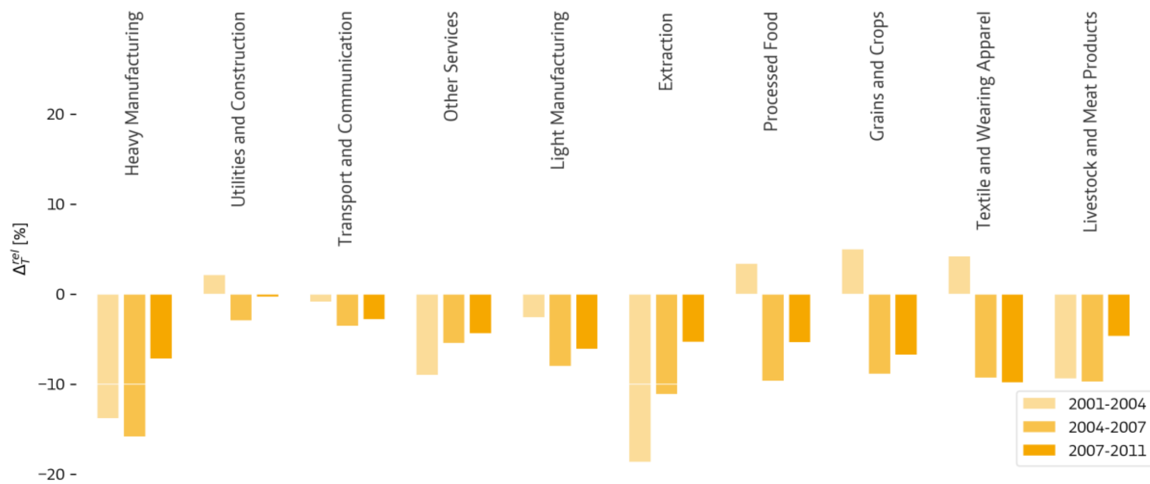

Figure 5: Annual percentage changes in sectoral energy intensities of macro sectors related to changes in the technology factor.

Even though some variance exists, only “Utilities and Construction”, “Textiles and Wearing Apparel”, “Grains and Crops” and “Processed Food” have a single period of positive contributions to energy consumption through changing technology. They are the only macro sectors that have seen a change in trend. Some sectors have experienced constantly decreasing improvement rates, i.e. “Extraction” and “Other services”. A recent decline in the improvement rate of more than 8 percentage points in “Heavy Manufacturing” is particular interesting in this respect as it is the largest energy consuming macro sector (~50% of world energy consumption). Note that in addition to this trend the delocalization factor for the same sector contributes to increases in energy intensities since 2004 (see also Figure 4).

As the macroeconomic sectors consist of multiple, non-homogeneous sectors, with contrasting shares of energy consumption, see Figure 2 and Table A3, a more detailed investigation is indispensable to understand observed developments at the macro sectoral level. Investigating the most relevant macro sector “Heavy Manufacturing” in more detail, see Table 2, we find substantial internal heterogeneity across the effects. While the dominant sector “Petroleum and

Coal Products" has shown very little changes due to delocalization[7], all other sectors except for "Mineral Products nec"'s first period, i.e. "Chemical, Rubber and Plastics", "Ferrous Metals", "Metals nec", "Machinery and Equipment" and "Electronic Equipment" demonstrate continuous and relevant increases in energy consumption due to delocalization. The contributions of "Ferrous Metals" and "Machinery and Equipment" have exceeded 4% for the entire period. For all cases, except for "Mineral Products nec" and "Electronic Equipment" in 2001-2004, delocalization-driven energy use increases are outweighed by technology effects. Observed reductions in energy intensity improvements also hold for all "Heavy Manufacturing" subsectors. Large reductions are identified for "Petroleum and Coal Products", "Ferrous Metals", "Metals nec" and "Machinery and Equipment nec". Please see the Discussion for potential reasons.

Also for other macro sectors, delocalization is relevant at the sub level. For the second and third most energy consuming macro sectors, i.e. "Utilities and Construction" and "Transportation and Communications", the subsectors "Electricity", "Construction", "Water" and "Communication" show continuously increasing energy consumption due to delocalization.

Taken together, subsectors of the three highest energy consuming macro sectors, showing continuously positive delocalization effects, accounted for approximately 280 Exajoules in 2011. That corresponds to more than 40% of global annual energy use and illustrates that delocalization is a relevant issue. In total, we observe that over the period 23 out of 57 GTAP sectors have constantly contributed to growing energy consumption due to delocalization. Seven sectors have constantly contributed to increases greater than 3%: "Ferrous metals", "Machinery and Equipment", "Construction", "Communication", "Motor Vehicles and Parts", "Dwellings" and "Transport Equipment". In contrast, only two sectors have demonstrated a constant decrease in their energy consumption due to delocalization: "Oil seeds" and "Sugar", possibly because of delocalization towards more productive regions, i.e. Brazil in case of "Oil seeds" (Bustos et al.,

[7] This sector is dependent on local endowments, thus finding little influence of delocalization makes perfect sense.

2016). The more detailed decomposition of micro sectors (see Table 2) confirms that changes in sectoral value added have primarily contributed to increasing energy use.

The contrary is true for technology development. Both findings are in line with observations at aggregated sectoral level. Remarkably, the contribution of value added significantly declined in 2007-2011 compared to 2004-2007 for almost all sectors. This is possibly because of the global crisis in 2008, see the Discussion for more detail.

Factor	**Delocalization**			**Technology**			**Value added**		
Year	2001-2004	2004-2007	2007-2011	2001-2004	2004-2007	2007-2011	2001-2004	2004-2007	2007-2011
Heavy Manufacturing	**-4.1**	**1.8**	**1.7**	**-13.8**	**-15.8**	**-7.1**	**22.0**	**15.9**	**7.2**
P_C	-5.9	0.9	1.0	-17.9	-18.6	-7.8	27.4	19.0	8.0
CRP	0.4	3.3	2.8	-2.9	-6.3	-4.9	6.3	6.2	5.0
I_S	4.9	5.3	4.0	-9.9	-9.1	-4.5	12.7	8.8	5.5
NMM	-3.1	6.0	5.3	14.9	-10.5	-8.2	0.7	8.8	5.3
NFM	5.5	4.0	1.0	-13.5	-13.5	-5.8	10.3	11.1	6.9
OME	4.9	5.9	5.2	-6.2	-11.1	-4.4	8.1	7.4	3.3
ELE	4.0	1.8	2.9	17.6	-4.0	-3.3	-4.4	4.0	2.7
Utilities and Construction	**1.9**	**1.0**	**0.2**	**2.1**	**-2.9**	**-0.3**	**1.3**	**6.3**	**2.6**
ELY	1.9	0.8	0.2	3.1	-2.4	-0.3	0.5	6.0	2.8
GDT	0.4	2.3	-2.4	-16.9	-11.1	4.3	14.8	13.1	-1.3
CNS	3.2	4.7	3.9	3.8	-7.3	-7.1	10.4	8.6	2.0
WTR	5.0	5.9	1.9	-8.7	-7.7	-2.8	5.0	7.7	3.7
Transport and Communication	**2.0**	**1.0**	**0.2**	**-0.8**	**-3.5**	**-2.8**	**5.0**	**4.9**	**3.6**
OTP	1.5	1.3	-0.1	-0.9	-3.5	-2.5	6.1	4.7	3.7
ATP	2.7	0.1	0.0	-1.5	-2.5	-1.5	2.2	3.7	1.5
TRD	-1.2	1.6	1.3	3.1	-4.7	-3.9	1.1	5.6	3.6
WTP	8.6	-0.1	0.6	-4.6	-3.9	-4.7	9.8	8.1	6.8
CMN	3.0	5.1	4.4	-7.0	-6.1	-5.8	10.1	6.7	3.8
Other Services	**2.2**	**2.9**	**2.1**	**-9.0**	**-5.4**	**-4.3**	**8.3**	**5.2**	**3.2**
OSG	1.3	2.8	2.3	-6.8	-5.3	-4.9	13.6	5.1	3.8
ROS	1.7	1.4	1.7	-11.5	-4.3	-4.0	-3.4	4.7	3.1
OBS	4.0	3.9	2.0	-8.2	-6.1	-3.4	9.3	5.6	2.0
OFI	6.0	2.8	1.6	-16.8	-5.6	-3.3	12.0	6.0	3.4
ISR	1.5	6.7	4.2	-17.5	-6.5	-4.4	7.4	4.5	3.0
DWE	11.2	5.3	3.7	0	-8.3	-1.1	26.1	3.8	3.2
Light Manufacturing	**-0.8**	**4.4**	**4.1**	**-2.5**	**-8.0**	**-6.0**	**3.8**	**5.7**	**2.7**
PPP	-2.1	3.6	3.1	0.8	-6.9	-7.4	2.4	4.6	2.6
FMP	-1.8	6.5	6.5	-7.9	-8.8	-4.6	7.1	6.6	2.1
MVH	4.2	3.4	3.9	-10.6	-4.1	-4.7	7.3	6.9	2.5
LUM	5.9	6.4	2.6	-7.4	-16.9	-2.2	1.5	4.9	0.8
OMF	-7.6	3.7	4.9	8.0	-7.1	-6.8	2.0	8.4	5.2

OTN	3.3	3.9	5.3	-8.8	-4.2	-5.2	6.0	7.1	3.8
LEA	-4.3	4.1	3.1	8.0	-10.9	-11.1	3.7	6.6	4.7
Extraction	**4.3**	**-0.1**	**-1.8**	**-18.6**	**-11.1**	**-5.3**	**17.9**	**15.0**	**9.4**
OIL	0.5	-0.8	0.3	-34.4	-15.8	-8.4	30.6	17.4	8.3
GAS	6.0	-3.2	-10.0	-12.4	-9.1	7.2	12.1	13.2	4.7
OMN	0.0	1.6	0.9	-6.5	-5.8	-7.9	18.1	16.5	10.7
FSH	0.6	-2.7	-2.3	-2.1	-7.1	-6.5	-4.3	10.0	10.8
COA	27.4	3.9	-0.2	-16.5	-13.4	-9.9	11.4	13.5	15.1
FRS	3.3	2.6	-2.4	-4.0	-8.5	-2.4	3.0	10.5	5.9
Processed Food	**0.0**	**3.6**	**2.4**	**3.4**	**-9.6**	**-5.3**	**2.8**	**7.1**	**4.7**
OFD	0.2	3.5	2.7	-0.2	-8.8	-4.9	6.6	6.0	4.4
B_T	-4.3	5.2	2.8	19.7	-8.8	-7.2	-1.9	5.5	4.5
MIL	6.7	4.8	2.6	0.3	-13.2	-4.0	9.1	8.8	3.4
SGR	-5.9	-2.1	-2.4	-3.0	-6.0	-2.8	-7.7	10.6	5.9
VOL	6.5	-0.6	1.8	-0.2	-13.5	-6.8	-6.9	15.5	10.2
Grains and Crops	**-3.1**	**1.1**	**-0.8**	**5.0**	**-8.8**	**-6.7**	**1.9**	**9.2**	**9.0**
V_F	0	0.6	-1.4	1.2	-7.6	-6.2	2.3	9.3	7.5
OCR	-2.5	0.0	-1.7	2.3	-8.1	-4.2	2.2	3.8	4.9
WHT	-13.4	2.5	1.9	15.1	-10.6	-6.5	-1.0	11.4	9.3
GRO	-0.8	3.2	-1.4	5.9	-11.6	-7.4	5.0	16.5	10.2
PCR	-12.9	4.5	0.4	0.5	-9.7	-5.6	-7.3	12.8	11.6
OSD	-1.5	-0.2	-1.7	7.6	-9.5	-7.7	16.5	9.3	11.3
PFB	-0.3	0.9	1.8	11.0	-8.5	-12.5	-3.4	6.9	12.7
PDR	5.9	0.2	-1.9	5.6	-7.2	-8.2	1.2	6.5	14.0
C_B	0.2	1.6	0.2	3.9	-9.8	-7.5	1.0	9.9	14.7
Textile and Wearing Apparel	**-1.9**	**3.9**	**3.7**	**4.2**	**-9.3**	**-9.8**	**-1.1**	**5.9**	**4.5**
TEX	-2.7	3.9	3.8	1.7	-8.9	-9.3	-1.1	5.9	4.8
WAP	1.1	4.0	3.5	13.7	-10.1	-11.2	-1.0	6.0	3.8
Livestock and Meat Products	**3.5**	**0.1**	**-1.4**	**-9.4**	**-9.7**	**-4.6**	**1.0**	**10.2**	**7.2**
OAP	2.8	-1.9	-1.1	-11.9	-8.2	-5.7	-0.1	11.0	8.1
RMK	8.7	-1.3	-1.9	-17.2	-8.6	-3.9	3.0	9.4	7.0
OMT	-1.7	-0.6	0.1	-6.1	-12.0	-2.9	-0.1	10.9	3.5
CTL	3.0	-0.3	-4.0	-8.4	-9.0	-5.6	2.7	8.2	10.5
CMT	4.3	5.3	-0.6	-3.0	-11.3	-3.7	1.8	9.8	5.3
WOL	7.8	1.3	0.5	19.5	-11.9	-7.9	-10.5	16.1	13.8

Table 2: Annual relative changes in energy use in percent, decomposed to the relative delocalization, energy efficiency and sectoral value added factors. Sorting of macro sectors and internal sorting of subsectors follows the share of energy consumption (see Table A3 in the Appendix).

4 Discussion and Conclusion

In this paper, we investigate the role of delocalization on annual changes in sectoral energy use for the period 2001-2011. Within this decade global energy use increased by one third, and sectoral energy use patterns have shifted significantly between regions. Our results, using a LMDI decomposition along sectoral lines, show that increases in (sectoral) value added have continuously been the dominating factor and boosted overall energy use. This effect is partly counterbalanced by technological improvements, which have, however, decelerated over time, at least for most energy intensive sectors. Although delocalization does not show a clear cross-sectoral trend, in most sectors it has increased energy consumption within the range of 1-6% per annum. This holds especially for sectors with high overall energy consumption.

Manufacturing sectors show a strong increase in production shares in more energy-intensive regions since 2004. More specifically, “Ferrous metals”, “Machinery and Equipment”, “Construction”, “Communication”, “Motor Vehicle and Parts”, “Dwellings” and “Transport Equipment” have experienced constant annual delocalization-driven increases of energy use by more than 3% per annum for the entire period (2001-2011). It is important to note that those manufacturing sectors are among the most flexible in terms of production location in the global economy (McMillan et al., 2014; Rodrik, 2015). Production can hence adjust relatively easily to changes in political or economic framework conditions. This could imply that an increasing segregation of climate policy across the world might well accelerate the delocalization of energy-intensive sectors from regulated towards non-regulated regions, leading to overall increasing energy demand and hence emissions. At least, our results give no indication that a stronger delocalization trend, which could be caused by environmental regulation, increases energy intensity improvement rates, as theoretically laid out by Gerlagh and Kuik (2014) and Grubb et al. (2002).

It is important to note that from a global perspective it seems as technological improvement rates in some manufacturing sectors also slow down in subsequence of delocalization, see Table 2. This coincides with technological research capacities and abilities to adopt efficient technologies being (currently) mainly located in industrialized countries (Dechezleprêtre et al., 2013, 2011). Delocalization might hence induce second order effects that impede achieving ambitious climate change mitigation as future energy intensity progress rates are negatively impacted. Our small sample does not allow to investigate this hypothesis statistically. In addition, other explanations need to be considered. Thus the global economic crises in 2008/2009[8], which majorly hit OECD economies (China for instance experienced only small impacts on GDP growth rates (The World Bank, 2017)) and led to declines in oil prices (Nasdaq, 2017) could have had relevant influence on the observed decline in energy intensity improvement rates (Csereklyei et al., 2016; Dechezleprêtre et al., 2011).

The applied approach allows to identify the *pure* sectoral relative delocalization effects within single sectors[9], which has not been done before. However, our analysis does not allow to give an ex-post explanation for the effects observed.[10] Nevertheless, multiple theoretical explanations and channels have been identified (Dechezleprêtre and Sato, 2017). An approximate understanding of potential policy impacts and their dynamics can currently only be gained by the application and evaluation of CGE models (Carbone and Rivers, 2017).

Considering the ambitious climate mitigation targets laid down in the Paris Agreement it is important to understand how the impacts associated to observed delocalization can be alleviated. Targeting emissions in specific economic sectors across all countries (or at least a relevant set of countries, e.g. within the G20) might be an effective and feasible second best option for climate policy as long as no global approach exists. Negotiations on specific targets or regulations could be faster and implementation easier compared to economy wide approaches (Ahman et al., 2016; den Elzen et al., 2008; Kuik et al., 2008; Schmidt et al., 2008). Such mitigation strategies might be

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[8] Note that according to Figure 1, the Middle East, Southern and East Asia saw significant increases in energy consumption for 2007-2011, while North America and the EU25 saw declines. The increases overcompensated the declines. Nevertheless, in subsequence of the global economic crisis, the growth rate of energy consumption declined (The annual growth rate for 2007-2011 is ~5.5% compared to 8.2% (2004-2007) and 13.6% (2001-2004)).

[9] This also implies that we can depict the real sectoral energy intensity progress rate as delocalization effects can be segregated.

[10] Inter alia no policy counterfactual exists and hence effects cannot be disentangled to their origin.

particularly feasible for manufacturing sectors, which are both prone to delocalization, responsible for a large share of energy consumption and show large efficiency variations across countries (Kim and Kim, 2012; Saygin et al., 2011). Given that manufacturing sectors also imply significant energy consumption in their supply chains, targeting selected energy intensive sectors might imply significant reductions in both, energy consumption and emissions in upstream sectors (Ward et al., 2017).

How to organize and incentivize intra-sectoral technology transfer is open to debate. Targeted development assistance and foreign direct investments could foster technological progress in developing countries (Javorcik, 2004; Peterson, 2008). One additional possibility would be to make entire sectors (e.g., in the form of industry associations) eligible for climate finance, for instance to enforce sector wide efficiency standards (Saygin et al., 2011) or targeted technological access (United Nations, 1992). Nevertheless, intellectual property rights in developing countries that have been identified as a major obstacle to technological progress and diffusion of efficient technologies will have to improve (Dechezleprêtre et al., 2013).

Carbon tariffs are frequently proposed to tackle delocalization resulting from environmental regulation, more specifically emission leakage (Böhringer et al., 2012). Our results do not necessarily support this claim. They do not allow to disentangle whether observed delocalization is caused by existing differences in environmental regulation (Jakob et al., 2014), differences in productivity as described by Rodrik (2015), ongoing fragmentation and specialization in global supply networks (Timmer et al., 2014) or differing regional growth dynamics leading to relative shifts in the production network (Voigt et al., 2014). Further, it is unclear whether delocalizing sectors are primarily producing for export or for domestic demand (Jakob et al. 2013). It is hence questionable whether carbon tariffs would trigger technological improvements in countries using inefficient technologies and thus abate impacts by delocalization. Future research could focus on trade patterns of delocalizing sectors along the lines of the sectoral decomposition we propose.

Acknowledgements

The authors want to thank Sabine Fuss and Michael Jakob for their valuable comments on this work. In addition, we would like to thank two anonymous referees.

Funding

This work was supported by the German Research Association (Deutsche Forschungsgemeinschaft), Collaborative Research Center 1026. Hauke Ward gratefully acknowledges funding by the *Bundesministerium für Bildung und Forschung* (BMBF) grant “Klimapolitische Maßnahmen und Transformationspfade zur Begrenzung der globalen Erwärmung auf 1.5°C (PEP1p5)”, with grant number 01LS1610B.

Statement on figure colors

No color should be used for any figures in print.

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Appendix

In GTAP, raw energy data are categorized according to three criteria. The first is the energy source or service: GTAP accounts for coal, gas, oil, electricity, petroleum and coal products and gas distribution. In the second, the origin is considered (domestic or imported). The third characteristic accounts for the type of final consumption where the energy is used (households, government use, company use). For the analysis carried out in this paper, only companies are used as they use energy in industrial production. Before energy data can be used in the decomposition analysis, the data has to be adapted to the input-output framework.

Single flows in GTAP raw energy use data consider the year t, sector s, region r, energy source e and origin o (domestic/import), so that each one can be written as $E_{s,r,t,e,o}$. First, values for imported and domestic energy for each energy source are totaled for each region and sector.

As energy flows are given in tons of oil equivalent (toe), they have to be transformed into Joules (J), the unit used by the International System and used in preference to indicate energy intensity (J/$). Since the calorific value depends on the fuel considered, the transformation is carried out by applying energy-source dependent conversion coefficients CC_e as displayed in Table A1.

Energy commodity	**conversion coefficient (MJ/toe)**
Coal	41868
Crude oil	41868
Natural gas	41868
Electricity	41868
Petroleum products	44500
Gas products (mainly LPG)	47310

Table A1: Conversion coefficients for different energy commodities (Lee, 2008).

In the next step, the energy use for different energy sources is aggregated, since this differentiation is not relevant for our analysis. As a result, three 140×57 matrices (for 2011, 2007and 2004) and one 87×57 matrix (2001) emerge:

$$E_{s,r,t} = \sum_e \left(\sum_o E_{s,r,t,e,o} \cdot CC_e\right) \quad (11)$$

As regions considered in GTAP versions 6 and 9 vary, it is necessary to harmonize the regional dimension. Regions that are available in GTAP 9 which are not separately covered in GTAP 6 are treated in a special way. Such regions are aggregated to the corresponding "X" ("rest of") region they geographically belong to, please see the corresponding GTAP manuals (Dimaranan, 2006; Narayanan et al., 2015). The Rest of the World (XTW) region was disregarded as it included different regions in the two versions. For this reason, we consider 86 regions instead of 87 that are available in GTAP 6 when analyzing development from 2001 to 2004.

The data contains regional sectors that have negative value added. Using those negative values would lead to negative energy intensities. For computational consistency we set all entries to zero (in both years for a decomposition analysis) if they exhibited negative value ex ante.

sector		**macro sector**	
abbreviation	**name**	**abbreviation**	**name**
PDR	Paddy rice	GrainsCrops	Grains and Crops
WHT	Wheat	GrainsCrops	Grains and Crops
GRO	Cereal grains nec	GrainsCrops	Grains and Crops
V_F	Vegetables, fruit, nuts	GrainsCrops	Grains and Crops
OSD	Oil seeds	GrainsCrops	Grains and Crops
C_B	Sugar cane, sugar beet	GrainsCrops	Grains and Crops
PFB	Plant-based fibers	GrainsCrops	Grains and Crops
OCR	Crops nec	GrainsCrops	Grains and Crops
CTL	Bovine cattle, sheep and goats, horses	MeatLstk	Livestock and Meat Products
OAP	Animal products nec	MeatLstk	Livestock and Meat Products
RMK	Raw milk	MeatLstk	Livestock and Meat Products
WOL	Wool, silk-worm cocoons	MeatLstk	Livestock and Meat Products
FRS	Forestry	Extraction	Mining and Extraction
FSH	Fishing	Extraction	Mining and Extraction
COA	Coal	Extraction	Mining and Extraction

OIL	Oil	Extraction	Mining and Extraction
GAS	Gas	Extraction	Mining and Extraction
OMN	Minerals nec	Extraction	Mining and Extraction
CMT	Bovine meat products	MeatLstk	Livestock and Meat Products
OMT	Meat products nec	MeatLstk	Livestock and Meat Products
VOL	Vegetable oils and fats	ProcFood	Processed Food
MIL	Dairy products	ProcFood	Processed Food
PCR	Processed rice	GrainsCrops	Grains and Crops
SGR	Sugar	ProcFood	Processed Food
OFD	Food products nec	ProcFood	Processed Food
B_T	Beverages and tobacco products	ProcFood	Processed Food
TEX	Textiles	TextWapp	Textile and Wearing Apparel
WAP	Wearing apparel	TextWapp	Textile and Wearing Apparel
LEA	Leather products	LightMnfc	Light Manufacturing
LUM	Wood products	LightMnfc	Light Manufacturing
PPP	Paper products, publishing	LightMnfc	Light Manufacturing
P_C	Petroleum, coal products	HeavyMnfc	Heavy Manufacturing
CRP	Chemical, rubber, plastic products	HeavyMnfc	Heavy Manufacturing
NMM	Mineral products nec	HeavyMnfc	Heavy Manufacturing
I_S	Ferrous metals	HeavyMnfc	Heavy Manufacturing
NFM	Metals nec	HeavyMnfc	Heavy Manufacturing
FMP	Metal products	LightMnfc	Light Manufacturing
MVH	Motor vehicles and parts	LightMnfc	Light Manufacturing
OTN	Transport equipment nec	LightMnfc	Light Manufacturing
ELE	Electronic equipment	HeavyMnfc	Heavy Manufacturing
OME	Machinery and equipment nec	HeavyMnfc	Heavy Manufacturing
OMF	Manufactures nec	LightMnfc	Light Manufacturing
ELY	Electricity	Util_Cons	Utilities and Construction
GDT	Gasmanufacture, distribution	Util_Cons	Utilities and Construction
WTR	Water	Util_Cons	Utilities and Construction
CNS	Construction	Util_Cons	Utilities and Construction
TRD	Trade	TransComm	Transport and Communication
OTP	Transport nec	TransComm	Transport and Communication
WTP	Water transport	TransComm	Transport and Communication
ATP	Air transport	TransComm	Transport and Communication
CMN	Communication	TransComm	Transport and Communication
OFI	Financial services nec	OthServices	Other Services
ISR	Insurance	OthServices	Other Services
OBS	Business services nec	OthServices	Other Services
ROS	Recreational and other services	OthServices	Other Services
OSG	Public Adm., Defense, Education, Health	OthServices	Other Services
DWE	Dwellings	OthServices	Other Services

Table A2: Sectors and macro sectors as from GTAP Data Base.

Year	2001	2004	2007	2011
Total	**511.4**	**581.3**	**628.5**	**674.3**
Heavy Manufacturing	**259.3**	**292.8**	**310.1**	**331.9**
P_C	192.5	213.4	222.8	233.4
CRP	36.1	40.3	44.2	49.3
I_S	11.4	14.0	16.2	19.3
NMM	10.2	14.0	15.9	17.4
NFM	5.1	5.4	5.7	6.2
OME	3.0	3.6	3.8	4.5
ELE	1.0	1.6	1.7	1.8
Utilities and Construction	**127.4**	**147.6**	**167.1**	**184.1**
ELY	118.6	138.1	156.2	173.0
GDT	5.5	5.3	6.0	6.1
CNS	1.7	2.6	3.1	2.9
WTR	1.5	1.5	1.8	2.1
Transport and Communication	**67.9**	**80.5**	**86.4**	**90.2**
OTP	38.4	46.3	49.8	52.0
ATP	13.7	15.1	15.7	15.7
TRD	9.4	10.4	11.1	11.6
WTP	5.5	7.8	8.7	9.7
CMN	0.8	1.0	1.1	1.3
Other Services	**19.7**	**20.8**	**22.4**	**23.4**
OSG	9.2	11.5	12.3	12.9
ROS	4.7	2.9	3.0	3.1
OBS	4.3	5.0	5.5	5.7
OFI	1.0	1.1	1.2	1.2
ISR	0.4	0.3	0.4	0.4
DWE	0.0	0.0	0.0	0.0
Light Manufacturing	**11.6**	**11.7**	**12.5**	**12.9**
PPP	5.2	5.4	5.6	5.2
FMP	2.2	2.0	2.3	2.6
MVH	1.2	1.2	1.5	1.6
LUM	1.2	1.2	1.0	1.1
OMF	1.0	1.1	1.2	1.4
OTN	0.5	0.5	0.6	0.7
LEA	0.2	0.3	0.3	0.2
Extraction	**11.5**	**12.7**	**14.2**	**15.5**
OIL	4.5	4.2	4.3	4.3
GAS	2.2	2.5	2.6	2.8
OMN	1.9	2.6	3.6	4.1
FSH	1.2	1.0	1.0	1.1
COA	1.2	1.9	2.2	2.6
FRS	0.4	0.5	0.5	0.5
Processed Food	**4.6**	**5.4**	**5.5**	**5.9**
OFD	2.3	2.8	2.8	3.1

B_T	0.9	1.2	1.3	1.3
MIL	0.5	0.8	0.8	0.9
SGR	0.5	0.2	0.3	0.3
VOL	0.3	0.3	0.3	0.4
Grains and Crops	**4.5**	**5.0**	**5.3**	**5.6**
V_F	1.4	1.6	1.7	1.7
OCR	0.8	0.9	0.8	0.7
WHT	0.6	0.6	0.7	0.8
GRO	0.4	0.6	0.7	0.8
PCR	0.3	0.1	0.2	0.2
OSD	0.3	0.5	0.5	0.5
PFB	0.3	0.3	0.3	0.3
PDR	0.2	0.3	0.3	0.3
C_B	0.1	0.1	0.1	0.2
Textile and Wearing Apparel	**2.6**	**2.7**	**2.7**	**2.6**
TEX	2.1	1.9	2.0	1.9
WAP	0.5	0.8	0.8	0.6
Livestock and Meat Products	**2.5**	**2.1**	**2.2**	**2.3**
OAP	0.8	0.6	0.6	0.6
RMK	0.4	0.3	0.3	0.4
OMT	0.4	0.3	0.3	0.3
CTL	0.4	0.4	0.3	0.4
CMT	0.4	0.4	0.5	0.5
WOL	0.0	0.1	0.1	0.1

Table A3: Sectoral annual energy use in Exajoules.

Country	**Region**	**Country**	**Region**
China	EastAsia	Austria	EU_25
Hong Kong	EastAsia	Belgium	EU_25
Japan	EastAsia	Cyprus	EU_25
Korea	EastAsia	Czech Republic	EU_25
Mongolia	EastAsia	Denmark	EU_25
Taiwan	EastAsia	Estonia	EU_25
Rest of East Asia	EastAsia	Finland	EU_25
Brunei Darassalam	EastAsia	France	EU_25
		Germany	EU_25
		Greece	EU_25
Bahrain	MENA	Hungary	EU_25
Iran Islamic Republic of	MENA	Ireland	EU_25
Israel	MENA	Italy	EU_25
Jordhan	MENA	Latvia	EU_25
Kuwait	MENA	Lithuania	EU_25
Oman	MENA	Luxembourg	EU_25
Qatar	MENA	Malta	EU_25
Saudi Arabia	MENA	Netherlands	EU_25
Turkey	MENA	Poland	EU_25

United Arab Emirates	MENA	Portugal	EU_25
Rest of Western Asia	MENA	Slovakia	EU_25
Egypt	MENA	Slovenia	EU_25
Morocco	MENA	Spain	EU_25
Tunisia	MENA	Sweden	EU_25
Rest of North Africa	MENA	United Kingdom	EU_25
Benin	SSA	Australia	Oceania
Burkina Faso	SSA	New Zealand	Oceania
Cameroon	SSA	Rest of Oceania	Oceania
Cote d'Ivoire	SSA		
Ghana	SSA	Cambodia	SEAsia
Guinea	SSA	Indonesia	SEAsia
Nigeria	SSA	Lao People's Democratic Republ	SEAsia
Senegal	SSA	Malaysia	SEAsia
Togo	SSA	Philippines	SEAsia
Rest of Western Africa	SSA	Singapore	SEAsia
Central Africa	SSA	Thailand	SEAsia
South Central Africa	SSA	Viet Nam	SEAsia
Ethiopia	SSA	Rest of Southeast Asia	SEAsia
Kenya	SSA		
Madagascar	SSA	Canada	NAmerica
Malawi	SSA	United States of America	NAmerica
Mauritius	SSA	Mexico	NAmerica
Mozambique	SSA	Rest of North America	NAmerica
Rwanda	SSA		
Tanzania	SSA	Bangladesh	SouthAsia
Uganda	SSA	India	SouthAsia
Zambia	SSA	Nepal	SouthAsia
Zimbabwe	SSA	Pakistan	SouthAsia
Rest of Eastern Africa	SSA	Sri Lanka	SouthAsia
Botswana	SSA	Rest of South Asia	SouthAsia
Namibia	SSA		
South Africa	SSA		
Rest of South African Customs	SSA		
Argentina	LatinAmer	Switzerland	RestofWorld
Bolivia	LatinAmer	Norway	RestofWorld
Brazil	LatinAmer	Rest of EFTA	RestofWorld
Chile	LatinAmer	Albania	RestofWorld
Colombia	LatinAmer	Bulgaria	RestofWorld
Ecuador	LatinAmer	Belarus	RestofWorld
Paraguay	LatinAmer	Croatia	RestofWorld
Peru	LatinAmer	Romania	RestofWorld

Uruguay	LatinAmer	Russian Federation	RestofWorld
Venezuela	LatinAmer	Ukraine	RestofWorld
Rest of South America	LatinAmer	Rest of Eastern Europe	RestofWorld
Costa Rica	LatinAmer	Rest of Europe	RestofWorld
Guatemala	LatinAmer	Kazakhstan	RestofWorld
Honduras	LatinAmer	Kyrgyztan	RestofWorld
Nicaragua	LatinAmer	Rest of Former Soviet Union	RestofWorld
Panama	LatinAmer	Armenia	RestofWorld
El Salvador	LatinAmer	Azerbaijan	RestofWorld
Rest of Central America	LatinAmer	Georgia	RestofWorld
Dominican Republic	LatinAmer	Rest of the World	RestofWorld
Jamaica	LatinAmer		
Puerto Rico	LatinAmer		
Trinidad and Tobago	LatinAmer		
Caribbean	LatinAmer		

Table A4: Overview of countries and regions used.