The Effect of Globalisation on Energy Footprints: Disentangling the Links of Global Value Chains

Oliver Kaltenegger*[1], Andreas Löschel†[1,2,3], and Frank Pothen‡

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[1]University of Münster, Center of Applied Economic Research Münster (CAWM), Am Stadtgraben 9, 48143 Münster, Germany
[2]Centre for European Economic Research (ZEW), L7, 1, 68161 Mannheim, Germany
[3]University of International Business and Economics, Beijing 100029, China
[4]Leibniz University of Hannover, Institute for Environmental Economics and World Trade, Königsworther Platz 1, 30167 Hannover, Germany

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Abstract

This paper investigates the impact of global value chains on energy footprints. Energy footprints are consumption-based indicators which record the energy used to produce a country's final demand. In order to disentangle key characteristics of global value chains and their effects on the global energy footprint, we employ structural decomposition analyses (SDA). Furthermore, the analysis combines a retrospective with a prospective SDA approach. After an analysis of the global energy footprint for the period between 1995 and 2009, we discuss three scenarios of international integration and their implications for energy footprints for the period from 2009 to 2030. Our results show that the global energy footprint has increased by 29.4% from 1995 to 2009, and the scenarios indicate that it will increase by another 23.5% until 2030. Economic activity is the most important driver for the increase in energy footprints. Rising final demand alone would have increased the global energy footprint by 47.0% between 1995 and 2009. The composition of countries from where consumption and investment goods come adds another 12.6%. Sectoral energy intensity reductions are the most important decelerator of energy use (-27.8%). There is a substantial contribution of changing global value chains on the rise in the global energy footprint (7.5%): Stronger backward linkages in global value chains increased the global energy footprint by 5.5% between 1995 and 2009. Changes in the regional composition of intermediate inputs raised it by another 1.8%. The shift of the world economy towards East Asia alone would have increased the global energy footprint by 3.0%. The sectoral composition of global value chains, on the other hand, had a negligible effect on energy footprints.

*Email: oliver.kaltenegger@wiwi.uni-muenster.de
†Email: loeschel@uni-muenster.de
‡Email: pothen@iuw.uni-hannover.de. Frank Pothen gratefully acknowledges funding for the project "NEDS – Nachhaltige Energieversorgung Niedersachsen" supported by the Lower Saxony Ministry of Science and Culture through the "Niedersächsisches Vorab" grant programme (grant ZN3043)

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Highlights

- SDA computes 5 supply-side effects of global value chains on national footprints.
- One fourth of rise in the global footprint is related to global value chains (7.5%).
- Rise of East Asia in global value chains alone boosted footprints by 3.0%.
- Globalisation of intermediates production was a stronger driver than regionalisation.
- Diffusion of energy-efficient technology will reduce regional effects on footprints.

1 Introduction

Modern history was marked by unprecedented growth in economic activity. Along with production and consumption, humanity's demand for natural resources such as water, material, land, and the atmosphere, has increased substantially (e.g. Hoekstra and Mekonnen [2012], Lan et al. [2016], Pothen and Schymura [2015], Weinzettel et al. [2013]). Hoekstra and Wiedmann [2014] concluded that the use of materials, carbon, and possibly blue water to produce the final demand along the entire value chains, has already surpassed maximum sustainable levels. Humanity has left the "safe operating space" [Rockström et al., 2009, p.472].

Energy plays a key role in these developments as ever since the days of the industrial revolution, energy was essential for facilitating economic growth, initially through coal-fired technologies, later through oil and natural gas. Lan et al. [2016] showed that between 1990 and 2010, the world's energy use increased by 211 exajoules, more than twice the total primary energy supply of the United States in 2013 [IEA, 2015a]. Today, our fossil-based global energy system is still the dominant contributor to greenhouse gas emissions and to the unsustainable global carbon footprint.

In recent decades, globalisation has significantly altered the world economy, transforming global value chains into a complex web of interrelations between countries and sectors. One of the new aspects was that producers split production processes into geographically separated steps.[1] Outsourcing parts of the value chain, measured by a rising usage of imported intermediate inputs, increased since the 1970s [Feenstra, 1998]. Hummels et al. [2001] quantified the growth of vertical specialisation, defined as the use of imported inputs in producing goods that are exported. Using input-output tables from 10 OECD members and 4 emerging economies, they estimated that vertical specialisation accounted for 21% of these countries' exports, and that vertical specialisation grew by almost 30% between 1970 and 1990. Value-added exports, that is the amount of domestic value added produced in a source country and absorbed abroad [Johnson and Noguera, 2012b], was about 70-75% of gross exports in 2008, down from about 85% in the 1970s and 1980s. Importantly, the decline occurred almost entirely after 1990 [Johnson, 2014]. Timmer et al. [2015b] analysed 560 global value chains between 1995 and 2008. They found that the share of foreign value-added has increased in 85% of the chains. The (unweighted) average share rose from 28% to 38%. This trend was briefly interrupted by the financial crisis in 2008, but continued again afterwards [Los et al., 2015].

The literature on energy footprints (e.g. Chen and Chen [2011], Hong et al. [2007], Xu et al. [2009]) has, so far, not addressed the role of increasingly globalised value chains, but focused on outsourcing: high-income countries have increasingly outsourced energy-intensive production activities into industrialising nations. Similar patterns have been observed for other resources as well (e.g. Arto and Dietzenbacher [2014], Bruckner et al. [2012], Chen and Chen [2013], Hoekstra and Chapagain [2007], Meyfroidt et al. [2010], Tukker et al. [2014], Wiedmann [2009], Wiedmann et al. [2013], Xu and Dietzenbacher [2014], Yu et al. [2013]). It is likely that these outsourcing processes are reflected in the structure of global value chains.

In this paper, we scrutinise the impact of globalisation in general and increasingly global value chains in particular on energy footprints. Our approach is twofold. Focusing on the evolution of global value chains, we first disentangle how changes in global production and final demand patterns affected the evolution of global and national energy footprints. We study 40 major economies as well as the global level between 1995 and 2009. For this purpose, we perform

[1] This phenomenon has also been labelled slicing up the value chain, disintegration of production, fragmentation, multi-stage production, intra-product specialisation, etc.

retrospective value-chain-oriented structural decomposition analyses (SDA). We contribute to the literature which studies footprints of resources in general and, in particular, extent the work of Lan et al. [2016], who presented the first global SDA of energy footprints, by disentangling the impacts of changing global value chains. Second, we combine the retrospective analyses with a prospective approach. Three scenarios for economic growth, structural change, and, in particular, economic integration are constructed to conduct a prospective SDA in order to illustrate how the global energy footprint is affected by potential future changes between 2009 and 2030.

Energy footprints are part of consumption-based accounting approaches [Owen et al., 2017] and consistent with the System of Environmental-Economic Accounting (SEEA 2012). Even though there are exceptions (e.g. Chen and Chen [2011]), studies on energy footprints at the global scale remain relatively scarce [Arto et al., 2016], especially studies that look at developments over several years. Kucukvar et al. [2016] recognised a lack of footprint applications for global supply chains and analysed, for energy and carbon, five common supply chain phases: upstream suppliers, on-site manufacturing, transportation, wholesale, and retail trade. SDA studies focusing on the production structure are also rare. In an early energy footprint study, Jacobsen [2000] investigated changes in trade patterns by separating domestic inputs from total inputs (in the Leontief inverse) and domestic final demand from total final demand in a single-region model for the Danish manufacturing industry. Wood [2009] decomposed the Leontief inverse of Australia's carbon footprint into forward linkages (sales of a producer to its industrial consumers), industrial structure, and backward linkages (purchases of a producer from its suppliers). These studies differ from our approach, since we take a multi-region (global) approach, focus on geographic regions, and look deeper into global value chains.

In their multi-region carbon footprint SDA, Hoekstra et al. [2016] distinguished the geographic origin of intermediate inputs and final demand goods, and calculated the domestic and foreign intermediate and final demand sourcing effects. The effects of foreign-sourced intermediate inputs and final demand goods was further separated into sourcing from low-wage, medium-wage, and high-wage countries. In our paper, we also separate domestic and foreign sourcing effects of intermediates and final demand. But unlike Hoekstra et al. [2016], we study energy rather than carbon and group countries according to geographic regions rather than wages.

This paper's focus on geographic regions is motivated by the literature on global value chains. Based on analyses of trade statistics, Baldwin and Lopez-Gonzalez [2015, p.1696] argue that supply chains are regional – the global production network is organised as regional blocks, to which one could refer to as "factory Asia, factory North America and factory Europe". Other authors draw similar conclusions (e.g. Johnson and Noguera [2012a]), while Los et al. [2015, p.66] suggest a transition from regional production systems to a "factory world", implying that global value chains indeed become global. Our approach allows us to separate the effects of regionalisation and globalisation of value chains on energy footprints. In the following we distinguish four regions, namely EU-27, East Asia, NAFTA, and Other. Additionally, we highlight the role of single countries within regions.

Our results show that the global energy footprint rose by 29.4% between 1995 and 2009. Increasing it by 47.0% ceteris paribus, rising final demand was the predominant driver of the global energy footprint. Falling energy intensities limited its growth (-27.8%). On the global level, changes in value chains accelerated the increase in energy footprints. More intermediate inputs have been used along the value chains, raising the global energy footprint by 5.5%. A regional shift of intermediate input production increased the global energy footprint further. The rising importance of East Asia in intermediate input production, mostly driven by China's integration in the global economy, increased it by 3.0%. On the country level, changes in value chains had heterogeneous effects. Rising amounts of intermediate inputs needed to produce goods had more pronounced effects in industrialising than in industrialised countries. Industrialised countries, furthermore, outsourced the production into nations which produce with higher energy inputs while industrialising countries reduced their energy footprints due to regional shifts in intermediate input production.

Our prospective SDA indicate that the global energy footprint will rise even further but at a slower pace. The average annual growth rate decreases from 1.9% to 1.0%, leading to a total increase in the global energy footprint of 23.5% between 2009 and 2030. Rising final demand and falling energy intensities remain to be most important accelerators and decelerators of energy use (+81.5% and -36.3%, respectively) but the impact of global value chains differs from the 1995 to 2009 period. Structural change in intermediates even reduces the global energy use by 3.9% and shifts in the regional composition of intermediate input production further diminishes it by 2.5%.

The remainder of this paper is organised as follows. Section 2 displays our data and methods: the computation of the energy footprints, the structural decomposition analyses, and the construction of the global multi-region input-output (GMRIO) tables for the prospective SDA. It, furthermore, shows the data we used. The results of our SDA are subsequently reported in Section 3. Section 4 summarises the major findings and draws conclusions.

2 Data and methods

This section outlines the methodology applied in our paper: the computation of the energy footprints, the structural decomposition analyses (both at the country-level and at the global level), as well as the data including the construction of the GMRIO tables up until 2030. Throughout the paper, we distinguish between R countries indexed r, s, and rr as well as between I sectors indexed i and j. Table 4 and Table 5 in Appendix A display the countries and sectors considered in this paper. t indexes time. The retrospective structural decomposition analyses are conducted for $t \in \{1995, \ldots, 2009\}$, the prospective SDA are conducted for $t \in \{2009, \ldots, 2030\}$.

2.1 Energy footprints

Let EF denote the vector of energy footprints. Its elements EF_s record the energy use induced by final demand in country s. EF can be computed as follows [Miller and Blair, 2009]:

$$EF^{\intercal} = q^{\intercal} \cdot L \cdot Y \tag{1}$$

where q is the vector of energy intensities. Each element $q_{i,r}$ equals the amount of energy which sector i in r uses to produce one dollar worth of output. L is the Leontief inverse. Its entries $L_{i,r,j,rr}$ record how many dollars worth of goods from sector i in r are necessary to produce one dollar worth of goods in sector j in rr. Y is the matrix of final demand. Each element $Y_{j,rr,s}$ shows s's expenditures on consumption and investment goods from sector j in rr.

The main objective of this paper is to isolate how changes in global value chains drive energy footprints. International production is increasingly organised in stages which are located across different countries and sectors, with value being added up from one activity to the other. The technical coefficients matrix (or direct input coefficients matrix), which records the expenditure share of each input used to produce one dollar worth of output in a sector, reflects direct linkages. The Leontief inverse L, which is used to calculate energy footprints, builds on those direct input coefficients, but reflects the total (rather than direct) input requirements for each sector and country (per monetary unit of final output). All inputs of a sector to another sector along the global value chains are recorded in L. The SDA approach uses the Leontief inverse L to disentangle the links in global value chains.

Note that changing value chains per se do not have an effect on energy footprints. Global value chains are organised across countries and sectors, which differ in their energy intensities q. Whether reconfiguring the global value chains, e.g. by replacing a domestic with a foreign input, affects energy footprints or not depends on whether these inputs differ in their energy inputs along their value chain.

For our SDA, we disaggregate L in order to isolate three types of changes in global value chains:

- Adding up all intermediate inputs used by sector j in rr to produce one dollar worth of output, the first factor reflects the demand for upstream products derived from incremental production of sector j in rr. This factor is denoted value chain backward linkage, $L^{vcb}_{j,rr} = \sum_{i,r} L_{i,r,j,rr}$. Since we use the Leontief inverse to compute it, all intermediate inputs along the value chain of j in rr are considered. An increase in $L^{vcb}_{j,rr}$ leads to a rise in energy footprints, ceteris paribus, because energy is necessary to produce the additional intermediate inputs.
- The second factor reflects the industrial structure of intermediate inputs needed to produce the sectoral output. It records the share of sector i in all intermediate inputs of sector j in rr, regardless of i's country of origin. It reveals the importance of upstream industries for sector j in rr. This factor is denoted value chain structure, $L^{vcs}_{i,j,rr} = \frac{\sum_r L_{i,r,j,rr}}{\sum_{i,r} L_{i,r,j,rr}}$. Changes in the value chain structure decrease energy footprints if it shifts towards less energy-intensive sectors, for instance from manufacturing to services.
- The third factor represents the regional structure of intermediate inputs. It corresponds to the share of intermediate input i in the value chain of sector j in rr which is produced in country r. It, therefore, reflects the importance of countries in the supplier portfolio of sector j in rr. This factor is denoted value chain region factor, $L^{vcr}_{i,r,j,rr} = \frac{L_{i,r,j,rr}}{\sum_r L_{i,r,j,rr}}$. If value chains move to energy intensive countries, the change in $L^{vcr}_{i,r,j,rr}$ implies an increase in energy footprints.

Even though the matrix of final demand Y does not yield additional information on global value chains, it is instructive with regard to the broader context of this paper, namely globalisation. The matrix Y is disaggregated into the following three factors:

- The first factor reflects the level of final demand. It adds up the expenditure on all final goods consumed in country s, regardless of country or sector of origin, $Y^{lev}_s = \sum_{j,rr} Y_{j,rr,s}$. If the level of final demand rises, energy footprints increase as well because energy is necessary to manufacture the additional goods.
- The second factor relates to the sectoral composition of goods consumed. It records the share of sector j (regardless of the country of origin) in final demand of country s,

$Y^{str}_{j,s} = \frac{\sum_{rr} Y_{j,rr,s}}{Y^{lev}_s}$. When the bundle of goods consumed in s shifts towards less energy-intensive goods, e.g. from manufacture to services, a change in $Y^{str}_{j,s}$ implies a decline in s's energy footprint.

- Representing the regional supplier structure of s's final demand, the third factor connects consumption and investment with global value chains. It corresponds to the share of final demand for j in s which is supplied by country rr, $Y^{sup}_{j,rr,s} = \frac{Y_{j,rr,s}}{Y^{str}_{j,s}}$. If s purchases a larger fraction of its final demand from countries with energy-intensive production, the change in $Y^{sup}_{j,rr,s}$ leads to an increase in s's energy footprint. Note that changes in the countries from which s purchases its final demand affect the importance of individual value chains.

Disaggregating Equation (1) and re-writing it in index notation yields the following expression for country s's energy footprint:

$$EF_s = \sum_{i,r,j,rr} q_{i,r} \cdot L^{vcb}_{j,rr} \cdot L^{vcs}_{i,j,rr} \cdot L^{vcr}_{i,r,j,rr} \cdot Y^{lev}_s \cdot Y^{str}_{j,s} \cdot Y^{sup}_{j,rr,s} \tag{2}$$

2.2 Structural decomposition analyses

To investigate the effects of globalisation, in particular of changes in global value chains, on countries' energy footprints, we employ country-level structural decomposition analyses. They estimate the impact of changes in the seven factors shown in Equation (2) on the energy footprints EF_s (Subsection 2.2.1). One factor relates to energy intensity, three factors to global value chains (supply side), and three factors to final demand. The regional structure of countries supplying final demand connects the supply and demand side. In a second step, we decompose one supply-side and one demand-side factor further into three sub-effects, respectively. On the supply side, it is the regional structure of intermediate inputs that is decomposed into domestic, regional, and foreign effects. In this way, it is possible to distinguish regionalisation from globalisation tendencies in global value chains. It allows for analysing the impacts of regional blocks in global value chains ("factory Asia, factory North America and factory Europe"; [Baldwin and Lopez-Gonzalez, 2015, p.1696]) versus the "factory world" [Los et al., 2015, p.66]. On the demand side, it is the regional structure of the final demand that is decomposed further in the second step. Consequently, our country-level SDA consists of eleven effects in total, five relating to global value chains, five to the demand side (three of which relate to globalisation), and one to energy intensity.

Our global-level SDA (Subsection 2.2.2), which is a slight modification of the country-level SDA, estimates how changes in global value chains and final demand affected the global energy footprint. In a second step, we distinguish between intermediate inputs and final demand sourced from four regions, namely EU-27, East Asia, NAFTA, and Other. This step reveals how changes in the importance of these regions for intermediate and final good production affected energy use.

Our approach differs from the one selected by Lan et al. [2016] who applied a widely-used six-factor decomposition model (see Lenzen [2016], Malik and Lan [2016], Malik et al. [2016]) to conduct the first global SDA of energy footprints. They decompose the change of the footprint into i) an energy intensity effect, ii) a production structure effect, and four final demand effects: iii) product mix, iv) destination, v) affluence, and vi) population. While i) captures changes due to the energy intensity of production (PJ/$), ii) looks at changes due to the industrial structure in the Leontief inverse ($/$), iii) measures changes due to the commodity structure of final demand (\$/\$), iv) calculates changes due to the destination structure of final demand (household, capital, export, etc.; \$/\$), v) computes changes due to the ratio of GDP/capita (\$/cap), and vi) quanifies changes due to population (cap). Pothen [2015] uses a similar decomposition in his SDA of global material footprints. Focusing on globalisation and global value chains, our work extents Lan et al. [2016] who concentrate on the structure of final demand.

2.2.1 Country-level structural decomposition analyses

Equation (2) shows that EF_s is a sum of products of seven factors. Let $D^{tot}_{s,t} = \frac{EF_{s,t}}{EF_{s,t-1}}$ denote the total effect, the change in s's energy footprint between the years $t-1$ and t. The country-level structural decomposition analyses disentangle this change into a product of forces exerted by seven effects as shown in Equation (3). These effects correspond to the seven factors in Equation (2):

$$D^{tot}_{s,t} = D^{int}_{s,t} \cdot D^{vcb}_{s,t} \cdot D^{vcs}_{s,t} \cdot D^{vcr}_{s,t} \cdot D^{lev}_{s,t} \cdot D^{str}_{s,t} \cdot D^{sup}_{s,t} \tag{3}$$

Four out of the seven effects reflect changes on the supply side of the global economy:

- $D^{int}_{s,t}$ is the intensity effect. It measures how falling or rising sectoral energy intensity affects the energy footprint of country s.
- The second supply-side effect is the value chain backward linkage effect, $D^{vcb}_{s,t}$. It takes a value greater than one if more intermediate inputs are used to manufacture goods along the value chain because additional energy inputs are necessary to produce these intermediates, ceteris paribus.
- $D^{vcr}_{s,t}$ is denoted value chain region effect. Indicating whether intermediate input production shifts towards energy-intensive countries, it quantifies how changes in the regional composition of value chains affect $D^{tot}_{s,t}$.
- The value chain structure effect $D^{vcs}_{s,t}$ reflects the impact of changes in the sectoral composition of the value chain on s's energy footprint. If, for instance, services replace energy-intensive manufacturing products in global value chains, the value chain structure effect will take a value less than one.

The three remaining effects reflect changes in the final demand of economy s:

- The level effect $D^{lev}_{s,t}$ measures the change in energy footprints due to an increasing or decreasing level of final demand in country s.
- $D^{str}_{s,t}$ represents the structure effect, the change in energy footprints attributed to changes in the composition of goods in final demand.
- $D^{sup}_{s,t}$ is the supplier effect, the impact of changes in the composition of countries from which country s purchases its consumption and investment goods.

Studies on carbon leakage, the pollution haven hypothesis or energy and carbon embedded in international trade (e.g. Babiker [2005], Paltsev [2001], Peters et al. [2011], Wiebe et al. [2012]) indicate that industrialised countries off-shore energy and carbon-intensive activities into industrialising nations. In the second step, we therefore decompose the value chain region effect $D^{vcr}_{s,t}$ to illustrate how country s's energy footprint is affected by the internationalisation of value chains or, to be more precise, by regionalisation and globalisation. Equation (4) shows the effects into which $D^{vcr}_{s,t}$ is decomposed:

$$D^{vcr}_{s,t} = D^{dim}_{s,t} \cdot D^{rim}_{s,t} \cdot D^{fim}_{s,t} \tag{4}$$

- The first effect shows how changes in the fraction of intermediate inputs produced domestically affects the value chain region effect. It is denoted domestic intermediates effect, $D_{s,t}^{dim}$. If intermediate input production is offshored, the fraction of domestic intermediates falls. The higher the energy intensity of the sectors in s, the more it falls, the lower $D_{s,t}^{dim}$, and, thus, the value chain region effect.
- The second effect records how changes in the fraction of intermediate inputs which are produced in s's region (but not in s itself) affect the value chain region effect. It is denoted regional intermediates effect, $D_{s,t}^{rim}$. If, for example, the United States outsource intermediate input production to Mexico or Canada (the other countries in the NAFTA), $D_{s,t}^{rim}$ rises. The higher the energy intensity in these nations, the higher the regional intermediates effect on energy footprints.
- The third effect quantifies how changes in the fraction of intermediate inputs produced outside of its region affect s's value chain region effect. It is denoted foreign intermediates effect, $D_{s,t}^{fim}$. If, for instance, the USA offshore intermediate input production to China, $D_{s,t}^{fim}$ increases. The higher the energy intensity in the Chinese sectors, the higher the foreign intermediates effect.

Analogously, on the demand side, the supplier effect $D_{s,t}^{sup}$ is decomposed into:

$$D_{s,t}^{sup} = D_{s,t}^{dsr} \cdot D_{s,t}^{rsr} \cdot D_{s,t}^{fsr} \tag{5}$$

The interpretation of the domestic supplier effect $D_{s,t}^{dsr}$, the regional supplier effect $D_{s,t}^{rsr}$, and the foreign supplier effect $D_{s,t}^{fsr}$ follows the interpretation of the domestic, regional, and foreign intermediates effect above. They, however, relate to changes in the fraction of final demand goods, not intermediate inputs, that a country purchases. It should be noted, that the increase in one effect in Equations (4) or (5) leads to a decrease in one or both of the other effects. The net effect is determined by the energy intensity with which the goods are produced in the respective countries.

We employ the multiplicative logarithmic mean Divisia index approach [LMDI; Ang and Liu, 2001] to estimate the individual effects. The LMDI approach is selected because it exhibits three advantageous properties. First, it allows for a perfect decomposition: $D_{s,t}^{tot}$ is disentangled into seven effects without leaving an unexplained residual. Second, the LMDI is invariant to time reversals. Third, by using the analytical limits approach [Ang and Liu, 2007, Wood and Lenzen, 2006], we ensure that the LMDI is robust to zero-values in the data. The LMDI estimation formulae are presented in Appendix B. To estimate the structural decomposition analyses between 1995 and 2009 as well as between 2009 and 2030, we multiply the year-by-year effects.

2.2.2 Global structural decomposition analyses

Analogical to the countries' energy footprints EF_s, we define a global energy footprint $\widehat{EF}$ which can be computed by the following equation:

$$\widehat{EF} = \sum_{i,r,j,rr,s} q_{i,rr} \cdot L_{j,rr}^{vcb} \cdot L_{i,r,j,rr}^{vcs} \cdot L_{i,j,rr}^{vcr} \cdot Y^{\widehat{lev}} \cdot Y_{s}^{reg} \cdot Y_{j,s}^{str} \cdot Y_{j,rr,s}^{sup} \tag{6}$$

Two new factors are introduced in Equation (6):

- $\widehat{Y^{lev}} = \sum_s Y_s^{lev}$ is the global level of final demand. It records the sum of consumption and investment expenditures in all countries. The global energy footprint rises in $\widehat{Y^{lev}}$ because energy is needed to produce the additional goods, ceteris paribus.
- $Y_s^{reg} = \frac{Y_s^{lev}}{\widehat{Y^{lev}}}$ is the share of country s in global final demand. The impact of changes in Y_s^{reg} depends on the mix of goods which the affected countries consume. It increases the global energy footprint if final demand shifts towards nations consuming energy-intensive goods and vice versa.

The global structural decomposition analyses disentangle the change in $\widehat{EF}$ between the years $t-1$ and t, which we denote total effect $D_t^{tot} = \frac{\widehat{EF}_t}{\widehat{EF}_{t-1}}$, into a product of eight effects:

$$D_t^{tot} = D_t^{int} \cdot D_t^{vcb} \cdot D_t^{vcs} \cdot D_t^{vcr} \cdot D_t^{\widehat{lev}} \cdot D_t^{reg} \cdot D_t^{str} \cdot D_t^{sup} \tag{7}$$

The global level effect $D_t^{\widehat{lev}}$ records how the global energy footprint changes in response to rising global final demand and the regional effect D_t^{reg} reflects the impact of changes in the regional composition of final demand on it (6). The intensity effect D_t^{int}, the value chain backward linkage effect D_t^{vcb}, the value chain structure effect D_t^{vcs}, the value chain region effect D_t^{vcr}, the structure effect D_t^{str}, and the supplier effect D_t^{sup} can be interpreted as in the county-level SDA.

The value chain region effect is decomposed further to study how the relative importance of the four regions in international value chains impacts $\widehat{EF}$:

$$D_t^{vcr} = D_t^{vcEU27} \cdot D_t^{vcNAFTA} \cdot D_t^{vcEASTASIA} \cdot D_t^{vcOTHER} \tag{8}$$

Each of the four effects in Equation (8) quantifies how a change in the share of a region in global value chains affects the global energy footprint. D_t^{vcEU27}, for instance, records whether a change in Europe's share in global value chains has increased or decreased the global energy footprint. We decompose the supplier effect similarly to show how the share of consumption and investment goods purchased in each region affected the change in the global energy footprint. As in Equations (4) and (5), if the share of one region in intermediate input production goes up, the share of one or more of the other regions goes down. The value chain region effect (D_t^{vcr}) is the net effect; it depends on the energy intensities of the respective regions.

2.3 Data

2.3.1 Retrospective structural decomposition analyses 1995-2009

All calculations in this paper are based on data from the World Input-Output Database (WIOD; Timmer et al. [2015a]). For the Leontief inverse L, which is based on the matrix of technical coefficients, as well as for the matrix of final demand Y, we use the WIOD's GMRIO tables (see Dietzenbacher et al. [2013] for details). These tables are available in current prices and previous year's prices up to 2009 (Los et al. [2014]) and contain data for 35 sectors in 40 countries plus a residual region (rest of the world). We group them into the four aforementioned regions: EU-27, East Asia, NAFTA, and Other. The vector of energy intensities q requires both energy use data from WIOD's environmental accounts [Genty et al., 2012] and gross outputs from the GMRIO tables, as energy intensities are computed dividing each sector's energy use (physical flows) by its gross output (monetary flows).

Related papers using the WIOD database analyse, inter alia, the development of energy intensity (Löschel et al. [2015]), (real unit) energy costs (Kaltenegger et al. [2016]), material use (Pothen and Schymura [2015]), natural resource footprints (Wu et al. [2016]), and the impacts of international trade and structural change on the environment (Löschel et al. [2013]). The WIOD has also been used to study the evolution of global value chains (e.g. Koopman et al. [2014], Los et al. [2015], Timmer et al. [2015b]).

2.3.2 Prospective structural decomposition analyses 2009-2030

In order to assess potential future developments of global energy footprints, we also perform prospective structural decomposition analyses for the time period between 2009 (the last year for which WIOD energy use data is available) and 2030. The multi-region input-output framework chosen in this paper requires us to construct suitable GMRIO tables and an energy intensity vector. Recalling Equation (1), assumptions have to be made concerning supply-side drivers, demand-side drivers and energy intensities.

We first turn to the supply side. In this paper, we are focusing on global value chains and globalisation. Both are, however, subject to considerable uncertainty with regard to the future. Frankel [2016] looked at emerging market economies, particularly China, and made the case that globalisation might have come to an end. He identified two factors behind the slowdown of trade after the global financial crisis of 2008-2009: a slowdown of trade-intensive physical investments and a maturing of global supply chains. The latter factor is of particular interest for our study. If global supply chains have truly matured after the global financial crisis, and if this is characteristic for the phase of the "new normal" [Hoekman, 2015, p.6] the world economy has entered after the crisis, then our supply-side drivers (i.e. the value chain backward linkage effect, the value chain structure effect and the value chain region effect) should only have a limited impact on energy footprints in the future. However, Frankel [2016] also drew the conclusion that global trade will continue to grow, and perhaps even faster than GDP.

For these reasons, we choose a conservative approach to this uncertainty by concentrating on growing global trade when constructing the GMRIO tables: We make no adjustments with regard to supply-side drivers other than for the export shares, both in intermediate and final goods. We define three scenarios. In the first, we assume that the internationalisation trends observed between 1995 and 2009 continue in all countries. This is done by extrapolating the historic trends in export shares of intermediate and final goods between 1995 and 2009 for each sector and each country. It implies that in some industries export shares continue to go up until 2030, and in other industries export shares continue to go down. The scenario is called "ContIntl". In the second scenario, export shares remain at the levels of 2009 for all countries, implying no further internationalisation ("NoMoreIntl" scenario). In the third scenario, we shift the world economy towards East Asia and the Other region as internationalisation continues for these countries but not in the EU-27 or NAFTA region ("PartialIntl" scenario). A continued shift towards East Asia and the Other region, with their relatively energy-intensive production, is in conformity with the notion of an Asian century and the pollution haven hypothesis.

On the demand side, we rely upon information provided by the IMF [2017] and IEA [2016], which publish projections of economic growth for each country. Again, we extrapolate the historic trends in value added generation for each sector and country, but adjust them in such a way, that projections published by IMF [2017] and IEA [2016] are met. Finally, we use a modified version of the widely-accepted RAS procedure [Miller and Blair, 2009] for rebalancing the GMRIO tables. The construction of the GMRIO tables 2010-2030 is shown in Appendix

C in more detail. Energy intensities develop in line with the INDC[2] scenario of the IEA [2015b].

3 Results

Before turning to the full results, we illustrate the evolution of energy footprints in the two largest economies in 2008, the USA and China. These examples show how differently individual countries are affected by globalisation and changes in value chains.

Falling sectoral energy intensity was, by far, the strongest factor decelerating the growth of China's energy footprint. All else equal, declining energy intensities would have more than halved it (-53.9%). Changes in global value chains were a substantial driver of China's energy footprint, increasing it by 29.3%. This was mostly due to an increased amount of intermediate inputs needed to produce final demand (+17.0%), but also due to the shift towards energy-intensive sectors in China's value chains (+11.1%). Changes in the regional structure of intermediate inputs had a minor impact on China's energy footprint (-0.5%). A weak decrease in the effect of domestic intermediates inputs (-1.3%) was mostly offset by a slight increase in foreign intermediate inputs (+0.8%). On the demand side, boosting final demand was the outstanding driver. Its effect (+262.1%) overcompensated the impact of falling energy intensities. It is the most important factor explaining China's energy footprint which more than doubled between 1995 and 2009 (+124.8%). Other demand-side drivers, such as the industrial (+3.0%) or regional (+1.1%) structure of the final demand goods were of secondary importance. We conclude that changes in the structure of global value chains amplified the increase in China's energy footprint.

The developments in the USA were in stark contrast to those in China. Falling energy intensities were the strongest decelerator of the USA's energy footprint, but they only reduced it by -12.7%. Unlike in China, changes in global value chains further decelerated the USA's energy footprint. These changes had a quantitatively similar impact as the declining energy intensities (-9.8%). This result is mainly caused by a shift in the industrial structure of intermediate inputs towards less energy-intensive sectors (-11.2%). Changes in the amount of intermediate inputs needed to produce the outputs had a minor effect (-0.6%). Outsourcing intermediate inputs production from the domestic market (-5.0%) to Canada and Mexico (+0.6%) and particularly to countries outside the NAFTA region (+7.0%) was pronounced, which constitutes another important difference compared to China. In total, the changes in the regional structure of intermediate input production increased the USA's energy footprint by 2.2%. On the demand side, the increased final demand was the most important driver (+46.6%). Unlike in China, the other demand-side drivers were also relevant. The shift in the industrial structure of final demand goods reduced the USA's energy footprint by 7.3%. With regard to the structure of countries supplying final demand (+2.8%), a shift from domestic goods (-2.7%) to goods (+5.2%) coming from outside the NAFTA region implied that globalisation was a major driver also on the demand side. In total, the USA's energy footprint rose by 10.0% between 1995 and 2009.

These results indicate that changes in backward linkages as well as in the regional and sectoral composition of global value chains have an important effect on the evolution of energy footprints. They, furthermore, suggest a notable heterogeneity between countries.

[2]Intended nationally determined contributions (INDC) are post-2020 climate actions that countries publicly outlined and intend to take under the new international climate agreement adopted at the U.N. Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in Paris in December 2015.

3.1 Retrospective structural decomposition analyses 1995-2009

3.1.1 Descriptives

Table 1 presents the evolution of energy footprints between 1995 and 2009. For each country s as well as the world as a whole (WORLD), it displays the per-capita energy use (EU_s^{pc}) in gigajoule (GJ) and the per-capita energy footprints (EF_s^{pc}) in GJ. We present per-capita values to ease comparison between the countries. Furthermore, Table 1 displays country s's share in global gross output (α_s) in per cent.

In 1995, the global energy footprint equalled 77.7 GJ per capita. This is equivalent to the energy content of about 2.200 litres of diesel. Developed countries had a higher per-capita energy footprint than developing countries. Five high-income countries in our sample exhibited an energy footprint of more than 200 GJ per capita: Canada, Finland, the Netherlands, Sweden, and the USA. China and India, in contrast, had energy footprints of 24.9 and 9.9 GJ per capita. Industrialised nations' energy footprints, furthermore, usually exceeded their direct energy use. This implies that industrialised nations generally import more energy embodied in final demand goods than they use in their own production. Notable exceptions are Canada and the Netherlands. The three largest economies in terms of both GDP and gross output were the USA, Japan, and Germany.

Up until 2009, the global energy footprint rose to 88.0 GJ per capita. Per-capita energy footprints of more than 200 GJ per capita were found in Australia, Canada, Finland, and the USA. Residents of Luxembourg exhibited the highest energy footprint (334.0 GJ). In China, the energy footprint more than doubled to 53.6 GJ per capita. Most industrialised countries remained net importers of energy. In 2009, China had overtaken Japan and Germany to become the second-largest economy in the world.

Table 1: Descriptives.

Region	Country	1995 EU_s^{pc}	1995 EF_s^{pc}	1995 α_s	2009 EU_s^{pc}	2009 EF_s^{pc}	2009 α_s
WORLD		77.7	77.7	100.0	88.0	87.4	100.0
EU-27	AUT	95.1	161.1	0.7	109.2	163.1	0.6
	BEL	159.3	184.6	1.0	159.4	194.2	0.9
	BGR	109.2	71.7	0.1	97.4	50.9	0.1
	CYP	82.7	128.9	0.0	95.0	112.1	0.0
	CZE	148.1	127.6	0.2	147.5	116.6	0.4
	DEU	136.4	179.6	7.8	130.3	151.8	5.2
	DNK	169.6	181.8	0.5	213.6	165.5	0.5
	ESP	82.5	95.4	2.1	92.0	106.5	2.5
	EST	133.0	106.9	0.0	137.9	105.5	0.0
	FIN	210.9	203.6	0.4	245.6	236.2	0.4
	FRA	136.4	153.8	5.0	131.6	164.9	4.2
	GBR	112.5	131.6	3.8	98.0	146.0	3.5
	GRC	76.1	99.5	0.4	106.4	122.8	0.4
	HUN	77.0	81.9	0.2	75.2	70.1	0.2
	IRL	92.6	110.5	0.2	112.5	152.9	0.4
	ITA	83.8	109.7	3.8	87.2	109.6	3.5
	LTU	98.2	93.4	0.0	100.0	80.4	0.1
	LUX	184.4	237.0	0.1	334.0	275.1	0.1
	LVA	62.7	70.2	0.0	61.7	56.3	0.0
	MLT	153.0	146.6	0.0	147.6	119.6	0.0
	NLD	215.8	167.8	1.4	168.6	157.2	1.3
	POL	87.9	75.2	0.5	84.5	82.0	0.8
	PRT	62.9	74.7	0.4	77.8	97.3	0.4
	ROM	77.5	63.7	0.1	53.6	57.9	0.3
	SVK	113.6	100.4	0.1	104.4	87.4	0.2
	SVN	94.7	109.2	0.1	116.3	137.4	0.1
	SWE	223.1	220.9	0.8	196.3	215.9	0.7
East Asia	CHN	24.9	20.7	3.4	53.6	42.0	13.3
	JPN	146.9	176.5	17.9	135.3	158.3	8.2
	KOR	115.4	116.3	2.0	163.9	130.6	1.8
	TWN	116.8	114.6	1.1	166.2	118.5	0.7
NAFTA	CAN	279.4	231.1	1.9	265.4	228.8	2.1
	MEX	41.4	40.2	1.0	47.4	50.6	1.3
	USA	267.1	281.5	24.4	233.5	268.8	21.7
Other	AUS	184.5	189.3	1.4	219.2	279.9	1.7
	BRA	28.4	30.0	2.3	38.4	37.9	2.4
	IDN	14.5	14.3	0.8	21.9	18.1	0.9
	IND	9.9	9.2	1.3	16.2	16.2	2.3
	RUS	177.1	130.1	1.1	180.0	140.7	1.9
	TUR	29.5	36.8	0.7	44.4	40.9	1.0

Notes: Per-capita energy use (EU_s^{pc}) and energy footprints (EF_s^{pc}) in GJ. Share of a country s in global gross output in per cent (α_s).
Source: Own elaboration based on WIOD.

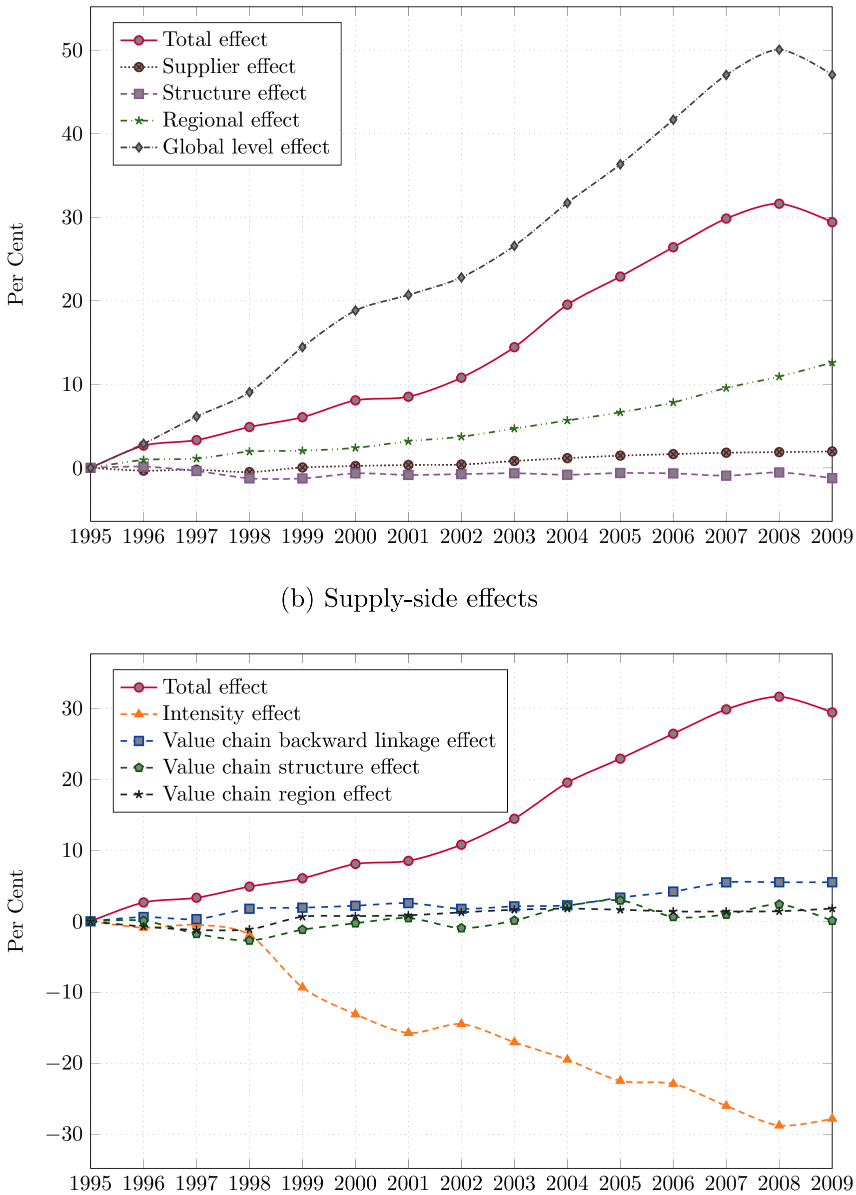
3.1.2 Global structural decomposition analyses

Figure 1a and Figure 1b present the results of the retrospective SDA of the global energy footprint. The solid red line in both Figures represents the total effect, the change in the global energy footprint. It is expressed as a percentage change compared to 1995.[3] The global energy footprint rose by 29.4% between 1995 and 2009 which equals an average annual growth rate of 1.9%. The Figures indicate that $\widehat{EF}$ increased particularly strongly after 2001. Due to the financial crisis, energy footprints fell by 2.2 percentage points from 2008 to 2009.

Figure 1: Results of the global SDA 1995-2009.

(a) Demand-side effects

(b) Supply-side effects



Source: Own elaboration based on WIOD.

Figure 1a presents the demand-side drivers of the global energy footprint: the global level effect ($\widehat{D^{lev}}$), the regional effect (D_t^{reg}), the structure effect (D_t^{str}), and the supplier effect (D_t^{sup}). Each line represents the partial impact of the corresponding effect on the global energy footprint in

[3] Thus, the values of the total effect displayed in Figure 1a and Figure 1b equal $(D_{t,1995}^{tot} - 1) \cdot 100$.

per cent, relative to 1995. The global level effect, for instance, is represented by a dark gray line. In 2009, it equalled 47.0%. Thus, if only final demand would have increased and all other factors would have remained unchanged, $\widehat{EF}$ would have increased by 47.0%. In line with the literature (e.g. the affluence effect in Lan et al. [2016]), we find rising economic activity to be the most important driver of energy use. The global level effect exceeds the total effect in all years, implying that the other drivers together slowed down the increase in energy footprints.

The regional effect, represented by a green line in Figure 1a, accelerated the growth of $\widehat{EF}$ further. Final demand shifted into countries demanding more energy-intensive goods. In 2009, this shift increased the global energy footprint by 12.6%, ceteris paribus. Both the structure effect (dashed purple line) and the supplier effect (dotted brown line) had moderate impacts on the global energy footprint. The former increased the global energy footprint by 1.2% in 2009, which implies that consumption and investment goods were purchased in more energy-intensive countries. The latter led to a 2.0% decrease in energy footprints. It means that the sectoral composition of final demand shifted to less energy-intensive goods. Structural change in final demand had a quantitatively smaller effect on the global energy footprint than on the global material footprint [Pothen, 2015].

Figure 1b displays the supply-side drivers of the global energy footprint between 1995 and 2009: the intensity effect (D_t^{int}), the value chain backward linkage effect (D_t^{vcb}), the value chain structure effect (D_t^{vcs}), and the value chain region effect (D_t^{vcr}). These effects can be interpreted analogically to those in Figure 1a.

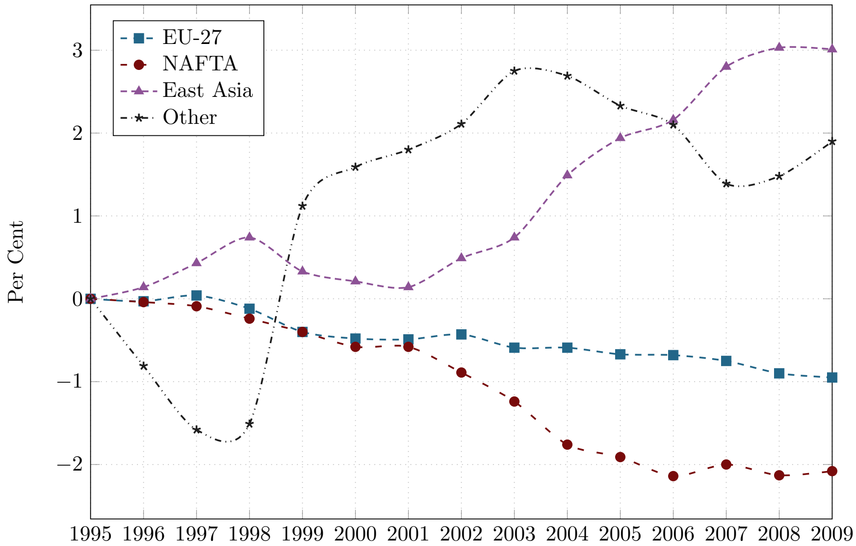
The dashed orange line in Figure 1b represents the intensity effect. In line with the examples of China and the USA, it reveals that falling sectoral energy intensities were the strongest factor decelerating the growth of the global energy footprint. An isolated improvement of energy intensity would have reduced it by 27.8% in 2009, compared to 1995. The intensity effect became particularly important from 1999 onwards.

The strongest supply-side factor driving the global energy footprint was the value chain backward linkage effect. Its impact is depicted by a dashed blue line in Figure 1b. It was positive in all years and attained a value of 5.5% in 2009. It implies that an increasing amount of intermediate inputs was necessary to produce goods in final demand, increasing the global energy footprint. The sectoral composition of global value chains, represented by the value chain structure effect (dashed green line), had an inconclusive impact on the global energy footprint. It fluctuated between values of -2.7% and 3.0% between 1995 and 2008. In 2009, the value chain structure effect equalled 0.1%.

The value chain region effect (dashed black line) was slightly positive in all years since 1999. Between 2003 and 2009, it took values between 1.4% and 1.8%. Like the regional composition of final demand, the regional composition of intermediate input production increased the global energy footprint. Quantitatively, the former was more important than the latter. The value chain region effect indicates that regional shifts in global value chains accelerated the growth of $\widehat{EF}$. It is not able to show, however, the importance of individual regions, in particular East Asia, in this process. Figure 2 displays the results of decomposing the value chain region effect into the contributions by the four regions. They represent partial impacts on the global energy footprint in per cent, relative to 1995.

As expected, Figure 2 shows that the increasing importance of East Asia and the Other region boosted the global energy footprint. The rising importance of East Asia for $\widehat{EF}$ coincided with the economic rise of China. In 2009, East Asia's rising share in global value chains increased

Figure 2: Regional effects in the global SDA 1995-2009.



Source: Own elaboration based on WIOD.

the global energy footprint by 3.0%. Value chains moving to East Asia became more important than the Other region by 2006. Figure 2 also shows that the (relative) shift of global chains out of the EU-27 and NAFTA reduced the global energy footprint by 0.9% and 2.1%, respectively.

A similar regional decomposition as in the case of the value chain region effect is conducted for the supplier effect. Changes in the fraction of final demand goods purchased in the EU-27, the NAFTA, and the Other region have small effects on the supplier effect (D_t^{sup}). Their impacts are all below 1%. The shift of final demand into East Asia, however, increased energy footprints by 2.6% in 2009.

In sum, changes in the global value chains increased the global energy footprint by 7.5%, ceteris paribus. This result is obtained by multiplying the value chain backward linkage effect, the value chain structure effect and the value chain region effect.[4] 7.5% is equivalent to one fourth of the total rise in the global energy footprint. More intermediate inputs were needed in 2009 than in 1995 to produce final demand. The composition of countries supplying intermediates has changed in favour of East Asia and the Other region. These results show that the changes in global value chains were an important factor to explain the growth in energy use from 1995 to 2009.

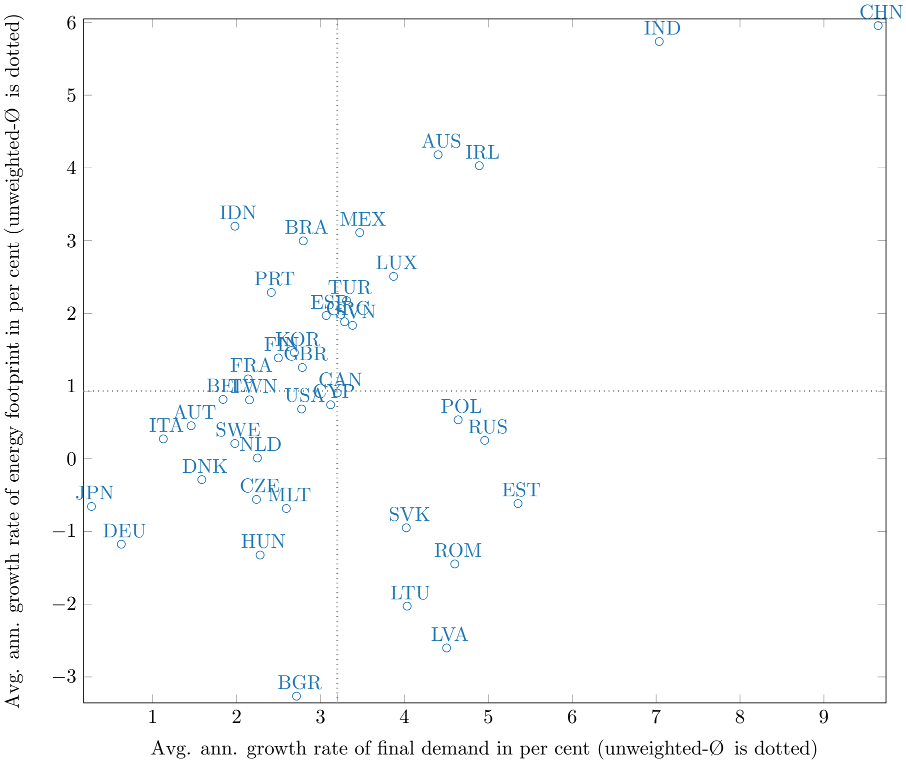
3.1.3 Country-level structural decomposition analyses

We now turn to the energy footprints of individual countries and their heterogeneity. Figure 3 plots the average annual growth rate of final demand against the average annual growth rate of energy footprints. Both are measured in per cent. The dotted lines denote the mean growth rates of these variables, showing that final demand in the countries in our sample grew, on average, by 3.2% between 1995 and 2009, and the energy footprint increased by 0.9% per year.

The two largest industrialising nations in our sample, China and India, exhibited above-average growth of final demand and above-average growth in energy footprints. Economic reforms, industrialisation, and population growth changed those two economies profoundly, increasing

[4] $D_t^{vcb} \cdot D_t^{vcs} \cdot D_t^{vcr} = 1.075$.

Figure 3: Final demand versus energy footprints.



Source: Own elaboration based on WIOD.

their demand for consumption and investment goods. At the same time, their energy footprints grew more than in all other countries, but remained under their respective growth rates of final demand.

The industrialised countries Germany and Japan, in contrast, combined below-average growth of final demand and below-average growth in energy footprints. These countries' final demand almost stagnated at their 1995 levels and their energy footprints fell slightly. The USA exhibited average growth rates both in final demand and energy footprints. Brazil and Korea are examples of countries with above-average growth rates in footprints but below-average growth rates in final demand. In Russia and some other Eastern European countries the situation is reversed.

Our country-level structural decomposition analyses reveal how supply and demand-side drivers affected the countries' change in energy footprints. It shows, in particular, the impacts of increasing globalisation. Table 2 and Table 3 present their results. Table 2 displays the total effect ($D^{tot}_{s,t}$) as well as its drivers. Table 3 displays sub-drivers of $D^{vcr}_{s,t}$ and $D^{sup}_{s,t}$ (see Equations (4) and (5)). All effects represent the percentage change between 1995 and 2009. The total effect in Australia, for instance, implies a 77.4% increase in energy footprints in 2009, compared to 1995. Twelve out of forty nations experienced a decline in energy footprints. The total effect ranged from 124.8% in China to -37.2% in Bulgaria.

Table 2: Country-level structural decomposition analysis.

Region	Country	D_s^{tot}	D_s^{int}	D_s^{vcb}	D_s^{vcs}	D_s^{vcr}	D_s^{sup}	D_s^{str}	D_s^{lev}
EU-27	AUT	6.5	-28.7	9.9	7.6	-3.5	7.0	0.1	22.3
	BEL	12.1	-20.6	2.9	1.9	5.8	4.3	-5.3	28.8
	BGR	-37.2	-58.4	14.9	15.4	-15.1	-10.7	4.0	44.5
	CYP	10.9	-37.4	12.7	13.9	-6.8	-7.1	4.2	53.0
	CZE	-7.6	-14.1	9.1	-19.2	-4.9	-0.6	-5.0	36.1
	DEU	-15.3	-29.4	4.2	3.5	0.4	7.2	-5.1	9.1
	DNK	-3.9	-21.7	6.9	-5.1	2.0	5.3	-9.3	24.1
	ESP	31.4	-28.2	7.3	7.1	0.3	3.8	0.2	52.5
	EST	-8.3	6.1	-3.9	-29.1	-12.5	-10.0	-20.3	102.1
	FIN	21.3	-12.3	6.4	-6.5	-1.7	0.5	0.0	40.9
	FRA	16.5	-0.7	6.4	-10.5	2.6	3.1	-13.3	34.3
	GBR	19.1	-22.3	1.5	-4.4	7.3	7.6	-6.6	46.6
	GRC	29.9	-27.1	4.2	7.4	1.3	3.6	-3.3	56.6
	HUN	-17.0	-5.2	5.8	-17.3	-10.2	-1.7	-17.2	36.8
	IRL	73.9	-27.6	4.3	2.0	6.5	4.0	5.1	94.0
	ITA	3.9	-16.2	6.4	0.2	0.5	4.5	-5.2	16.9
	LTU	-24.9	-27.6	-6.0	-19.2	-7.3	-7.5	-8.1	73.1
	LUX	41.4	-16.7	7.1	-2.2	-1.1	-3.0	0.4	68.5
	LVA	-30.9	-37.2	-2.0	-18.5	-10.0	-5.4	-12.4	84.6
	MLT	-9.2	-38.1	13.5	4.6	-3.6	1.0	-10.9	42.6
	NLD	0.1	-26.2	2.5	0.7	3.0	2.8	-8.9	36.3
	POL	7.8	-29.2	7.4	-16.6	-4.5	-1.8	-3.7	88.1
	PRT	37.2	-22.6	6.3	7.5	0.3	0.5	10.5	39.3
	ROM	-18.5	-39.1	10.8	-18.7	-11.3	-3.6	-7.0	86.9
	SVK	-12.5	-4.6	-5.5	-33.9	-2.9	0.8	-12.6	71.8
	SVN	29.0	-13.1	0.8	0.2	-1.5	4.4	-9.8	58.4
	SWE	3.0	-21.7	5.0	-6.1	2.4	3.0	-3.7	31.3
East Asia	CHN	124.8	-53.9	17.0	11.1	-0.5	1.1	3.0	262.1
	JPN	-8.8	-13.7	-1.6	-1.9	4.5	5.1	-4.0	3.8
	KOR	22.5	-26.2	5.8	6.1	2.9	1.7	-2.6	45.0
	TWN	12.0	-33.7	22.2	2.8	-1.2	4.2	-2.9	34.6
NAFTA	CAN	13.4	-24.7	4.1	-4.7	2.3	1.8	-6.2	55.2
	MEX	53.5	-14.6	4.6	2.9	1.8	3.2	-1.2	61.0
	USA	10.0	-12.7	-0.6	-11.2	2.2	2.8	-7.3	46.6
Other	AUS	77.4	-2.5	4.9	-9.7	4.0	4.0	-2.6	82.4
	BRA	51.2	5.2	-1.6	-2.5	2.3	1.8	-2.1	47.0
	IDN	55.4	-26.5	6.6	18.9	7.6	-6.5	23.4	34.3
	IND	118.4	-21.4	3.4	-4.4	0.5	0.9	7.3	158.3
	RUS	3.6	-21.7	13.9	-23.5	-3.7	-7.8	-12.9	96.4
	TUR	35.2	-32.6	21.1	10.0	-7.4	5.8	-2.3	57.2

Source: Own elaboration based on WIOD.

Table 3: Country-level structural decomposition analysis – subeffects of D_s^{vcr} and D_s^{sup}.

Region	Country	D_s^{vcr}	D_s^{din}	D_s^{rin}	D_s^{fin}	D_s^{sup}	D_s^{dsr}	D_s^{rsr}	D_s^{fsr}
EU-27	AUT	-3.5	-1.1	-2.2	-0.2	7.0	-6.9	8.5	6.0
	BEL	5.8	-6.8	2.5	10.7	4.3	-7.2	2.8	9.2
	BGR	-15.1	0.9	-1.4	-14.6	-10.7	-12.6	2.2	0.0
	CYP	-6.8	4.4	-1.4	-9.4	-7.1	-5.3	4.4	-6.1
	CZE	-4.9	-7.7	1.9	1.1	-0.6	-7.0	2.7	4.1
	DEU	0.4	-2.9	-0.5	3.9	7.2	-6.9	4.5	10.1
	DNK	2.0	-4.7	0.0	7.0	5.3	-6.5	4.9	7.3
	ESP	0.3	-1.8	-1.0	3.2	3.8	-5.8	2.5	7.6
	EST	-12.5	-10.3	1.1	-3.5	-10.0	-12.4	3.4	-0.6
	FIN	-1.7	-3.4	-0.1	1.9	0.5	-3.9	1.7	2.9
	FRA	2.6	-2.1	-0.3	5.0	3.1	0.3	-0.9	3.8
	GBR	7.3	-3.5	0.5	10.7	7.6	-8.2	6.4	10.2
	GRC	1.3	-2.0	-1.2	4.7	3.6	-3.9	1.7	6.0
	HUN	-10.2	-9.0	4.4	-5.5	-1.7	-12.6	9.4	2.8
	IRL	6.5	-2.6	0.3	9.1	4.0	-3.5	0.7	7.0
	ITA	0.5	-2.3	-0.4	3.2	4.5	-4.8	4.1	5.5
	LTU	-7.3	-3.9	1.1	-4.7	-7.5	-8.1	5.2	-4.3
	LUX	-1.1	-0.9	-3.2	3.1	-3.0	0.4	-1.4	-2.1
	LVA	-10.0	1.4	-2.9	-8.6	-5.4	-7.6	7.1	-4.4
	MLT	-3.6	-3.0	-1.4	0.8	1.0	-9.6	6.1	5.3
	NLD	3.0	-3.4	-0.6	7.2	2.8	-7.2	3.1	7.5
	POL	-4.5	-10.5	1.8	4.8	-1.8	-6.9	2.0	3.4
	PRT	0.3	-2.5	-0.7	3.6	0.5	-5.3	4.7	1.4
	ROM	-11.3	-13.9	3.3	-0.3	-3.6	-7.2	2.7	1.1
	SVK	-2.9	-7.9	0.6	4.8	0.8	-5.1	-0.4	6.6
	SVN	-1.5	-6.4	0.6	4.7	4.4	-10.4	7.5	8.5
	SWE	2.4	-4.2	0.3	6.5	3.0	-4.1	3.8	3.5
East Asia	CHN	-0.5	-1.3	0.0	0.8	1.1	1.2	-0.1	0.0
	JPN	4.5	-1.8	5.3	0.9	5.1	-2.2	5.6	1.8
	KOR	2.9	0.4	5.5	-2.8	1.7	-3.9	4.7	1.2
	TWN	-1.2	-2.8	3.6	-1.9	4.2	-1.0	5.5	-0.2
NAFTA	CAN	2.3	1.1	-3.4	4.7	1.8	0.9	-2.3	3.4
	MEX	1.8	-4.2	-1.8	8.3	3.2	-6.0	1.7	8.0
	USA	2.2	-5.0	0.6	7.0	2.8	-2.7	0.3	5.2
Other	AUS	4.0	-7.4	5.3	6.7	4.0	-4.4	3.8	4.9
	BRA	2.3	-1.6	2.2	1.6	1.8	-0.7	0.7	1.8
	IDN	7.6	8.0	-0.2	-0.2	-6.5	-9.5	1.1	2.1
	IND	0.5	-4.5	3.2	2.0	0.9	-2.9	2.3	1.6
	RUS	-3.7	-5.2	0.5	1.1	-7.8	-10.5	0.9	2.1
	TUR	-7.4	2.6	-10.4	0.8	5.8	-7.5	7.6	6.3

Source: Own elaboration based on WIOD.

The level effect ($D^{lev}_{s,t}$) represents the impact of growing final demand on a country's energy footprint. It was positive for all countries in our sample. Thus, rising consumption and investment increased energy footprints. Three countries exhibit a level effect of more than 100%: Estonia (102.1%), India (158.3%), and China (262.1%). An isolated increase of final demand in the People's Republic, for instance, would have more than tripled its energy footprint.

The structure effect ($D^{str}_{s,t}$), which represents the impact of changes in the sectoral composition of final demand, was negative in most countries. Almost all high-income economies shifted their final demand towards less energy-intensive goods. The same is the case for the Eastern European nations showing a strong decrease in energy footprints. Countries such as Russia exhibited structure effects of -10% or less. China and India, on the other hand, shifted their final demand towards more energy-intensive goods.

Most countries have exhibited an increase in energy footprints due to the supplier effect ($D^{sup}_{s,t}$) which implies that they have increasingly purchased their consumption and investment goods in more energy-intensive countries. Almost only Eastern European countries show a negative supplier effect. In line with Figure 1a, these results indicate that the globalisation of markets for final demand goods increased energy footprints. In the following, we decompose the supplier effect further to highlight the geographical restructuring.

The domestic supplier effect ($D^{dsr}_{s,t}$) is negative in almost all countries, with the notable exceptions of France and China. This means that the domestically supplied fraction of final demand goods fell, reducing energy footprints. Countries purchased an increasing part of consumption and investment goods in their own region, leading to an increase in energy footprints which is recorded by a positive regional supplier effect ($D^{rsr}_{s,t}$). Again, France and China are exceptions. However, this effect is generally weaker in absolute terms than the domestic supplier effect. Thus, the remaining part of the supply of consumption and investment goods has shifted into countries outside s's own region. The corresponding foreign supplier effect ($D^{fsr}_{s,t}$) was, again, positive in most countries. The foreign supplier effect was higher than the regional supplier effect in NAFTA countries, implying that globalisation had a stronger impact on energy footprints than regionalisation. The opposite is the case in East Asia, where the increasing supply of final demand goods by China was more important than the offshoring of final good production to the rest of the world. Both results are in line with the results of the global SDA: East Asia, in particular China, has expanded its share in the provision of consumption and investment goods, leading to an increase in energy footprints. It, thus, appears that China's integration in the world economy is crucial for whether regionalisation or globalisation had a higher importance for countries' energy footprints.

Next, we study how changes in global value chains affected individual countries. The value chain backward linkage effect ($D^{vcb}_{s,t}$) has led to an increase in energy footprints in the majority of countries. Almost all industrialising nations purchased more intermediate inputs and, thereby, experienced increasing energy footprints. Eight nations experienced a rise in EF_s of more than 10% due to the value chain backward linkage effect. All of these except one (Taiwan) are industrialising countries.

Changes in the sectoral composition of international value chains had highly diverse effects on the countries in our sample. The value chain structure effect ($D^{vcs}_{s,t}$) ranged from -33.9% in Slovakia to 18.9% in Indonesia. This is in line with the inconclusive estimates of the value chain structure effect in the global SDA.

The value chain region effect ($D^{vcr}_{s,t}$) had positive values in the majority of industrialised countries but negative in industrialising nations. Changes in the regional composition of intermediate inputs raised the energy footprint by 7.3% in the UK, for instance, but reduced it by 7.4% in Turkey. The value chain region effect is decomposed further to illuminate these differences.

The domestic intermediates effect ($D^{din}_{s,t}$), which represents how the share of domestically manufactured intermediate goods affected energy footprints, is negative in most countries in our sample. In countries which exhibit a positive domestic intermediates effect, its impact is small. The decreasing importance of domestic goods in intermediate input production has reduced most countries' energy footprints. The regional intermediates effect ($D^{rin}_{s,t}$) does not have a clear impact on energy footprints. Outsourcing of intermediate good production had mixed results both in the EU-27 and in the NAFTA. Only for East Asia, which encompasses China, Japan, South Korea, and Taiwan, we find a clear result. The effect is positive for all countries except China, implying that the rising share of intermediate inputs manufactured in China increased energy footprints in the three other nations. Outsourcing intermediate input production into nations outside their own region leads to rising energy footprints in most nations. The corresponding foreign intermediates effect ($D^{fin}_{s,t}$) is positive in the majority of economies in our sample. Some Eastern European countries are an exception to this pattern. While most nations shifted parts of their value chains into countries where production is more energy-intensive, these countries appear to have gained access to more sophisticated technologies.

In line with the global SDA's results, we find improving sectoral energy intensities to be the most important factor reducing energy footprints. The intensity effect ($D^{int}_{s,t}$), the impact of changing sectoral energy intensities on countries' energy footprints, had a decreasing effect in all but two countries (Brazil and Estonia). Sectors in almost all countries in our sample adopted more efficient technologies, decreasing the amount of energy necessary to produce each dollar worth of output. The most substantial reductions in energy intensity can be found in industrialising countries: in China and Bulgaria, for instance, energy footprints would have been halved by the intensity effect, ceteris paribus.

3.2 Prospective structural decomposition analyses 2009-2030

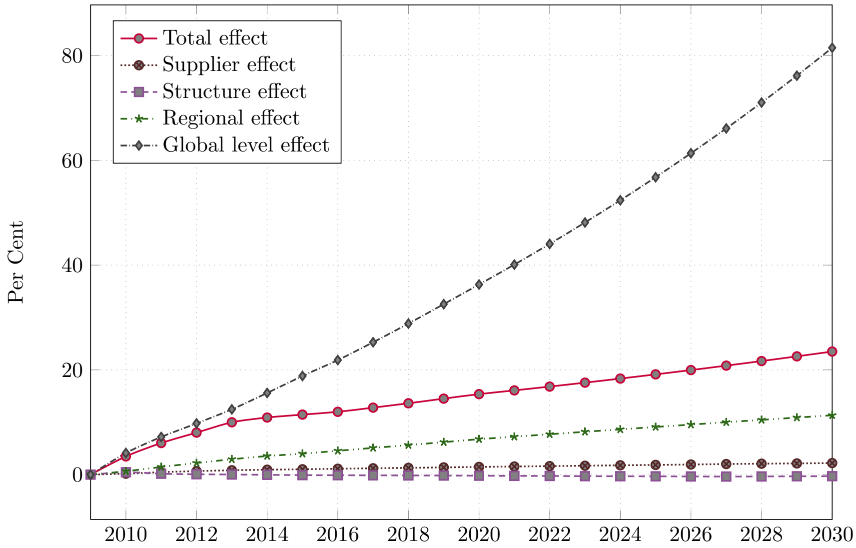
This subsection presents the results of our prospective global structural decomposition analyses. Figure 4a displays the results for the demand-side drivers of energy footprints while Figure 4b shows the supply-side drivers for the ContIntl scenario. We depict only this scenario for demand-side drivers as our calculation indicates that the results are relatively similar in the three scenarios. The disaggregated value chain region effect will by presented by scenario. All effects can be interpreted as in Figure 1a and Figure 1b.

The global energy footprint rises continuously between 2009 and 2030. The total effect equals 23.5% in 2030, implying that the global energy footprint rises by roughly a quarter from 2009 to 2030. Its average annual growth rate is smaller than between 1995 and 2009, at 1.0%. The most rapid increase can be observed between 2009 and 2013.

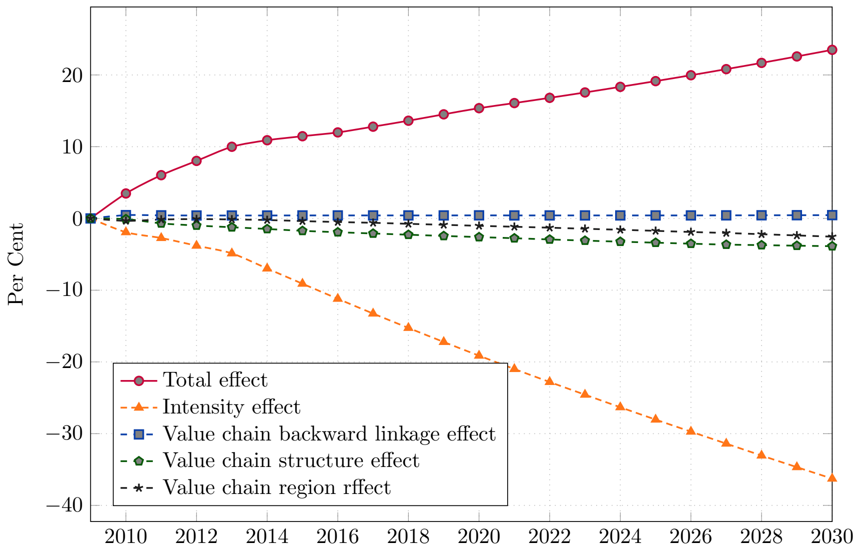
As in the retrospective SDA, the global level effect is the predominant factor increasing the global energy footprint. According to our projections, rising consumption and investment lead to an 81.5% rise in the global energy footprint, ceteris paribus. Since industrialising countries grow faster than high-income nations, final demand continues shifting into these nations. The corresponding regional effect increases $\widehat{EF}$ by 11.3%. The supplier effect, the change in countries which supply final demand, increases the global energy footprint by another 2.2% in 2030 compared to 2009. The sectoral composition of final demand does not have a notable effect on

Figure 4: Results of the global SDA 2009-2030 (ContIntl scenario).

(a) Demand-side effects



(b) Supply-side effects



Source: Own elaboration based on WIOD.

energy footprints. The structure effect reduces $\widehat{EF}$ by only 3 per mill in 2030.

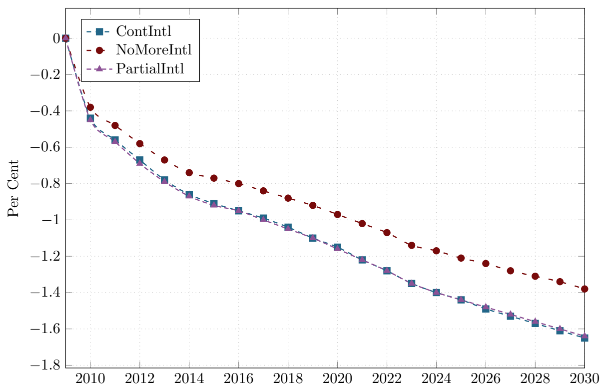
Figure 4b indicates that energy intensity improvements remain the most important factor limiting the growth in energy use. The intensity effect reduces the global energy footprint by 36.3% in 2030 relative to 2009. The role of global value chains for the global energy footprint is found to change. The value chain backward linkage effect has a negligible impact on $\widehat{EF}$. The scenarios do not anticipate a continued increase in the share of intermediates in total inputs. They should be interpreted as a conservative projection in this respect.

The value chain structure effect (D_t^{vcs}), which reflects how changes in the sectoral composition of global value chains affects the global energy footprint, is negative. A shift towards goods produced with less energy inputs reduces $\widehat{EF}$ by 3.9%. Changes in the regional composition of global value chains decelerate the global energy footprint further. The corresponding value chain region effect equals -2.5% in 2030.

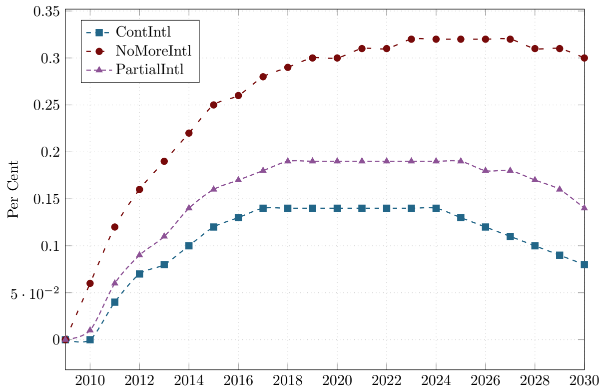
As described above, we distinguish between three scenarios which differ in their assumptions about how internationalisation evolves in the future. Figures 5a to 5d display the contribution of the four regions to the global energy footprint. Results are depicted by region and scenario. The four graphs show that changes in the regional composition of global value chains are expected to have a limited impact on the development of the global energy footprint. Changes in EU's and the Other's shares in global value chains lead to a decrease in $\widehat{EF}$ of around 1.6% in the ContIntl and PartialIntl scenarios (Figure 5a and Figure 5d). An increasing importance of East Asia and NAFTA in global value chains leads to a positive, albeit weaker, effect on the global energy footprint. In the NoMoreIntl scenario, the influence of regional shifts in global value chains is even milder.

Figure 5: Regional effects in the global SDA 2009-2030 per scenario.

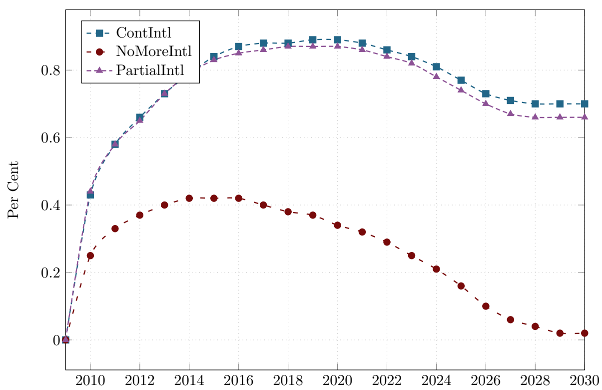
(a) EU-27



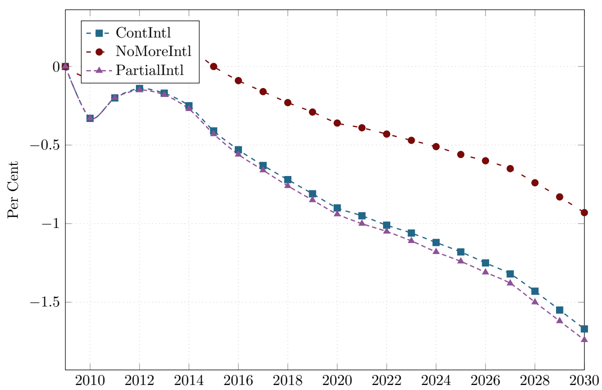
(b) NAFTA



(c) East Asia



(d) Other



Source: Own elaboration based on WIOD and own projections.

4 Conclusions

This paper investigates how globalisation in general and increasingly globalised value chains in particular affect energy footprints, the input of energy needed to produce a country's final demand. We first apply retrospective structural decomposition analyses to study how changes in final demand and production structures impacted energy footprints between 1995 and 2009. Then, we generate three scenarios of growth, structural change, and economic integration between 2009 and 2030. These are decomposed by using prospective SDA. We employ the logarithmic mean Divisia index approach [LMDI; Ang and Liu, 2001] in our SDA. Data is taken from the World Input-Output Database (WIOD; Timmer et al. [2015a]) and combined with various sources to generate the prospective scenarios.

The global energy footprint increased by 29.4% between 1995 and 2009. Our retrospective global structural decomposition analyses indicate that rising final demand, which increased the global energy footprint by 47.0%, was the predominant driver. Final demand shifting into countries consuming more energy-intensive goods further accelerated its growth (+12.6%). Sectoral energy intensity reductions were the most important factor slowing down the growth of global energy use (-27.8%).

Changes in global value chains further accelerated the growth of the global energy footprint. Rising backward linkages in global value chains, i.e. increasing intermediate inputs along the value chain, were particularly important. They increased the global energy footprint by 5.5% in 2009, compared to 1995. Intermediate input production moving to countries using more energy-intensive production technologies increased the global energy footprint by 1.8%.

The country-level structural decomposition analyses reveal substantial heterogeneity in how changes in global value chains affected the countries in our sample. They indicate that industrialising and industrialised countries were impacted differently by these changes. The increasing amount of intermediates used along the value chain increased energy footprints in most countries. Industrialising countries were affected more strongly. Regional shifts in global value chains had an increasing effect on high-income countries' energy footprints while they reduced the footprint of industrialising nations. The former outsourced the production of intermediates into energy-intensive countries while the latter gained access to sophisticated production technologies abroad, reducing their energy footprints.

The scenarios for future energy footprints indicate that global energy use will rise by another 23.5% between 2009 and 2030. Rising final demand remains the principal driver of this development (+81.5%). The regional shift in final demand further contributes to the growing global energy footprint (11.3%). Improving sectoral energy intensity is the strongest force limiting the growth of energy footprints (36.3%).

The prospective SDA indicate that impacts of global value chains on energy footprints change in the future. The regional composition of global value chains reduces the global energy footprint by 2.5%. Energy intensities converge internationally, which means that outsourcing production does not lead to rising energy footprints in the long run. Furthermore, changes in the sectoral composition of global value chains reduce the global energy footprint by another 3.9%. Structural change in intermediate inputs, thus, begins to decelerate the growth in energy use.

Our results confirm that the evolution of global value chains had large impacts on global energy use which were, thus far, overlooked. Based on our analyses, we are able to derive three major insights for future energy and climate policy:

First, reducing energy intensities was and will be of major importance for limiting energy use. The globalisation of value chains has to be accompanied by an accelerated diffusion of energy-efficient production technologies in order to dampen the further increase in energy footprints. Policy makers should, however, keep in mind that these technologies are subject to decreasing returns and that their effectiveness is limited by physics.

Second, structural change in intermediate inputs and final demand might indeed contribute to the reduction of energy use. Our results indicate that changes in the sectoral composition of intermediate inputs - contrary to past developments - reduces the global energy footprint in the future.

Third, while changes in global value chains are expected to reduce energy use in the future, it is unlikely that they can compensate for the rising final demand, in particular in industrialising nations. Global energy use should, therefore, be expected to grow. This highlights the importance of shifting energy generation from coal, oil, and gas towards carbon-free energy sources such as renewables in order to reduce carbon emissions in a world of rising energy footprints.

A Countries and sectors in the WIOD

Table 4: Countries in the WIOD.

Region	Country code	Country	Region	Country code	Country
	AUT	Austria		CHN	China
	BEL	Belgium	East Asia	JPN	Japan
	BGR	Bulgaria		KOR	Korea
	CYP	Cyprus		TWN	Taiwan
	CZE	Czech Republic		CAN	Canada
	DEU	Germany	NAFTA	MEX	Mexico
	DNK	Denmark		USA	United States
	ESP	Spain		AUS	Australia
	EST	Estonia		BRA	Brazil
	FIN	Finland	Other	IDN	Indonesia
	FRA	France		IND	India
	GBR	United Kingdom		RUS	Russia
	GRC	Greece		TUR	Turkey
EU-27	HUN	Hungary			
	IRL	Ireland			
	ITA	Italy			
	LTU	Lithuania			
	LUX	Luxembourg			
	LVA	Latvia			
	MLT	Malta			
	NLD	Netherlands			
	POL	Poland			
	PRT	Portugal			
	ROM	Romania			
	SVK	Slovakia			
	SVN	Slovenia			
	SWE	Sweden			

Source: WIOD.

Table 5: Sectors in the WIOD.

NACE	WIOD sectors
AtB	Agriculture, hunting, forestry and fishing
C	Mining and quarrying
15t16	Food, beverages and tobacco
17t18	Textiles and textile products
19	Leather, leather products and footwear
20	Wood and products of wood and cork
21t22	Pulp, paper, paper products, printing and publishing
23	Coke, refined petroleum and nuclear fuel
24	Chemicals and chemical products
25	Rubber and plastics
26	Other non-metallic mineral products
27t28	Basic metals and fabricated metal products
29	Machinery nec
30t33	Electrical and optical equipment
34t35	Transport equipment
36t37	Manufacturing nec, recycling
E	Electricity, gas and water supply
F	Construction
50	Sale, maintenance and repair of motor vehicles
51	Wholesale trade and commission trade
52	Retail trade, except of motor vehicles and motorcycles
H	Hotels and restaurants
60	Inland transport
61	Water transport
62	Air transport
63	Supporting and auxiliary transport activities
64	Post and telecommunications
J	Financial intermediation
70	Real estate activities
71t74	Renting of machinery and equipment and other business activities
L	Public administration and defence, social security
M	Education
N	Health and social work
OtP	Other community, social and personal services, private households with employed persons

Source: WIOD.

B Formulae of the country-level SDA

In this section, we present the estimation formulae for the structural decomposition analyses. See Ang and Liu [2001] for the detailed derivation of the logarithmic mean Divisia index (LMDI) approach. For the country-level SDA, we use Equations (B2) to (B8) to estimate the total effect (Equation (B1)). The same formulae are used for the retrospective and the prospective SDA:

$$D_{s,t}^{tot} = \frac{EF_{s,t}}{EF_{s,t-1}} \tag{B1}$$

$$D_{s,t}^{int} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr} \ln\left(\frac{q_{i,r,t}}{q_{i,r,t-1}}\right)\right] \tag{B2}$$

$$D_{s,t}^{vcb} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr} \ln\left(\frac{L_{j,rr,t}^{vcb}}{L_{j,rr,t-1}^{vcb}}\right)\right] \tag{B3}$$

$$D_{s,t}^{vcs} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr} \ln\left(\frac{L_{i,j,rr,t}^{vcs}}{L_{i,j,rr,t-1}^{vcs}}\right)\right] \tag{B4}$$

$$D_{s,t}^{vcr} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr} \ln\left(\frac{L_{i,r,j,rr,t}^{vcr}}{L_{i,r,j,rr,t-1}^{vcr}}\right)\right] \tag{B5}$$

$$D_{s,t}^{lev} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr} \ln\left(\frac{Y_{s,t}^{lev}}{Y_{s,t-1}^{lev}}\right)\right] \tag{B6}$$

$$D_{s,t}^{str} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr} \ln\left(\frac{Y_{j,s,t}^{str}}{Y_{j,s,t-1}^{str}}\right)\right] \tag{B7}$$

$$D_{s,t}^{sup} = \exp\left[\sum_{i,r,j,rr} \omega_{i,r,j,rr} \ln\left(\frac{Y_{j,rr,s,t}^{sup}}{Y_{j,rr,s,t-1}^{sup}}\right)\right] \tag{B8}$$

The following formulae are used to decompose the value chain region effect ($D_{s,t}^{vcr}$) into the domestic intermediates effect ($D_{s,t}^{dim}$), the regional intermediates effect ($D_{s,t}^{rim}$), and the foreign intermediates effect ($D_{s,t}^{fim}$):

$$D_{s,t}^{dim} = \exp\left[\sum_{i,r,j,rr \ \forall \ r=s} \omega_{i,r,j,rr} \ln\left(\frac{L_{i,r,j,rr,t}^{vcr}}{L_{i,r,j,rr,t-1}^{vcr}}\right)\right] \tag{B9}$$

$$D_{s,t}^{rim} = \exp\left[\sum_{i,r,j,rr\ \forall\ rg(r,s)=1} \omega_{i,r,j,rr} \ln\left(\frac{L_{i,r,j,rr,t}^{vcr}}{L_{i,r,j,rr,t-1}^{vcr}}\right)\right] \tag{B10}$$

$$D_{s,t}^{fim} = \exp\left[\sum_{i,r,j,rr\ \forall\ rg(r,s)=0 \wedge r \neq s} \omega_{i,r,j,rr} \ln\left(\frac{L_{i,r,j,rr,t}^{vcr}}{L_{i,r,j,rr,t-1}^{vcr}}\right)\right] \tag{B11}$$

For the domestic intermediates effect, we add up the expression $\omega_{i,r,j,rr} \ln\left(\frac{L_{i,r,j,rr,t}^{vcr}}{L_{i,r,j,rr,t-1}^{vcr}}\right)$ whenever r equals s. For the regional intermediates effect, we sum up the expression if $rg(r,s)$, which indicates whether r and s are in the same region, equals one. For the foreign intermediates effect, the remaining addends are added up.

Analogously, the domestic supplier effect ($D_{s,t}^{dsr}$), the regional supplier effect ($D_{s,t}^{rsr}$), and the foreign supplier effect ($D_{s,t}^{fsr}$) are estimated as follows:

$$D_{s,t}^{dsr} = \exp\left[\sum_{i,r,j,rr\ \forall\ r=s} \omega_{i,r,j,rr} \ln\left(\frac{Y_{j,rr,s,t}^{sup}}{Y_{j,rr,s,t-1}^{sup}}\right)\right] \tag{B12}$$

$$D_{s,t}^{rsr} = \exp\left[\sum_{i,r,j,rr\ \forall\ rg(r,s)=1} \omega_{i,r,j,rr} \ln\left(\frac{Y_{j,rr,s,t}^{sup}}{Y_{j,rr,s,t-1}^{sup}}\right)\right] \tag{B13}$$

$$D_{s,t}^{fsr} = \exp\left[\sum_{i,r,j,rr\ \forall\ rg(r,s)=0 \wedge r \neq s} \omega_{i,r,j,rr} \ln\left(\frac{Y_{j,rr,s,t}^{sup}}{Y_{j,rr,s,t-1}^{sup}}\right)\right] \tag{B14}$$

The $\omega_{i,r,j,rr}$ is a weighting parameter. It is computed according to Equation (B15):

$$\omega_{i,r,j,rr} = \frac{\mathrm{L}\left(ef_{i,r,j,rr,s,t}, ef_{i,r,j,rr,s,t-1}\right)}{\mathrm{L}\left(ef_{s,t}, ef_{s,t-1}\right)} \tag{B15}$$

L is the logarithmic mean between a and b. It is defined as $\mathrm{L}(a,b) = \frac{a-b}{\ln a - \ln b}$ for $a \neq b$ and $\mathrm{L}(a,b) = a$ for $a = b$. For the global structural decomposition analyses, we use analogical formulae.

C Construction of GMRIO tables for the years 2010-2030

We use a modified version of the widely-accepted "RAS" procedure for constructing GMRIO tables for the years after 2009.

Step 1:

For applying the RAS technique, we extrapolate value added and gross output (2010-2030) for suitable row and column sums. In order to take historic sectoral trends (1995-2009) into account, we first perform a simple OLS regression to explain value added:

$$va_{i,r,t} = \alpha_{i,r} + \beta_{i,r} \times t + \epsilon_{i,r,t}, \tag{C.1}$$

where va is the value added of sector i in region r in year t with $t \in \{1995, \ldots, 2009\}$. α is the intercept, β is the regression coefficient, and ϵ an error term.

Extrapolated value added (and gross output) Figures for 2010-2030 are adjusted by using GDP growth projections by country until 2030 published by IMF [2017] and IEA [2016]:

$$va^{adj}_{i,r,t} = va_{i,r,t} \times \frac{GDP_{r,t}}{\sum_s va_{i,r,t}}, \tag{C.2}$$

where va ($va^{adj}_{i,r,t}$) is the (adjusted) value added of sector i in region r in year t with $t \in \{2009, \ldots, 2030\}$.

Step 2:
Export shares in each country and sector are adjusted in such a way that three different scenarios of internationalisation are derived: continued internationalisation (ContIntl scenario), no further internationalisation (NoMoreIntl scenario); internationalisation only in East Asia and the Other region (PartialIntl scenario). This reconfiguration of the world economy is applied in intermediate and final goods.

In order to take historic trends in export shares of intermediate (and final) goods between 1995 and 2009 into account, we estimate the following equation:

$$exps_{i,r,t} = \alpha_{i,r} + \beta_{i,r} \times \ln(t) + \epsilon_{i,r,t}, \tag{C.3}$$

where $exps_{i,r,t}$ is the export share of the good of sector i in region r in year t with $t \in \{1995, \ldots, 2009\}$. α is the intercept, β is the regression coefficient, and ϵ an error term.

Because export shares are bounded between 0 and 1, using $\ln(t)$ instead of t yields better results as extrapolated Figures approach boundaries slower.

Step 3:

Having calculated column and row sums as well as intended export shares, rebalancing of the GMRIO tables is the next task. To this end, we follow Miller and Blair [2009] and the RAS procedure (equations without matrix Z) but extend it to incorporate the aspect of internationalisation through modifying the export shares (equations including matrix Z):

$$\begin{aligned}
A(1) &= \hat{r}(1)A(0) \\
A(2) &= A(1)\hat{s}(1) \\
Z(1) &= A(2)\hat{x} \odot E(1) \\
A(3) &= Z(1)\hat{x}^{-1} \\
A(4) &= \hat{r}(2)A(3) \\
A(5) &= A(4)\hat{s}(2) \\
Z(2) &= A(5)\hat{x} \odot E(2) \\
A(6) &= Z(2)\hat{x}^{-1} \\
&\vdots \\
A(3n-2) &= \hat{r}(n)A(3n-3) \\
A(3n-1) &= A(3n-2)\hat{s}(n) \\
Z(n) &= A(3n-1)\hat{x} \odot E(n) \\
A(3n) &= Z(n)\hat{x}^{-1},
\end{aligned} \tag{C.4}$$

where A is the matrix of technical coefficients, $\hat{r}$ is the diagonal matrix of row adjustment ratios per sector (target row sum divided by sum of individual rebalanced rows), $\hat{s}$ is the diagonal matrix of column adjustment ratios per sector (target column sum divided by sum of individual rebalanced columns), Z is the matrix of interindustry transactions, $\hat{x}$ is the diagonal matrix of gross output per sector and (n) is an index number. We use the matrix of export share adjustment ratios E to incorporate (via Hadamard product) the aspect of internationalisation. In a two country-two sector model, this matrix would take the form:

$$E = \begin{bmatrix} 1 & 1 & e_1 & e_1 \\ 1 & 1 & e_2 & e_2 \\ e_3 & e_3 & 1 & 1 \\ e_4 & e_4 & 1 & 1 \end{bmatrix}, \tag{C.5}$$

where e_s are sectoral export share adjustment ratios.

In our study, matrix adjustments are continued until

- the absolute differences between target column sums and sums of individual rebalanced columns,
- the absolute differences between target row sums and sums of individual rebalanced rows and
- the absolute differences between target export shares and rebalanced export shares

for each country and sector are smaller than 0.001, respectively.

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