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Energy footprints and the international trade network: A new dataset.

Is the European Union doing it better?*

Octavio Fernández-Amador[†] Joseph F. Francois[‡]
Doris A. Oberdabernig[§] Patrick Tomberger[¶]

Abstract

Understanding the global energy network and the developments of energy efficiency is key to advance energy regulation and fight climate change. We develop a global panel dataset on energy usage inventories based on territorial production, final production and consumption over 1997–2014. We apply structural decomposition analysis to isolate energy efficiency changes and study the effectiveness of the European Union Energy Services Directive (2006/32/EC) on energy efficiency. High-income regions are net-importers of embodied energy and use a larger share of non-renewable energy than developing countries. The effectiveness of the Directive is mixed. The different ambition of national energy policies of the European Union members and some complementarity in supply chains underlie the different dynamics found. High-income countries share efficiency gains and changes in the mix of energy sources. These trends are not specific to the European Union. Energy policies in high-income countries are less effective for energy footprints. Our findings are indicative of energy leakage. Energy regulation should account for global supply chains and target energy footprints.

Keywords: Energy usage, energy efficiency, energy footprints, renewable energy, MRIO analysis, Structural Decomposition Analysis, EU Energy Services Directive.

JEL-codes: F18, F64, O13, O44, Q40, Q54, Q56.

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1 Introduction

Projections of increasing global energy demand, mostly covered by fossil fuels, contrast with the goal of greenhouse gas (GHG) emission abatement set in the Paris Agreement (2015). This calls for a change of environmental policies, in particular energy policies. Improving energy efficiency is a way to substantially reduce energy usage and GHG emissions without compromising economic growth. Many countries target energy efficiency in their nationally determined contributions (NDC) to the Paris Agreement, and the United Nations emphasizes energy efficiency in the Sustainable Development Goals.

National energy policies focus on energy usage for production activities within the national territory and do not address energy embodied in final production and consumption. In a globalized world where international trade is characterized by vertical specialization and global supply chains (e.g. Koopman et al., 2014; Johnson and Noguera, 2012), energy usage of territorial production can differ substantially from the energy required for final production and consumption of a country. Energy policies aimed at territorial production fail to account for energy embodied in imported intermediates and final goods and fall short for improving the energy footprint of nations (see also Hertwich, 2020; Chen et al., 2019). Moreover, energy policies targeting territorial production may change relative costs of production and goods prices and induce the relocation of energy-intensive production processes towards countries with relatively lax energy policies (see Hertwich, 2020). This is the energy equivalent to carbon leakage.

This paper introduces a dataset of energy usage inventories for a global panel of 66 countries and 12 composite regions, disaggregated to seven energy commodities and 57 economic sectors (plus private households) for six years between 1997 and 2014. We construct energy usage inventories based on territorial production and, using multi-regional input-output (MRIO) techniques, calculate two energy footprint inventories, associated with final production and consumption, which account for the energy used in the production of intermediates and final goods, respectively, traded along global supply chains. Energy embodied in final production and consumption differs from the definition of final energy consumption commonly used.¹ Embodied-energy footprints refer to the energy used along all production stages in the supply chain of a final product that is assembled (final production) or consumed (final consumption) in a country, regardless of where this energy usage takes place. Thus, our dataset provides relevant information on the responsibility for energy usage from a footprint perspective. It also supplements other existing datasets

¹ The term energy consumption is used to refer to energy usage based on territorial production e.g. in decomposition analyses (Voigt et al., 2014; Löschel et al., 2015; Forin et al., 2018), in convergence analyses (Berk et al., 2020), and in the literature on the relationship between energy usage and economic growth (Chica-Olmo et al., 2020; Huang et al., 2008; Inglesi-Lotz, 2016; Dogan et al., 2020).

on energy inventories that include embodied energy consumption and extends them in one or several dimensions (energy commodity disaggregation, sectoral disaggregation, country and time coverage).²

This paper also puts forward a proxy for energy efficiency derived from structural decomposition analysis (SDA). We apply multiplicative Logarithmic Mean Divisia Index decomposition to energy usage and to the ratio of energy usage per unit of value added (a common measure of energy intensity), derived from the three inventories calculated. Previous research applies index decomposition analysis (IDA) to analyze the determinants of changes in energy usage and intensity. Löschel et al. (2015) and Voigt et al. (2014) analyze the determinants of energy intensity of production for the European Union (EU) aggregate and its members and for a panel of 40 economies, respectively. Forin et al. (2018) find evidence for de-localization in sectoral energy usage over 2001–2011. This de-localization increases sectoral energy use for most sectors. IDA can also be used in SDA based on MRIO tables, such that international trade effects can be identified. Closer to our research, Lan et al. (2016) quantify drivers of changes in global energy footprints over 1990–2010 for 186 nations. They find that the level of development and population mainly drive footprints worldwide and that countries with higher GDP per capita import energy-intensive goods from other nations, such that their energy footprint is increasingly concentrated on imports and consumption. Kaltenecker et al. (2017) analyze the effects of global supply chains on consumption-based energy footprints for 40 economies over 1995–2009. They conclude that the increase of the global energy footprint is mainly driven by economic activity, demand, and to a lesser extent by changes in global supply chains associated with globalization of intermediates, whereas efficiency improvements decelerate the growth of energy footprints.

We decompose changes in energy usage and intensity over 1997–2014 into seven factors reflecting changes in the scale of economic activity, changes in the composition of production and consumption, and changes in the energy-production technology, in spirit of the scale, composition and technology effects used in the pollution–growth literature (Antweiler et al., 2001; Copeland and Taylor, 2005). To minimize aggregation bias and better identify changes in energy efficiency, we carry out our SDA at the bilateral commodity-sector-country dimension of the MRIO framework. The energy intensity factor derived from the SDA is shown to be a better proxy for energy efficiency than the ratio of energy usage per value added, the measure of energy intensity typically used in the literature. This is be-

² These datasets include Eora (Lenzen et al., 2012, 2013), EXIOBASE (Stadler et al., 2018a), GTAP (Aguilar et al., 2019) and WIOD (Timmer et al., 2015, 2016; Genty et al., 2012). The data on embodied energy consumption from the Industrial Ecology Program compiles different releases of these datasets, although only for total energy usage, not disaggregated by energy commodity, and for a small number of countries and sectors.

cause energy per value added is not only affected by changes in sectoral energy efficiency but also by changes in national and international supply chain relations, international trade patterns, and economic growth, among others. The intensity factor is shown to be weakly correlated with energy per value added. Therefore, the SDA disentangles energy efficiency changes from other factors that affect energy per value added, such that the contribution of improvements in energy efficiency to observed changes in energy usage and intensity across countries can be correctly measured by the intensity factor (which we name efficiency factor).

This paper finally analyzes whether developments of energy usage in the EU from 1997–2014 are related to the EU Energy Services Directive (2006/32/EC) and whether these developments differ from those of other countries and regions. The Energy Services Directive (2006/32/EC), issued in 2006, aims at stronger energy efficiency improvements as compared to previous regulation, and introduces specific targets. Already the 1993 Council Directive (93/76/EEC) aims at limiting carbon dioxide (CO₂) emissions by improving energy efficiency but it does not specify quantifiable efficiency targets. Conversely, the Energy Services Directive specifies an overall national indicative, not legally enforceable, energy savings target of 9%, to be achieved from 2008–2016 through energy services and other energy efficiency improvements, and the need to promote the production of renewable energy. The Directive requires the EU member states to bring into force national policies by May 2008 and to prepare and periodically update Energy Efficiency Action Plans (EEAP), outlining which national measures are taken to achieve the 9% target. Yet, the implementation and achievements following the Directive differ across the EU member states. Follow-up regulation strengthens the targets for energy usage and renewable energy. The Energy Efficiency Directive (2012/27/EU) formulates an energy target of a 20% reduction in primary energy usage as compared to projections until 2020 and supplements it with targets for CO₂ emissions and renewable energy, while the Directive on Energy Efficiency (2018/2002) increases the target to a 32.5% reduction in energy usage as compared to projections until 2030.

Our inventories dataset, covering 1997–2014, allows us to study whether the EU Energy Services Directive, the first EU policy with an explicit target for energy savings to be achieved through efficiency gains, is effective at improving energy efficiency associated with territorial-based energy and energy footprints. In a difference-in-difference (DID) analysis, we compare changes in the energy efficiency factor derived from the SDA in EU countries before and after the implementation of the Directive to similar changes observed in other countries over the same periods. Using the efficiency factor, instead of the ratio of energy per value added, reduces potential endogeneity that arises if the implementation of the Directive depends on trends in trade patterns or prospects of economic growth.

We also analyze the effects of the Directive on changes in the shares in the energy mix of seven energy commodities. The analysis is conducted for the three energy inventories calculated—territorial production-, final production- and consumption-based energy usage. To the best of our knowledge, such an analysis is novel in the literature.

Our results highlight similarities in energy usage across high-income regions worldwide and reveal some particularities of the EU. High-income regions are net-importers of embodied energy and use a larger share of non-renewable energy compared to developing countries. Net-imports of embodied energy generally increase in high-income countries between 1997 and 2014, but the share of fossil energy decreases in this period. In the EU, energy usage for production declines over 1997–2014, while energy footprints increase. The reduction of energy usage for production is due to improvements in energy intensity and changes in the production structure. The reduction of fossil energy sources and the expansion of renewable energy used for production is particularly strong in the EU and the Organisation for Economic Co-operation and Development (OECD) compared to other regions. After 2007, the expansion of solar energy in the EU15 (i.e. the 15 EU members prior to the 2004 accession) is stronger than in other OECD countries. We find stronger energy efficiency gains of production in the EU15 members after the implementation of the Directive, but similar developments take place in other OECD countries. These changes are accompanied by a shift of energy-intensive production from EU15 and OECD countries towards non-high-income countries. The footprint-based energy efficiency in EU15 and OECD countries is not improved. The EU Energy Services Directive does not determine a trend specific to the EU but rather seems part of a trend common to other high-income countries.

The following section briefly describes the construction of the dataset containing the three energy inventories and the methods applied. Section 3 presents an overview of global and regional patterns of the energy usage found in our data. In Section 4 we discuss the results of the SDA of energy usage and intensity and study the effects of the EU Energy Services Directive on energy efficiency. Section 5 concludes.

2 Data construction and methods

This section summarizes the construction of the energy inventories and shortly outlines the methodology used in the empirical analysis. We first describe the construction of the production-based energy inventory and the derivation of the footprint (final production- and consumption-based) inventories. After that we briefly describe the methods used for the empirical analysis, the SDA of the three energy inventories including the extraction of the efficiency factor, and the DID regression applied. Further details on the calculation of the inventories and the SDA are provided in Appendix B.

2.1 Construction of the energy inventories

The construction of production-based energy inventories relies on raw data from the World Energy Balances database (2018 edition) of the IEA, which provides information on the territorial usage of 62 energy commodities by 98 economic activities (flows, in IEA terms) in the territories of 171 countries and several regional aggregates (see IEA, 2018). Tables (A.2) and (A.3) in Appendix A provide an overview of these energy flows. The raw IEA data are processed in four steps to link them to the monetary MRIO and trade data, sourced from the Global Trade Analysis Project (GTAP), used to calculate the footprint inventories. First, we map the regional aggregation used in the IEA data to the regional aggregation of the MRIO data used, which comprises 66 single countries and 12 composite regions.³

Second, we allocate the 98 IEA energy flows to the 57 economic sectors and private households present in our database, following the International Standard Industrial Classification (ISIC) of the United Nations (UN, 2008). Most IEA flows are directly matched to a specific economic sector. These directly matched flows cover 91.5% of total energy usage covered by the database. In cases where the sectoral structure in the MRIO tables includes more disaggregated sectors than the economic activities in the IEA data, we split the flows of these activities according to purchases of intermediates from sectors that predominantly produce the energy commodities in the IEA data.

Third, we correct the IEA energy balances, which follow a strict territorial system boundary (IEA, 2018), for the residential principle that underlies the MRIO data and is enshrined in the system of national accounts (SNA). While the territorial principle assigns energy usage to geographic national boundaries, the residential principle assigns economic activities to the residents of a country (World Bank, 2009). This correction is especially relevant for international road, air, and sea transport. Completing this step results in a database on the usage of 62 energy commodities by 57 economic sectors plus private households of the residents of 66 countries and 12 composite regions.

Fourth, we aggregate the 62 IEA energy commodities into seven energy commodity groups that we report in our final database and correct the data for double-counting. The seven energy commodities comprise four renewable (hydro, wind, solar, and other renewable energy) and three non-renewable energy sources (fossil, nuclear, and other non-renewable energy). For this, we aggregate all primary fossil fuels, i.e. crude oil, coal, and natural gas, to the category *fossil fuels*. We keep *nuclear energy* as a specific category and assign the remaining non-renewable energy sources, such as non-renewable waste from industry

³ The aggregation is determined by the coverage of the IO tables for 1997 sourced from GTAP and used to calculate our energy footprint measures. For consistency, we keep the same aggregation across years.

and municipalities, to the category *other non-renewable energy*. For the renewable energy sources, we keep separate categories for *hydro*, *solar*, and *wind energy*. The remaining renewable energy sources, mainly biofuels from biomass, geothermal, and tide energy, are assigned to the category *other renewable energy*. To avoid double counting, we disregard all commodities derived from fossil fuels (*derived fuels*); and because we take an input perspective of energy usage, we also disregarded the usage of *heat and electricity* from our data (see Table A.1 in Appendix A for the aggregation, and Appendix B.1 for further details).

The resulting dataset comprises territorial-based energy inventories disaggregated to 57 economic sectors (plus private households) on the usage of seven energy commodities for 78 regions (66 single countries and 12 composite regions) for the years 1997, 2001, 2004, 2007, 2011 and 2014.

Other MRIO databases offer energy inventories at a sectoral level. The most popular are Eora (Lenzen et al., 2012, 2013), EXIOBASE (Stadler et al., 2018a), WIOD releases (Genty et al., 2012; Timmer et al., 2015, 2016) and GTAP (Aguilar et al., 2019). Our dataset extends them in one or several dimensions (energy commodity disaggregation, sectoral disaggregation, country and time coverage). These sources offer data only until a less recent year (EXIOBASE 3 until 2011, WIOD until 2009) or for fewer regions (EXIOBASE 3, WIOD) and sectors (WIOD). The energy volume database of GTAP is restricted to fossil fuels, though the electricity sector of the database has been disaggregated recently in order to include also electricity produced from nuclear and several renewable energy sources by Peters (2016) and Chepeliev (2020). These databases do not provide pre-prepared energy footprints, such that they have to be processed by the user.

Based on the production-based energy data, we calculate two footprint-based energy inventories (final production and consumption inventories). These inventories differ from territorial production-based energy usage in that they account for the energy used throughout the whole (national and international) supply chain, energy embodied in traded intermediates and final goods, using MRIO techniques (see e.g. Peters, 2008; Davis and Caldeira, 2010; Fernández-Amador et al., 2016, 2020). These inventories assign the responsibility for energy usage from final production and consumption perspectives, respectively.

We first construct global intermediate requirements matrices from national input-output tables and international trade data for the regions and years covered. These matrices capture the direct input requirements sourced from all other sectors to produce one unit of output in each sector in each region. Second, to account for indirect input requirements through global supply chain linkages, we calculate a global Leontief-inverse matrix for each year, which captures direct and indirect input requirements to produce one unit of output in each sector in each region. Third, to trace embodied flows of each primary energy

commodity through the global supply chain, we re-scale the Leontief-inverse matrices with sectoral energy intensities from the production-based energy inventory, separately for each energy commodity. Finally, to derive the national energy footprint inventories, we allocate these flows to the country where the final good is assembled (final production inventory) and consumed (consumption inventory) by multiplying the re-scaled Leontief-inverse matrices with matrices of final production and consumption, respectively (see Appendix B.2 for details).

2.2 Structural decomposition analysis of national energy usage

Let's denote $\tilde{\psi}^{\omega,r}$ the energy usage of region r for inventory ω —alternatively, (standard) territorial production, final production, and final consumption. National inventories for value added, $\phi^{\omega,r}$, are obtained through a similar procedure, after all monetary values in the MRIO tables are expressed in real terms with 1997 as base year (see Appendix B.2). Accordingly, we derive consistent measures for energy intensity as the ratio of energy usage per value added, $\theta^{\omega,r} = \tilde{\psi}^{\omega,r} / \phi^{\omega,r}$, and calculate indices of the relative change of regional energy usage and intensity within a given period as $\underline{\Delta}\tilde{\psi}^{\omega,r}$ and $\tilde{\Theta}^{\omega,r}$, respectively, such that for years 0 and t , the first and the last year of any given period, $\underline{\Delta}\tilde{\psi}^{\omega,r} = \tilde{\psi}^{\omega,r,t} / \tilde{\psi}^{\omega,r,0}$ and $\tilde{\Theta}^{\omega,r} = \theta^{\omega,r,t} / \theta^{\omega,r,0}$.

Energy usage and intensity, and their associated relative-change indices, result from the effects of economic scale, structural composition, and technology (and their changes). We calculate the contribution of different factors to these changes by applying a structural decomposition analysis (SDA) to the MRIO tables underlying the construction of the energy inventories (see e.g. Miller and Blair, 2009; Xu and Dietzenbacher, 2014). In particular, we apply the multiplicative Logarithmic Mean Divisia Index decomposition method I (LMDI-I; see Ang and Liu, 2001; Ang, 2004, 2015) to derive the contributions of seven factors to changes in energy usage and intensity of a region. The seven factors comprise changes in the energy mix to produce final goods and intermediates (*mix*), in sectoral energy intensity (*int*), in the sourcing pattern of foreign and local intermediates (*sup*), in the sectoral composition of final goods produced and consumed (*str*), in the geographic composition of trading partners of final goods (*trd*),⁴ in the volume of production and consumption of final goods (*act*) and in direct primary energy usage by private households (*ehh*). From these seven factors, one refers to the scale of economic activity (*act*), two to energy-production technology (*mix* and *int*), three to the composition of production or consumption (*sup*, *str*, *trd*) and one to energy usage by private households (*ehh*).

⁴ The geographic composition of trading partners of final goods can only be derived for territorial production and final consumption inventories, as from a final production perspective there is no trade in final goods.

We decompose the index of the change in region r 's energy usage of inventory ω , $\underline{\Delta}\tilde{\psi}^{\omega,r}$, as $\underline{\Delta}\tilde{\psi}^{\omega,r} = \prod_a \underline{\Delta}\psi_a^{\omega,r}$ and the index of the change in region r 's energy intensity of inventory ω , $\tilde{\Theta}^{\omega,r}$, as $\tilde{\Theta}^{\omega,r} = \prod_a \Theta_a^{\omega,r}$, where $a = \{act, mix, int, sup, str, trd, eh\}$. The seven sub-indices $\underline{\Delta}\psi_a^{\omega,r}$ and $\Theta_a^{\omega,r}$ report the contribution of each of these seven factors to changes in the energy index decomposed—i.e. energy usage ($\underline{\Delta}\tilde{\psi}^{\omega,r}$) and intensity ($\tilde{\Theta}^{\omega,r}$) for each of the three energy-inventories ω —when holding all other factors constant. Like $\underline{\Delta}\tilde{\psi}^{\omega,r}$ and $\tilde{\Theta}^{\omega,r}$, the contributions are expressed as relative-change indices. A sub-index $\underline{\Delta}\psi_a^{\omega,r}$ and $\Theta_a^{\omega,r}$ can be smaller (larger) than one, indicating that the underlying factor contributes to a decrease (increase) in the aggregate energy indicator over the time period considered, while a sub-index equal to one indicates that this factor has no influence on the relative change of energy use ($\underline{\Delta}\tilde{\psi}^{\omega,r}$) or intensity ($\tilde{\Theta}^{\omega,r}$).⁵ Appendix B.3 offers a detailed explanation of the derivation of $\underline{\Delta}\tilde{\psi}^{\omega,r}$, $\tilde{\Theta}^{\omega,r}$ and their sub-indices from the underlying MRIO tables.

From the decomposition of $\underline{\Delta}\tilde{\psi}^{\omega,r}$ and $\tilde{\Theta}^{\omega,r}$, it is apparent that energy usage and intensity are affected by (i) economic scale; (ii) sectoral composition and geographical sourcing of goods and services; and (iii) the energy technology used in the production of goods and services, both through the mix of energy commodities used and the sectoral energy intensity associated with each input of production. Technological change is thus defined by the change in the mix of energy commodities and the change in sectoral energy intensities. The change in the mix of commodities refers to the mix of energy sources that feed production, which is typically determined by the technology of production of the energy sector. The change in sectoral energy intensities is related to the energy required to produce goods and services provided by a sector. Therefore, this factor, $\Theta_{int}^{\omega,r}$, is a better proxy for changes in energy efficiency than the most commonly used ratio of energy per value added, energy intensity ($\tilde{\Theta}^{\omega,r}$), which is affected by other factors related to economic scale and composition. We name the sectoral intensity factor as efficiency factor, accordingly.

The efficiency factor $\Theta_{int}^{\omega,r}$ has the form

$$\Theta_{int}^{\omega,r} = \frac{\underline{\Delta}\psi_{int}^{\omega,r}}{\underline{\Delta}\phi_{int}^{\omega,r}} = \underline{\Delta}\psi_{int}^{\omega,r} \quad (1)$$

where the last equality results from the fact that $\underline{\Delta}\phi_{int}^{\omega,r} = 1$ because the intensity factor does not exist in the decomposition of value added (i.e. $\Delta\phi_{int}^{\omega,r} = 0$ where the sub-indicator $\Delta\phi_{int}^{\omega,r}$ denotes the absolute change in region r 's energy usage due to changes in sector energy intensity; see details and Table B.2 in Appendix B.3).

We can express region r 's efficiency factor for inventory ω , $\Theta_{int}^{\omega,r} = \underline{\Delta}\psi_{int}^{\omega,r}$, as the product of efficiency factors across all sectors ($k \in [1, s]$) and across all partner regions (p). For the

⁵ For the final production inventory, $\underline{\Delta}\psi_{trd}^{\omega,r} = \Theta_{trd}^{\omega,r} = 1$ by definition.

production-based energy inventory the partner regions are destination regions ($p = u \in [1, n]$) where the production of the origin-region ($r = m \in [1, n]$) is consumed, while for the final production- and consumption-based energy inventories the partner regions are the origin regions ($p = m$) of production used for final production or consumption in the destination-region ($r = u$; see Table 1).

| energy inventory | origin region (m) | destination region (u) |
|--------------------------------|-----------------------|----------------------------|
| production | r | p |
| final production & consumption | p | r |

Table 1: Origin and destination regions for the derivation of energy inventories

Thus,

$$\underline{\Delta}\psi_{int}^{\omega,r} = \prod_p^n \prod_k^s \underline{\Delta}\psi_{int,k}^{\omega,mu} = \prod_p^n \prod_k^s \exp \left[\frac{\underline{\Delta}\psi_{int,k}^{\omega,mu}}{L(\tilde{\psi}^{\omega,r,t}, \tilde{\psi}^{\omega,r,0})} \right]. \quad (2)$$

The second equality in Equation (2) follows from the definition of $\underline{\Delta}\psi_{int,k}^{\omega,mu}$, the efficiency factor for inventory ω in region r , specific to partner p and sector k . This factor depends on the change in bilateral embodied energy ($\underline{\Delta}\psi_{int,k}^{\omega,mu}$) if only the efficiency factor for inventory ω , partner p and sector k in region r changes. In the denominator, $L(\cdot)$ denotes the logarithmic mean, which is defined as $L(x, y) = (x - y)/\ln(x/y)$ and $L(x, x) = x$ for positive numbers, and $\tilde{\psi}^{\omega,r,t}$ and $\tilde{\psi}^{\omega,r,0}$ refer to the national energy usage of region r for inventory ω in periods t and 0. Thus, the term in the denominator is the logarithmic mean of the change in national energy usage of inventory ω in region r .

Finally, we use the definition of $\underline{\Delta}\psi_{int,k}^{\omega,mu}$, shown in Table (B.2) and Equation (B.17) in Appendix B.3, to derive

$$\underline{\Delta}\psi_{int}^{\omega,r} = \prod_p^n \prod_k^s \exp \left[\frac{\sum_g^n \sum_j^s \sum_q^f W_{\psi,kj}^{\omega,mgu,q} \ln \left(\frac{e_k^{m,t}}{e_k^{m,0}} \right)}{L(\tilde{\psi}^{\omega,r,t}, \tilde{\psi}^{\omega,r,0})} \right], \quad (3)$$

where g refers to regions and j to sectors along the supply chain between origin-region m and destination-region u . $W_{\psi,kj}^{\omega,mgu,q} = L(v_{\psi,kj}^{\omega,mgu,q,t}, v_{\psi,kj}^{\omega,mgu,q,0})$ are weights, where $v_{\psi,kj}^{\omega,mgu,q,t}$ and $v_{\psi,kj}^{\omega,mgu,q,0}$ are bilateral flows of embodied energy commodity q from the sector-region of origin (k, m) via the intermediate sector-region (j, g) to the region of destination (u) in periods t and 0, respectively. These weights multiply the change in energy intensities captured by the logarithm in the numerator, where $e_k^{m,t}$ and $e_k^{m,0}$ refer to the energy intensity of sector k in origin-region m in periods t and 0. Thus, the efficiency factor, $\Theta_{int}^{\omega,r} = \underline{\Delta}\psi_{int}^{\omega,r}$,

is calculated at the most disaggregated level available in our MRIO framework and then aggregated across regions p and g , sectors k and j , and energy commodities q . In general, the decomposition is carried out at the sector-country and energy commodity level to avoid aggregation bias. See Appendix B.3 for further details.

2.3 Difference-in-difference analysis

A set of difference-in-difference (DID) regressions is carried out to investigate whether the EU countries experience significantly stronger energy efficiency improvements after the implementation of the EU Energy Services Directive and relative to other countries. For that purpose, we distinguish two sub-periods 1997–2007 and 2007–2014. The dependent variable is the average annual growth rate of the efficiency factor resulting from the SDA, $\hat{\Theta}_{int}^{\omega,r}$, such that we account for the different lengths of the two sub-periods. We implement the analysis using our data disaggregated at the level of 77 countries and regions.⁶

$$\hat{\Theta}_{int,it}^{\omega,r} = \alpha + \beta P_2 + \sum \gamma_g D_g + \sum \delta_g P_2 D_g + u_{it} \quad (4)$$

where P_2 is a dummy for the second period of analysis (2007–2014), D_g are dummies for the groups specified in different specifications—namely EU, EU15, the Eastern European Union (EEU), and rest of OECD—and $P_2 D_g$ are interactions of both. The intercept α stands for the base group in the first period of analysis (1997–2007). The base group is regression specific, the countries in the base group change depending on the specific group dummies included in the regressions.

Additionally, we run similar DID regressions to study whether the EU’s switch from fossil fuels towards wind and solar energy was particularly rapid relative to other regions. In these regressions, the dependent variable is the average annual change in the share of each of the seven energy commodities in the energy mix.

3 Energy inventories at the beginning of the 21st century

The analysis of the three energy inventories calculated reveals several stylized facts. Table 2 shows the global energy demand and the shares of the seven energy commodities from 1997–2014. Two main findings can be highlighted from it. First, global energy demand

⁶ It is not possible to further isolate individual countries forming part of composite regions in the underlying IO tables that form the basis of the SDA (see Table A.4 for the countries and regions included). Malta reports zero energy usage in 1997 but a positive value thereafter, what results in infinite growth rates of energy usage. Accordingly, Malta is excluded from the analysis.

increases by 44.3% from 1997–2014. The annual growth rates are larger between 1997 and 2007 as compared to later years. Global energy usage increases on average by 2.7% per year from 1997 and 2007 but only by 2.1% and 1.6% per year from 2007–2011 and from 2011–2014, respectively.

| Year | Total <i>mtoe</i> | Fossil % | Nuclear % | Oth. NR % | Hydro % | Wind % | Solar % | Oth. R % |
|------|----------------------|-------------|--------------|--------------|------------|-----------|------------|-------------|
| 1997 | 10883.0 | 78.3 | 5.9 | 0.1 | 2.5 | 0.0 | 0.0 | 13.2 |
| 2001 | 11562.3 | 78.4 | 6.1 | 0.2 | 2.4 | 0.0 | 0.0 | 12.8 |
| 2004 | 12777.7 | 79.2 | 5.8 | 0.2 | 2.4 | 0.1 | 0.1 | 12.4 |
| 2007 | 13838.1 | 79.8 | 5.3 | 0.2 | 2.5 | 0.1 | 0.1 | 12.0 |
| 2011 | 14987.0 | 79.9 | 4.7 | 0.2 | 2.6 | 0.3 | 0.2 | 12.1 |
| 2014 | 15703.0 | 79.8 | 4.4 | 0.2 | 2.7 | 0.4 | 0.3 | 12.1 |

Table 2: Global energy usage

Total energy usage denoted in megatons of oil equivalents (*mtoe*), the usage of the seven different energy commodities is denoted as shares of the global total. The category “Oth. NR” (other non-renewables) includes primarily non-renewable industrial waste. The category “Oth. R” (other renewables) is comprised mainly by energy commodities produced from crops and wood (charcoal) but also includes renewable waste and other renewable energy sources that did not fit into any of the other categories, such as energy from geothermal and tide installations.

Second, the global energy mix stays stable from 1997 through 2014. The share of renewable (hydro, wind, solar, and other renewable) relative to non-renewable (fossil, nuclear, and other non-renewable) energy remains broadly constant. Fossil fuels account for almost 80% of the world’s energy usage in that period. Their share in total energy usage increases slightly, by 1.5 percentage points, between 1997 and 2014, whereas the share of nuclear energy decreases by the same amount. The share of other non-renewable energy commodities increases only marginally. Within the group of renewables, the share of other renewables, including biomass as the most important renewable energy source, decreases by 1.1 percentage points from 1997–2014. The share of the second most important renewable, hydro energy, increases marginally by 0.2 percentage points until 2014. By contrast, wind- and solar energy experience remarkable increases and their shares in global energy usage quadruple and triple over 2007–2014, respectively, although both remain a minor sources of energy in 2014.

The stable global structure of energy usage hides important dynamics at the regional level. Table 3 shows the energy inventories for the key regions in terms of global energy demand—high-income regions and China.⁷ It reports energy usage from production and energy embodied in final production and consumption, disaggregated to the seven energy commodities, in 1997 and 2014. As already mentioned, the energy footprint inventories (based on final production and consumption) account for the energy used in the production

⁷ The high-income regions include the European Union (EU 28), the United States of America (USA), Japan, the members of the European Free Trade Association (EFTA—i.e. Norway, Iceland, Switzerland, and Liechtenstein), and the rest of the members of the Organisation for Economic Co-operation and Development (R.o. OECD).

of imported intermediates and final goods and are, thus, different from the usual concept of energy usage or energy consumption, which refers to energy used within a country for domestic, territorial production.

For high-income regions, standard energy usage based on territorial production is typically lower than energy embodied in their final production and consumption, such that they are net-importers of embodied energy. Together, the high-income regions are responsible for about 47% of the world's energy usage in 1997, based on territorial production. When accounting for energy embodied in trade, their energy footprint becomes larger, 51% and 53% of global energy usage for final production and consumption inventories, respectively. The difference between territorial production- and footprint-based energy usage widens over time. Production-based energy usage increases by about 5% between 1997 and 2014, whereas the growth rate of energy embodied in final production and consumption amounts to more than 11% and 12%. Two exceptions are Japan, where energy usage decreases for all inventories from 1997–2014, and the EU 28, which reduces its territorial energy usage but increases its final production- and consumption-based energy usage.

In contrast to high-income regions, China is a net-exporter of embodied energy in 1997. However, from 1997 through 2014, its energy usage for territorial production almost triples, such that China is the world's largest user of energy for domestic production in 2014. Because of the importance of final goods assembly in China, energy embodied in final production exceeds its usage for territorial production in 2014, although energy embodied in consumption remains below the level of energy used for territorial production.

From the breakdown of energy demand by energy commodity in Table 3, it is apparent that high-income regions use a larger share of non-renewable energy commodities in their energy mix for territorial production as compared to the global average in 1997 and 2014 (compare with Table 2), because of their strong reliance on fossil energy. The only exception is the EFTA, which shows a high usage of hydro-energy.⁸ Nevertheless, the share of non-renewable energy in high-income regions falls from 1997–2014. The relative decline of fossil energy contributes to this development and is more pronounced in the EU 28, where the share of fossil energy falls below the global average in 2014.⁹ The share of renewable energy in high-income regions increases mainly because of the expansion of wind and solar energy, particularly in the EU 28.

China uses a larger share of renewable energy (mainly from biomass within the other renewable category) than the global average in 1997. Although hydro-, wind-, and solar

⁸ In developing countries, biomass is an important source of energy. This explains their higher reliance on renewable energy commodities. Data not shown due to space constraints.

⁹ The increase in the share of fossil energy in Japan is related to a quicker reduction of energy usage from other sources, especially nuclear energy, such that total energy usage measured in *mtoe* decreases.

| | | production | | | final production | | | consumption | | |
|----------|---------|-------------|-----------------|------|------------------|-----------------|------|-------------|-----------------|------|
| | | mtoe | % of mix/global | | mtoe | % of mix/global | | mtoe | % of mix/global | |
| | | 1997 | | | | | | | | |
| EU 28 | Total | 1694.4 | 100.0 | 15.6 | 1888.1 | 100.0 | 17.3 | 1939.8 | 100.0 | 17.8 |
| | Fossil | 1352.3 | 79.8 | 15.9 | 1530.0 | 81.0 | 18.0 | 1578.2 | 81.4 | 18.5 |
| | Nuclear | 244.4 | 14.4 | 38.2 | 237.5 | 12.6 | 37.1 | 231.1 | 11.9 | 36.1 |
| | Oth. NR | 5.9 | 0.3 | 36.6 | 5.8 | 0.3 | 35.7 | 5.7 | 0.3 | 35.2 |
| | Hydro | 29.0 | 1.7 | 10.6 | 38.4 | 2.0 | 14.0 | 40.5 | 2.1 | 14.8 |
| | Wind | 0.6 | 0.0 | 55.6 | 0.6 | 0.0 | 51.7 | 0.6 | 0.0 | 49.3 |
| | Solar | 0.3 | 0.0 | 10.9 | 0.3 | 0.0 | 10.9 | 0.3 | 0.0 | 11.1 |
| | Oth. R | 61.8 | 3.6 | 4.3 | 75.6 | 4.0 | 5.3 | 83.6 | 4.3 | 5.8 |
| USA | Total | 2160.8 | 100.0 | 19.9 | 2234.4 | 100.0 | 20.5 | 2325.1 | 100.0 | 21.4 |
| | Fossil | 1874.5 | 86.7 | 22.0 | 1929.4 | 86.3 | 22.7 | 2003.7 | 86.2 | 23.5 |
| | Nuclear | 173.6 | 8.0 | 27.2 | 175.5 | 7.9 | 27.5 | 177.6 | 7.6 | 27.8 |
| | Oth. NR | 6.4 | 0.3 | 40.0 | 6.5 | 0.3 | 40.2 | 6.5 | 0.3 | 40.2 |
| | Hydro | 28.6 | 1.3 | 10.5 | 38.0 | 1.7 | 13.9 | 42.1 | 1.8 | 15.4 |
| | Wind | 0.3 | 0.0 | 24.6 | 0.3 | 0.0 | 24.4 | 0.3 | 0.0 | 24.6 |
| | Solar | 0.2 | 0.0 | 7.6 | 0.2 | 0.0 | 7.3 | 0.2 | 0.0 | 7.2 |
| | Oth. R | 77.1 | 3.6 | 5.4 | 84.5 | 3.8 | 5.9 | 94.7 | 4.1 | 6.6 |
| Japan | Total | 480.6 | 100.0 | 4.4 | 594.2 | 100.0 | 5.5 | 627.5 | 100.0 | 5.8 |
| | Fossil | 380.7 | 79.2 | 4.5 | 489.0 | 82.3 | 5.7 | 520.5 | 82.9 | 6.1 |
| | Nuclear | 83.2 | 17.3 | 13.0 | 81.0 | 13.6 | 12.7 | 79.2 | 12.6 | 12.4 |
| | Oth. NR | 0.1 | 0.0 | 0.5 | 0.2 | 0.0 | 0.9 | 0.2 | 0.0 | 1.2 |
| | Hydro | 7.4 | 1.5 | 2.7 | 9.7 | 1.6 | 3.6 | 10.4 | 1.7 | 3.8 |
| | Wind | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 1.2 |
| | Solar | 1.0 | 0.2 | 31.7 | 1.0 | 0.2 | 31.8 | 1.0 | 0.2 | 31.8 |
| | Oth. R | 8.3 | 1.7 | 0.6 | 13.3 | 2.2 | 0.9 | 16.2 | 2.6 | 1.1 |
| EFTA | Total | 51.8 | 100.0 | 0.5 | 56.8 | 100.0 | 0.5 | 78.4 | 100.0 | 0.7 |
| | Fossil | 28.1 | 54.4 | 0.3 | 36.5 | 64.3 | 0.4 | 55.5 | 70.8 | 0.7 |
| | Nuclear | 6.7 | 13.0 | 1.1 | 6.7 | 11.7 | 1.0 | 8.4 | 10.7 | 1.3 |
| | Oth. NR | 0.6 | 1.2 | 3.7 | 0.5 | 0.9 | 3.1 | 0.5 | 0.6 | 3.0 |
| | Hydro | 12.8 | 24.8 | 4.7 | 9.1 | 16.1 | 3.3 | 8.8 | 11.2 | 3.2 |
| | Wind | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.8 | 0.0 | 0.0 | 1.5 |
| | Solar | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.3 |
| | Oth. R | 3.4 | 6.7 | 0.2 | 4.0 | 7.0 | 0.3 | 5.1 | 6.6 | 0.4 |
| R.o.OECD | Total | 758.3 | 100.0 | 7.0 | 775.2 | 100.0 | 7.1 | 754.7 | 100.0 | 6.9 |
| | Fossil | 626.0 | 82.6 | 7.3 | 653.7 | 84.3 | 7.7 | 637.5 | 84.5 | 7.5 |
| | Nuclear | 44.3 | 5.8 | 6.9 | 42.4 | 5.5 | 6.6 | 41.2 | 5.5 | 6.4 |
| | Oth. NR | 0.8 | 0.1 | 5.1 | 0.7 | 0.1 | 4.3 | 0.6 | 0.1 | 3.8 |
| | Hydro | 41.1 | 5.4 | 15.0 | 33.2 | 4.3 | 12.1 | 30.4 | 4.0 | 11.1 |
| | Wind | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 1.8 | 0.0 | 0.0 | 2.2 |
| | Solar | 0.3 | 0.0 | 11.0 | 0.3 | 0.0 | 11.0 | 0.3 | 0.0 | 10.8 |
| | Oth. R | 45.6 | 6.0 | 3.2 | 44.9 | 5.8 | 3.1 | 44.6 | 5.9 | 3.1 |
| China | Total | 1097.5 | 100.0 | 10.1 | 1075.8 | 100.0 | 9.9 | 1005.8 | 100.0 | 9.2 |
| | Fossil | 870.4 | 79.3 | 10.2 | 843.1 | 78.4 | 9.9 | 774.6 | 77.0 | 9.1 |
| | Nuclear | 3.8 | 0.3 | 0.6 | 8.3 | 0.8 | 1.3 | 8.1 | 0.8 | 1.3 |
| | Oth. NR | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.3 | 0.1 | 0.0 | 0.4 |
| | Hydro | 16.9 | 1.5 | 6.2 | 16.1 | 1.5 | 5.9 | 14.6 | 1.5 | 5.3 |
| | Wind | 0.0 | 0.0 | 1.6 | 0.0 | 0.0 | 1.7 | 0.0 | 0.0 | 1.6 |
| | Solar | 0.4 | 0.0 | 14.1 | 0.4 | 0.0 | 14.0 | 0.4 | 0.0 | 14.0 |
| | Oth. R | 206.1 | 18.8 | 14.4 | 207.9 | 19.3 | 14.5 | 207.9 | 20.7 | 14.5 |

Table 3: Energy usage, selected regions – continued on next page

Total energy usage for all three inventories is shown in megatons of oil equivalents (*mtoe*), disaggregated to seven energy commodities. *% of mix* refers to the share of the different energy commodities in the region's energy mix. *% global* refers to the region's share in global energy demand for each energy commodity. R.o.OECD stands for the rest of the OECD aggregate.

| | | production | | | final production | | | consumption | | |
|-------------|---------|------------|-----------------|------|------------------|-----------------|------|-------------|-----------------|------|
| | | mtoe | % of mix/global | | mtoe | % of mix/global | | mtoe | % of mix/global | |
| 2014 | | | | | | | | | | |
| EU 28 | Total | 1606.6 | 100.0 | 10.2 | 2121.8 | 100.0 | 13.5 | 2180.0 | 100.0 | 13.9 |
| | Fossil | 1161.4 | 72.3 | 9.3 | 1645.3 | 77.5 | 13.1 | 1703.9 | 78.2 | 13.6 |
| | Nuclear | 228.4 | 14.2 | 33.1 | 222.3 | 10.5 | 32.3 | 213.1 | 9.8 | 30.9 |
| | Oth. NR | 13.2 | 0.8 | 33.9 | 12.4 | 0.6 | 31.8 | 11.8 | 0.5 | 30.3 |
| | Hydro | 32.2 | 2.0 | 7.7 | 49.4 | 2.3 | 11.7 | 52.4 | 2.4 | 12.4 |
| | Wind | 21.8 | 1.4 | 32.6 | 20.9 | 1.0 | 31.3 | 20.1 | 0.9 | 30.1 |
| | Solar | 12.0 | 0.7 | 24.5 | 11.4 | 0.5 | 23.2 | 10.9 | 0.5 | 22.2 |
| | Oth. R | 137.6 | 8.6 | 7.2 | 160.2 | 7.5 | 8.4 | 167.9 | 7.7 | 8.8 |
| USA | Total | 2297.5 | 100.0 | 14.6 | 2391.2 | 100.0 | 15.2 | 2512.8 | 100.0 | 16.0 |
| | Fossil | 1923.7 | 83.7 | 15.3 | 1995.7 | 83.5 | 15.9 | 2096.5 | 83.4 | 16.7 |
| | Nuclear | 216.4 | 9.4 | 31.4 | 216.3 | 9.0 | 31.4 | 218.6 | 8.7 | 31.7 |
| | Oth. NR | 4.9 | 0.2 | 12.5 | 5.0 | 0.2 | 12.9 | 5.2 | 0.2 | 13.4 |
| | Hydro | 22.5 | 1.0 | 5.3 | 33.8 | 1.4 | 8.0 | 40.7 | 1.6 | 9.7 |
| | Wind | 15.8 | 0.7 | 23.7 | 16.1 | 0.7 | 24.2 | 16.7 | 0.7 | 24.9 |
| | Solar | 4.8 | 0.2 | 9.7 | 4.9 | 0.2 | 10.1 | 5.2 | 0.2 | 10.5 |
| | Oth. R | 109.5 | 4.8 | 5.7 | 119.2 | 5.0 | 6.3 | 129.9 | 5.2 | 6.8 |
| Japan | Total | 420.0 | 100.0 | 2.7 | 513.5 | 100.0 | 3.3 | 531.5 | 100.0 | 3.4 |
| | Fossil | 395.7 | 94.2 | 3.2 | 477.8 | 93.1 | 3.8 | 491.4 | 92.5 | 3.9 |
| | Nuclear | 0.0 | 0.0 | 0.0 | 3.9 | 0.8 | 0.6 | 5.2 | 1.0 | 0.8 |
| | Oth. NR | 4.1 | 1.0 | 10.5 | 3.8 | 0.7 | 9.9 | 3.7 | 0.7 | 9.6 |
| | Hydro | 7.2 | 1.7 | 1.7 | 9.3 | 1.8 | 2.2 | 10.0 | 1.9 | 2.4 |
| | Wind | 0.4 | 0.1 | 0.7 | 0.8 | 0.2 | 1.2 | 0.9 | 0.2 | 1.4 |
| | Solar | 2.3 | 0.5 | 4.6 | 2.2 | 0.4 | 4.4 | 2.1 | 0.4 | 4.3 |
| | Oth. R | 10.3 | 2.5 | 0.5 | 15.7 | 3.1 | 0.8 | 18.2 | 3.4 | 1.0 |
| EFTA | Total | 68.6 | 100.0 | 0.4 | 93.8 | 100.0 | 0.6 | 110.1 | 100.0 | 0.7 |
| | Fossil | 36.7 | 53.5 | 0.3 | 63.9 | 68.1 | 0.5 | 79.4 | 72.1 | 0.6 |
| | Nuclear | 7.3 | 10.6 | 1.1 | 8.1 | 8.6 | 1.2 | 8.6 | 7.8 | 1.2 |
| | Oth. NR | 1.1 | 1.6 | 2.8 | 1.0 | 1.1 | 2.6 | 1.0 | 0.9 | 2.6 |
| | Hydro | 16.0 | 23.4 | 3.8 | 11.5 | 12.3 | 2.7 | 10.7 | 9.7 | 2.5 |
| | Wind | 0.2 | 0.3 | 0.3 | 0.4 | 0.5 | 0.7 | 0.5 | 0.5 | 0.8 |
| | Solar | 0.1 | 0.2 | 0.3 | 0.2 | 0.2 | 0.4 | 0.3 | 0.2 | 0.5 |
| | Oth. R | 7.2 | 10.5 | 0.4 | 8.6 | 9.2 | 0.5 | 9.7 | 8.8 | 0.5 |
| R.o.OECD | Total | 990.8 | 100.0 | 6.3 | 1052.3 | 100.0 | 6.7 | 1083.8 | 100.0 | 6.9 |
| | Fossil | 809.7 | 81.7 | 6.5 | 882.2 | 83.8 | 7.0 | 915.8 | 84.5 | 7.3 |
| | Nuclear | 71.2 | 7.2 | 10.3 | 63.4 | 6.0 | 9.2 | 60.2 | 5.6 | 8.7 |
| | Oth. NR | 3.0 | 0.3 | 7.7 | 2.8 | 0.3 | 7.3 | 2.7 | 0.3 | 7.1 |
| | Hydro | 45.6 | 4.6 | 10.8 | 40.3 | 3.8 | 9.6 | 39.0 | 3.6 | 9.3 |
| | Wind | 4.5 | 0.5 | 6.8 | 4.5 | 0.4 | 6.7 | 4.6 | 0.4 | 6.9 |
| | Solar | 2.2 | 0.2 | 4.5 | 2.3 | 0.2 | 4.7 | 2.3 | 0.2 | 4.7 |
| | Oth. R | 54.5 | 5.5 | 2.9 | 56.8 | 5.4 | 3.0 | 59.2 | 5.5 | 3.1 |
| China | Total | 2940.1 | 100.0 | 18.7 | 2984.2 | 100.0 | 19.0 | 2788.2 | 100.0 | 17.8 |
| | Fossil | 2658.0 | 90.4 | 21.2 | 2656.5 | 89.0 | 21.2 | 2455.9 | 88.1 | 19.6 |
| | Nuclear | 34.5 | 1.2 | 5.0 | 43.7 | 1.5 | 6.3 | 42.1 | 1.5 | 6.1 |
| | Oth. NR | 5.6 | 0.2 | 14.4 | 6.1 | 0.2 | 15.8 | 6.2 | 0.2 | 16.0 |
| | Hydro | 90.4 | 3.1 | 21.5 | 86.6 | 2.9 | 20.6 | 78.8 | 2.8 | 18.7 |
| | Wind | 13.4 | 0.5 | 20.1 | 12.5 | 0.4 | 18.8 | 11.4 | 0.4 | 17.1 |
| | Solar | 22.5 | 0.8 | 45.8 | 22.4 | 0.7 | 45.6 | 22.1 | 0.8 | 45.1 |
| | Oth. R | 115.6 | 3.9 | 6.1 | 156.3 | 5.2 | 8.2 | 171.8 | 6.2 | 9.0 |

Table 2: – continued from last page.

energy gain importance between 1997 and 2014, the share of renewables in the Chinese energy mix drops below the global average by 2014, as a result of the substantial increase in the use of fossil energy and the reduction in the share of biomass within the other renewable energy category.

The energy mix across countries is more similar from a footprint than from a territorial-production perspective. That is, accounting for energy embodied in trade smooths differences in their energy mix. There are some exceptions, which can be explained by international trade patterns. In the rest of the OECD, the share of non-renewable energy used in production is slightly above the world average, but imports show an even larger share of non-renewable energy; consequently, final production and consumption inventories present a higher share of non-renewable energy than the production inventory. A similar pattern is observed in the EU 28 in 2014. For China, it is the opposite: Chinese imports show a lower share of non-renewable energy as compared to China's domestic production, such that final production and consumption are characterized by a smaller share of non-renewable energy.

In contrast to most high-income regions, production-based energy usage in the EU declines between 1997 and 2014, and the switch from fossil energy towards wind and solar energy is particularly rapid. However, as for other high-income regions, final production and consumption-based energy usage increase in this period, and imports of the EU rely more heavily on fossil energy than domestic production. The next section evaluates these specific developments of the EU in detail and in the context of the EU's energy policy.

4 The EU's Energy Services Directive

The Energy Services Directive (2006/32/EC), issued in 2006, specifies an overall national indicative energy savings target of 9%, to be achieved from 2008–2016 through energy services and other energy efficiency improvements, and the need to promote the production of renewable energy. Theoretically, energy savings may be reached through different channels. Energy savings may result from a contraction of economic activity. Energy savings may also result from improved energy efficiency, because of technological change that reduces the energy intensity of production or because of production structures change towards production in less energy intensive sectors. The incentives to promote technological progress to improve energy efficiency vary across the EU countries depending on the expectations about the level of future economic activity and structural re-locations. Yet, only technological progress that increases energy efficiency leads to sustainable reductions in energy usage, since declines in economic activity merely lead to transitional reductions in energy usage and the relocation of energy-intensive production processes to other coun-

tries does not reduce energy usage at a global scale. Thus, to assess whether the EU Energy Services Directive implies sustainable energy efficiency gains, it is necessary to isolate the influence of other factors that contribute to the energy savings targeted by the Directive.

We apply the SDA to energy usage and to the ratio of energy usage per unit of value added (energy intensity) for the period 1997–2014, and analyze their factor compositions in Section 4.1. The efficiency factor from the SDA on energy usage is a better measure of energy efficiency developments than energy per value added and is only weakly correlated with the latter. In Section 4.2 we estimate the effects of the EU Energy Services Directive on the efficiency factor.

4.1 Changes in energy usage and intensity

We decompose the change of energy usage to isolate the contribution of changes in sectoral energy intensity (*int*) from changes in other factors that contribute to a reduction in overall energy usage, such as economic activity (*act*), sourcing patterns of intermediates (*sup*), sectoral composition (*str*) and trading partners (*trd*) of final goods, energy mix (*mix*) and energy usage by households (*ehh*). Figure 1 presents the results of the decomposition for all three energy inventories for the EU 28 and selected regions between 1997 and 2014. The overall change in energy usage in percent, $\underline{\Delta}\tilde{\psi}^{\omega,r}$, is represented by the black dots, while the colored bars represent the percentage changes of the seven factors, $\underline{\Delta}\psi_a^{\omega,r}$, where $a = \{act, int, sup, str, trd, mix, ehh\}$. Positive (negative) values of the bars indicate that, holding the other factors fixed, changes in the corresponding factor contribute to an increase (decrease) in energy usage. The height of the bars reflects the growth rate of energy usage, in percent, caused by changes in the underlying factors.¹⁰ Four main outcomes can be highlighted from Figure 1. First, in line with Table 3, energy usage associated with all three inventories increases between 1997 and 2014 in all regions but Japan and, for production-based energy usage, the EU 28.

Second, the development of energy usage is mostly influenced by changes in economic activity (*act*), changes in sectoral energy intensity (*int*), and changes in the structure of supply chains for intermediates (*sup*). The effects of changes in the remaining factors are negligible. Increasing economic activity (*act*) is the main factor contributing to higher energy usage in all regions and inventories.

¹⁰ Due to the conversion of the sub-indices corresponding to the factors to percentage changes, the bars do not add up to the percentage changes of energy usage (the black dots). Table C.1 in Appendix C.1 presents detailed results where the values of the sub-indices are retained such that the multiplication of the sub-indices is equal to the index of total changes in energy usage.

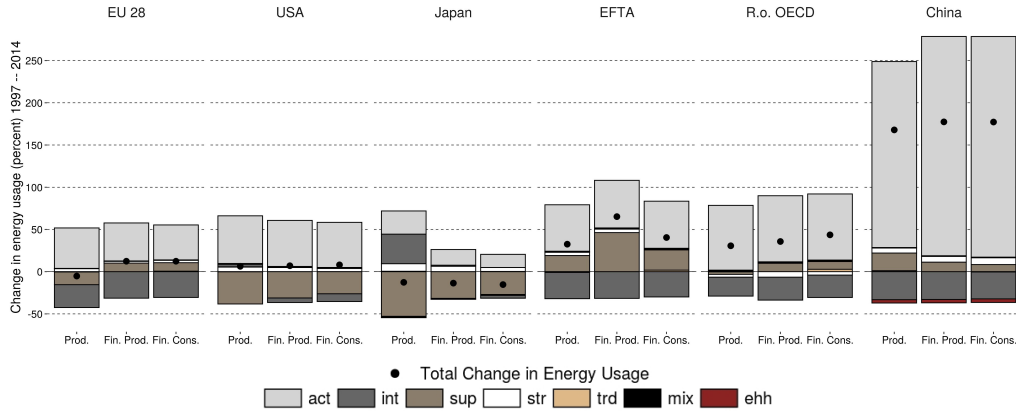


Figure 1: Decomposition of changes in energy usage, 1997–2014.

Note: Prod. stands for production-based energy usage, Fin. Prod. and Fin. Cons. for energy embodied in final production and final consumption, respectively. *act* stands for economic activity, *int* for sectoral energy intensity, *sup* for the structure of supply chains for intermediates, *str* for the sectoral composition of final goods trade, *trd* for the geographic composition of final goods trade, *mix* for the energy mix, and *ehh* for the energy usage by households. The black dots denote the change of energy usage over the period considered in percent. The stacked bars summarize the contribution of each of the seven factors considered to the overall change in energy usage, assuming all the other factors to be fixed. They are constructed by transforming the sub-indices obtained from the multiplicative LMDI-I decomposition, as described in Appendix B.3.2, to percentage changes. As such, they do not add up to the percentage changes of total energy, but indicate which factors contributed to higher, and which factors to lower energy usage as well as their relative importance.

Third, efficiency gains (negative *int* term) reduce energy usage in most inventories and regions shown, partially counteracting the effect of increasing economic activity. There are two exceptions. The first one is the USA for production-based energy usage, where the efficiency factor grows slightly and contributes to higher energy usage. The second one is Japan, where the efficiency factor of production increases substantially between 1997 and 2014 and contributes significantly to higher energy usage. In Japan, also the efficiency factor of final production increases slightly.

Fourth, the contribution of changes in sourcing patterns of intermediates (*sup*) is in general smaller as compared to the contribution of economic activity, and the direction of its effect varies across inventories and regions. For production-based energy, a decreasing effect (negative *sup* term), indicating that production of intermediates decreased or shifted towards sectors with lower energy usage, is apparent in all regions but in the EFTA and China. For the footprint-based inventories, the increasing effect (positive *sup* term) suggests a shift in the sourcing of intermediates towards sectors and/or countries with higher energy usage in all regions but the USA and Japan.

The pattern observed for the sourcing of intermediates (*sup*) in the EU 28 and the OECD suggests outsourcing of energy-intensive intermediates to other countries. In both regions,

the production of intermediates declines and/or shifts towards sectors with lower energy usage, while the energy content of imported intermediates increases. This reduction in the energy content of domestically produced intermediates, together with improvements in energy-intensity, is not strong enough to counterweight the influence of economic activity on production-based energy usage in the OECD but contributes to a decrease in energy usage for production in the EU 28. Without the observed restructuring of its intermediate supply chains, the efficiency improvements in the EU 28 alone are not strong enough to reduce energy usage for production. By contrast, the higher energy content of imported intermediates observed for footprint-based energy inventories contributes to the increase in energy footprints.

Energy intensity, defined as the ratio of energy usage per unit of value added, can itself be affected by the same of factors as energy usage. Figure 2 displays the results of the decomposition of energy intensity. The overall change in energy intensity in percent, $\tilde{\Theta}^{\omega,r}$, is represented by the black dots, while the colored bars represent the percentage changes of the seven factors, $\Theta_a^{\omega,r}$ where $a = \{act, int, sup, str, trd, mix, eh\}$. As explained in Section 2.2, the efficiency factor (*int*) affects only the numerator of energy intensity (i.e. energy usage), such that changes in energy intensity and usage caused by this factor are numerically identical ($\Theta_{int}^{\omega,r} = \underline{\Delta}\psi_{int}^{\omega,r}$).

From Figure 2, it is apparent that energy intensity decreases in all regions and inventories, with the exception of final production in the EFTA. EFTA countries import increasingly energy-intensive intermediates for final production, which contributes to the decrease in energy intensity of final production.

The main factors affecting changes in energy intensity are changes in sectoral energy intensity (*int*) and in the structure of supply chains for intermediates (*sup*). Unlike for energy usage, economic growth (*act*) improves energy efficiency in all regions and inventories but the production-based inventory in Japan. The effects of the four other factors are smaller.

The efficiency factor (*int*) is not always the largest contributor, being surpassed by the sourcing patterns of intermediates (*sup*) in some cases. Consequently, the correlation between energy intensity and the efficiency factor in our sample is 0.27. Furthermore, the efficiency factor and energy intensity move into opposite directions in some cases—e.g. in the USA and Japan for the production-based energy inventory and in the EFTA for the final production inventory.

A comparison between production- and footprint-based energy efficiency shows that although the efficiency factor of domestic production may increase, it may decline for footprint-based inventories (e.g. in the USA and Japan). For footprint-based inventories, the efficiency factor decreases (i.e. improves) when the sectoral energy intensity of

the suppliers of intermediates embodied in final production or consumption declines. Since changes in other factors also affect the energy intensity of final production and consumption, the efficiency factor can move in the opposite direction to energy intensity of footprint inventories. Therefore, using changes of energy intensity as a proxy for efficiency gains may lead to invalid conclusions about efficiency developments, and the efficiency factor from the SDA is a better proxy for energy efficiency.

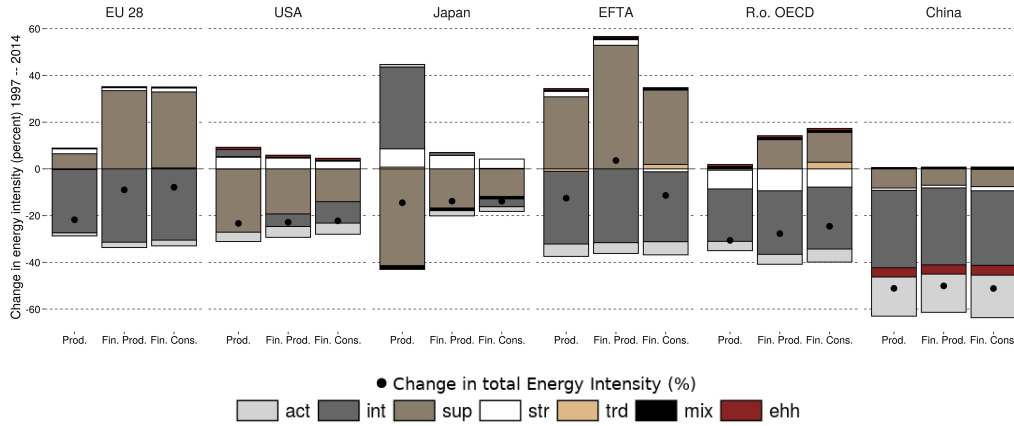


Figure 2: Decomposition of changes in energy intensity, 1997–2014.

Note: Energy intensity is defined as energy usage by an economy divided by its total value added. Other notes as in Figure 1.

In the EU 28, energy intensity reductions are mainly driven by reductions in the efficiency factor, in contrast to the USA or Japan. In general, the patterns found for the EU 28 are similar to the EFTA and to some extent to the rest of the OECD.

In Figure 3 we present the decomposition of energy intensity for the periods before and after the implementation of the EU Energy Services Directive (1997–2007 and 2007–2014).¹¹ After 2007, the contribution of the efficiency factor is much larger than the contribution of changes in supply chains for intermediates in most regions, suggesting that the correlation between energy intensity and the efficiency factor is not constant over time and increases after 2007. In this sub-period, the developments in the EU 28 are more similar to those of the rest of the OECD, but the EFTA shows different developments. All in all, although there are stronger efficiency gains after 2007, coincident with the implementation of the Directive, as compared to before, similar developments take place in other high-income regions.¹²

¹¹ We present the numerical results for the analysis in Figures (2) and (3) in Tables (C.2) – (C.4) in Appendix C.1.

¹² See also Table C.5 in Appendix C.2, which reports average annual growth rates of energy intensity and the efficiency factor. The results for similar decompositions at the level of individual EU countries are reported in Appendix C.3, and data on average annual growth rates of efficiency factor of production for individual countries is available in Appendix C.4.

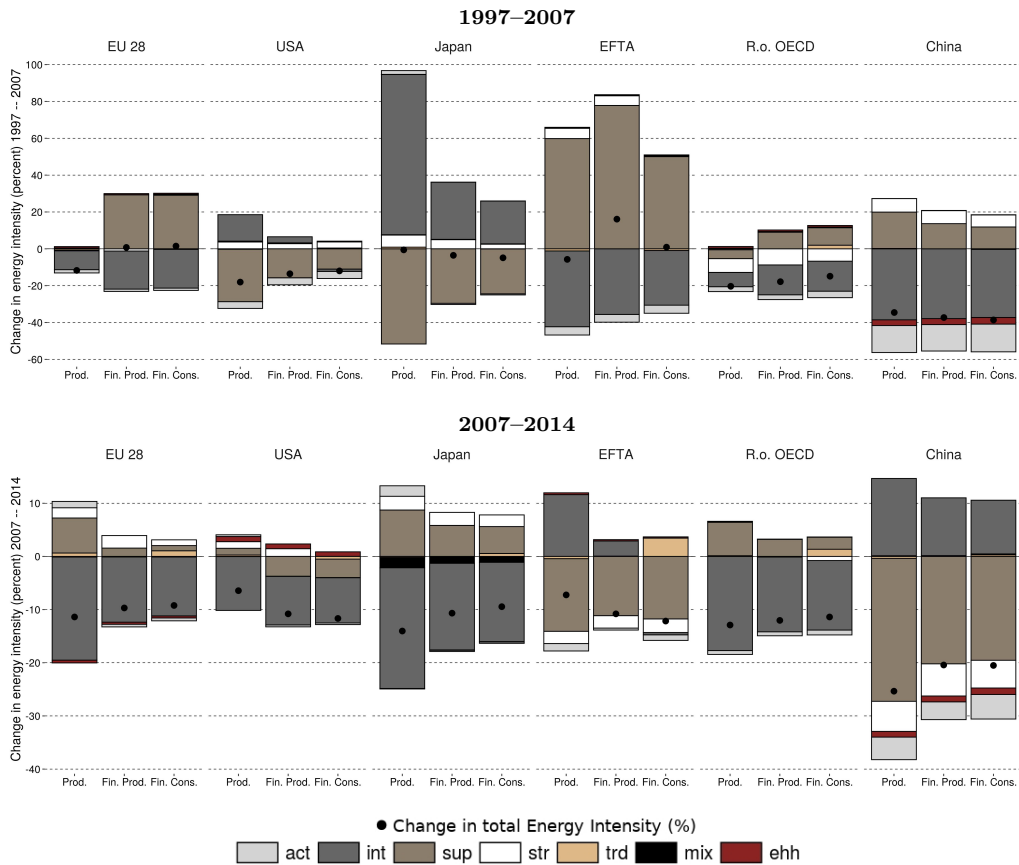


Figure 3: Decomposition of changes in energy intensity, sub-periods.

Note: Decompositions of changes in energy intensity between 1997 and 2007 (upper graph) and between 2007 and 2014 (lower graph). Other notes as in Figure 1 and Figure 2.

4.2 Difference-in-differences analysis

We carry out DID regressions to investigate whether the EU countries experienced significantly stronger energy efficiency improvements after the implementation of the EU Energy Services Directive (2007) and relative to other countries. For that purpose, we use our data disaggregated at the level of 77 individual countries and regions, for the sub-periods 1997–2007 and 2007–2014. The dependent variable is the average annual growth rate of the efficiency factor resulting from the SDA ($\hat{\Theta}_{int}^{\omega,r}$), such that we account for the different lengths of the two sub-periods. Table 3 presents the DID regressions for the production-based energy inventory in five columns. In each regression, the performance of specific country-groups is contrasted against each other and against a base group before and after the implementation of the Directive. The base group is regression specific, it includes countries and regions that are not part of the country-groups that enter as dummies.

The first column presents the simplest specification, separating EU countries from all other countries (the base group). We regress the average annual growth rate of the efficiency factor on dummy variables for the period 2007–2014, for EU countries, and their interaction. Subsequently, in columns 2 and 3 we split EU countries and distinguish specific effects for EU15 and EEU countries, including their interactions with the 2007–2014 dummy. In columns 4 and 5, the model distinguishes the EU15, EEU, and other OECD countries from all remaining countries (the base group). This specification adds a dummy for the group of OECD countries and its interaction with the 2007–2014 dummy to test if the developments of the EU15 and EEU countries are different from those of other OECD countries. In columns 3 and 5, we exclude Switzerland, which is an outlier.¹³ The top panel in Table 3 reports the main output of the regressions. To facilitate the reading of the regression results, the middle panel shows the average annual growth rate of the efficiency factor of the corresponding country-groups for 1997–2007 (P1) and 2007–2014 (P2). The bottom panel displays a series of Wald tests for differences in the average annual growth rates of the efficiency factors across country-groups and/or periods. Had the EU Energy Services Directive an effect on the efficiency factor in EU countries that is not observed in non-EU countries, we would notice an accelerated reduction of the efficiency factor in the EU after 2007 above and beyond that of other countries—this would result in a statistically significant and negative coefficient of the EU–period interaction. If similar accelerations took place in other OECD countries, the difference between the EU–period and the OECD–period interactions would not be statistically significant.

¹³ We included sector energy intensity and GDP per capita (ppp-adjusted) at the beginning of the period as control variables, but both were statistically insignificant (see Table (C.10) in Appendix C.5). We also interacted GDP per capita with the period-dummy, but this interaction was also insignificant at conventional levels. Thus, we report the DID regressions without additional controls.

| Average annual growth rate of the energy efficiency factor for production | | | | | |
|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | (1) | (2) | (3) | (4) | (5) |
| Constant | -1.828*** (-3.574) | -1.828*** (-3.550) | -1.778*** (-3.399) | -2.360*** (-4.446) | -2.360*** (-4.444) |
| 2007–2014 | 2.566*** (3.159) | 2.566*** (3.138) | 2.084*** (2.959) | 3.196*** (4.228) | 3.196*** (4.227) |
| EU | -0.668 (-0.694) | | | | |
| EU · (2007–2014) | -2.162* (-1.743) | | | | |
| EU15 | | 0.888 (0.749) | 0.838 (0.704) | 1.419 (1.184) | 1.419 (1.183) |
| EU15 · (2007–2014) | | -3.806** (-2.540) | -3.324** (-2.309) | -4.435*** (-3.012) | -4.435*** (-3.011) |
| EEU | | -2.613** (-2.288) | -2.664** (-2.324) | -2.082* (-1.801) | -2.082* (-1.801) |
| EEU · (2007–2014) | | -0.107 (-0.074) | 0.375 (0.268) | -0.736 (-0.514) | -0.736 (-0.514) |
| R.o.OECD | | | | 2.415* (1.772) | 2.852** (2.032) |
| R.o.OECD · (2007–2014) | | | | -2.860 (-1.085) | -5.445*** (-3.306) |
| N | 154 | 154 | 152 | 154 | 152 |
| R ² | 0.109 | 0.142 | 0.140 | 0.163 | 0.200 |
| P1: base | -1.828 | -1.828 | -1.778 | -2.360 | -2.360 |
| P1: EU | -2.497 | | | | |
| P1: EU15 | | -0.940 | -0.940 | -0.940 | -0.940 |
| P1: EEU | | -4.442 | -4.442 | -4.442 | -4.442 |
| P1: R.o. OECD | | | | 0.055 | 0.492 |
| P2: base | 0.738 | 0.738 | 0.307 | 0.836 | 0.836 |
| P2: EU | -2.092 | | | | |
| P2: EU15 | | -2.180 | -2.180 | -2.180 | -2.180 |
| P2: EEU | | -1.983 | -1.983 | -1.983 | -1.983 |
| P2: R.o. OECD | | | | 0.391 | -1.757 |
| p-value: P1 EU15 – EEU | | 0.019 | 0.019 | 0.020 | 0.020 |
| p-value: P1 EU15 – OECD | | | | 0.548 | 0.397 |
| p-value: P1 EEU – OECD | | | | 0.006 | 0.003 |
| p-value: P2 base – EU | 0.000 | | | | |
| p-value: P2 base – EU15 | | 0.002 | 0.003 | 0.001 | 0.001 |
| p-value: P2 base – EEU | | 0.003 | 0.005 | 0.001 | 0.001 |
| p-value: P2 base – OECD | | | | 0.844 | 0.003 |
| p-value: P2 EU15 – EEU | | 0.831 | 0.831 | 0.832 | 0.832 |
| p-value: P2 EU15 – OECD | | | | 0.263 | 0.656 |
| p-value: P2 EEU – OECD | | | | 0.301 | 0.811 |
| p-value: P1-P2 base | 0.002 | 0.002 | 0.004 | 0.000 | 0.000 |
| p-value: P1-P2 EU | 0.667 | | | | |
| p-value: P1-P2 EU15 | | 0.325 | 0.325 | 0.328 | 0.329 |
| p-value: P1-P2 EEU | | 0.044 | 0.044 | 0.045 | 0.045 |
| p-value: P1-P2 OECD | | | | 0.894 | 0.127 |
| p-value: DID EU15 – EEU | | 0.035 | 0.036 | 0.037 | 0.037 |
| p-value: DID EU15 – OECD | | | | 0.578 | 0.603 |
| p-value: DID EEU – OECD | | | | 0.450 | 0.015 |

Table 3: Difference-in-differences regressions: energy efficiency factor—production

Note: t -statistics, based on robust standard errors, in parenthesis. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable measures the average annual percentage change in the energy efficiency factor from the SDA for production-based energy usage. R.o.OECD stands for the rest of the OECD aggregate. The panel below the R^2 reports the average annual percentage change in the energy efficiency factor for each of the country-groups and periods. $P1$ refers to the period 1997–2007, $P2$ to the period 2007–2014. *base* stands for the base-group (i.e. non-EU countries in regressions (1)–(3), non-EU non-OECD countries in regressions (4) and (5)). The bottom panel reports a series of Wald-tests for differences across country-groups and/or periods. *DID* stands for difference-in-differences and tests for differences in the interaction-terms (i.e. differences in changes from $P1$ to $P2$ across country-groups). Regressions (3) and (5) exclude Switzerland in both periods.

The results in column 1 point to a better performance of the EU relative to the base group after 2007. The efficiency factor decreases in EU countries before and after 2007, whereas in the base group (non-EU countries) it decreases before 2007 but increases afterward. The difference between the annual reductions in the EU countries (-2.50%) and the base group (-1.83%) is not statistically significant in the first period (1997–2007), but because of the different evolution of the efficiency factors between 2007 and 2014 (with annual growth rates of -2.09% in the EU countries and 0.74% in the base group), the differential increases to 2.83% and becomes statistically significant (p-value P2 base-EU).¹⁴ Therefore, the difference in the growth rates of the efficiency factor between EU countries and the base group increases from the first to the second period, as also indicated by the EU–period interaction, which is statistically significant at the 10% level.

The patterns found for the EU mainly concern the old EU15 members (see column 2) and indicate that the Directive may contribute to larger efficiency gains in the EU15 members but not in the EEU. Prior to 2007, the reductions in the efficiency factor in the EU15 are not significantly different from the base group of non-EU countries. These reductions in the EU15 accelerate after 2007, however, from -0.94% to -2.18% , such that the difference becomes significant in the second period (p-value P2 base-EU15). The EU15–period interaction is statistically significant, suggesting that the large efficiency gains in the EU15 across the two periods are not accompanied by similar developments in the base group. By contrast, in the EEU, the reductions in the efficiency factor are significantly stronger (-4.44%) than those in the base group before 2007. These reductions in the EEU slow down to -1.98% annually after 2007, but the differential to the base group remain statistically significant (p-value P2 base-EEU). The comparison between EU15 and EEU countries shows that improvements in energy efficiency are significantly larger in the EEU before 2007 (p-value P1 EU15-EEU) but are not statistically different across the groups after 2007 (p-value P2 EU15-EEU). These results are robust to the exclusion of Switzerland from the regression (column 3).

The different dynamics of the EU15 and the EEU detected finds its underpinning in the different implementation of the Directive by the member states (see EC, 2014). Of the national Energy Efficiency Action Plans (EEAPs) submitted for the first reporting period of Directive in 2007, the European Commission considers only eight of them as being ambitious. Only one of these ambitious EEAPs belongs to an EEU country, Slovenia. The rest of EEAPs are considered as business-as-usual scenarios. From the second reporting

¹⁴ The average annual growth rate in the second period for non-EU countries (the base group) is the sum of the constant and the coefficient of the period dummy. For EU-countries, the growth rate is calculated by adding to this the coefficients of the EU- and the EU–period dummy. These values are reported in the middle panel of Table 3. The p-value for the difference between the growth rates is based on a Wald test reported in the lower panel.

round in 2011, the Commission adds Poland and Cyprus to the group of ambitious EEAPs, while ten of the EU15 countries are included in that group.

The larger rates of decrease of the efficiency factor in the EU15 after 2007 can reflect a general trend of high-income countries, e.g. from CO₂ emission reduction programs implemented in the first commitment period of the Kyoto Protocol. All EU countries and most OECD countries, as part of Annex B to the Kyoto Protocol, face binding CO₂ emission targets. Improving energy efficiency may be a strategy to reach these targets common to these countries. Thus, we test whether the developments in the EU15 are different from developments in other OECD countries (column 4). We segregate the remaining OECD countries from the countries in the base group. The new base group shows the same patterns as in the previous regressions: the efficiency factor decreases before 2007 but increases afterward. However, the group of other OECD countries presents a different pattern. It experiences an increase in the efficiency factor in both periods (0.06% and 0.39%). Yet, the differential between the OECD and the EU15 is not statistically significant for any of the periods (p-values P1 EU15-OECD and P2 EU15-OECD). From 1997–2007, the differences between the EEU and these two groups are significant (p-values P1 EU15-EEU and P1 EEU-OECD), whereas from 2007–2014 they are not (p-values P2 EU15-EEU, and P2 EEU-OECD). Also, the differential between the EU15 or the EEU and the other OECD countries remain statistically similar across the two periods (p-values DID EU15-OECD and DID EEU-OECD).

This similarity in the developments in EU15 and other OECD countries is robust to the exclusion of Switzerland (column 5). Notably, some patterns change for the OECD group, however. The stronger decrease of the efficiency factors of both the OECD and the EU15 after 2007 compared to the period before is significantly different from the developments in the EEU (p-value DID EEU-OECD and DID EU15-EEU) and the base group (significant group–period interactions). The difference between the EU15 and other OECD countries is not significant, similar to before (p-value DID EU15-OECD).

Although the EU Energy Services Directive does not target footprint-based energy measures, it can impact on the energy intensity of suppliers of intermediates indirectly through two main channels. First, the Directive may induce a re-direction of domestic production towards sectors with lower energy usage and increase the demand for imports of energy-intensive products or from energy-intensive countries, increasing the energy intensity of final production and consumption relative to territorial production. Second, potential technological improvements in domestic production processes in EU countries may spill over to suppliers of intermediates (see Mandel et al., 2020, on the contribution of technological diffusion to climate change mitigation). In this case, the energy intensity of final production and consumption would decrease. Nevertheless, the difference between the

results for footprint-based energy intensity and for production-based energy intensity may be relatively small, as a large part of domestic production ends up in domestic consumption (see, e.g. Fernández-Amador et al., 2016), and because a large share of trade occurs between the EU members, all affected by the Directive.

| | P1 (1997–2007) | P2 (2007–2014) | Difference (P2–P1) |
|--|----------------|----------------|--------------------|
| <i>Production-based energy efficiency factor</i> | | | |
| Base | -2.360 | 0.836 | 3.196 |
| EEU | -4.442 | -1.983 | 2.459 |
| EU15 | -0.940 | -2.180 | -1.240 |
| R.o.OECD | 0.492 | -1.757 | -2.249 |
| <i>Final production-based energy efficiency factor</i> | | | |
| Base | -2.585 | 0.608 | 3.193 |
| EEU | -4.464 | -1.296 | 3.168 |
| EU15 | -2.110 | -1.641 | 0.469 |
| R.o.OECD | -1.221 | -1.529 | -0.308 |
| <i>Consumption-based energy efficiency factor</i> | | | |
| Base | -2.518 | 0.577 | 3.095 |
| EEU | -4.171 | -1.153 | 3.018 |
| EU15 | -2.155 | -1.465 | 0.690 |
| R.o.OECD | -1.312 | -1.413 | -0.101 |

Table 4: Comparison of production- and footprint-based results

Note: Results from the difference-in-differences regressions analyzing the average annual percentage change in the efficiency factor from the SDA for the respective energy inventory (production, final production or consumption). The numbers show the average annual percentage change in the energy efficiency factor for each of the country-groups, periods, and energy inventories. *Base* stands for the base-group of non-EU non-OECD countries, *R.o.OECD* stands for the rest of the OECD aggregate. The detailed DID results including Wald-tests for significant differences across country-groups and periods are reported in Tables 3, C.11, and C.12 for production, final production, and consumption-based energy intensity, respectively. The numbers reported here refer to the model specification in column (5) of the DID regression tables: The regressions exclude Switzerland in both periods.

For the footprint inventories, the differences in the efficiency factor across country-groups are less pronounced than for the production-based inventory (see Table 4, which compares the results for production- and footprint-based inventories. See Tables C.11 and C.12 in Appendix C.5.1 for details of the DID specifications for footprints). The estimates for the footprint inventories reflect the different patterns of sourcing of intermediates. Before 2007, the EU15 and the group of other OECD countries show larger efficiency gains in footprint-based than in production-based inventories, because of their large shares of energy embodied in intermediates from the EEU and the base group (non-EU non-OECD countries), which present stronger improvements in production-based energy efficiency. Notably, although the footprint-based efficiency factor decreases in the other OECD countries, their production-based efficiency factor increases, leaving the energy-efficiency improvements

of suppliers of embodied intermediates as the source of the observed footprint-efficiency gains. After 2007, the gains in production-based efficiency slow down in EEU countries and reverse in the base group, while they accelerate in EU15 and other OECD countries. Consequently, in this period the energy-efficiency of footprints in EU15 and OECD countries improves less than production-based energy efficiency.

The comparison of the efficiency gains between footprint- and production-based inventories suggests that the EU15 relies more heavily on imports of energy-intensive embodied intermediates than the rest of OECD group after 2007. This is apparent from the larger difference between production-based and footprint-based efficiency gains in the EU15 relative to the OECD in that period. While the reductions in the efficiency factor for production-based inventories in the EU15 and the OECD (excluding Switzerland) are larger after 2007, for footprint inventories this is the case only in the OECD (see difference P2–P1). Nevertheless, the footprint-based efficiency gains are slightly larger in the EU15 than in the EEU and the rest of the OECD after 2007 (the difference being statistically insignificant).

Despite the quantitative differences across the energy inventories, there are some qualitative similarities between footprint-based and production-based estimates. First, the footprint-based efficiency factor increases after 2007 in the base group, such that the relative performance of both the OECD and the EU15 compared to the base-group improves after 2007 also for footprint inventories (significant interaction terms). Second, the differences between EU15 and other OECD countries are not statistically significant in any period. Third, EEU countries show faster improvements in the footprint-based efficiency factor than EU15 and OECD countries before 2007 but not afterward (see Tables C.11 and C.12 for details).

All in all, EU15 and OECD countries experience stronger efficiency gains in production-based energy inventories after 2007 as compared to before. Yet, the estimated dynamics of production- and footprint-based estimates indicate a shift of energy-intensive production from EU15 and OECD countries towards countries in the EEU and non-EU, non-OECD countries. Given the analogous dynamics estimated for EU15 and OECD countries, it is unlikely that the EU Energy Services Directive constitute an idiosyncratic pattern but rather is part of a common trend of increasing energy efficiency in high-income countries which may be related to the Kyoto Protocol implementation.

Finally, the analysis in Section 3 suggests that the EU's switch from fossil fuels towards wind and solar energy is faster than in other regions. We run DID regressions using the average annual change in the share of the seven energy commodities in the energy mix

| | non-renewable | | | renewable | | | |
|------------------------|-----------------------|--------------------|---------------------|---------------------|---------------------|---------------------|----------------------|
| | fossil | nuclear | other n-ren | hydro | wind | solar | other ren |
| Constant | 0.213** (2.182) | -0.008 (-0.618) | 0.003* (1.838) | 0.031 (0.578) | 0.002** (2.577) | 0.003 (1.447) | -0.243** (-2.574) |
| 2007–2014 | -0.065 (-0.414) | 0.016 (1.209) | 0.000 (0.153) | -0.039 (-0.497) | 0.016** (2.447) | 0.005 (1.478) | 0.065 (0.411) |
| EU15 | -0.458*** (-3.627) | -0.050 (-1.220) | 0.028*** (2.709) | -0.070 (-1.265) | 0.068*** (3.712) | 0.004 (1.377) | 0.479*** (4.425) |
| EU15 · (2007–2014) | -0.501** (-2.315) | 0.053 (0.572) | 0.016 (1.145) | 0.142* (1.692) | 0.089* (1.953) | 0.076*** (3.221) | 0.125 (0.674) |
| EEU | -0.406** (-2.512) | 0.085 (0.756) | -0.006 (-0.432) | -0.054 (-0.959) | 0.003* (1.863) | -0.002 (-1.161) | 0.380*** (3.353) |
| EEU · (2007–2014) | -0.668 (-1.442) | -0.133 (-0.359) | 0.076** (2.466) | 0.234* (1.659) | 0.050** (2.341) | 0.032*** (2.741) | 0.410** (2.104) |
| R.o.OECD | -0.219 (-1.517) | 0.029 (0.520) | 0.012 (1.291) | -0.111* (-1.770) | 0.009** (2.043) | 0.001 (0.289) | 0.279** (2.291) |
| R.o.OECD · (2007–2014) | -0.053 (-0.188) | -0.240 (-1.303) | -0.002 (-0.154) | 0.121 (1.324) | 0.026* (1.940) | 0.021** (2.517) | 0.126 (0.572) |
| N | 152 | 152 | 152 | 152 | 152 | 152 | 152 |
| R ² | 0.243 | 0.025 | 0.290 | 0.044 | 0.415 | 0.391 | 0.218 |
| P1: base | 0.213 | -0.008 | 0.003 | 0.031 | 0.002 | 0.003 | -0.243 |
| P1: EU15 | -0.245 | -0.059 | 0.031 | -0.039 | 0.069 | 0.006 | 0.236 |
| P1: EEU | -0.193 | 0.077 | -0.002 | -0.024 | 0.005 | 0.000 | 0.137 |
| P1: R.o.OECD | -0.007 | 0.021 | 0.015 | -0.080 | 0.011 | 0.003 | 0.036 |
| P2: base | 0.148 | 0.008 | 0.003 | -0.008 | 0.018 | 0.007 | -0.177 |
| P2: EU15 | -0.811 | 0.011 | 0.047 | 0.065 | 0.175 | 0.087 | 0.426 |
| P2: EEU | -0.926 | -0.040 | 0.074 | 0.171 | 0.071 | 0.038 | 0.612 |
| P2: R.o.OECD | -0.124 | -0.203 | 0.014 | 0.002 | 0.053 | 0.029 | 0.228 |
| p-value: P1: EU15–EEU | 0.734 | 0.254 | 0.043 | 0.524 | 0.001 | 0.003 | 0.230 |
| p-value: P1: EU15–OECD | 0.076 | 0.236 | 0.261 | 0.257 | 0.002 | 0.275 | 0.035 |
| p-value: P1: EEU–OECD | 0.266 | 0.651 | 0.263 | 0.142 | 0.216 | 0.119 | 0.313 |
| p-value: P2: base–EU15 | 0.000 | 0.976 | 0.000 | 0.255 | 0.000 | 0.001 | 0.000 |
| p-value: P2: base–EEU | 0.015 | 0.891 | 0.013 | 0.166 | 0.013 | 0.010 | 0.000 |
| p-value: P2: base–OECD | 0.259 | 0.231 | 0.255 | 0.876 | 0.006 | 0.007 | 0.030 |
| p-value: P2: EU15–EEU | 0.791 | 0.889 | 0.367 | 0.371 | 0.026 | 0.060 | 0.134 |
| p-value: P2: EU15–OECD | 0.005 | 0.273 | 0.010 | 0.172 | 0.005 | 0.020 | 0.203 |
| p-value: P2: EEU–OECD | 0.087 | 0.680 | 0.042 | 0.165 | 0.424 | 0.544 | 0.020 |
| p-value: P1–P2 base | 0.680 | 0.229 | 0.878 | 0.620 | 0.016 | 0.141 | 0.682 |
| p-value: P1–P2 EU15 | 0.000 | 0.451 | 0.238 | 0.001 | 0.021 | 0.001 | 0.049 |
| p-value: P1–P2 EEU | 0.095 | 0.753 | 0.014 | 0.099 | 0.001 | 0.001 | 0.000 |
| p-value: P1–P2 OECD | 0.615 | 0.225 | 0.897 | 0.090 | 0.000 | 0.001 | 0.215 |
| p-value: DID EU15–EEU | 0.718 | 0.626 | 0.076 | 0.453 | 0.428 | 0.096 | 0.057 |
| p-value: DID EU15–OECD | 0.107 | 0.156 | 0.343 | 0.718 | 0.175 | 0.028 | 0.994 |
| p-value: DID EEU–OECD | 0.215 | 0.796 | 0.021 | 0.378 | 0.300 | 0.421 | 0.139 |

Table 5: Difference-in-differences regressions: energy mix of production

Note: t -statistics, based on robust standard errors, in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *other n-ren* and *other ren* stand for the group of other non-renewable energy commodities, and other renewable energy commodities, respectively. The dependent variables measure the average annual change in the share (expressed in percent) of the respective energy commodity in the total energy mix. The panel below the R^2 reports the average annual change in the share of the energy commodity for each of the country-groups and periods. $P1$ refers to the period 1997–2007, $P2$ to the period 2007–2014. *base* stands for the base-group of non-EU non-OECD countries. The bottom panel reports a series of Wald-tests for differences across country-groups and/or periods. *DID* stands for difference-in-differences and tests for differences in the interaction-terms (i.e. differences in changes from $P1$ to $P2$ across country-groups). Cyprus is excluded from the regressions.

as dependent variables.¹⁵ The regressions for production-based energy usage, reported in Table 5, point to a reduction in the share of fossil fuels that accelerated after 2007 in the EU15 and the EEU, and a faster increase after 2007 in the shares of all four renewable energy categories in these countries. The shares of hydro-, wind-, and solar energy also increase in other OECD countries after 2007 (see p-values P1-P2). The shares of many renewable commodities increase significantly stronger in the EU after 2007 when compared to the base group (significant interactions). However, when compared to OECD countries they increase significantly stronger only in the EU15 for solar energy (p-value DID EU15-OECD). The faster reduction of the share of fossil fuels in the EU15 after 2007 is similar to the rest of the OECD (the differential is marginally insignificant, see p-value DID EU15-OECD). The EEU experience an increase of the share of other non-renewable energy after 2007 that is faster than that of the OECD (p-value DID EEU-OECD). For the energy mix of footprint inventories, our findings are qualitatively similar to the ones described for the production-based energy mix (see Tables C.13 and C.14 in Appendix C).

5 Conclusion

The new dataset put forward in this paper shows that high-income regions are net-importers of embodied energy and that their net-imports increase between 1997 and 2014, with few exceptions. Compared with developing economies, high-income regions use a larger share of non-renewable energy, but this share decreases over time following the decline of fossil fuels in high-income regions. Across countries, the shares of the different energy commodities in the energy mix are more similar from a footprint perspective, highlighting the role of international trade and global supply chains. Notably, the patterns found for embodied energy inventories provide underpinnings to the results of the literature on CO₂ emissions (see e.g. Aichele and Felbermayr, 2012, 2015; Fernández-Amador et al., 2016), since the bulk of these emissions relates to fossil fuel combustion.

Energy usage in the EU shows some peculiarities which are not present in other high-income regions. The EU's energy usage for production declines between 1997 and 2014, while its energy footprints from final production and consumption increase. Also, the EU experiences a strong reduction in fossil energy and a rapid expansion of wind and solar energy used for production. Our results indicate that the EU's Energy Services Directive (2006/32/EC) may have triggered policies that lead to stronger energy efficiency gains in production, but not in final production and consumption, in the EU15 after 2007.

¹⁵ An outlier, Cyprus, is excluded from the regression: Cyprus reports an energy usage from fossil fuels of about 1.1 *mtoe* in 1997, which drops to 0.03 *mtoe* in 2007. The usage of renewable energy increases over that period. This results in a huge increase in the share of renewable energy in the energy mix.

The effectiveness of the Directive is mixed. It differs between EU15 and EEU member states. EU15 countries show accelerated efficiency improvements in production after 2007, whereas the newer EEU members realize important energy efficiency gains before 2007 but only limited gains afterward. The different ambition between the national EEAPs of the EU15 and EEU countries and some complementarity in supply chains seem to underlie the different dynamics of energy efficiency found between EU15 and EEU member states.

The developments of energy efficiency and changes in the energy mix observed in other OECD countries are similar to those of the EU15. The efficiency of territorial production energy usage of EU15 and OECD countries relative to non-high-income countries increases after 2007. Also, the shift towards renewable energy sources for production- and footprint-based energy inventories seen in the EU15 and the EEU after 2007 is shared by other OECD countries, although to a smaller extent for solar energy. Overall, gains in energy efficiency and changes the mix of energy sources are common to high-income countries and not a specific trend of EU members. The EU Energy Services Directive does not determine a specific EU trend but rather seems part of a trend common to other high-income countries.

Our results are consistent with the existence of energy leakage. The EU15 and other OECD countries experience a shift toward more energy-intensive imports from non-high-income countries after 2007, and their better efficiency for territorial-production energy usage, relative to non-high-income countries, does not extend to footprint inventories. EU15 members reduce their energy usage for production from 1997–2014, because improvements in energy efficiency are coupled with compositional changes towards the production of less energy intensive intermediates and/or a reduction of the volume of intermediates produced. However, despite the gains in energy efficiency, changes supply chains contribute to larger footprints of energy embodied in final production and consumption. These supply chain changes point to a larger reliance on relatively energy-intensive imports and reduce the efficiency improvements of energy footprints in the EU15 after 2007. Although energy regulation has the potential to reduce domestic energy usage for territorial production, it is less effective in reducing energy footprints, which account for the energy used in the production of imports accruing final production and consumption. Energy regulation should account for global supply chains and target energy footprints. The identification of the existence and the degree of energy leakage and the evaluation of alternatives to make energy policy robust to it deserve further research.

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A Data appendix

| IEA Commodity | IEA Code | Energy Type | |
|--|-------------|----------------------|------------------------|
| Anthracite | ANTCOAL | Primary Fossil Fuels | |
| Coking Coal | COKCOAL | | |
| Other Bituminous Coal | BITCOAL | | |
| Sub-Bituminous Coal | SUBCOAL | | |
| Lignite | LIGNITE | | |
| Peat | PEAT | | |
| Oil Shale and Oil Sands | OILSHALE | | |
| Natural Gas | NATGAS | | |
| Crude, nat. gas liquids and feedstocks | CRNGFEED | | |
| Crude Oil | CRUDEOIL | | |
| Natural Gas Liquids | NGL | | |
| Patent Fuel | PATFUEL | | Processed Fossil Fuels |
| Brown Coal Briquettes | BKB | | |
| Peat Products | PEATPROD | | |
| Refinery Feedstocks | REFFEEDS | | |
| Additives and Blending Components | ADDITIVE | | |
| Other Hydrocarbons | NONCRUDE | | |
| Coke Oven Coke | OVENCOKE | | |
| Gas Coke | GASCOKE | | |
| Coal Tar | COALTAR | | |
| Coke Oven Gas | COKEOVGS | | |
| Gas Works Gas | GASWKSGS | | |
| Blast Furnace Gas | BLFURGS | | |
| Other Recovered Gases | OGASES | | |
| Refinery Gas | REFINGAS | | |
| Ethane | ETHANE | | |
| Liquefied Petroleum Gases | LPG | | |
| Motor Gasolines excl. Biofuels | NONBIOGASOL | | |
| Aviation Gasoline | AVGAS | | |
| Gasoline Type Jet Fuel | JETGAS | | |
| Kerosene Type Jet Fuel excl. Biofuels | NONBIOJETK | | |
| Other Kerosene | OTHKERO | | |
| Gas Diesel Oil excl. Biofuels | NONBIODIES | | |
| Fuel Oil | RESFUEL | | |
| Naphtha | NAPHTA | | |
| White Spirit | WHITESP | | |
| Lubricants | LUBRIC | | |
| Bitumen | BITUMEN | | |
| Paraffin Waxes | PARWAX | | |
| Petroleum Coke | PETCOKE | | |
| Other Oil Products | ONONSPEC | | |
| Elec/Heat Output from non-Specified | MANGAS | | |
| Manufactured Gases | | | |

Table A.1: IEA energy commodities matched to broad energy types. The table denotes all of the 62 energy commodities included in the 2018 edition of the IEA extended energy balances and their allocation to the final energy commodities of our database.

| IEA Commodity | IEA Code | Energy Type |
|-------------------------------|-----------------|----------------------------|
| Nuclear | NUCLEAR | Nuclear Energy |
| Hydro | HYDRO | Hydro Energy |
| Solar Photovoltaics | SOLARPV | Solar Energy |
| Solar Thermal | SOLARTH | |
| Wind | WIND | Wind Energy |
| Biogasoline | BIOGASOL | Other Renewable Energy |
| Biodiesels | BIODIESEL | |
| Bio Jet Kerosene | BIOJETKERO | |
| Other Liquid Biofuels | OBIOLIQ | |
| Municipal Waste Renewable | MUNWASTER | |
| Primary Solid Biofuels | PRIMSBIO | |
| Biogases | BIOGASES | |
| Geothermal | GEO THERM | |
| Tide Wave and Ocean | TIDE | |
| Charcoal | CHARCOAL | |
| Industrial Waste | INDWASTE | Other non-Renewable Energy |
| Municipal Waste non-Renewable | MUNWASTEN | |
| Other Resources | OTHER | |
| Gross Electricity Production | ELECTR | Heat and Electricity |
| Heat | HEAT | |

Table A.1: – continued.

| IEA Flow | IEA Code | Sector Name | Sector Code |
|--|------------------------|--------------------------|-------------|
| <i>IEA flows associated with transformation to electricity:</i> | | | |
| Main activity producer electricity plants | MAINELEC | Electricity | ely |
| Autoproducer electricity plants | AUTOELEC ^a | | |
| Main activity producer CHP plants | MAINCHP | | |
| Autoproducer CHP plants | AUTOCHP ^a | | |
| Main activity producer heat plants | MAINHEAT | | |
| Autoproducer heat plants | AUTOHEAT ^a | | |
| Heat pumps | HEAT | | |
| Electric boilers | BOILER | | |
| Chemical heat for electricity production | ELE | | |
| <i>IEA flows associated to transformation activities not related to electricity:</i> | | | |
| Gas works | TGASWKS | Gas Distribution | gdt |
| For blended natural gas | BLENDGAS | | |
| Charcoal production plants | TCHARCOAL | Electricity | ely |
| Patent fuel plants | TPATFUEL | | |
| BKB/peat briquette plants | BKB | | |
| Oil refineries | TREFINER | | |
| Coal liquefaction plants | TCOALLIQ | | |
| Gas-to-liquids (GTL) plants | TGTL | | |
| Blast furnaces | TBLASTFUR ^b | Iron & Steel | i_s |
| Coke ovens | TCOKEOVS ^b | | |
| Petrochemical plants | TPETCHEM | Chemical Rubber Products | crp |
| <i>IEA flows associated to energy usage by the energy sector itself:</i> | | | |
| Coal mines | MINES | Coal | coa |
| Gas works | GASWKS | Gas Distribution | gdt |
| Liquefaction (LNG) / regasification plants | LNG | | |
| Pumped storage plants | PUMPST | Electricity | ely |
| Charcoal production plants | CHARCOAL | | |
| Gasification plants for biogases | BIOGAS | Other Ser. (Government) | osg |
| Blast furnaces | BLASTFUR | Iron & Steel | i_s |
| Coke ovens | COKEOVS | | |
| Patent fuel plants | PATFUEL | Petroleum & Coke | p-c |
| BKB/peat briquette plants | BKB | | |
| Oil refineries | REFINER | | |
| Coal liquefaction plants | COALLIQ | | |
| Gas-to-liquids (GTL) plants | GTL | | |
| Own use in electricity, CHP and heat plants | POWERPLT | | |
| Nuclear industry | NUC | | |

Table A.2: Energy flows from the IEA Extended World Energy Balances matched to a single sector.

| IEA Flow | IEA Code | Sector Name | Sector Code |
|---|-----------------|--------------------------------|--------------------|
| <i>IEA flows associated to industrial activities matched to a single economic sector:</i> | | | |
| Iron and steel | IRONSTL | Iron & Steel | i_s |
| Chemical and petrochemical | CHEMICAL | Chemical Rubber Products | crp |
| Non-ferrous metals | NONFERR | Non-Ferrous Metals | nfm |
| Non-metallic minerals | NONMET | Non-Metallic Minerals | nmm |
| Transport equipment | TRANSEQ | Motor Motor vehicles and parts | mvh |
| Transport equipment | TRANSEQ | Other Transport Equipment | otn |
| Machinery | MACHINE | Other Machinery & Equipment | ome |
| Mining and quarrying | MINING | Other Mining | omn |
| Paper, pulp and print | PAPERPRO | Paper & Paper Products | ppp |
| Wood and wood products | WOODPRO | Lumber | lum |
| Construction | CONSTRUC | Construction | cns |
| <i>Other IEA flows that can be matched to a single economic sector:</i> | | | |
| Transfers | TRANSFER | Petroleum & Coke | p-c |
| Fishing | FISHING | Fishing | fsh |
| Residential | RESIDENT | Private Households | HH |
| <i>IEA flows associated to transport activities:</i> | | | |
| Domestic aviation | DOMESAIR | Air transport | atp |
| World aviation bunkers | WORLDAV | | |
| Rail | RAIL | Other Transport | otp |
| Pipeline transport | PIPELINE | | |
| Non-specified (transport) | TRNONSPE | | |
| World marine bunkers | WORLDMAR | Water Transport | wtp |
| Domestic navigation | DOMESNAV | | |

Table A.2: – continued.

| IEA Flow | IEA Code | Sector Name | Sector Code | | |
|--|----------|--------------------------------|-------------|-----------------|-----|
| <i>IEA flows related to industrial activities matched to several economic sectors:</i> | | | | | |
| Oil and gas extraction | OILGASEX | Oil | oil | | |
| | | Gas | gas | | |
| Agriculture and forestry | AGRICULT | Paddy Rice | pdr | | |
| | | Wheat | wht | | |
| | | Other Grains | gro | | |
| | | Vegetables and Fruits | v_f | | |
| | | Oil Seeds | osd | | |
| | | Cane and Beet | c_b | | |
| | | Plant Fibres | pfb | | |
| | | Other Crops | ocr | | |
| | | Cattle | ctl | | |
| | | Other Animal Products | oap | | |
| | | Raw Milk | rmk | | |
| | | Wool | wol | | |
| | | Forestry | frs | | |
| | | Food and tobacco | FOODPRO | Cattle Meat | cmt |
| Other Meat | omt | | | | |
| Vegetable Oils | vol | | | | |
| Milk Products | mil | | | | |
| Processed Rice | pcr | | | | |
| Sugar | sgr | | | | |
| Other Food | ofd | | | | |
| Beverages and Tobacco products | b.t | | | | |
| Textile and leather | TEXTILES | | | Textiles | tex |
| | | | | Wearing Apparel | wap |
| | | Leather | lea | | |
| Machinery | MACHINE | Other Machinery & Equipment | ome | | |
| | | Fabricated Metal Products | fmp | | |
| | | Electronic Equipment | ele | | |
| Transport Equipment | TRANSEQ | Motor Vehicles and Parts | mvh | | |
| | | Other Transport Equipment | otn | | |
| Non-specified industry | INONSPEC | Other Machinery & Equipment | ome | | |
| | | Other Manufacturing | omf | | |
| | | Electronic Equipment | ele | | |
| Commercial and public services | COMMPUB | Communications | cmn | | |
| | | Other Financial Intermediation | ofi | | |
| | | Insurance | isr | | |
| | | Other Business Services | obs | | |
| | | Recreation & Other Services | ros | | |
| | | Other Ser. (Government) | osg | | |
| | | Dwellings | dwe | | |
| | | Road | ROAD | Other Transport | otp |
| Private Households ^a | HH | | | | |

Table A.3: Energy flows from the IEA data that have to be matched to more than one economic sector. Note: ^a The ROAD activity includes also the usage of gasoline and diesel, including their renewable derivatives. Some of them is used by non-residents such that this flow item had to be bridged from the territorial to the residency principle as discussed in the main text.

| Aggregate | Countries and regions included |
|--------------------------------------|---|
| <i>Single Countries and Regions:</i> | |
| The 66 single countries and regions | Albania, Argentina, Australia, Austria, Belgium, Bangladesh, Bulgaria, Brazil, Botswana, Canada, Chile, China, Colombia, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Malawi, Malaysia, Malta, Mexico, Morocco, Mozambique, Netherlands, New Zealand, Peru, Philippines, Poland, Portugal, Romania, Russia, Singapore, Slovakia, Slovenia, Spain, Sri Lanka, Sweden, Switzerland, Taiwan, Tanzania, Thailand, Turkey, Uganda, United Kingdom, United States, Uruguay, Venezuela, Vietnam, Zambia and Zimbabwe. |
| <i>The 12 Composite Regions:</i> | |
| Rest of Andean Pact | Bolivia and Ecuador |
| Central America, Caribbean | Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Montserrat, Netherl. Antilles, Nicaragua, Panama, Puerto Rico, Saint Helena, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, British Virgin Islands, US Virgin Islands. |
| Rest of EFTA | Iceland, Liechtenstein and Norway. |
| Rest of Former Soviet Union | Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan. |
| Middle East | Bahrain, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates and Yemen. |
| Rest of North Africa | Algeria, Egypt, Libya and Tunisia. |
| Other Southern Africa | Angola and Congo (DPR). |
| Rest of South African Customs Union | Lesotho, Namibia, South Africa and Swaziland. |
| Rest of South America | Guyana, Paraguay and Suriname. |
| Rest of South Asia | Bhutan, Maldives, Nepal and Pakistan. |
| Rest of Sub-Saharan Africa | Benin, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Mali, Mauritania, Mauritius, Mayotte, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan and Togo. |
| Rest of World | Antarctica, Afghanistan, American Samoa, Andorra, British Indian Ocean territory, Bosnia and Herzegovina, Bouvet Island, Brunei Darussalam, Cambodia, Macao SAR, Cook Islands, Democratic People's Republic of Korea, Falkland Islands (Malvinas), Faroe Islands, Fiji, French Guyana, French Polynesia, French Southern Territories, Gibraltar, Greenland, Guam, Guernsey, Holy See, Isle of Man, Jersey, Kiribati, Lao People's Democratic Republic, Marshall Islands, Micronesia (Federated States of), Monaco, Mongolia, Montenegro, Myanmar, Nauru, New Caledonia, Niue, Norfolk Island, Northern Mariana Islands, Occupied Palestinian Territory, Palau, Papua New Guinea, Pitcairn, Saint Pierre and Miquelon, Samoa, San Marino, Serbia, Solomon Islands, South Georgia and the South Sandwich Islands, The former Yugoslav Republic of Macedonia, Timor-Leste, Tokelau, Tonga, Tuvalu, US Minor Outlying Islands, Vanuatu, Western Sahara and Wallis and Futuna Islands. |

Table A.4: Countries and composite regions in the database. Note: Computations were performed using the regional aggregation of GTAP 5. The table shows also countries which appear in later GTAP databases, which are, however, too small to change results. They are mainly small islands states or territories belonging to the jurisdiction of another country, which show up in one of the later composite regions (Wallis and Futuna, or Jersey for example). The only notable exceptions are Timor-Leste and Greenland.

| Aggregate | Countries and regions included |
|--|---|
| <i>Countries that are part of an aggregate region in IEA data:</i> | |
| France | Monaco* |
| Italy | San Marino |
| Other non-OECD Asia | Cook Islands, Fiji, French Polynesia, Kiribati, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga , Vanuatu, Macau (SAR), Lao People's Democratic Republic, Timor-Leste, Afghanistan, Bhutan, Maldives. |
| Other non-OECD America | Guyana, Belize, Puerto Rico, Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Dominica, Grenada, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Turks and Caicos Islands, Bermuda. |
| Europe | Liechtenstein, Andorra, Occupied Palestinian Territory. |
| <i>GTAP countries that have been discarded</i> | |
| Discarded | American Samoa, Niue, Pitcairn, US Minor Outlying Islands, Saint Pierre and Miquelon, French Guyana, Netherl. Antilles, Faroe Islands, Holy See, Jersey, Saint Helena, Antarctica, British Indian Ocean Territory, Guam, Northern Mariana Islands, Tokelau, Wallis and Futuna, Falkland Islands (Malvinas), South Georgia and the South Sandwich Islands, US Virgin Islands Guernsey, Isle of Man, Western Sahara, Mayotte, Bouvet Island, French Southern Territories, Micronesia (Federated States of). |

* The usage of nuclear energy was not splitted between France and Monaco according to their GDP shares because Monaco does not run a nuclear program.

Table A.5: Imputed and discarded GTAP countries and regions.

B Methodological appendix

B.1 Methodology to construct territorial production data

In this appendix we discuss in detail all the steps required for the construction of the production-based national energy inventories. First, we match the usage of the different energy commodities in the countries and regions of our database, distinguished by the economic activities as captured in the IEA extended energy balances (“flows” in IEA terms), to the final economic sectors and private households in our database. We then bridge the purely territorial system boundary of the IEA data to the residential principle underlying the multi-region input-output (MRIO) tables underlying the construction of the energy footprints. This last step ensures the comparability of our standard production and footprint inventories.

B.1.1 Matching the IEA flows to 57 sectors and private HH

The matching-process of the first step follows the International Standard Industrial Classification (ISIC) of the United Nations (see UN, 2008). We had to deviate from a strict application of the ISIC classification in some cases due to lack of information, problematic conventions or known misreporting in the IEA data. Most importantly, this was necessary for the treatment of combined heat and and power plants, electricity and heat production by industrial plants outside the electricity sector (“autoproducers”) and the potential double counting of coal usage by coke ovens and blast furnaces in the IEA data. We refer to McDougall and Lee (2006) and Genty et al. (2012) for related discussions. Also, in the case of pure transformation processes, such as the usage of fossil fuels by the petroleum and coke industry it requires to produce petroleum products, the IEA data tracks the inflow as well as the outflow of energy commodities. Those outflows, however, become an inflow again in industries further downstream in the economy. Thus, in order to avoid double counting, we disregard the outflow of energy commodities in industries.

In some cases the sectors in our final dataset are more disaggregated than the economic activities in the IEA data, see also Table (A.3) in Appendix A. We split the usage of all 62 energy energy commodities used by the economic flows in Table (A.3) to the more disaggregated sectors in our final database as follows. First, each of the 62 commodities is linked to the sector in our database which predominantly produces this commodity. For example, the coal-based energy commodities, such as anthracite, are matched to the coal extraction sector (“coa”). This matching process is documented in Table (B.1) and

is informed by ISIC classifications.¹⁶ Second, from our input-output tables we observe the purchases of each of the detailed sectors in Table (A.3) from the energy commodity producing sectors in Table (B.1) in monetary terms. For each energy commodity we then split the IEA energy flows in (A.3) to the more detailed sectors in proportion to the intermediate purchases by the detailed sectors it is disaggregated to.¹⁷

¹⁶ We deviated from a strict application of ISIC in if the overall sales pattern of a sector is not representative for the sales of an energy commodity it produces. Specifically, following ISIC the production of bio-fuels should be allocated to the chemical sector (“crp” in our data) in Table (B.1). Bio-fuels, however, are only a tiny fraction of the sectors’s overall production of intermediates such that its sales of intermediates cannot be considered to be representative for the sales-patterns of bio-fuels. Thus, we match bio-fuels to petroleum and coke (“p_c”) sector, which also produces gasolines and diesels that show a similar sales pattern as bio-fuels. We refer to Genty et al. (2012) for a related discussion.

¹⁷ For example, let’s look at the usage of anthracite by the “textile and leather” (TEXTILES) flow which has to be split to textiles (“tex”), wearing apparel (“wap”), and leather (“lea”) sectors in our data. Assume now that each of these three sectors accounts for a third of total intermediates purchased from the coal extraction (coa) sector. Then one third of the total anthracite used by “textile and leather” is allocated to each of the three sectors.

| IEA Commodity | IEA Code | Sector Name | Sector Code |
|---|-------------|------------------|-------------|
| <i>Correspondence of IEA energy products to economic sectors:</i> | | | |
| Anthracite | ANTCOAL | Coal | coa |
| Coking Coal | COKCOAL | | |
| Other Bituminous Coal | BITCOAL | | |
| Sub-Bituminous Coal | SUBCOAL | | |
| Lignite | LIGNITE | | |
| Patent Fuel | PATFUEL | | |
| Brown Coal Briquettes | BKB | | |
| Peat | PEAT | | |
| Peat Products | PEATPROD | | |
| Oil Shale and Oil Sands | OILSHALE | | |
| Natural Gas | NATGAS | Oil + Gas | oil + gas |
| Crude, nat. gas liquids and feedstocks | CRNGFEED | | |
| Crude Oil | CRUDEOIL | | |
| Natural Gas Liquids | NGL | | |
| Refinery Feedstocks | REFFEEDS | | |
| Additives and Blending Components | ADDITIVE | | |
| Other Hydrocarbons | NONCRUDE | | |
| Coke Oven Coke | OVENCOKE | Petroleum & Coke | p.c |
| Gas Coke | GASCOKE | | |
| Coal Tar | COALTAR | | |
| Coke Oven Gas | COKEOVGS | | |
| Blast Furnace Gas | BLFURGS | | |
| Other Recovered Gases | OGASES | | |
| Refinery Gas | REFINGAS | | |
| Ethane | ETHANE | | |
| Liquefied Petroleum Gases | LPG | | |
| Motor Gasolines excl. Biofuels | NONBIOGASOL | | |
| Aviation Gasoline | AVGAS | | |
| Gasoline Type Jet Fuel | JETGAS | | |
| Kerosene Type Jet Fuel excl. Biofuels | NONBIOJETK | | |
| Other Kerosene | OTHKERO | | |
| Gas Diesel Oil excl. Biofuels | NONBIODIES | | |
| Fuel Oil | RESFUEL | | |
| Naphtha | NAPHTA | | |
| White Spirit | WHITESP | | |
| Lubricants | LUBRIC | | |
| Bitumen | BITUMEN | | |
| Paraffin Waxes | PARWAX | | |
| Petroleum Coke | PETCOKE | | |
| Other Oil Products | ONONSPEC | | |

Table B.1: Energy products in the IEA extended energy balances (2018 ed.) matched to economic sectors. Note: ^a Pure output flows as a result of transformation activities in the IEA data. Will be discarded in the final dataset. ^b In practice the use of energy released by nuclear fission or fusion is restricted to the electricity sector in all countries in all years such that there is no need to split this flow among several sectors.

| IEA Commodity | IEA Code | Sector Name | Sector Code |
|---|------------|---|--------------------|
| <i>Correspondence of IEA energy products to economic sectors:</i> | | | |
| Biogasoline | BIOGASOL | | |
| Biodiesels | BIODIESEL | | |
| Bio Jet Kerosene | BIOJETKERO | | |
| Other Liquid Biofuels | OBIOLIQ | | |
| Non Specified Primary Biofuels and Waste | RENEWNS | | |
| Elec/Heat Output from non-Specified | MANGAS | | |
| Manufactured Gases | | | |
| Industrial Waste | INDWASTE | Other Ser. (Government) | osg |
| Municipal Waste Renewable | MUNWASTER | | |
| Municipal Waste non-Renewable | MUNWASTEN | | |
| Primary Solid Biofuels | PRIMSBIO | Cattle + Other Animal Prod. + Forestry | ctl + oap + frs |
| Gas Works Gas | GASWKSGS | Electricity + Gas Distribution | ely + gdt |
| Biogases | BIOGASES | | |
| Heat Output from non-Specified | HEATNS | | |
| Combustible Fuels ^a | | | |
| Nuclear ^b | NUCLEAR | | |
| Hydro | HYDRO | | |
| Geothermal | GEO THERM | | |
| Solar Photovoltaics | SOLARPV | | |
| Solar Thermal | SOLARTH | | |
| Tide Wave and Ocean | TIDE | | |
| Wind | WIND | | |
| Other Sources ^a | OTHER | | |
| Electricity ^a | ELECTR | | |
| Heat ^a | HEAT | | |
| Charcoal | CHARCOAL | Chemical Rubber Products | crp |

Table B.1: – continued.

B.1.2 Bridging the territorial and residential principles

The IEA energy balances were compiled according to a strict territorial system boundary, while the input-output (IO) data we require for the construction of the energy footprints follows the “residential principle”. As the residents of a country mainly operate within the territory of their country residence, the difference in the system boundaries is inconsequential most cases (see Peters, 2008; Peters and Hertwich, 2008). Considerable deviations between both concepts can occur, however, in the case of international road, -air, and -sea transport.

Specifically, the IEA assigns fuels used for international aviation and navigation (“international bunker fuels”) to the country from which territory the fuels are supplied, i.e. the location of harbours and airports. In the IO data, however, the economic activities of those air and shipping lines are accounted to their country of residency. As a result, the

fuels captured in the IEA’s “international bunker fuel” entries have to be distributed to the countries of residence of the air- and shipping lines that use those fuels. To do so, we rely on monetary data on the usage of modes of transport by country sourced from the Global Trade Analysis Project (GTAP, see Peters et al., 2011b, for a related application in the construction of multi-region input-output tables). Specifically, we first aggregate purchases of international aviation and navigation services of all countries, as well as all bunker fuel entries of the IEA data, to global pools. Then, we calculate for each country its share of usage of the global transportation service pool and assign the usage of bunker fuels to the individual countries based on those shares.

For similar reasons the territorial usage of energy in road transport in the IEA data has to be corrected for the residency principle. Especially in small European countries so called “tank tourism”, i.e. fuels used by non-residents on a country’s territory, can contribute a large amount of total fuel usage in that sector.¹⁸ Data on energy usage in road transport by (non-)residents is scarce, however, so we relied on EUROSTAT data on carbon dioxide (CO₂) emissions from road transport as a proxy. It includes data on emissions from non-residents on the domestic territory of a country as well as emissions caused by residents abroad for EU and EFTA member states. A drawback of this approach is that non-European data is not available. However, most of the other other countries in the world have either more limited cross-border traffic, are islands, or cross-border traffic is relatively small compared to the overall road sector of a country (see Stadler et al., 2018b).

The correction of fuel usage for cross-border road traffic is undertaken in two steps. First, we calculate for each country in the EUROSTAT data the ratios of CO₂ emissions from road transport caused by non-residents on its territory and by its residents abroad with respect to its territorial road sector total. We then multiply those ratios with IEA total fuel usage in road transport (“ROAD”), resulting in energy used by residents and non-residents in that sector. With those totals we bridge the territorial fuel usage of the IEA data to the usage of residents in our final dataset.¹⁹

¹⁸ According to BMLFUW (2004) the purchases of gasoline and diesels by non-residents in Austria accounted for 23 and 32% of total sales in 2003. In Germany in 2006, on the other hand, about 5 and 8% of total used gasoline and diesels in that country was purchased abroad (see Ratzenberger, 2007).

¹⁹ This last step results in an amount of fuels that is not allocated to any country, since fuel usage by (non-)residents typically does not cancel out at the European level. The surplus fuels are allocated to the European countries for which EUROSTAT does not provide data, i.e. Greece, Slovakia and Slovenia, based on their total size of the road sector in monetary terms. As a result we treat the EU and EFTA as a closed system, an approach that was applied by Stadler et al. (2018b).

B.1.3 Summary

As a result our energy data follows a gross energy use perspective (see Genty et al., 2012, for a more detailed discussion) which allows to focus on a large variety on energy-related questions, ranging from carbon dioxide emissions from fossil fuel consumption, the efficiency of the transformation of primary energy to electricity and heat production, or to determine patterns of the efficiency of electricity usage by private households. In our study we are interested in assessing the determinants of the primary energy mix used in the European Union in order keep its economy producing. This includes the amount of primary fossil fuels and renewable sources directly used by firms and private household produce energy, but also amount of primary fossil fuels for the transformation into processed fuels, for example diesel and gasoline, used by the European industry and private households. Thus, in order to avoid double counting we disregard the category of derived fuels from our data. Also, as we take a input-perspective of energy usage we also disregard the electricity and heat category from our data.

B.2 Methodology to construct energy footprint data

Here we provide a detailed discussion on the construction of the two energy footprints. We denote gross output produced by each of the s sectors (57 in our case) in one of the $i \subseteq [1, n]$ regions in our dataset as $x^i = (x_1^i, x_2^i, \dots, x_s^i)'$, where n denotes the total number of regions which is 78. Each sector produces either intermediates, sold for further processing to other sectors at home or abroad, Ax , or final goods, purchased by domestic or foreign consumers for final consumption, $Y\iota_n$. That is,

$$x = Ax + Y\iota_n \quad (\text{B.1})$$

or

$$\begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & A^{13} & \dots & A^{1n} \\ A^{21} & A^{22} & A^{23} & \dots & A^{2n} \\ A^{31} & A^{32} & A^{33} & \dots & A^{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & A^{n3} & \dots & A^{nn} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{pmatrix} + \begin{pmatrix} y^{11} & y^{12} & \dots & y^{1n} \\ y^{21} & y^{22} & \dots & y^{2n} \\ y^{31} & y^{32} & \dots & y^{3n} \\ \vdots & \vdots & \ddots & \vdots \\ y^{n1} & y^{n2} & \dots & y^{nn} \end{pmatrix} \iota_n. \quad (\text{B.2})$$

The $ns \times n$ dimensional matrix Y on the right-hand side of Equation (B.2), denotes the final goods demanded in each region by sector and country of origin. Accordingly, its elements, i.e. $y^{rp} = (y_1^{rp}, y_2^{rp}, \dots, y_s^{rp})'$ are column-vectors of dimension s . Each y_z^{rp} denotes the final goods from sector z in country r demanded by region p .²⁰ We collapse Y to a column vector of final demand with dimension $ns \times 1$ by multiplying it with ι_n , a column vector of ones with dimension n .

The matrix A on the right-hand side of Equation (B.2), the so-called global input requirements matrix, collects all the direct requirements of a specific sector from all the other sectors in the global economy to produce one unit of output. Its elements, i.e. A^{rp} , are matrices of dimension $s \times s$ that capture the intermediates exported by region r to region p , such that they denote domestic transactions whenever $r = p$. The elements of A^{rp} , i.e. a_{kj}^{rp} , are normalized to the output of the purchasing sector j such that a_{kj}^{rp} denotes the direct inputs required by sector j in country p from sector k in country r to produce one real dollar of output, where $k, j \subseteq [1, s]$.

²⁰ We follow the standard conventions of the input-output literature and denote with the first super- or subscript the region or sector of origin and the second super- or subscript the region or sector of destination.

We construct matrices A and Y for each year in our database by linking national input-output (IO) tables with international trade data as described in Peters et al. (2011a), where the raw trade and IO data is sourced from the Global Trade Analysis Project (GTAP). We deflated all monetary values in the final tables to the year 1997. The next step is then to account for the indirect requirements of production, i.e. the requirements of the direct suppliers themselves, but also the suppliers of the suppliers, and so on.

To account for those indirect requirements of production we solve Equation (B.1) for x , the companion vector of gross output. This results in $x = (I - A)^{-1}y$, where I denotes the $ns \times ns$ dimensional identity matrix and $y = Y \iota_n$. Matrix $(I - A)^{-1}$, also of dimension $ns \times ns$, is denoted as the Leontief-inverse or total requirements matrix in the input-output literature. The elements of its sub-matrices, i.e. \tilde{a}_{kj}^{rp} in $(I - A)_{rp}^{-1}$, denote the direct and indirect inputs sourced by sector j in region p from sector k in region r to produce one dollar of output. Thus, it accounts for global production structures along international supply chains, denoted in gross output.

As a next step we transform the direct and indirect linkages among the sectors in the world economy to value added as

$$\Lambda = V(I - A)^{-1}, \quad (\text{B.3})$$

where V is a diagonal matrix of dimension $ns \times ns$. The elements on the main diagonal of V , i.e. $v = (v^1, v^2, \dots, v^n)$, contain the value added intensity of production of the sectors in each region r . Each of these $s \times s$ dimensional elements v^r is also a diagonal matrix. Their elements v_k^r on the main diagonal contain the value added of sector k in region r denoted in the prices of 1997 divided by its total gross output produced, x_k^r . As a result, an element λ_{kj}^{rp} of Λ captures the direct and indirect usage of value added provided by sector k in region r to sector j in region p in order to produce one real dollar of gross output.

In order to obtain the amount of value added embodied in final goods assembled or consumed in a specific region, we multiply Λ with matrix Y and the $ns \times n$ dimensional matrix Y^o , respectively. While Y is defined as above and captures the value of final goods produced by each sector according to region of consumption, Y^o captures the total amount of final goods produced by the sectors of a specific region, i.e. its aggregated sector output of final goods produced for the domestic and foreign markets. Therefore,

$$\Phi^o = \Lambda Y^o \quad (\text{B.4})$$

and

$$\Phi^c = \Lambda Y . \quad (\text{B.5})$$

We derive Y^o by defining first the ns dimensional vector $y^o = Y\iota_n$, where ι_n is a row-summation vector of ones with dimension n . The s dimensional elements of $y^o = (y^{1*}, y^{2*}, \dots, y^{n*})'$, denote all the final goods produced for the domestic and foreign markets by the s sectors of region r , i.e. $y^{r*} = y^{r1} + y^{r2} + \dots + y^{rn}$. As a next step we define the $ns \times n$ dimensional matrix $I_{[ns,n]}$ as $\hat{\iota}_n \otimes \iota_s$, where ι_s is a s dimensional column-vector of ones, $\hat{\iota}_n$ is a diagonal matrix with the elements of ι_n on its main diagonal, and \otimes denotes the Kronecker product. Matrix Y^o is then obtained as $Y^o = \hat{y}^o I_{[ns,n]}$ and its n columns capture the n elements y^{r*} of y^o . Specifically, its r^{th} column is equal to $y^o \circ o$, where o is a selection-vector of the same dimension as y^o that contains ones at the positions of elements y^{r*} and zero otherwise and \circ is the Hadamard element-wise product.

Multiplying Y^o and Y by the re-scaled Leontief-inverse matrix Λ allows us to assess the total usage of value added required for final goods production (Φ^o) in each region as well as for the final goods consumed by region and sector of origin (Φ^c), respectively. By construction (see equations (B.4) and (B.5)) the energy usage embodied in these final goods is a function of the bundle of intermediates used in local and global supply chains, as determined by the re-scaled Leontief-inverse matrix, Λ . Specifically, the s dimensional elements of $\Phi^o = (\phi^{o,1r}, \phi^{o,2r}, \dots, \phi^{o,nr})'$ denote the total amount of value added embodied in the intermediates used to produce final goods in region r , which are sourced worldwide, i.e. from sectors 1 to s in region 1 to n . The components of $\Phi^c = (\phi^{c,1r}, \phi^{c,2r}, \dots, \phi^{c,nr})'$, which are also of dimension s , denote the amount of value added embodied in the domestic or imported final goods consumed in region r .

As a next step we complement matrices Φ^o and Φ^c with comparable matrices that capture the embodied flow of energy through the world's supply chains to the final goods assembled and consumed in each region of our dataset. For this, we pre-multiply both matrices with a matrix containing sectoral energy intensities, E , as

$$\Psi^o = E\Phi^o = E\Lambda Y^o \quad (\text{B.6})$$

and

$$\Psi^c = E\Phi^c = E\Lambda Y . \quad (\text{B.7})$$

Matrix E is a diagonal matrix of dimension $ns \times ns$ with main diagonal elements $e = (e^1, e^2, \dots, e^n)$ that contain the energy intensity of production of the sectors in each region r . Each of those elements e^r is a diagonal matrix again. They are of dimension $s \times s$ and an element e_k^r on its main diagonal contains the amount of energy, denoted in megatons of oil equivalents (*mtoe*), used by sector k in region r divided by its total value added v_k^r . Thus, the product of E and the Leontief-inverse, i.e. $E\Lambda$, is a matrix that captures the total usage of energy embodied in transactions of intermediates between all sectors in the global economy.

Matrices Ψ^o and Ψ^c are also of dimension $ns \times n$ and their s dimensional elements, i.e. $\Psi^o = (\psi^{o,1r}, \psi^{o,2r}, \dots, \psi^{o,nr})'$ and $\Psi^c = (\psi^{c,1r}, \psi^{c,2r}, \dots, \psi^{c,nr})'$, denote the amount of energy embodied in final goods production and consumption in region r by the sectors in the regions of origin 1 to n , respectively. Those flows of embodied energy are additionally determined by the energy intensity of all sectors involved in the supply chain of those final goods.

We aggregate the sectors by source regions from Ψ^o and Ψ^c . For this we create aggregation matrix $I_{[n,ns]} = \hat{l}_n \otimes l'_s$, which is of dimension $n \times ns$. The s elements of row-vector l'_s are ones and \hat{l}_n is defined as above. Multiplying $I_{[n,ns]}$ with Ψ^o and Ψ^c results in the $n \times n$ dimensional matrices $\Psi_a^o = I_{[n,ns]}\Psi^o$ and $\Psi_a^c = I_{[n,ns]}\Psi^c$. The scalar elements of those matrices, i.e. $\psi_a^{o,rp} = l'_s \psi^{o,rp}$ and $\psi_a^{c,rp} = l'_s \psi^{c,rp}$, denote the amount of energy originating in country r that is embodied in the final goods produced ($\psi_a^{o,rp}$) or consumed ($\psi_a^{c,rp}$) in region p . Thus, whenever $r \neq p$ those elements can be used to assess exports and imports of energy commodities embodied in intermediates and final goods between the regions in our dataset. These trade flows of embodied energy are related to the concept of trade in value added as defined by Johnson and Noguera (2012) in the sense that the energy commodities originating in region r can cross several sectors and borders before being absorbed in final goods produced or consumed in region p .²¹

It is straightforward to derive national energy inventories from matrices Ψ^o, Ψ_a^o, Ψ^c and Ψ_a^c , respectively. Remember, we obtain energy embodied in national final production by summing over all foreign and domestic sources of embodied energy in intermediate imports that ends up embodied in the final goods produced by a region. Thus, we obtain the vector of the n national final production-based energy inventories ψ^o by taking the column-sums of Ψ_a^o , or Ψ^o , respectively. Formally we derive $\psi^o = l'_n \Psi_a^o = l'_{ns} \Psi^o$, where l'_n and l'_{ns} are row vectors of ones of dimension n and ns , respectively. Similarly, we sum over all source-regions 1 to n to obtain the energy embodied in the final goods consumed

²¹ As a result, whenever $r = p$ the elements of Ψ_a^o and Ψ_a^c denote energy originating within the region of final production and consumption. This includes, however, energy embodied in intermediates that left the country for further processing to other countries before being assembled to a final good in the country of origin (see Koopman et al., 2014).

in region r . Formally we are taking the column-sum of Ψ_a^c and Ψ^c , which results in a vector ψ^c that captures the n national final consumption-based energy inventories, i.e. $\psi^c = \iota'_n \Psi_a^c = \iota'_{ns} \Psi^c$. The n scalar elements of ψ^o and ψ^c , i.e. $\psi^{o,r}$ and $\psi^{c,r}$, denote region r 's national final production and -consumption footprints, respectively.

Matrices Ψ^o, Ψ_a^o, Ψ^c , and Ψ_a^c offer an alternative way to calculate the national territorial production-based energy inventories. We defined territorial production of energy as the amount of energy that is used in the territory of a region to produce intermediates and final goods. Some of those intermediates are assembled to final goods at home or become embodied in final goods consumed at home. Other final goods are exported for consumption abroad as are some of the intermediates that are produced on a region's territory. Thus, summing over all destination regions of embodied energy in matrices Ψ_a^o, Ψ_a^c and over all source sectors and destination regions in Ψ^o, Ψ^c , i.e. taking the row-sums of those matrices, results in vector ψ^v which n elements correspond to the territorial production-based inventories of regions 1 to n . We calculate vector ψ^v as $\psi^v = \Psi_a^o \iota_n = \Psi_a^c \iota_n = I_{[n,ns]} \Psi^o \iota_n = I_{[n,ns]} \Psi^c \iota_n$, where $I_{[n,ns]}$ and ι_n are defined as above.

The scalar elements $\psi^{\omega,r}$ of vectors ψ^ω , where $\omega \subseteq \{o, c, v\}$, thus, denote the national energy inventories according to final production (o), final consumption (c), and territorial production (v), respectively. So far we accounted only for the energy used in industrial activities to produce goods and services. Some energy commodities in our data, specifically fossil fuels, solar/photovoltaic, and biomass²², are used by private households directly for heating and, to some degree, for electricity production. In a final step we add total energy usage by private households, denoted as ψ_{ehh}^r , to the elements elements of $\psi^{\omega,r}$ as $\hat{\psi}^{\omega,r} = \psi^{\omega,r} + \psi_{ehh}^r$. Similar aggregations can be performed for the matrices of embodied value added, i.e. Φ^o and Φ^c , where we will denote the national value added inventories as $\phi^{\omega,r}$.

B.3 Structural decomposition analysis

We now describe in detail how we derive the determinants of energy usage and intensity by applying the logarithmic mean divisia index I (LMDI-I) index decomposition to our detailed MRIO framework. We first discuss an extension of our MRIO framework in order to derive more detailed determinants for the national inventories derived above. Then we introduce the LMDI-I decomposition and apply it on the detailed components of the MRIO framework derived in the first step. Finally, we extend the decomposition method to energy intensity.

²² Biomass is part of the “other renewable energy” aggregate in our data.

B.3.1 Extending the MRIO framework

As an inspection of Equations (B.4) to (B.7) reveals, changes in the national energy ($\tilde{\psi}^{\omega,r}$) and value added ($\phi^{\omega,r}$) inventories are determined by changes in the Leontief-inverse matrix Λ , which elements capture direct and indirect supply-chain linkages, and and by changes in the matrices Y and Y^o , which elements capture the volume and composition of final goods produced and consumed, respectively. The energy inventories are also subject to changes in matrix E , which elements capture sector energy intensity defined as usage of energy per unit of value added produced and the direct usage of primary energy by private households.

We extend the framework derived in (B.4) to (B.7) further along two dimensions. First, we decompose Y and Y^o to separate matrices that contain information on (i) the volume of final goods produced and consumed in each region; (ii) the sector composition of those final goods, in the case of production and final consumption also by trading partner; (iii) and the geographical composition of trading partners.²³ Second, for the energy inventories we additionally derive explicitly the information on the energy mix used by the sectors to produce final goods and intermediates.

We begin with the decomposition of matrix Y in order to obtain the geographical composition of the trading partners of final goods for each region, separate for exports and imports. For the geographical composition of the imports of final goods in each region we first create the $n \times n$ dimensional matrix $Y_a = I_{[n,ns]}Y$, where $I_{[n,ns]}$ is defined as above, and which elements are the sums of the s dimensional elements of Y , i.e. $y_a^{rp} = \iota'_s y^{rp}$, where ι'_s is the s dimensional row vector of ones as defined in subsection B.2. Next, we calculate vector τ by taking the column-sums of matrix Y as $\tau = \iota'_{ns} Y$, where ι'_{ns} is again the ns dimensional row vector of ones as defined in subsection B.2. Each of the n elements in $\tau = (\tau^1, \tau^2, \dots, \tau^n)'$ denotes the value of final goods consumed by regions 1 to n . From this we construct the $n \times n$ dimensional matrix $M = Y_a \hat{\tau}^{-1}$, where $\hat{\tau}^{-1}$ is a $n \times n$ dimensional diagonal matrix with the inverse elements of τ on its main diagonal. An element of M , i.e. μ^{pr} , captures the share of final goods imported by region r from region p with respect to the total amount of final goods consumed in region r .

In a similar way we obtain the geographical composition of region r 's bilateral final goods exports. We define the $n \times n$ dimensional matrix X , which elements, i.e. χ^{rp} , denote final goods exported by region r to p as shares of region r 's value of total final goods exports. For its construction we first require vector $\eta = (\eta^1, \eta^2, \dots, \eta^n)'$, which n elements are the amount of final goods produced in regions 1 to n , either for the domestic market or for

²³ The geographic composition of trading partners can only be derived for the final consumption inventories, as from a final production perspective there is no trade in final goods.

exports. It is constructed as $\eta = Y_a \iota_n$, where ι_n is the n dimensional vector of ones as defined in subsection B.2. Matrix X is then calculated as $X = \hat{\eta}^{-1} Y_a$, where $\hat{\eta}^{-1}$ is a diagonal matrix with the inverse of the elements of η on its main diagonal.

The next step consists in the calculation of the sectoral composition of traded final goods, including the final goods sold domestically. For this we first derive the matrix $\Gamma = Y \oslash (Y_a \otimes \iota_s)$, where \oslash denotes the Hadamard element-wise division operator and ι_s is defined as above. The elements of Γ , i.e. $\gamma^{pr} = (\gamma_1^{pr}, \gamma_2^{pr}, \dots, \gamma_s^{pr})'$, are vectors of dimension s which elements denote region r 's imports of final goods from sector s in region p as a share of the total value of region r 's final goods imports from p .²⁴ As a result, the sectoral composition of the final goods consumed within a region r is a function of the sector composition of the final goods produced for the domestic market and the sectoral composition of final goods imports from each of its trading partners. Similarly, the composition of final goods produced in a region r is a function of the sector composition of final goods produced for the domestic market and the sector composition of final goods produced for each export partner.

We continue to derive a matrix capturing the sector composition of final goods assembled in each region.²⁵ For this we calculate the $ns \times n$ dimensional matrix $B = Y^o \hat{\eta}^{-1}$, where $\hat{\eta}^{-1}$ is defined as above. Its elements, i.e. β^{rp} , are vectors of dimension s and are zero whenever $r \neq p$. Whenever $r = p$, each scalar in β^{rp} denotes the share of the value of final goods assembled in sector s in region r relative to the value of all final goods assembled in that region.²⁶

Finally, and for the energy inventories only, we derive the energy mix applied by each of the sectors in all the regions of our database. For this, we define Ξ^q as an $ns \times ns$ dimensional diagonal matrix. The elements on its main diagonal, i.e. $\xi^q = (\xi^{1,q}, \xi^{2,q}, \dots, \xi^{n,q})'$, capture the usage of energy commodity q , where $q \subseteq [1, f]$ and f is the number of energy commodities (seven in our dataset), in each of the s sectors in each of the n regions in our dataset as a share of its usage of all energy commodities. Accordingly, each $\xi^{r,q}$ is an $s \times s$ dimensional diagonal matrix and the elements $\xi_k^{r,q}$ on their main diagonal denote the share of energy commodity q used by sector k in region r with respect to the total energy usage of sector k .²⁷ As a final step we stack all six matrices Ξ^q , one for each energy commodity in our dataset, together, such that the resulting matrix Ξ is of dimension $fns \times ns$.

²⁴ Similarly, the same element denotes the exports of final goods from sector s in region p as a share of the value of region p 's total final goods exports to region r .

²⁵ Note that there is not trade of final goods in the final production footprints. As a result, we do not have to construct a matrix that captures the geographical composition of final goods trading partners for this inventory.

²⁶ As a result the all elements of β^{rp} sum to one.

²⁷ Note that as a result $I = \Xi^1 + \Xi^2 + \dots + \Xi^f$, the $ns \times ns$ dimensional identity matrix

Using matrices Ξ, M, X, B , and Γ we extend Equations (B.6) to (B.7) that describe the determinants of embodied energy to

$$\Psi^o = I_{[ns, fns]} [\Xi E \Lambda B I_{[n, ns]} Y^o], \quad (\text{B.8})$$

$$\Psi^c = I_{[ns, fns]} [\Xi E \Lambda (\Gamma \circ M \hat{\tau} \otimes \iota_s)], \quad (\text{B.9})$$

where the aggregation matrix $I_{[ns, fns]}$ is of dimension $ns \times fns$ and sums over all f energy commodities. It is calculated as $I_{[ns, fns]} = i'_f \otimes \hat{i}_{ns}$, where i'_f is a row-vector of ones with dimension f and \hat{i}_{ns} is a $ns \times ns$ dimensional diagonal matrix with ones on its main diagonal. Matrix I_s and vector ι_s are defined as above, and \circ denotes the Hadamard element-wise product.

Analogously, we extend the expressions for embodied flows of value added, as described in Equations (B.4) and (B.5) to

$$\Phi^o = \Lambda B I_{[n, ns]} Y^o \quad (\text{B.10})$$

and

$$\Phi^c = \Lambda (\Gamma \circ M \hat{\tau} \otimes \iota_s). \quad (\text{B.11})$$

Finally, in order to assess the effect of the composition of final goods export partners in the production-based inventories of energy and value added we decompose

$$\Psi^v = I_{[ns, fns]} \{ \Xi E \Lambda [\Gamma \circ (X' \hat{\eta})' \otimes \iota_s] \}, \quad (\text{B.12})$$

and

$$\Phi^v = \Lambda [\Gamma \circ (X' \hat{\eta})' \otimes \iota_s], \quad (\text{B.13})$$

where $\hat{\eta}$ is a diagonal matrix with the elements of η on its main diagonal and X' is the transpose of X .

The decomposition described above does neither change matrices Ψ^ω and Φ^ω , nor their elements $\psi^{\omega, rp}$ and $\phi^{\omega, rp}$, respectively, where ω alternatively denotes final production (o), final consumption (c), or standard productions (v). The scalars $\psi_k^{o, pr}$, $\phi_k^{o, pr}$, and $\psi_k^{c, pr}$, $\phi_k^{c, pr}$,

denote the volume of energy or value added used in region r for final production or consumption, respectively, which is sourced from sector k in region p . Their counterparts for the territorial production inventories, $\psi_k^{v,rp}$ and $\phi_k^{v,rp}$, denote the amount of energy or value added used by sector k in region r to produce intermediates or final goods that are eventually consumed in region p . As such those elements denote the most detailed of embodied transactions of energy and value added in our database and are, therefore, the starting point of our decomposition exercise.

B.3.2 Deriving the determinants of energy usage

We will now present the detailed decomposition of matrices Ψ^ω and their elements, respectively. For this, we turn to element-wise notation as a first step and then introduce the logarithmic mean divisia index I (LMDI-I) method in order to decompose the absolute usage of energy over time into six different factors for standard production and final consumption and five different factors for final production, respectively. Specifically, we will assess how the energy inventories of a specific region changes over time due to changes in the energy mix on the sector level (mix), the amount of energy used per unit of value added at the sector level (int), changes in the organization of supply chains (sup), changes in the sector composition of final goods produced and consumed (str), and due to changes in the volume of final goods produced or consumed (act). The value added inventories will be decomposed to the same factors, except the energy-specific energy mix and intensity factors. We will then turn from this indicator-based decomposition of absolute energy usage to an index-based decomposition of the relative energy usage over time.

We now use element-wise sum notation to illustrate how the elements in Ψ^ω are determined by the elements of the matrices on the right-hand side of Equations (B.8), (B.9), and (B.12):

$$\psi_k^{o,pr} = \sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n \xi_k^{p,q} e_k^p \lambda_{kj}^{pg} \beta_j^{gr} \eta^r, \quad (\text{B.14})$$

$$\psi_k^{c,pr} = \sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n \xi_k^{p,q} e_k^p \lambda_{kj}^{pg} \gamma_j^{gr} \mu^{gr} \tau^r, \quad (\text{B.15})$$

$$\psi_k^{v,rp} = \sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n \xi_k^{r,q} e_k^r \lambda_{kj}^{rg} \gamma_j^{gp} \chi^{gp} \eta^g. \quad (\text{B.16})$$

Scalars $\xi_k^{m,q}$, e_k^m , λ_{kj}^{mu} , γ_j^{mu} , β_j^{mu} , χ^{mu} , μ^{mu} , η^u , and τ^u denote the elements of matrices Ξ , E , Λ , Γ , B , X , M , and vectors η , and τ , respectively. These elements are interpreted as six different factors that determine energy usage: energy mix $\xi_k^{m,q}$ and energy-intensity (e_k^m), the sourcing of local and foreign intermediates along supply chains (λ_{kj}^{mu}), the sector composition of domestic final goods production (β_j^{mu}), the sector composition of domestically produced and traded final goods (γ_j^{mu}), the geographical composition of trading partners for exported (χ^{mu}) and imported (μ^{mu}) final goods, and the value of final goods produced (η^m) and consumed (τ^m), respectively.

Obviously, sectoral elements $\psi_k^{\omega,mu}$, will change over time due to changes in one, more, or all of the factors defined above, and with them the national inventories $\tilde{\psi}^{\omega,r}$. In what follows we isolate and quantify the contribution of changes in each factor to $\Delta\psi_k^{\omega,mu} = \psi_k^{\omega,mu,t} - \psi_k^{\omega,mu,0}$, the absolute change in the level of $\psi_k^{\omega,mu}$ between base period 0 and comparison period t . This kind of decomposition is known as structural decomposition analysis (SDA) in the input-output literature and we apply the ‘‘Logarithmic Mean Divisia Method I’’ (LMDI-I), as established by the work of Ang and Liu (2001) and Ang (2015), to quantify the determinants of $\Delta\psi_k^{\omega,mu}$ and $\Delta\phi_k^{\omega,mu}$, respectively.²⁸ In order to implement this decomposition we first express the changes bilateral embodied energy as

$$\begin{aligned} \Delta\psi_k^{\omega,mu} &= \sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n (v_{\psi,kj}^{\omega,mgu,q,t} - v_{\psi,kj}^{\omega,mgu,q,0}) = \\ &= \sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n L(v_{\psi,kj}^{\omega,mgu,q,t}, v_{\psi,kj}^{\omega,mgu,q,0}) \ln \left(\frac{v_{\psi,kj}^{\omega,mgu,q,t}}{v_{\psi,kj}^{\omega,mgu,q,0}} \right), \end{aligned} \quad (\text{B.17})$$

where $v_{\psi,kj}^{v,rgp,q} = \xi_k^{r,q} e_k^r \lambda_{kj}^{rg} \gamma_j^{gp} \chi^{gp} \eta^g$, $v_{\psi,kj}^{o,pgr,q} = \xi_k^{p,q} e_k^p \lambda_{kj}^{pr} \beta_j^{gr} \eta^r$, and $v_{\psi,kj}^{c,pgr,q} = \xi_k^{p,q} e_k^p \lambda_{kj}^{pg} \gamma_j^{gr} \mu^{gr} \tau^r$ and $L(\cdot)$ denotes the logarithmic mean.²⁹

The next step is to express indicator $\Delta\psi_k^{\omega,mu}$, as defined in Equation (B.17), as a sum of sub-indicators, where each of those sub-indicators represents one of the factors introduced

²⁸ As described by de Boer and Rodrigues (2020) the LMDI-I approach can be seen as a generalization of the price indicator developed by Montgomery (1929, 1937). The Montgomery indicator was developed as a solution to the ‘‘classical’’ indicator problem: the decomposition of expenditures in a base and comparison period into two indicators, one representing changes in prices, and one representing changes in quantities (see de Boer, 2008; de Boer and Rodrigues, 2020). The generalized version of the Montgomery indicator extends this principle to more than two factors.

²⁹ For positive numbers the logarithmic mean is defined as

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

above. Let's define a' to denote the factors from 1 to \bar{a} , where $\bar{a} = 6$ such that $a' \subseteq [1, \bar{a}]$. Then the desired sub-indicator for factor a' can be expressed as $\Delta\psi_{a',k}^{\omega,mu}$, such that

$$\Delta\psi_k^{\omega,mu} = \sum_{a'=1}^{\bar{a}} \Delta\psi_{a',k}^{\omega,mu}, \quad (\text{B.18})$$

where $\Delta\psi_{a',k}^{\omega,mu} = 0$ if $\omega = o$ and $a' = trd$. Each sub-indicator $\Delta\psi_{a',k}^{\omega,mu}$ measures by how much $\Delta\psi_k^{\omega,mu}$ would change if only the factor it represents changes, while keeping all other factors constant.

To create sub-indicators $\Delta\psi_{a',k}^{\omega,mu}$ we first take the ratio of each element on the right-hand sides in Equations (B.14) – (B.16) in period t to its value in a base period 0 and take the natural logarithm thereof, which denote all the factors determining embodied energy transactions in periods 0 and t . Multiplying the logarithm of each of those ratios with $L(v_{\psi,kj}^{\omega,mgu,q,t} - v_{\psi,kj}^{\omega,mgu,q,0})$ results in the desired sub-indicators. As the term $L(v_{\psi,kj}^{\omega,mgu,q,t} - v_{\psi,kj}^{\omega,mgu,q,0})$ is the same in the calculations for all sub-indicators of an inventory, it acts as a weight in their calculations such that we denote it as $W_{\psi,kj}^{\omega,mgu,q} = L(v_{\psi,kj}^{\omega,mgu,q,t} - v_{\psi,kj}^{\omega,mgu,q,0})$.³⁰ We present the sub-indicators for each energy inventories in the upper part of Table (B.2).

B.3.3 Deriving the determinants of value added

We decompose the flows of embodied value added to a sum of factor-specific sub-indicators in an analogue way as

$$\Delta\phi_k^{\omega,mu} = \sum_{a'=1}^{\bar{a}} \Delta\phi_{a',k}^{\omega,mu}, \quad (\text{B.19})$$

where again, $\Delta\phi_{a',k}^{\omega,mu} = 0$ if $\omega = o$ and $a' = trd$. It should be noted that for value added there are no sub-indicators for the energy-specific factors *mix* and *int* (see the lower part of Table (B.2), where the value added sub-indicators are presented in detail).³¹

³⁰ Using the logarithmic mean in our decomposition offers two advantages for our analysis (see also de Boer and Rodrigues, 2020). First, due to its symmetry the indicator is robust to time reversal, i.e. $\Delta\psi_k^{\omega,mu} = \psi_k^{\omega,mu,t} - \psi_k^{\omega,mu,0} = \psi_k^{\omega,mu,0} - \psi_k^{\omega,mu,t}$. Second, well developed methods are available to deal with zeroes in the data, which is important in our case because not all energy commodities in our data are used by all of the countries. Ang and Choi (1997) and Ang et al. (1998) suggest to replace the zeroes in the data with small positive numbers. Wood and Lenzen (2006), however, demonstrate that such an approach can lead to significant errors in the decomposition. As an alternative, Ang et al. (1998) and Wood and Lenzen (2006) suggest the usage of analytical limits whenever zero values occur. We follow this second approach in our analysis.

³¹ Note that for value added $v_{\phi,kj}^{v,rgp} = \lambda_{kj}^{rg} \gamma_j^{gp} \chi^{gp} \eta^g$, $v_{\phi,kj}^{o,pgg} = \lambda_{kj}^{pr} \beta_j^{gr} \eta^r$, and $v_{\phi,kj}^{c,pgg} = \lambda_{kj}^{pg} \gamma_j^{gr} \mu^{gr} \tau^r$. Accordingly, the weight for the value added sub-indicators is $W_{\phi,kj}^{\omega,mgu,q} = L(v_{\phi,kj}^{\omega,mgu,t} - v_{\phi,kj}^{\omega,mgu,0})$.

| Indicator | Production | Final Production | Consumption |
|---|--|--|--|
| <i>LMDI-I decomposition of energy usage</i> | | | |
| $\Delta\psi_{mix,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{v,rgu,q} \ln\left(\frac{\xi_k^{r,q,t}}{\xi_k^{r,q,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{o,mgr,q} \ln\left(\frac{\xi_k^{m,q,t}}{\xi_k^{m,q,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{c,mgr,q} \ln\left(\frac{\xi_k^{m,q,t}}{\xi_k^{m,q,0}}\right)$ |
| $\Delta\psi_{int,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{v,rgu,q} \ln\left(\frac{e_k^{r,t}}{e_k^{r,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{o,mgr,q} \ln\left(\frac{e_k^{m,t}}{e_k^{m,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{c,mgr,q} \ln\left(\frac{e_k^{m,t}}{e_k^{m,0}}\right)$ |
| $\Delta\psi_{sup,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{v,rgu,q} \ln\left(\frac{\lambda_{\psi,kj}^{rg,t}}{\lambda_{\psi,kj}^{rg,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{o,mgr,q} \ln\left(\frac{\lambda_{\psi,kj}^{mgr,t}}{\lambda_{\psi,kj}^{mgr,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{c,mgr,q} \ln\left(\frac{\lambda_{\psi,kj}^{mgr,t}}{\lambda_{\psi,kj}^{mgr,0}}\right)$ |
| $\Delta\psi_{str,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{v,rgu,q} \ln\left(\frac{\gamma_j^{gu,t}}{\gamma_j^{gu,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{o,mgr,q} \ln\left(\frac{\beta_j^{r,t}}{\beta_j^{r,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{c,mgr,q} \ln\left(\frac{\gamma_j^{gr,t}}{\gamma_j^{gr,0}}\right)$ |
| $\Delta\psi_{trd,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{v,rgu,q} \ln\left(\frac{\chi_j^{gu,t}}{\chi_j^{gu,0}}\right)$ | -- | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{c,mgr,q} \ln\left(\frac{\mu_j^{gr,t}}{\mu_j^{gr,0}}\right)$ |
| $\Delta\psi_{act,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{v,rgu,q} \ln\left(\frac{n_k^{g,t}}{n_k^{g,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{o,mgr,q} \ln\left(\frac{r_k^{r,t}}{r_k^{r,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\psi,kj}^{c,mgr,q} \ln\left(\frac{\tau_k^{r,t}}{\tau_k^{r,0}}\right)$ |
| <i>LMDI-I decomposition of value added</i> | | | |
| $\Delta\phi_{sup,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{v,rgu,q} \ln\left(\frac{\lambda_{\phi,kj}^{rg,t}}{\lambda_{\phi,kj}^{rg,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{o,mgr,q} \ln\left(\frac{\lambda_{\phi,kj}^{mgr,t}}{\lambda_{\phi,kj}^{mgr,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{c,mgr,q} \ln\left(\frac{\lambda_{\phi,kj}^{mgr,t}}{\lambda_{\phi,kj}^{mgr,0}}\right)$ |
| $\Delta\phi_{str,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{v,rgu,q} \ln\left(\frac{\gamma_j^{gu,t}}{\gamma_j^{gu,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{o,mgr,q} \ln\left(\frac{\beta_j^{r,t}}{\beta_j^{r,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{c,mgr,q} \ln\left(\frac{\gamma_j^{gr,t}}{\gamma_j^{gr,0}}\right)$ |
| $\Delta\phi_{trd,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{v,rgu,q} \ln\left(\frac{\chi_j^{gu,t}}{\chi_j^{gu,0}}\right)$ | -- | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{c,mgr,q} \ln\left(\frac{\mu_j^{gr,t}}{\mu_j^{gr,0}}\right)$ |
| $\Delta\phi_{act,k}^{\omega,mu}$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{v,rgu,q} \ln\left(\frac{n_k^{g,t}}{n_k^{g,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{o,mgr,q} \ln\left(\frac{r_k^{r,t}}{r_k^{r,0}}\right)$ | $\sum_{q=1}^f \sum_{j=1}^s \sum_{g=1}^n W_{\phi,kj}^{c,mgr,q} \ln\left(\frac{\tau_k^{r,t}}{\tau_k^{r,0}}\right)$ |

Table B.2: Energy and VA sub-indicators for each of the seven factors and each inventory. Note: $\Delta\psi_{a,k}^{\omega,mu}$ and $\Delta\phi_{a,k}^{\omega,mu}$ denote the absolute change in energy and value added, respectively, due to a change in factor a on the most detailed level of our MRIO framework involving region r either as the region of origin or destination. Whether r is the region of origin or the region of destination varies by inventory ω , as can be inferred from columns 2 – 5 in the Figure.

B.3.4 Aggregating to changes in national inventories

The LMDI-I approach offers two further advantages. First, the indicators for the different factors sum up to total changes in embodied energy and value added without leaving a residual (“completeness”). Second, the indicators are consistent in aggregation, such that changes in national energy usage by inventory in region r ($\Delta\psi^{\omega,r}$) can be derived by first summing $\Delta\psi_k^{\omega,mu}$ over all s source sectors, or $\Delta\psi_{a',k}^{\omega,mu}$ over all s source sectors and all \bar{a} factors. For final production and consumption inventories we then sum over all n source regions m that provide a region with embodied energy while for territorial production we aggregate over all n destination regions u of a region’s embodied energy. As a result, we

derive the total change of the final production ($\omega = o$) and consumption ($\omega = c$) footprints of a specific region r , i.e. $\Delta\psi^{\omega,r}$, as

$$\Delta\psi^{\omega,r} = \sum_{k=1}^s \sum_{m=1}^n \Delta\psi_k^{\omega,mr} = \sum_{a'=1}^{\bar{a}} \left(\sum_{k=1}^s \sum_{m=1}^n \Delta\psi_{a',k}^{\omega,mr} \right) = \sum_{a'=1}^{\bar{a}} \Delta\psi_{a'}^{\omega,r}. \quad (\text{B.20})$$

In a similar way we calculate the change in a region r 's territorial production, i.e. $\Delta\psi^{\omega,r}$ where $\omega = v$, as

$$\Delta\psi^{\omega,r} = \sum_{k=1}^s \sum_{u=1}^n \Delta\psi_k^{\omega,ru} = \sum_{a'=1}^{\bar{a}} \left(\sum_{k=1}^s \sum_{u=1}^n \Delta\psi_{a',k}^{\omega,ru} \right) = \sum_{a'=1}^{\bar{a}} \Delta\psi_{a'}^{\omega,r}. \quad (\text{B.21})$$

The procedure for aggregating the value added inventories is exactly the same such that its description is omitted for the sake of brevity.

Until this point, $\Delta\psi^{\omega,r}$ does not account for the change in primary energy usage by private households. We treat changes in this energy usage by private households over time as separate factor in our empirical analysis, denoted as $ehh = \Delta\psi_{ehh}^r = \psi_{ehh}^{r,t} - \psi_{ehh}^{r,0}$. The overall change in absolute energy usage by region is

$$\Delta\tilde{\psi}^{\omega,r} = \Delta\psi^{\omega,r} + \Delta\psi_{ehh}^r = \sum_{a=1}^{\tilde{a}} \Delta\psi_a^{\omega,m} + \Delta\psi_{ehh}^r, \quad (\text{B.22})$$

where \tilde{a} denotes now the number of the final seven factors, i.e. $\tilde{a} = 7$ and $a \subseteq [1, \tilde{a}]$.

B.3.5 Energy indicators for country aggregates

Changes in national energy usage can further be aggregated to country groups, such as the European Union or income aggregates. Let's define with z a region that is part of an aggregate country group such that $z \subseteq [1, \bar{z}]$ and \bar{z} is the number of countries in that group. In order to obtain an indicator for the total change in the energy footprints of a country aggregate z^* , i.e. $\Delta\tilde{\psi}^{\omega,z^*}$ when $\omega = o$ or $\omega = c$, we add the individual indicators or factor-specific sub-indicators of all countries included in the group as

$$\Delta\tilde{\psi}^{\omega,z^*} = \sum_{z=1}^{\bar{z}} \Delta\tilde{\psi}^{\omega,z} = \sum_{z=1}^{\bar{z}} \left(\sum_{k=1}^s \sum_{m=1}^n \Delta\psi_k^{\omega,mz} + \Delta\psi_{ehh}^z \right) =$$

$$= \sum_{z=1}^{\bar{z}} \left[\sum_{a=1}^{\bar{a}} \left(\sum_{k=1}^s \sum_{m=1}^n \Delta \psi_{a,k}^{\omega,mz} \right) \right]. \quad (\text{B.23})$$

The procedure is similar if an indicator for a country aggregate describing its change in territorial energy production, i.e. $\Delta \tilde{\psi}^{\omega,z^*}$ where $\omega = \nu$, should be derived:

$$\begin{aligned} \Delta \tilde{\psi}^{\omega,z^*} &= \sum_{z=1}^{\bar{z}} \Delta \tilde{\psi}^{\omega,z} = \sum_{z=1}^{\bar{z}} \left(\sum_{k=1}^s \sum_{u=1}^n \Delta \psi_k^{\omega,zu} + \Delta \psi_{ehh}^z \right) = \\ &= \sum_{z=1}^{\bar{z}} \left[\sum_{a=1}^{\bar{a}} \left(\sum_{k=1}^s \sum_{u=1}^n \Delta \psi_{a,k}^{\omega,zu} \right) \right]. \end{aligned} \quad (\text{B.24})$$

Aggregating the (sub-)indicators of changes in embodied value added to country aggregates is done analogously and we omit its discussion for the sake of brevity.

B.3.6 Deriving indices for the relative change of the energy inventories

One disadvantage of the additive LMDI-I decomposition arises when the energy usage of regions that are different in size is to be compared. A more insightful comparison of the development in energy usage in different regions can be obtained by the comparison of relative changes. Furthermore, targets for energy efficiency in directive 2006/32/EC and its successors are measured in relative changes as well. Thus, we first define the relative change of $\psi_k^{\omega,mu}$ between periods 0 and t as

$$\underline{\Delta} \psi_k^{\omega,mu} = \frac{\psi_k^{\omega,mu,t}}{\psi_k^{\omega,mu,0}}. \quad (\text{B.25})$$

The next step is to decompose Equation (B.25) into the product sub-indices, one for each factor in our analysis. Each of those sub-indices $\underline{\Delta} \psi_{a',k}^{\omega,mu}$ measures the change of $\underline{\Delta} \psi_k^{\omega,mu}$ that would arise if only a specific factor changes, while the others remain constant. Index $\underline{\Delta} \psi_k^{\omega,mu}$ can then be represented as the product of its sub-indices as

$$\underline{\Delta} \psi_k^{\omega,mu} = \prod_{a'=1}^{\bar{a}} \underline{\Delta} \psi_{a',k}^{\omega,mu}. \quad (\text{B.26})$$

For the construction of sub-indices $\underline{\Delta} \psi_{a',k}^{\omega,mu}$ we exploit that sub-indicators obtained from the LMDI-I approach, which belongs to the class of indicator decompositions based on the

logarithmic mean, can easily be transformed to indices (compare de Boer and Rodrigues, 2020). When we look at region r 's footprint inventories we construct $\underline{\Delta}\psi_{a',k}^{\omega,mr}$ as

$$\underline{\Delta}\psi_{a',k}^{\omega,mr} = \exp \left[\frac{\Delta\psi_{a',k}^{\omega,mr}}{L(\tilde{\psi}^{\omega,r,t}, \tilde{\psi}^{\omega,r,0})} \right], \quad (\text{B.27})$$

and for its territorial production of energy we construct $\underline{\Delta}\psi_{a',k}^{\omega,ru}$ as

$$\underline{\Delta}\psi_{a',k}^{\omega,ru} = \exp \left[\frac{\Delta\psi_{a',k}^{\omega,ru}}{L(\tilde{\psi}^{\omega,r,t}, \tilde{\psi}^{\omega,r,0})} \right], \quad (\text{B.28})$$

where $L(\tilde{\psi}^{\omega,r,t}, \tilde{\psi}^{\omega,r,0})$ is the logarithmic mean of region r 's national energy inventory ω , including primary energy used directly by private households. It serves as the weight for the sub-indices in the resulting index decomposition of $\underline{\Delta}\psi_k^{\omega,mu}$, which is known in the literature as the ‘‘multiplicative Logarithmic Mean Divisia method I’’, (compare Ang and Liu, 2001; Ang, 2015).³²

Analogue to the additive decomposition, we derive indices for energy usage at the regional level as

$$\underline{\Delta}\psi^{\omega,r} = \prod_{k=1}^s \prod_{m=1}^n \underline{\Delta}\psi_k^{\omega,mr} = \prod_{a'=1}^{\bar{a}} \underline{\Delta}\psi_{a'}^{\omega,r} = \prod_{a'=1}^{\bar{a}} \left(\prod_{k=1}^s \prod_{m=1}^n \underline{\Delta}\psi_{a',k}^{\omega,mr} \right), \quad (\text{B.29})$$

and

$$\underline{\Delta}\psi^{\omega,r} = \prod_{k=1}^s \prod_{u=1}^n \underline{\Delta}\psi_k^{\omega,ru} = \prod_{a'=1}^{\bar{a}} \underline{\Delta}\psi_{a'}^{\omega,r} = \prod_{a'=1}^{\bar{a}} \left(\prod_{k=1}^s \prod_{u=1}^n \underline{\Delta}\psi_{a',k}^{\omega,ru} \right), \quad (\text{B.30})$$

depending on inventory ω . The construction of (sub-)indices for country aggregates is done by further aggregating of $\underline{\Delta}\psi^{\omega,r}$ and its factor-specific sub-indices. Again, $\underline{\Delta}\psi^{\omega,r}$ does not consider changes from the usage of energy directly by private households. For this we define an own sub-index for the factor ehh as

$$\underline{\Delta}\psi_{ehh}^r = \exp \left[\frac{\Delta\psi_{ehh}^r}{L(\tilde{\psi}^{\omega,r,t}, \tilde{\psi}^{\omega,r,0})} \right], \quad (\text{B.31})$$

³² As discussed in de Boer and Rodrigues (2020), the multiplicative version of the LMDI-I approach can also be described as a generalization of the price index developed independently by Montgomery (1929, 1937) and Vartia (1974, 1976). Like the Montgomery price indicator, the Montgomery-Vartia price index was developed to solve the ‘‘classical’’ index problem (compare de Boer and Rodrigues, 2020): the decomposition of the ratio of two expenditures of a base and comparison period into the product of a price- and a quantity index.

such that

$$\underline{\Delta}\tilde{\psi}^{\omega,r} = \underline{\Delta}\psi^{\omega,r} * \underline{\Delta}\psi_{ehh}^{\omega,r} = \prod_{a=1}^{\bar{a}} \underline{\Delta}\psi_a^{\omega,r}. \quad (\text{B.32})$$

B.3.7 Structural decomposition analysis of national energy efficiency

We conclude this section on our methodology by extending the results derived so far to an analysis of energy intensity.

We express the energy intensity for inventory ω of region r as $\theta^{\omega,r} = \frac{\tilde{\psi}^{\omega,r}}{\phi^{\omega,r}}$, which at the most detailed level in our MRIO framework becomes $\theta_k^{\omega,mu} = \frac{\psi_k^{\omega,mu}}{\phi_k^{\omega,mu}}$, where, depending on the inventory, r is either the region of origin (m) or destination (u). As a result, the change of this ratio in inventory ω between period 0 and period t is (see also Su and Ang, 2015)

$$\Theta_k^{\omega,mu} = \frac{\theta_k^{\omega,mu,t}}{\theta_k^{\omega,mu,0}} = \frac{\psi_k^{\omega,mu,t}/\phi_k^{\omega,mu,t}}{\psi_k^{\omega,mu,0}/\phi_k^{\omega,mu,0}} = \frac{\psi_k^{\omega,mu,t}/\psi_k^{\omega,mu,0}}{\phi_k^{\omega,mu,t}/\phi_k^{\omega,mu,0}} = \frac{\underline{\Delta}\psi_k^{\omega,mu}}{\underline{\Delta}\phi_k^{\omega,mu}}. \quad (\text{B.33})$$

We proceed by decomposing $\Theta_k^{\omega,mu}$ into changes of the six factors derived above, relying again on the multiplicative LMDI-I procedure.³³ As a first step we decompose separately the numerator and denominator of Equation (B.33) into indices for all the factors in our analysis:

$$\Theta_k^{\omega,mu} = \frac{\underline{\Delta}\psi_k^{\omega,mu}}{\underline{\Delta}\phi_k^{\omega,mu}} = \prod_{a'=1}^{\bar{a}} \exp \left[\underline{\Delta}\psi_{a',k}^{\omega,mu} - \underline{\Delta}\phi_{a',k}^{\omega,mu} \right] = \prod_{a'=1}^{\bar{a}} \Theta_{a',k}^{\omega,mu}, \quad (\text{B.35})$$

where both terms in the brackets of Equation (B.35) are zero when $a' = trd$ and $\omega = o$. Also, $\underline{\Delta}\phi_{a',k}^{\omega,mu}$ is zero whenever $a' = mix$ or $a' = int$ because these factors do not exist for the value added inventories. As a result, for those two factors energy efficiency, i.e. $\Theta_k^{\omega,mu}$, is only driven by relative changes in energy usage and not by change in value added. Finally, $\Theta_k^{\omega,mu}$ can be easily aggregated to indices expressing the national changes

³³ Note that the multiplicative LMDI-I decomposition of $\underline{\Delta}\phi_k^{\omega,mu}$ is defined as

$$\underline{\Delta}\phi_k^{\omega,mr} = \prod_{a'=1}^{\bar{a}} \exp \left[\frac{\Delta\phi_{a,k}^{\omega,mr}}{L(\phi^{\omega,r,t}, \phi^{\omega,r,0})} \right] \quad \text{and} \quad \underline{\Delta}\phi_k^{\omega,ru} = \prod_{a'=1}^{\bar{a}} \exp \left[\frac{\Delta\phi_{a,k}^{\omega,ru}}{L(\phi^{\omega,r,t}, \phi^{\omega,r,0})} \right], \quad (\text{B.34})$$

depending on the inventory.

in energy intensity of a specific region r , not accounting for changes in energy usage by private households, in each inventory ω as

$$\Theta^{\omega,r} = \prod_{m=1}^n \prod_{k=1}^s \Theta_k^{\omega,mr} = \prod_{a'=1}^{\bar{a}} \Theta_{a'}^{\omega,r} = \prod_{a'=1}^{\bar{a}} \left(\prod_{m=1}^n \prod_{k=1}^s \Theta_{a',k}^{\omega,mr} \right), \quad (\text{B.36})$$

and

$$\Theta^{\omega,r} = \prod_{u=1}^n \prod_{k=1}^s \Theta_k^{\omega,ru} = \prod_{a'=1}^{\bar{a}} \Theta_{a'}^{\omega,r} = \prod_{a'=1}^{\bar{a}} \left(\prod_{u=1}^n \prod_{k=1}^s \Theta_{a',k}^{\omega,ru} \right), \quad (\text{B.37})$$

where $\Theta_{a'}^{\omega,r}$ denotes the sub-index for factor a' aggregated for the specific region r .

In order to account for changes in national energy efficiency due to change in the primary energy usage of private households we define first index

$$\Theta_{ehh}^r = \exp[\Delta\psi_{ehh}^r], \quad (\text{B.38})$$

such that

$$\tilde{\Theta}^{\omega,r} = \Theta^{\omega,r} * \Theta_{ehh}^r = \prod_{a=1}^{\bar{a}} \Theta_a^{\omega,r} \quad (\text{B.39})$$

denotes the relative change in the energy efficiency of region r that takes into account changes in household energy usage.

Further aggregations to country-groups, such as the European Union, can be achieved by further aggregating $\tilde{\Theta}^{\omega,r}$ and its sub-indices on the right-hand side of Equation (B.36) as has been shown for the additive decompositions in Equations (B.23) and (B.24).

C Supplementary analyses

C.1 Decomposition results for selected regions

Table C.1 presents the results of the multiplicative LMDI-I decomposition of changes in energy usage according to the three energy inventories for selected regions in the period 1997–2014 in index-form. The indices refer to changes in the aggregate energy usage inventories (in the column *total*) and in the seven contributing factors (*act*, *int*, *sup*, *str*, *trd*, *mix*, and *ehh*) expressed as ratios of their values in 2014 relative to 1997. Thus, each of the seven factor indices denotes the contribution of the respective factor to the change in aggregate energy usage if only this specific factor changes, while the others are held constant. An index smaller (larger) than 1 indicates that the factor contributed to a decrease (increase) in aggregate energy usage. The product of all seven indices results in the overall energy ratio reported in the column *total*.

| Region | act | int | sup | str | trd | mix | ehh | total |
|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| <i>Territorial Production</i> | | | | | | | | |
| EU 28 | 1.4792 | 0.7290 | 0.8492 | 1.0350 | 0.9968 | 1.0009 | 1.0027 | 0.9482 |
| USA | 1.5646 | 1.0300 | 0.6187 | 1.0541 | 0.9989 | 1.0029 | 1.0098 | 1.0633 |
| Japan | 1.2750 | 1.3502 | 0.4717 | 1.0893 | 1.0045 | 0.9839 | 0.9996 | 0.8738 |
| EFTA | 1.5506 | 0.6885 | 1.1907 | 1.0386 | 0.9917 | 1.0058 | 1.0065 | 1.3255 |
| R.o. OECD | 1.7676 | 0.7756 | 0.9700 | 0.9671 | 0.9981 | 1.0089 | 1.0089 | 1.3066 |
| China | 3.2027 | 0.6683 | 1.2091 | 1.0594 | 1.0113 | 1.0057 | 0.9605 | 2.6789 |
| <i>Final Production</i> | | | | | | | | |
| EU 28 | 1.4503 | 0.6862 | 1.1016 | 1.0204 | NA | 1.0023 | 1.0022 | 1.1238 |
| USA | 1.5459 | 0.9463 | 0.6887 | 1.0488 | NA | 1.0032 | 1.0095 | 1.0702 |
| Japan | 1.1861 | 1.0128 | 0.6842 | 1.0638 | NA | 0.9888 | 0.9997 | 0.8642 |
| EFTA | 1.5642 | 0.6841 | 1.4627 | 1.0410 | NA | 1.0086 | 1.0053 | 1.6519 |
| R.o. OECD | 1.7829 | 0.7281 | 1.0992 | 0.9352 | NA | 1.0086 | 1.0085 | 1.3574 |
| China | 3.5970 | 0.6706 | 1.1124 | 1.0682 | NA | 1.0076 | 0.9605 | 2.7739 |
| <i>Final Consumption</i> | | | | | | | | |
| EU 28 | 1.4145 | 0.6950 | 1.1008 | 1.0279 | 1.0055 | 1.0025 | 1.0022 | 1.1238 |
| USA | 1.5340 | 0.9083 | 0.7383 | 1.0373 | 1.0001 | 1.0035 | 1.0090 | 1.0807 |
| Japan | 1.1562 | 0.9667 | 0.7301 | 1.0471 | 1.0021 | 0.9895 | 0.9997 | 0.8470 |
| EFTA | 1.5577 | 0.7008 | 1.2396 | 1.0089 | 1.0179 | 1.0065 | 1.0042 | 1.4046 |
| R.o. OECD | 1.7834 | 0.7348 | 1.0914 | 0.9599 | 1.0283 | 1.0087 | 1.0085 | 1.4361 |
| China | 3.6122 | 0.6810 | 1.0844 | 1.0798 | 0.9968 | 1.0079 | 0.9578 | 2.7722 |

Table C.1: Decomposition of changes in energy usage, 1997–2014 – index form

Results from the multiplicative LMDI-I decomposition. The same results are summarized graphically in Figure 1 in the main text.

We additionally present the results of the multiplicative LMDI-I decomposition of changes in national energy efficiency for all three inventories in index form. For the selected regions discussed in the main text these results are given in Table (C.2) for the period 1997 – 2014. In Tables (C.3) and (C.4) the same results are presented for the sub-periods from 1997 to 2007 and from 2007 to 2014, respectively. The indices refer to changes in

energy intensity, defined as usage of energy per unit of value added. Each of the seven indices we consider, denotes the contribution of the factor that it represents to the change in energy intensity, if all the other factors would stay constant. Thus, indices smaller (larger) than 1 indicate that their factor contributed to an improvement (deterioration) in energy efficiency. The product of all seven indices results in the overall ratio of energy intensity reported in the column *total*.

Note that changes in three of the seven factors, i.e. the energy mix (*mix*), sector energy intensity (*int*) and energy usage by private households (*ehh*), affect only energy usage, or the nominator of energy intensity. As a result, the indices representing those factors are the same as for the decomposition of energy usage. Changes in the remaining factors, i.e. activity (*act*), supply chains (*sup*), final goods sector composition (*str*) and geographical composition of final goods trading partners (*trd*), affect the nominator as well as the denominator of energy intensity, as can be seen in Section (B.3).

| Region | act | int | sup | str | trd | mix | ehh | total |
|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| <i>Territorial Production</i> | | | | | | | | |
| EU 28 | 0.9866 | 0.7290 | 1.0645 | 1.0209 | 0.9973 | 1.0009 | 1.0027 | 0.7823 |
| USA | 0.9601 | 1.0300 | 0.7299 | 1.0497 | 0.9992 | 1.0029 | 1.0098 | 0.7667 |
| Japan | 1.0112 | 1.3502 | 0.5862 | 1.0779 | 1.0076 | 0.9839 | 0.9996 | 0.8548 |
| EFTA | 0.9472 | 0.6885 | 1.3083 | 1.0230 | 0.9896 | 1.0058 | 1.0065 | 0.8745 |
| R.o. OECD | 0.9600 | 0.7756 | 1.0008 | 0.9199 | 0.9943 | 1.0089 | 1.0089 | 0.6938 |
| China | 0.8323 | 0.6683 | 0.9181 | 0.9903 | 1.0001 | 1.0057 | 0.9605 | 0.4886 |
| <i>Final Production</i> | | | | | | | | |
| EU 28 | 0.9770 | 0.6862 | 1.3349 | 1.0123 | NA | 1.0023 | 1.0022 | 0.9100 |
| USA | 0.9535 | 0.9463 | 0.8071 | 1.0459 | NA | 1.0032 | 1.0095 | 0.7713 |
| Japan | 0.9775 | 1.0128 | 0.8328 | 1.0573 | NA | 0.9888 | 0.9997 | 0.8617 |
| EFTA | 0.9539 | 0.6841 | 1.5288 | 1.0240 | NA | 1.0086 | 1.0053 | 1.0357 |
| R.o. OECD | 0.9574 | 0.7281 | 1.1248 | 0.9062 | NA | 1.0086 | 1.0085 | 0.7228 |
| China | 0.8364 | 0.6706 | 0.9299 | 0.9886 | NA | 1.0076 | 0.9605 | 0.4990 |
| <i>Final Consumption</i> | | | | | | | | |
| EU 28 | 0.9753 | 0.6950 | 1.3251 | 1.0168 | 1.0040 | 1.0025 | 1.0022 | 0.9213 |
| USA | 0.9523 | 0.9083 | 0.8604 | 1.0327 | 0.9992 | 1.0035 | 1.0090 | 0.7776 |
| Japan | 0.9802 | 0.9667 | 0.8819 | 1.0401 | 1.0018 | 0.9895 | 0.9997 | 0.8614 |
| EFTA | 0.9436 | 0.7008 | 1.3181 | 0.9875 | 1.0188 | 1.0065 | 1.0042 | 0.8864 |
| R.o. OECD | 0.9441 | 0.7348 | 1.1275 | 0.9221 | 1.0282 | 1.0087 | 1.0085 | 0.7544 |
| China | 0.8178 | 0.6810 | 0.9262 | 0.9823 | 0.9978 | 1.0079 | 0.9578 | 0.4881 |

Table C.2: Decomposition of changes in energy efficiency, 1997–2014 – index form

Results from the multiplicative LMDI-I decomposition. The same results are summarized graphically in Figure (2). in the main text.

| Region | act | int | sup | str | trd | mix | ehh | total |
|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| <i>Territorial Production</i> | | | | | | | | |
| EU 28 | 0.9824 | 0.8977 | 0.9960 | 1.0043 | 0.9930 | 1.0001 | 1.0077 | 0.8828 |
| USA | 0.9636 | 1.1438 | 0.7155 | 1.0370 | 0.9977 | 1.0046 | 0.9999 | 0.8195 |
| Japan | 1.0207 | 1.8698 | 0.4835 | 1.0656 | 1.0089 | 1.0018 | 1.0005 | 0.9944 |
| EFTA | 0.9551 | 0.5884 | 1.5981 | 1.0559 | 0.9887 | 1.0030 | 1.0026 | 0.9427 |
| R.o. OECD | 0.9735 | 0.9222 | 0.9521 | 0.9254 | 0.9946 | 1.0034 | 1.0092 | 0.7966 |
| China | 0.8532 | 0.6146 | 1.1975 | 1.0733 | 1.0017 | 1.0003 | 0.9692 | 0.6545 |
| <i>Final Production</i> | | | | | | | | |
| EU 28 | 0.9875 | 0.7932 | 1.2927 | 0.9881 | NA | 1.0008 | 1.0063 | 1.0076 |
| USA | 0.9619 | 1.0333 | 0.8429 | 1.0278 | NA | 1.0043 | 0.9999 | 0.8647 |
| Japan | 0.9938 | 1.3100 | 0.7044 | 1.0495 | NA | 1.0019 | 1.0004 | 0.9647 |
| EFTA | 0.9578 | 0.6440 | 1.7781 | 1.0525 | NA | 1.0038 | 1.0021 | 1.1611 |
| R.o. OECD | 0.9740 | 0.8378 | 1.0900 | 0.9126 | NA | 1.0035 | 1.0088 | 0.8216 |
| China | 0.8566 | 0.6212 | 1.1366 | 1.0704 | NA | 1.0012 | 0.9675 | 0.6271 |
| <i>Final Consumption</i> | | | | | | | | |
| EU 28 | 0.9876 | 0.7898 | 1.2908 | 1.0038 | 0.9971 | 1.0010 | 1.0061 | 1.0148 |
| USA | 0.9612 | 0.9877 | 0.8900 | 1.0330 | 1.0042 | 1.0044 | 0.9999 | 0.8803 |
| Japan | 0.9941 | 1.2323 | 0.7564 | 1.0250 | 0.9993 | 1.0019 | 1.0004 | 0.9513 |
| EFTA | 0.9562 | 0.7030 | 1.5003 | 1.0050 | 0.9911 | 1.0028 | 1.0016 | 1.0090 |
| R.o. OECD | 0.9649 | 0.8370 | 1.0950 | 0.9330 | 1.0193 | 1.0035 | 1.0088 | 0.8514 |
| China | 0.8494 | 0.6305 | 1.1185 | 1.0653 | 0.9970 | 1.0012 | 0.9640 | 0.6140 |

Table C.3: Decomposition of changes in energy efficiency, 1997–2007 – index form
Results from the multiplicative LMDI-I decomposition. The same results are summarized graphically in Figure (3) in the main text.

| Region | act | int | sup | str | trd | mix | ehh | total |
|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| <i>Territorial Production</i> | | | | | | | | |
| EU 28 | 1.0120 | 0.8061 | 1.0659 | 1.0192 | 1.0063 | 0.9988 | 0.9948 | 0.8861 |
| USA | 1.0033 | 0.8986 | 1.0127 | 1.0124 | 1.0026 | 0.9998 | 1.0097 | 0.9356 |
| Japan | 1.0198 | 0.7730 | 1.0872 | 1.0259 | 0.9981 | 0.9806 | 0.9991 | 0.8597 |
| EFTA | 0.9861 | 1.1162 | 0.8633 | 0.9769 | 0.9958 | 1.0000 | 1.0035 | 0.9276 |
| R.o. OECD | 0.9928 | 0.8229 | 1.0629 | 1.0013 | 1.0012 | 1.0005 | 1.0000 | 0.8710 |
| China | 0.9575 | 1.1454 | 0.7311 | 0.9434 | 0.9964 | 1.0012 | 0.9893 | 0.7465 |
| <i>Final Production</i> | | | | | | | | |
| EU 28 | 0.9951 | 0.8773 | 1.0156 | 1.0236 | NA | 0.9991 | 0.9960 | 0.9031 |
| USA | 0.9964 | 0.9086 | 0.9628 | 1.0144 | NA | 0.9998 | 1.0090 | 0.8920 |
| Japan | 0.9978 | 0.8370 | 1.0583 | 1.0246 | NA | 0.9871 | 0.9992 | 0.8933 |
| EFTA | 0.9963 | 1.0285 | 0.8886 | 0.9766 | NA | 1.0005 | 1.0026 | 0.8920 |
| R.o. OECD | 0.9925 | 0.8593 | 1.0321 | 0.9989 | NA | 1.0004 | 1.0000 | 0.8797 |
| China | 0.9666 | 1.1088 | 0.7980 | 0.9395 | NA | 1.0014 | 0.9890 | 0.7958 |
| <i>Final Consumption</i> | | | | | | | | |
| EU 28 | 0.9945 | 0.8891 | 1.0099 | 1.0108 | 1.0105 | 0.9990 | 0.9962 | 0.9078 |
| USA | 0.9970 | 0.9149 | 0.9653 | 1.0001 | 0.9949 | 0.9997 | 1.0085 | 0.8834 |
| Japan | 0.9975 | 0.8508 | 1.0507 | 1.0220 | 1.0054 | 0.9890 | 0.9993 | 0.9055 |
| EFTA | 0.9896 | 0.9956 | 0.8824 | 0.9744 | 1.0344 | 1.0002 | 1.0022 | 0.8785 |
| R.o. OECD | 0.9909 | 0.8693 | 1.0226 | 0.9922 | 1.0135 | 1.0004 | 1.0000 | 0.8861 |
| China | 0.9538 | 1.1011 | 0.8047 | 0.9478 | 1.0029 | 1.0018 | 0.9878 | 0.7950 |

Table C.4: Decomposition of changes in energy efficiency, 2007–2014 – index form
Results from the multiplicative LMDI-I decomposition. The same results are summarized graphically in Figure (3) in the main text.

C.2 Average annual growth rates of energy intensity for selected regions

Table C.5 reports average annual growth rates in energy intensity and in energy efficiency factor for selected regions for the period 1997–2014 and the two sub-periods 1997–2007 and 2007–2014. The last two columns in the table show energy intensity (defined as energy usage divided by value added) at the beginning of each sub-period.

| Region | %Δ Energy Intensity | | | %Δ Energy Efficiency Factor | | | Energy Intensity | |
|-------------------------|---------------------|---------|---------|-----------------------------|---------|---------|------------------|------|
| | 97 – 14 | 97 – 07 | 07 – 14 | 97 – 14 | 97 – 07 | 07 – 14 | 1997 | 2007 |
| | <i>percent</i> | | | | | | <i>kgoe/USD</i> | |
| <i>Production</i> | | | | | | | | |
| EU 28 | -1.28 | -1.17 | -1.63 | -1.59 | -1.02 | -2.77 | 0.24 | 0.21 |
| USA | -1.37 | -1.81 | -0.92 | 0.18 | 1.44 | -1.45 | 0.29 | 0.23 |
| Japan | -0.85 | -0.06 | -2.00 | 2.06 | 8.70 | -3.24 | 0.14 | 0.14 |
| EFTA | -0.74 | -0.57 | -1.03 | -1.83 | -4.12 | 1.66 | 0.15 | 0.14 |
| R.o. OECD | -1.80 | -2.03 | -1.84 | -1.32 | -0.78 | -2.53 | 0.41 | 0.33 |
| China | -3.01 | -3.46 | -3.62 | -1.95 | -3.85 | 2.08 | 1.64 | 1.07 |
| <i>Final Production</i> | | | | | | | | |
| EU 28 | -0.53 | 0.08 | -1.38 | -1.85 | -2.07 | -1.75 | 0.27 | 0.27 |
| USA | -1.35 | -1.35 | -1.54 | -0.32 | 0.33 | -1.31 | 0.30 | 0.26 |
| Japan | -0.81 | -0.35 | -1.52 | 0.08 | 3.10 | -2.33 | 0.17 | 0.17 |
| EFTA | 0.21 | 1.61 | -1.54 | -1.86 | -3.56 | 0.41 | 0.18 | 0.21 |
| R.o. OECD | -1.63 | -1.78 | -1.72 | -1.60 | -1.62 | -2.01 | 0.42 | 0.34 |
| China | -2.95 | -3.73 | -2.92 | -1.94 | -3.79 | 1.55 | 1.50 | 0.94 |
| <i>Consumption</i> | | | | | | | | |
| EU 28 | -0.46 | 0.15 | -1.32 | -1.79 | -2.10 | -1.58 | 0.28 | 0.28 |
| USA | -1.31 | -1.20 | -1.67 | -0.54 | -0.12 | -1.22 | 0.31 | 0.27 |
| Japan | -0.82 | -0.49 | -1.35 | -0.20 | 2.32 | -2.13 | 0.18 | 0.17 |
| EFTA | -0.67 | 0.09 | -1.74 | -1.76 | -2.97 | -0.06 | 0.24 | 0.24 |
| R.o. OECD | -1.44 | -1.49 | -1.63 | -1.56 | -1.63 | -1.87 | 0.41 | 0.35 |
| China | -3.01 | -3.86 | -2.93 | -1.88 | -3.69 | 1.44 | 1.50 | 0.92 |

Table C.5: Average annual growth rates of energy intensities

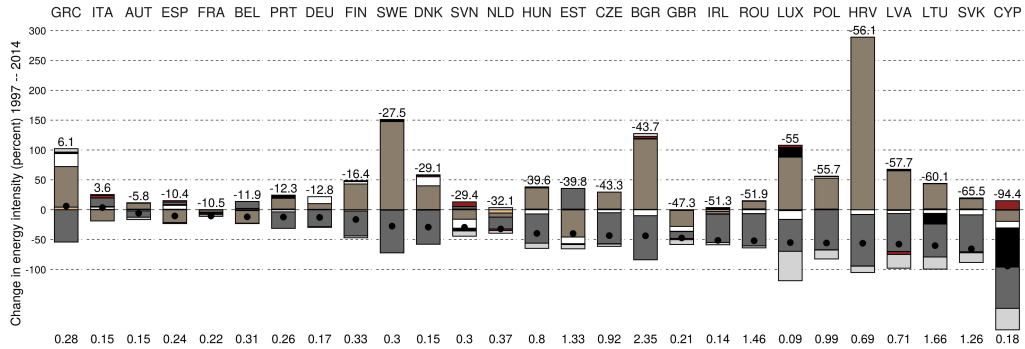
Note: Energy intensity is defined as economy-wide energy usage in kilogram of oil equivalents (*kgoe*) per unit of national value added expressed in 1997 US dollars.

C.3 Decomposition results for individual EU countries

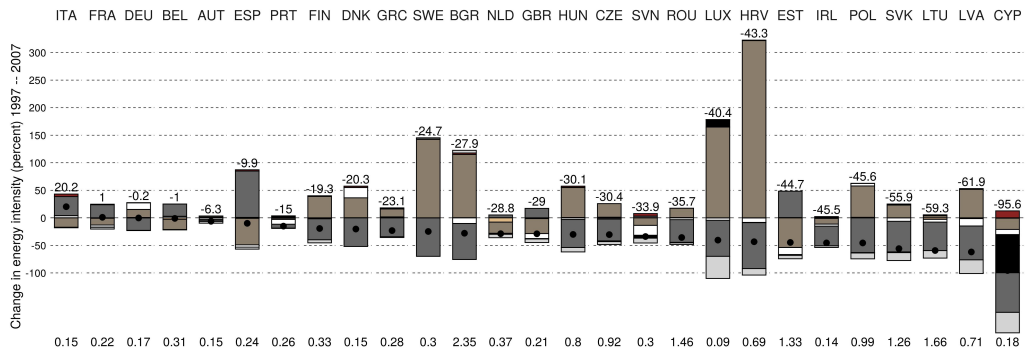
Figures C.1 – C.3 provide a graphical summary of the results of the multiplicative LMDI-I decompositions for 27 members of the EU 28. Malta was excluded from the analysis because of it reported no energy usage in some of the earlier years in our sample, which resulted in problems for the decompositions. We present the same information as in Figures C.1–C.3 in index form in Tables C.6 – C.8.

Decomposition results: production inventory

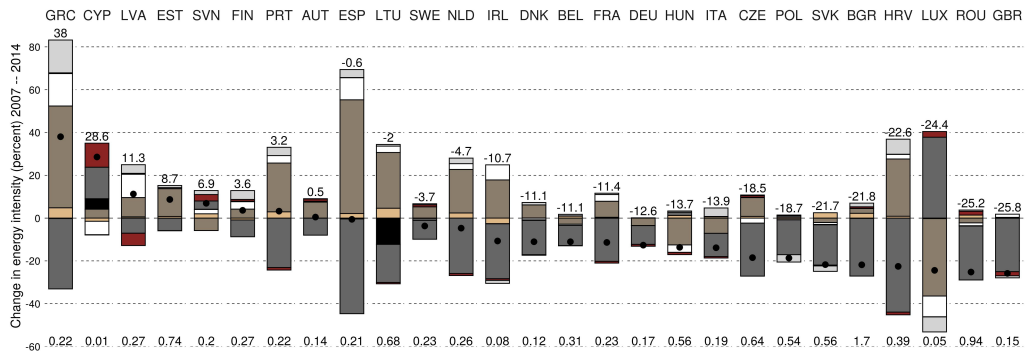
1997–2014



1997–2007



2007–2014

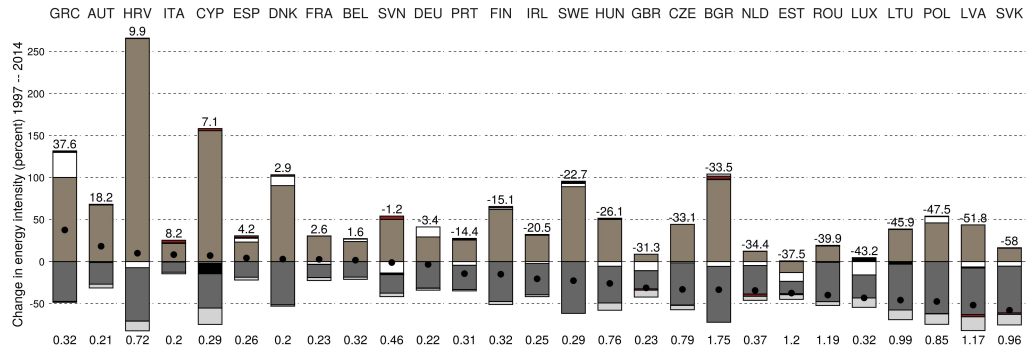


● Change in total Energy Intensity (%)
 act
 int
 sup
 str
 trd
 mix
 eh

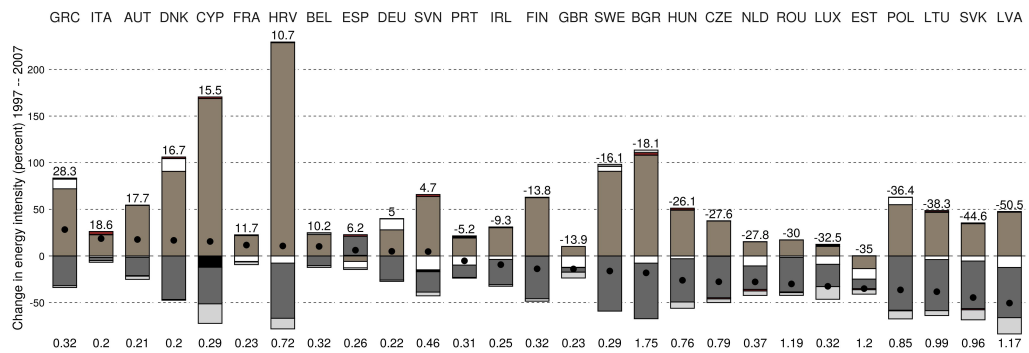
Figure C.1: Decomposition of changes in energy intensity (production inventory)

Note: Countries, referred to by their ISO-3 codes, are sorted according to the magnitude of the change in their energy intensity, which is shown at the top of the stacked bars (and denoted by the black dots). The values reported beneath the x-axis refer to the energy intensity of the member-state at the beginning of the period (measured in *kgoe* per dollar of value added). All monetary values are deflated using the base year 1997.

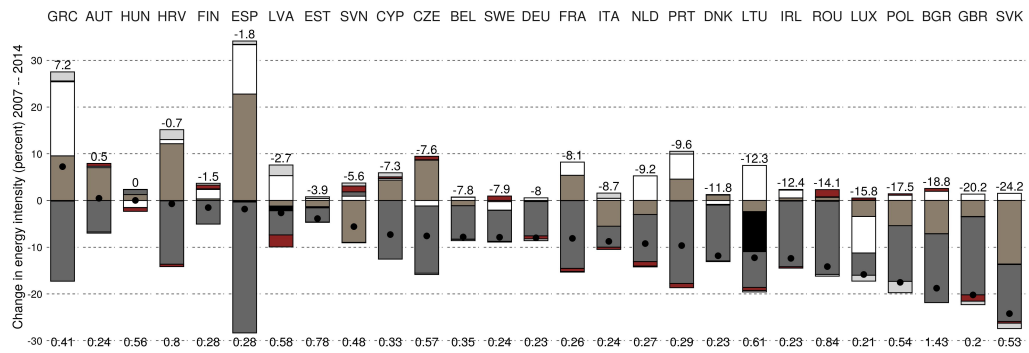
Decomposition results: final production inventory 1997–2014



1997–2007



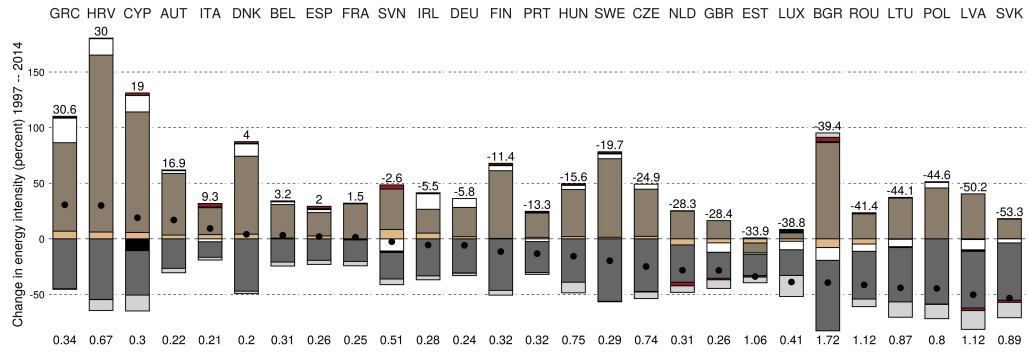
2007–2014



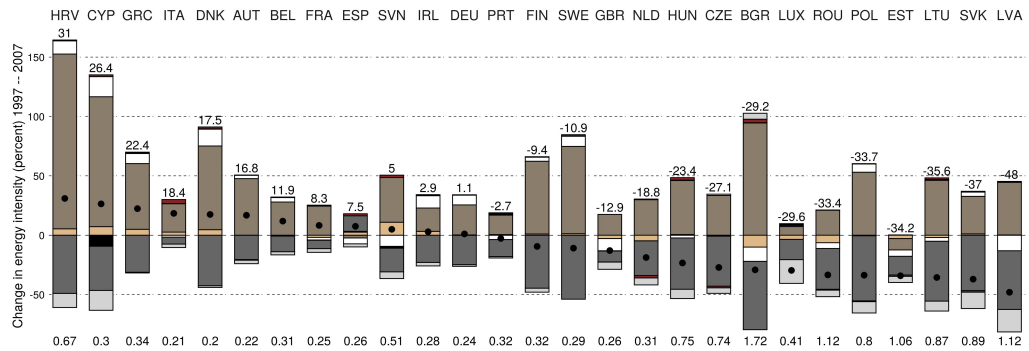
● Change in total Energy Intensity (%)
 act
 int
 sup
 str
 trd
 mix
 eh

Figure C.2: Decomposition of changes in energy intensity (final production inventory)
 Notes as in Figure C.1.

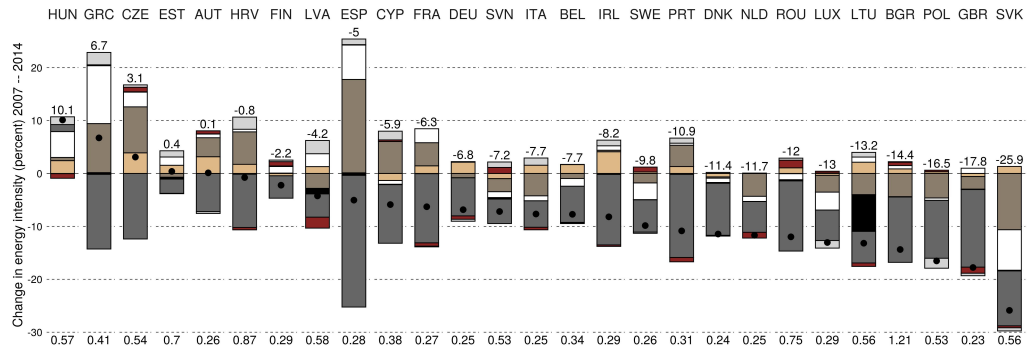
Decomposition results: consumption inventory 1997–2014



1997–2007



2007–2014



● Change in total Energy Intensity (%)
 act
 int
 sup
 str
 trd
 mix
 eh

Figure C.3: Decomposition of changes in energy intensity (consumption inventory)
 Notes as in Figure C.1.

For all energy inventories, the majority of the member states improved their energy intensity between 1997 and 2014. This pattern was most pronounced for energy usage for territorial production, where all members except two (Greece and Italy) showed such improvements. For the footprint-based inventories, nine member states (Greece, Italy, and also Austria, Belgium, Croatia, Cyprus, Denmark, France, and Spain) did not show improvements. Energy intensity gains in the new Central and Eastern European (EEU) members states were above average in general. These countries started out with a relatively high energy intensity in 1997.

| Region | act | int | sup | str | trd | mix | ehh | Total |
|-----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| <i>Total Period: 1997 – 2014</i> | | | | | | | | |
| AUT | 0.9599 | 0.8951 | 1.1007 | 0.9800 | 1.0082 | 1.0057 | 1.0022 | 0.9418 |
| BEL | 0.9939 | 1.1153 | 0.7892 | 1.0178 | 0.9850 | 1.0039 | 1.0002 | 0.8807 |
| BGR | 1.0496 | 0.2614 | 2.1782 | 0.9004 | 1.0051 | 1.0066 | 1.0349 | 0.5634 |
| CYP | 0.6401 | 0.3093 | 0.8118 | 0.8897 | 0.9940 | 0.3446 | 1.1507 | 0.0564 |
| CZE | 0.9606 | 0.4809 | 1.2834 | 0.9499 | 1.0109 | 1.0008 | 0.9953 | 0.5671 |
| DEU | 0.9919 | 0.7174 | 1.0957 | 1.1164 | 1.0059 | 0.9993 | 0.9961 | 0.8716 |
| DNK | 1.0100 | 0.4274 | 1.3972 | 1.1515 | 1.0024 | 0.9945 | 1.0234 | 0.7087 |
| ESP | 0.9833 | 1.0410 | 0.7850 | 1.0652 | 1.0076 | 1.0129 | 1.0253 | 0.8957 |
| EST | 0.9279 | 1.3474 | 0.5453 | 0.8888 | 0.9980 | 1.0093 | 0.9856 | 0.6015 |
| FIN | 0.9684 | 0.5840 | 1.4304 | 1.0396 | 0.9777 | 1.0037 | 1.0131 | 0.8362 |
| FRA | 0.9721 | 0.9777 | 0.9626 | 0.9845 | 0.9968 | 0.9949 | 1.0019 | 0.8949 |
| GBR | 0.9184 | 0.8844 | 0.7334 | 0.9181 | 0.9878 | 0.9954 | 0.9799 | 0.5269 |
| GRC | 1.0573 | 0.4591 | 1.6786 | 1.2181 | 1.0431 | 1.0088 | 1.0159 | 1.0608 |
| HRV | 0.8933 | 0.1374 | 3.8883 | 0.9225 | 0.9985 | 1.0009 | 0.9975 | 0.4387 |
| HUN | 0.9131 | 0.5106 | 1.3546 | 0.9297 | 1.0100 | 1.0048 | 1.0130 | 0.6035 |
| IRL | 0.9604 | 0.5276 | 0.9594 | 0.9950 | 0.9708 | 1.0334 | 1.0026 | 0.4866 |
| ITA | 1.0145 | 1.1424 | 0.8123 | 1.0387 | 1.0051 | 1.0093 | 1.0441 | 1.0356 |
| LTU | 0.7971 | 0.4478 | 1.4219 | 0.9389 | 1.0133 | 0.8222 | 1.0050 | 0.3990 |
| LUX | 0.5071 | 0.4660 | 1.8800 | 0.8536 | 0.9849 | 1.1602 | 1.0388 | 0.4501 |
| LVA | 0.7701 | 0.3650 | 1.6511 | 0.9482 | 0.9883 | 1.0254 | 0.9496 | 0.4235 |
| NLD | 0.9549 | 0.8023 | 0.9320 | 1.0334 | 0.9444 | 1.0014 | 0.9729 | 0.6789 |
| POL | 0.8499 | 0.3299 | 1.5175 | 1.0270 | 1.0107 | 1.0065 | 0.9962 | 0.4427 |
| PRT | 1.0146 | 0.7237 | 1.1803 | 0.9642 | 1.0109 | 1.0378 | 1.0005 | 0.8771 |
| ROU | 0.9668 | 0.4623 | 1.1291 | 0.9356 | 1.0128 | 0.9967 | 1.0089 | 0.4809 |
| SVK | 0.8380 | 0.3813 | 1.1725 | 0.9146 | 1.0120 | 1.0135 | 0.9830 | 0.3455 |
| SVN | 0.9116 | 1.0416 | 0.8411 | 0.8496 | 1.0111 | 0.9545 | 1.0787 | 0.7063 |
| SWE | 1.0005 | 0.2848 | 2.4748 | 1.0145 | 0.9933 | 1.0096 | 1.0107 | 0.7250 |
| <i>First Period: 1997 – 2007</i> | | | | | | | | |
| AUT | 0.9671 | 0.9711 | 1.0205 | 0.9736 | 1.0089 | 1.0045 | 0.9914 | 0.9374 |
| BEL | 0.9934 | 1.2223 | 0.8136 | 1.0245 | 0.9743 | 1.0030 | 1.0011 | 0.9901 |
| BGR | 1.0482 | 0.3463 | 2.1479 | 0.8979 | 1.0026 | 1.0007 | 1.0260 | 0.7206 |
| CYP | 0.6274 | 0.2816 | 0.7957 | 0.9063 | 0.9947 | 0.3071 | 1.1262 | 0.0438 |
| CZE | 0.9468 | 0.6034 | 1.2468 | 0.9815 | 1.0110 | 0.9965 | 0.9874 | 0.6956 |
| DEU | 0.9956 | 0.7738 | 1.1460 | 1.1198 | 1.0052 | 0.9992 | 1.0048 | 0.9978 |
| DNK | 1.0007 | 0.4803 | 1.3618 | 1.1867 | 1.0013 | 1.0002 | 1.0242 | 0.7967 |
| ESP | 0.9633 | 1.8414 | 0.5179 | 0.9588 | 0.9919 | 1.0076 | 1.0235 | 0.9009 |
| EST | 0.9372 | 1.4797 | 0.4624 | 0.8716 | 1.0014 | 1.0027 | 0.9860 | 0.5534 |
| FIN | 0.9441 | 0.6182 | 1.3881 | 1.0082 | 0.9877 | 0.9962 | 1.0041 | 0.8069 |
| FRA | 0.9672 | 1.2376 | 0.8765 | 0.9630 | 0.9931 | 0.9965 | 1.0098 | 1.0098 |
| GBR | 0.9345 | 1.1715 | 0.7283 | 0.9094 | 0.9868 | 0.9942 | 0.9987 | 0.7105 |
| GRC | 0.9867 | 0.6566 | 1.1446 | 1.0008 | 1.0160 | 1.0073 | 1.0120 | 0.7686 |
| HRV | 0.8830 | 0.1650 | 4.2168 | 0.9196 | 0.9976 | 0.9964 | 1.0089 | 0.5665 |
| HUN | 0.9188 | 0.4922 | 1.5437 | 0.9705 | 1.0055 | 1.0036 | 1.0223 | 0.6990 |
| IRL | 0.9690 | 0.6431 | 0.8970 | 0.9628 | 0.9900 | 1.0119 | 1.0107 | 0.5449 |
| ITA | 0.9897 | 1.3460 | 0.8299 | 1.0374 | 1.0003 | 1.0023 | 1.0455 | 1.2022 |
| LTU | 0.8635 | 0.4831 | 1.0383 | 0.9496 | 0.9733 | 1.0050 | 1.0115 | 0.4069 |
| LUX | 0.5984 | 0.3458 | 2.6478 | 0.9582 | 0.9980 | 1.1334 | 1.0027 | 0.5955 |
| LVA | 0.7505 | 0.3859 | 1.5164 | 0.8664 | 0.9860 | 1.0030 | 1.0115 | 0.3806 |
| NLD | 0.9371 | 1.0507 | 0.7971 | 0.9996 | 0.9229 | 1.0015 | 0.9825 | 0.7124 |
| POL | 0.8931 | 0.3697 | 1.5696 | 1.0459 | 1.0085 | 1.0027 | 0.9929 | 0.5443 |
| PRT | 0.9942 | 0.9294 | 0.9778 | 0.9128 | 0.9938 | 1.0230 | 1.0132 | 0.8495 |
| ROU | 0.9683 | 0.5886 | 1.1687 | 0.9670 | 1.0049 | 1.0006 | 0.9928 | 0.6430 |
| SVK | 0.8551 | 0.4441 | 1.2321 | 0.9380 | 0.9997 | 1.0187 | 0.9876 | 0.4414 |
| SVN | 0.9115 | 1.0302 | 0.8641 | 0.8200 | 1.0005 | 0.9480 | 1.0468 | 0.6606 |
| SWE | 1.0040 | 0.3018 | 2.4231 | 1.0218 | 0.9995 | 1.0026 | 1.0013 | 0.7527 |
| <i>Second Period: 2007 – 2014</i> | | | | | | | | |
| AUT | 1.0016 | 0.9204 | 1.0746 | 1.0037 | 0.9998 | 1.0001 | 1.0105 | 1.0047 |
| BEL | 1.0075 | 0.9054 | 0.9717 | 0.9943 | 1.0089 | 1.0011 | 0.9991 | 0.8894 |
| BGR | 1.0173 | 0.7306 | 1.0224 | 0.9985 | 1.0223 | 1.0011 | 1.0069 | 0.7818 |
| CYP | 0.9985 | 1.1472 | 1.0415 | 0.9373 | 0.9853 | 1.0488 | 1.1125 | 1.2856 |
| CZE | 1.0029 | 0.7521 | 1.0877 | 0.9767 | 1.0079 | 1.0013 | 1.0080 | 0.8152 |
| DEU | 0.9995 | 0.9124 | 0.9652 | 1.0005 | 1.0007 | 0.9998 | 0.9914 | 0.8735 |
| DNK | 1.0114 | 0.8397 | 1.0611 | 0.9919 | 1.0003 | 0.9975 | 0.9973 | 0.8895 |
| ESP | 1.0375 | 0.5571 | 1.5312 | 1.1032 | 1.0213 | 0.9962 | 1.0010 | 0.9943 |
| EST | 1.0103 | 0.9418 | 1.1295 | 1.0048 | 1.0077 | 0.9997 | 0.9992 | 1.0869 |
| FIN | 1.0416 | 0.9213 | 1.0418 | 1.0348 | 0.9914 | 1.0023 | 1.0081 | 1.0362 |
| FRA | 1.0064 | 0.7983 | 1.0748 | 1.0314 | 1.0037 | 0.9998 | 0.9917 | 0.8862 |
| GBR | 0.9902 | 0.7504 | 1.0028 | 1.0150 | 1.0004 | 0.9994 | 0.9808 | 0.7417 |
| GRC | 1.1536 | 0.6709 | 1.4756 | 1.1515 | 1.0480 | 0.9982 | 1.0033 | 1.3802 |
| HRV | 1.0706 | 0.5608 | 1.2674 | 1.0214 | 1.0085 | 1.0007 | 0.9873 | 0.7744 |
| HUN | 1.0059 | 1.0149 | 0.8748 | 0.9653 | 1.0123 | 0.9998 | 0.9895 | 0.8634 |
| IRL | 0.9858 | 0.7435 | 1.1782 | 1.0706 | 0.9742 | 0.9991 | 0.9924 | 0.8930 |
| ITA | 1.0400 | 0.8913 | 0.9290 | 1.0011 | 1.0061 | 1.0001 | 0.9932 | 0.8615 |
| LTU | 1.0079 | 0.8220 | 1.2604 | 1.0298 | 1.0459 | 0.8774 | 0.9936 | 0.9805 |
| LUX | 0.9298 | 1.3777 | 0.6382 | 0.9031 | 0.9978 | 0.9992 | 1.0268 | 0.7558 |
| LVA | 1.0404 | 0.9296 | 1.0902 | 1.1090 | 1.0055 | 1.0043 | 0.9421 | 1.1125 |
| NLD | 1.0260 | 0.7412 | 1.2036 | 1.0268 | 1.0237 | 1.0001 | 0.9904 | 0.9530 |
| POL | 0.9656 | 0.8372 | 0.9918 | 1.0054 | 1.0055 | 1.0001 | 1.0032 | 0.8133 |
| PRT | 1.0389 | 0.7691 | 1.2280 | 1.0346 | 1.0291 | 1.0000 | 0.9882 | 1.0324 |
| ROU | 1.0062 | 0.7479 | 0.9778 | 0.9867 | 1.0139 | 0.9985 | 1.0176 | 0.7479 |
| SVK | 0.9743 | 0.8119 | 0.9794 | 0.9911 | 1.0250 | 0.9982 | 0.9962 | 0.7826 |
| SVN | 1.0188 | 1.0386 | 0.9418 | 1.0204 | 1.0199 | 1.0009 | 1.0300 | 1.0692 |
| SWE | 1.0049 | 0.9123 | 1.0524 | 0.9937 | 0.9952 | 1.0000 | 1.0096 | 0.9632 |

Table C.6: Decomposition of changes in EU member energy intensity – index form

Note: Results from the multiplicative LMDI-I decomposition on production-based energy usage of the individual EU member states. Identical results are summarized graphically in Figure (C.1) in this appendix.

| Region | act | int | sup | str | trd | mix | ehh | Total |
|-----------------------------------|--------|--------|--------|--------|-----|--------|--------|--------|
| <i>Total Period: 1997 – 2014</i> | | | | | | | | |
| AUT | 0.9550 | 0.7424 | 1.6732 | 0.9884 | NA | 1.0069 | 1.0015 | 1.1822 |
| BEL | 0.9733 | 0.8150 | 1.2377 | 1.0290 | NA | 1.0057 | 1.0002 | 1.0162 |
| BGR | 1.0255 | 0.3346 | 1.9745 | 0.9428 | NA | 1.0059 | 1.0356 | 0.6652 |
| CYP | 0.8053 | 0.5915 | 2.5569 | 0.9838 | NA | 0.8715 | 1.0258 | 1.0711 |
| CZE | 0.9478 | 0.4992 | 1.4428 | 0.9845 | NA | 0.9995 | 0.9953 | 0.6686 |
| DEU | 0.9772 | 0.6852 | 1.2928 | 1.1191 | NA | 1.0000 | 0.9970 | 0.9659 |
| DNK | 0.9830 | 0.4862 | 1.9033 | 1.1115 | NA | 1.0028 | 1.0152 | 1.0292 |
| ESP | 0.9664 | 0.8137 | 1.2317 | 1.0451 | NA | 1.0094 | 1.0202 | 1.0424 |
| EST | 0.9445 | 0.8534 | 0.8697 | 0.8952 | NA | 1.0083 | 0.9873 | 0.6247 |
| FIN | 0.9650 | 0.5241 | 1.6187 | 1.0187 | NA | 1.0043 | 1.0139 | 0.8491 |
| FRA | 0.9641 | 0.8449 | 1.3031 | 0.9680 | NA | 0.9972 | 1.0016 | 1.0263 |
| GBR | 0.9183 | 0.7843 | 1.0874 | 0.8920 | NA | 0.9990 | 0.9840 | 0.6867 |
| GRC | 0.9888 | 0.5261 | 2.0009 | 1.2979 | NA | 1.0067 | 1.0115 | 1.3758 |
| HRV | 0.8844 | 0.3655 | 3.6534 | 0.9270 | NA | 1.0055 | 0.9985 | 1.0993 |
| HUN | 0.9136 | 0.5625 | 1.5010 | 0.9446 | NA | 1.0044 | 1.0105 | 0.7395 |
| IRL | 0.9775 | 0.6281 | 1.3129 | 0.9766 | NA | 1.0079 | 1.0013 | 0.7945 |
| ITA | 0.9814 | 0.8786 | 1.2153 | 0.9945 | NA | 1.0068 | 1.0317 | 1.0824 |
| LTU | 0.8849 | 0.4543 | 1.3811 | 0.9991 | NA | 0.9699 | 1.0063 | 0.5413 |
| LUX | 0.8883 | 0.7261 | 1.0067 | 0.8409 | NA | 1.0325 | 1.0073 | 0.5679 |
| LVA | 0.8358 | 0.4461 | 1.4363 | 0.9363 | NA | 0.9866 | 0.9738 | 0.4817 |
| NLD | 0.9520 | 0.6609 | 1.1210 | 0.9529 | NA | 1.0027 | 0.9728 | 0.6556 |
| POL | 0.8755 | 0.3814 | 1.4599 | 1.0740 | NA | 1.0065 | 0.9962 | 0.5249 |
| PRT | 0.9839 | 0.7108 | 1.2557 | 0.9560 | NA | 1.0195 | 1.0004 | 0.8563 |
| ROU | 0.9546 | 0.5320 | 1.1842 | 0.9913 | NA | 0.9997 | 1.0088 | 0.6013 |
| SVK | 0.8744 | 0.4441 | 1.1588 | 0.9455 | NA | 1.0056 | 0.9816 | 0.4200 |
| SVN | 0.9583 | 0.7797 | 1.5008 | 0.8639 | NA | 0.9805 | 1.0404 | 0.9884 |
| SWE | 1.0080 | 0.3832 | 1.8907 | 1.0384 | NA | 1.0076 | 1.0112 | 0.7726 |
| <i>First Period: 1997 – 2007</i> | | | | | | | | |
| AUT | 0.9654 | 0.8033 | 1.5417 | 0.9861 | NA | 1.0037 | 0.9943 | 1.1767 |
| BEL | 0.9811 | 0.8962 | 1.2291 | 1.0160 | NA | 1.0030 | 1.0009 | 1.1023 |
| BGR | 1.0277 | 0.4038 | 2.0798 | 0.9233 | NA | 1.0014 | 1.0264 | 0.8190 |
| CYP | 0.7904 | 0.6078 | 2.6870 | 0.9980 | NA | 0.8811 | 1.0180 | 1.1554 |
| CZE | 0.9607 | 0.5549 | 1.3740 | 1.0031 | NA | 0.9972 | 0.9874 | 0.7235 |
| DEU | 0.9857 | 0.7423 | 1.2796 | 1.1175 | NA | 0.9996 | 1.0038 | 1.0498 |
| DNK | 0.9914 | 0.5338 | 1.9067 | 1.1366 | NA | 1.0023 | 1.0155 | 1.1674 |
| ESP | 0.9820 | 1.2040 | 0.9415 | 0.9315 | NA | 1.0064 | 1.0178 | 1.0619 |
| EST | 0.9525 | 0.8976 | 0.8643 | 0.8877 | NA | 1.0023 | 0.9884 | 0.6499 |
| FIN | 0.9736 | 0.5433 | 1.6240 | 1.0014 | NA | 0.9981 | 1.0042 | 0.8622 |
| FRA | 0.9706 | 0.9974 | 1.2179 | 0.9412 | NA | 0.9977 | 1.0087 | 1.1168 |
| GBR | 0.9376 | 0.9516 | 1.1024 | 0.8784 | NA | 0.9972 | 0.9989 | 0.8607 |
| GRC | 0.9805 | 0.6813 | 1.7197 | 1.1031 | NA | 1.0049 | 1.0075 | 1.2829 |
| HRV | 0.8861 | 0.4085 | 3.2856 | 0.9236 | NA | 1.0026 | 1.0055 | 1.1072 |
| HUN | 0.9323 | 0.5365 | 1.4903 | 0.9704 | NA | 1.0033 | 1.0188 | 0.7393 |
| IRL | 0.9828 | 0.7293 | 1.3020 | 0.9632 | NA | 1.0040 | 1.0048 | 0.9068 |
| ITA | 0.9810 | 0.9672 | 1.2266 | 0.9840 | NA | 1.0025 | 1.0332 | 1.1862 |
| LTU | 0.9479 | 0.4523 | 1.4666 | 0.9613 | NA | 1.0070 | 1.0135 | 0.6169 |
| LUX | 0.8644 | 0.7604 | 1.1020 | 0.9109 | NA | 1.0220 | 1.0006 | 0.6747 |
| LVA | 0.8256 | 0.4617 | 1.4686 | 0.8768 | NA | 1.0028 | 1.0053 | 0.4949 |
| NLD | 0.9522 | 0.7485 | 1.1514 | 0.8934 | NA | 1.0021 | 0.9829 | 0.7222 |
| POL | 0.9136 | 0.4187 | 1.5494 | 1.0781 | NA | 1.0030 | 0.9930 | 0.6364 |
| PRT | 0.9921 | 0.8677 | 1.1919 | 0.9025 | NA | 1.0136 | 1.0098 | 0.9478 |
| ROU | 0.9704 | 0.6293 | 1.1711 | 0.9852 | NA | 1.0015 | 0.9926 | 0.7004 |
| SVK | 0.8926 | 0.4901 | 1.3454 | 0.9457 | NA | 1.0089 | 0.9869 | 0.5542 |
| SVN | 0.9596 | 0.7819 | 1.6369 | 0.8518 | NA | 0.9792 | 1.0220 | 1.0469 |
| SWE | 1.0188 | 0.4086 | 1.9074 | 1.0522 | NA | 1.0025 | 1.0013 | 0.8386 |
| <i>Second Period: 2007 – 2014</i> | | | | | | | | |
| AUT | 0.9975 | 0.9326 | 1.0702 | 1.0028 | NA | 1.0002 | 1.0062 | 1.0047 |
| BEL | 0.9974 | 0.9284 | 0.9889 | 1.0069 | NA | 1.0005 | 0.9994 | 0.9219 |
| BGR | 1.0000 | 0.8526 | 0.9290 | 1.0196 | NA | 0.9998 | 1.0059 | 0.8123 |
| CYP | 1.0087 | 0.8745 | 1.0437 | 1.0032 | NA | 1.0004 | 1.0033 | 0.9270 |
| CZE | 0.9973 | 0.8560 | 1.0863 | 0.9883 | NA | 1.0007 | 1.0075 | 0.9241 |
| DEU | 0.9961 | 0.9265 | 0.9980 | 1.0056 | NA | 0.9998 | 0.9936 | 0.9201 |
| DNK | 1.0010 | 0.8804 | 1.0117 | 0.9917 | NA | 0.9986 | 0.9986 | 0.8817 |
| ESP | 1.0072 | 0.7197 | 1.2277 | 1.1057 | NA | 0.9968 | 1.0007 | 0.9816 |
| EST | 1.0036 | 0.9695 | 0.9868 | 1.0043 | NA | 0.9976 | 0.9994 | 0.9613 |
| FIN | 1.0039 | 0.9495 | 1.0034 | 1.0202 | NA | 1.0012 | 1.0081 | 0.9848 |
| FRA | 0.9987 | 0.8551 | 1.0538 | 1.0283 | NA | 0.9996 | 0.9934 | 0.9189 |
| GBR | 0.9925 | 0.8329 | 0.9658 | 1.0137 | NA | 0.9994 | 0.9865 | 0.7979 |
| GRC | 1.0194 | 0.8284 | 1.0954 | 1.1586 | NA | 0.9989 | 1.0018 | 1.0724 |
| HRV | 1.0212 | 0.8644 | 1.1215 | 1.0089 | NA | 0.9993 | 0.9949 | 0.9929 |
| HUN | 1.0004 | 1.0107 | 1.0126 | 0.9850 | NA | 0.9996 | 0.9921 | 1.0002 |
| IRL | 1.0015 | 0.8594 | 1.0054 | 1.0168 | NA | 0.9989 | 0.9969 | 0.8762 |
| ITA | 1.0112 | 0.9552 | 0.9449 | 1.0046 | NA | 1.0001 | 0.9952 | 0.9125 |
| LTU | 0.9970 | 0.9233 | 0.9763 | 1.0750 | NA | 0.9143 | 0.9934 | 0.8775 |
| LUX | 0.9874 | 0.9523 | 0.9659 | 0.9218 | NA | 1.0006 | 1.0046 | 0.8417 |
| LVA | 1.0229 | 0.9483 | 0.9881 | 1.0531 | NA | 0.9900 | 0.9743 | 0.9735 |
| NLD | 0.9981 | 0.8992 | 0.9701 | 1.0527 | NA | 1.0000 | 0.9905 | 0.9078 |
| POL | 0.9757 | 0.8808 | 0.9462 | 1.0112 | NA | 1.0001 | 1.0030 | 0.8248 |
| PRT | 1.0060 | 0.8237 | 1.0457 | 1.0536 | NA | 0.9988 | 0.9909 | 0.9035 |
| ROU | 0.9962 | 0.8434 | 1.0068 | 1.0009 | NA | 0.9984 | 1.0156 | 0.8585 |
| SVK | 0.9884 | 0.8783 | 0.8640 | 1.0153 | NA | 0.9988 | 0.9963 | 0.7579 |
| SVN | 1.0064 | 1.0093 | 0.9104 | 1.0091 | NA | 0.9991 | 1.0125 | 0.9441 |
| SWE | 0.9985 | 0.9335 | 0.9975 | 0.9819 | NA | 0.9997 | 1.0095 | 0.9213 |

Table C.7: Decomposition of changes in EU member final production-based energy intensity – index form

Note: Results from the multiplicative LMDI-I decomposition on final production-based energy usage of the individual EU member states. Identical results are summarized graphically in Figure (C.2) in this appendix.

| Region | act | int | sup | str | trd | mix | ehh | Total |
|-----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| <i>Total Period: 1997 – 2014</i> | | | | | | | | |
| AUT | 0.9601 | 0.7347 | 1.5542 | 1.0245 | 1.0337 | 1.0056 | 1.0013 | 1.1692 |
| BEL | 0.9642 | 0.7912 | 1.3014 | 1.0246 | 1.0064 | 1.0083 | 1.0002 | 1.0324 |
| BGR | 1.0398 | 0.3659 | 1.8655 | 0.8847 | 0.9221 | 1.0071 | 1.0401 | 0.6064 |
| CYP | 0.8573 | 0.5998 | 2.0835 | 1.1475 | 1.0573 | 0.8943 | 1.0233 | 1.1896 |
| CZE | 0.9412 | 0.5275 | 1.4247 | 1.0452 | 1.0217 | 0.9996 | 0.9948 | 0.7511 |
| DEU | 0.9786 | 0.6942 | 1.2633 | 1.0805 | 1.0189 | 0.9995 | 0.9972 | 0.9416 |
| DNK | 0.9782 | 0.5295 | 1.7009 | 1.1109 | 1.0418 | 1.0049 | 1.0155 | 1.0404 |
| ESP | 0.9635 | 0.8068 | 1.2109 | 1.0262 | 1.0256 | 1.0091 | 1.0209 | 1.0205 |
| EST | 0.9487 | 0.8084 | 0.9115 | 0.9871 | 0.9627 | 1.0083 | 0.9867 | 0.6609 |
| FIN | 0.9573 | 0.5364 | 1.6085 | 1.0454 | 1.0037 | 1.0074 | 1.0143 | 0.8855 |
| FRA | 0.9608 | 0.8060 | 1.3144 | 1.0046 | 0.9928 | 0.9979 | 1.0015 | 1.0146 |
| GBR | 0.9224 | 0.7666 | 1.1637 | 0.9156 | 0.9638 | 0.9996 | 0.9863 | 0.7160 |
| GRC | 0.9946 | 0.5513 | 1.7960 | 1.2205 | 1.0686 | 1.0065 | 1.0104 | 1.3062 |
| HRV | 0.9019 | 0.4551 | 2.5912 | 1.1472 | 1.0610 | 1.0055 | 0.9987 | 1.2998 |
| HUN | 0.9043 | 0.6101 | 1.4225 | 1.0373 | 1.0207 | 1.0039 | 1.0115 | 0.8437 |
| IRL | 0.9648 | 0.6670 | 1.2144 | 1.1392 | 1.0513 | 1.0082 | 1.0012 | 0.9447 |
| ITA | 0.9756 | 0.8599 | 1.2419 | 0.9738 | 1.0376 | 1.0065 | 1.0318 | 1.0933 |
| LTU | 0.8624 | 0.5113 | 1.3661 | 0.9334 | 0.9963 | 0.9916 | 1.0067 | 0.5592 |
| LUX | 0.8104 | 0.7691 | 1.0526 | 0.9238 | 0.9782 | 1.0265 | 1.0056 | 0.6119 |
| LVA | 0.8308 | 0.4908 | 1.4043 | 0.9081 | 0.9935 | 0.9860 | 0.9768 | 0.4975 |
| NLD | 0.9412 | 0.6648 | 1.2493 | 1.0002 | 0.9455 | 1.0036 | 0.9670 | 0.7174 |
| POL | 0.8718 | 0.4141 | 1.4568 | 1.0499 | 1.0003 | 1.0065 | 0.9961 | 0.5538 |
| PRT | 0.9837 | 0.7212 | 1.2188 | 0.9753 | 1.0131 | 1.0146 | 1.0004 | 0.8673 |
| ROU | 0.9318 | 0.5707 | 1.2241 | 0.9343 | 0.9536 | 1.0016 | 1.0088 | 0.5860 |
| SVK | 0.8619 | 0.4848 | 1.1767 | 0.9636 | 1.0008 | 1.0043 | 0.9805 | 0.4669 |
| SVN | 0.9488 | 0.7614 | 1.3633 | 0.8909 | 1.0840 | 0.9867 | 1.0379 | 0.9742 |
| SWE | 0.9951 | 0.4387 | 1.7066 | 1.0429 | 1.0136 | 1.0082 | 1.0114 | 0.8032 |
| <i>First Period: 1997 – 2007</i> | | | | | | | | |
| AUT | 0.9704 | 0.7955 | 1.4763 | 1.0277 | 0.9996 | 1.0029 | 0.9947 | 1.1679 |
| BEL | 0.9734 | 0.8680 | 1.2796 | 1.0371 | 0.9929 | 1.0040 | 1.0009 | 1.1188 |
| BGR | 1.0505 | 0.4242 | 1.9450 | 0.8801 | 0.9000 | 1.0022 | 1.0295 | 0.7082 |
| CYP | 0.8324 | 0.6280 | 2.0942 | 1.1692 | 1.0717 | 0.9073 | 1.0156 | 1.2639 |
| CZE | 0.9538 | 0.5786 | 1.3342 | 1.0115 | 0.9942 | 0.9978 | 0.9859 | 0.7285 |
| DEU | 0.9861 | 0.7522 | 1.2531 | 1.0818 | 1.0022 | 0.9996 | 1.0036 | 1.0108 |
| DNK | 0.9858 | 0.5745 | 1.7054 | 1.1415 | 1.0460 | 1.0031 | 1.0157 | 1.1749 |
| ESP | 0.9740 | 1.1312 | 0.9771 | 0.9504 | 1.0254 | 1.0065 | 1.0176 | 1.0747 |
| EST | 0.9481 | 0.8424 | 0.9040 | 0.9465 | 0.9721 | 1.0025 | 0.9884 | 0.6583 |
| FIN | 0.9664 | 0.5539 | 1.6126 | 1.0341 | 1.0101 | 1.0000 | 1.0044 | 0.9057 |
| FRA | 0.9686 | 0.9293 | 1.2449 | 0.9781 | 0.9819 | 0.9978 | 1.0082 | 1.0827 |
| GBR | 0.9391 | 0.9076 | 1.1751 | 0.8971 | 0.9720 | 0.9980 | 0.9991 | 0.8708 |
| GRC | 0.9939 | 0.6882 | 1.5536 | 1.0850 | 1.0493 | 1.0049 | 1.0066 | 1.2239 |
| HRV | 0.8812 | 0.5101 | 2.4724 | 1.1107 | 1.0533 | 1.0027 | 1.0048 | 1.3098 |
| HUN | 0.9214 | 0.5678 | 1.4549 | 0.9771 | 1.0056 | 1.0034 | 1.0211 | 0.7663 |
| IRL | 0.9702 | 0.7711 | 1.1969 | 1.1035 | 1.0320 | 1.0046 | 1.0045 | 1.0290 |
| ITA | 0.9707 | 0.9416 | 1.2384 | 0.9839 | 1.0261 | 1.0026 | 1.0333 | 1.1841 |
| LTU | 0.9163 | 0.4956 | 1.4620 | 0.9690 | 0.9804 | 1.0075 | 1.0136 | 0.6441 |
| LUX | 0.8003 | 0.8288 | 1.0725 | 1.0088 | 0.9653 | 1.0153 | 1.0005 | 0.7037 |
| LVA | 0.8103 | 0.5059 | 1.4428 | 0.8692 | 1.0020 | 1.0040 | 1.0045 | 0.5195 |
| NLD | 0.9413 | 0.7075 | 1.2987 | 1.0030 | 0.9529 | 1.0028 | 0.9798 | 0.8123 |
| POL | 0.9048 | 0.4518 | 1.5302 | 1.0694 | 0.9954 | 1.0032 | 0.9930 | 0.6634 |
| PRT | 0.9881 | 0.8563 | 1.1640 | 0.9637 | 1.0051 | 1.0111 | 1.0087 | 0.9729 |
| ROU | 0.9450 | 0.6564 | 1.2102 | 0.9515 | 0.9368 | 1.0023 | 0.9928 | 0.6658 |
| SVK | 0.8621 | 0.5335 | 1.3161 | 1.0360 | 1.0109 | 1.0069 | 0.9868 | 0.6299 |
| SVN | 0.9435 | 0.8005 | 1.3770 | 0.9064 | 1.1089 | 0.9846 | 1.0200 | 1.0496 |
| SWE | 1.0092 | 0.4610 | 1.7352 | 1.0856 | 1.0124 | 1.0028 | 1.0013 | 0.8909 |
| <i>Second Period: 2007 – 2014</i> | | | | | | | | |
| AUT | 0.9965 | 0.9279 | 1.0360 | 1.0070 | 1.0315 | 1.0003 | 1.0059 | 1.0012 |
| BEL | 0.9985 | 0.9316 | 0.9905 | 0.9854 | 1.0168 | 1.0003 | 0.9993 | 0.9228 |
| BGR | 1.0011 | 0.8764 | 0.9562 | 1.0063 | 1.0086 | 0.9994 | 1.0062 | 0.8563 |
| CYP | 1.0166 | 0.8892 | 1.0603 | 0.9929 | 0.9868 | 0.9992 | 1.0030 | 0.9412 |
| CZE | 1.0046 | 0.8762 | 1.0870 | 1.0278 | 1.0389 | 1.0006 | 1.0086 | 1.0310 |
| DEU | 0.9962 | 0.9279 | 0.9920 | 1.0012 | 1.0212 | 0.9999 | 0.9936 | 0.9315 |
| DNK | 1.0020 | 0.9016 | 0.9976 | 0.9918 | 0.9936 | 0.9985 | 0.9986 | 0.8855 |
| ESP | 1.0107 | 0.7510 | 1.1766 | 1.0650 | 1.0011 | 0.9965 | 1.0007 | 0.9496 |
| EST | 1.0118 | 0.9730 | 0.9929 | 1.0157 | 1.0154 | 0.9964 | 0.9994 | 1.0040 |
| FIN | 1.0031 | 0.9575 | 1.0006 | 1.0125 | 0.9957 | 1.0010 | 1.0081 | 0.9778 |
| FRA | 0.9986 | 0.8692 | 1.0437 | 1.0265 | 1.0143 | 0.9997 | 0.9937 | 0.9371 |
| GBR | 0.9952 | 0.8533 | 0.9761 | 1.0100 | 0.9943 | 0.9993 | 0.9885 | 0.8222 |
| GRC | 1.0235 | 0.8589 | 1.0927 | 1.1095 | 1.0015 | 0.9984 | 1.0016 | 1.0673 |
| HRV | 1.0230 | 0.8992 | 1.0613 | 1.0049 | 1.0173 | 0.9987 | 0.9956 | 0.9923 |
| HUN | 1.0146 | 1.0134 | 1.0060 | 1.0489 | 1.0241 | 0.9997 | 0.9912 | 1.1011 |
| IRL | 1.0108 | 0.8666 | 1.0029 | 1.0083 | 1.0409 | 0.9983 | 0.9972 | 0.9180 |
| ITA | 1.0137 | 0.9499 | 0.9578 | 0.9907 | 1.0155 | 1.0000 | 0.9952 | 0.9234 |
| LTU | 1.0089 | 0.9402 | 0.9600 | 1.0097 | 1.0212 | 0.9306 | 0.9935 | 0.8682 |
| LUX | 0.9857 | 0.9423 | 0.9682 | 0.9661 | 0.9966 | 1.0007 | 1.0035 | 0.8695 |
| LVA | 1.0251 | 0.9560 | 0.9719 | 1.0243 | 1.0129 | 0.9896 | 0.9793 | 0.9576 |
| NLD | 1.0003 | 0.9418 | 0.9569 | 0.9902 | 1.0004 | 0.9999 | 0.9891 | 0.8832 |
| POL | 0.9812 | 0.8905 | 0.9537 | 0.9956 | 1.0032 | 0.9999 | 1.0030 | 0.8347 |
| PRT | 1.0097 | 0.8429 | 1.0402 | 1.0039 | 1.0130 | 0.9983 | 0.9918 | 0.8915 |
| ROU | 1.0040 | 0.8673 | 0.9996 | 0.9886 | 1.0106 | 0.9978 | 1.0144 | 0.8802 |
| SVK | 0.9940 | 0.8961 | 0.8937 | 0.9235 | 1.0132 | 0.9987 | 0.9964 | 0.7412 |
| SVN | 1.0104 | 0.9537 | 0.9753 | 0.9889 | 0.9903 | 0.9972 | 1.0113 | 0.9281 |
| SWE | 0.9977 | 0.9390 | 0.9822 | 0.9684 | 1.0028 | 0.9997 | 1.0093 | 0.9015 |

Table C.8: Decomposition of changes in EU member final consumption-based energy intensity – index form

Note: Results from the multiplicative LMDI-I decomposition on final consumption-based energy usage of the individual EU member states. The same results are summarized graphically in Figure (C.3) in this appendix.

As for the EU as a whole, changes in energy intensity in territorial production in the member states were mainly determined by changes in sector energy intensities (*int*) and changes in supply chains (*sup*). Sector energy intensity was the most important factor in improving energy intensity in a majority of the members, in general more so for the Eastern European (EEU) members. Changes in supply chains acted typically as a counterforce to those gains, but different patterns between old EU-15 and new EEU members could be observed. Unlike for EEU members, and contrary to the European trend, seven EU-15 states reorganized their supply chains in a way that improved energy-wide energy efficiency. This points to a reduction of and/or changes in the composition of the production of intermediates towards less energy-intensive products. In three further EU-15 countries, the supply chain factor led only to minor deteriorations of energy efficiency. The development of the supply chain factor in the EEU members indicates that part of the production of those intermediates may have shifted towards EEU countries as this factor contributes significantly to a deterioration of their energy efficiency.

Of the remaining factors that determine energy intensity of the EU member states in territorial production, the most important ones were changes in the sector composition of final goods produced (*str*), changes in economic activity (*act*), and changes in the usage of primary energy by private households (*ehh*). In general, changes in the sector composition of final goods led to a deterioration of energy efficiency in EU-15 states, but improved it in EEU members. Similarly, we observe that economic activity tended to improve energy efficiency in EEU members. This points towards a catch-up in income of the new member states relative to the old ones between 1997 and 2014. For some specific regions also the energy mix (*mix*) and the composition of trading partners for final goods (*trd*) had some effect on their energy intensity. Interestingly, in the period from 2007 to 2014, energy usage by private households contributed to deteriorating efficiency in many EU members. This could reflect the promotion of solar energy and biomass, both produced at the household level, in the EU.

For the two footprint inventories, the general pattern was roughly the same as for energy used for production, with the exception that changes in the supply chain factor were more pronounced and contributed to a deterioration in energy intensity in more member states. This indicates that improvements in energy intensity were partly achieved by outsourcing of energy intensive productions stages, especially by EU-15. At the same time, efficiency gains from declining sectoral energy intensity were less pronounced in the footprints, indicating the less efficient technology of the trading partners of the EU. Also, some of the remaining factors were more important in the footprints than in territorial production, especially in the second sub-period from 2007 to 2014. Specifically, this was the case for changes in the composition of final goods produced and consumed, the composition

of the trading partners of final goods consumed, and household energy usage. As a result, energy intensity gains were lower in the footprint inventories of the members than for territorial production, explaining the EU-wide result.

Comparing the developments for efficiency measured in territorial production across the two sub-periods, we find that while for the EU as a whole efficiency gains after 2007 were larger than in the period before, a detailed perspective on the individual EU member states offers a very heterogeneous picture. More EU members showed energy intensity gains in the first compared to the second period. While from 1997 to 2007 only Italy, and, to a very moderate degree, France became less efficient, this was the case for eight countries between 2007 and 2014. Their effect on the EU's energy intensity was low, however, as all of them were among the smaller members of the EU. Furthermore, except in four cases, sector energy intensity in those countries improved in all member states between 2007 and 2014, while the contribution of other factors decreased energy intensity.

As a result, reductions in sector energy intensity are almost the only source by which the EU members became more efficient in the period 2007–2014. While in between 1997 and 2007 this factor contributed to improving energy efficiency in only 19 of the EU members, this was the case for 23 members after 2007. Responsible for this was primarily a reverse in the trend of the growth rate of sector energy intensity in many of the EU-15 states, especially in the large energy users France, Great Britain, Italy, and Spain, but also in the Netherlands, Belgium, and Estonia. For the larger energy users, changes in the pattern of sector energy intensity have a large effect on the Union's energy intensity, explaining the aggregate effects described in the main text.

C.4 Average annual growth rates of energy intensity at country level

Table C.9 reports the average annual growth rate of the energy efficiency factor (*int*) for individual countries and composite regions for the period 1997–2014 and the sub-periods 1997–2007 and 2007–2014. The last two columns in the table show the energy intensity (defined as energy usage by all sectors of an economy divided by their value added) at the beginning of each sub-period.

| Region | % Δ Efficiency Factor | | | Sector Intensity | |
|---------------------|------------------------------|---------|---------|------------------|------|
| | 97 – 14 | 97 – 07 | 07 – 14 | 1997 | 2007 |
| | <i>percent</i> | | | <i>kgoe/USD</i> | |
| <i>EU-15</i> | | | | | |
| Austria | -0.62 | -0.29 | -1.14 | 0.14 | 0.13 |
| Belgium | 0.68 | 2.22 | -1.35 | 0.29 | 0.29 |
| Germany | -1.66 | -2.26 | -1.25 | 0.16 | 0.16 |
| Denmark | -3.37 | -5.20 | -2.29 | 0.15 | 0.11 |
| Spain | 0.24 | 8.41 | -6.33 | 0.23 | 0.20 |
| Finland | -2.45 | -3.82 | -1.12 | 0.32 | 0.26 |
| France | -0.13 | 2.38 | -2.88 | 0.21 | 0.21 |
| United Kingdom | -0.68 | 1.71 | -3.57 | 0.18 | 0.13 |
| Greece | -3.18 | -3.43 | -4.70 | 0.28 | 0.21 |
| Ireland | -2.78 | -3.57 | -3.66 | 0.13 | 0.07 |
| Italy | 0.84 | 3.46 | -1.55 | 0.14 | 0.16 |
| Luxembourg | -3.14 | -6.54 | 5.40 | 0.07 | 0.05 |
| Netherlands | -1.16 | 0.51 | -3.70 | 0.33 | 0.24 |
| Portugal | -1.63 | -0.71 | -3.30 | 0.25 | 0.21 |
| Sweden | -4.21 | -6.98 | -1.25 | 0.30 | 0.22 |
| <i>EEU</i> | | | | | |
| Bulgaria | -4.34 | -6.54 | -3.85 | 2.33 | 1.63 |
| Cyprus | -4.06 | -7.18 | 2.10 | 0.18 | 0.00 |
| Czechia | -3.05 | -3.97 | -3.54 | 0.82 | 0.58 |
| Estonia | 2.04 | 4.80 | -0.83 | 1.18 | 0.68 |
| Croatia | -5.07 | -8.35 | -6.27 | 0.58 | 0.33 |
| Hungary | -2.88 | -5.08 | 0.21 | 0.68 | 0.47 |
| Lithuania | -3.25 | -5.17 | -2.54 | 1.56 | 0.63 |
| Latvia | -3.74 | -6.14 | -1.01 | 0.48 | 0.19 |
| Poland | -3.94 | -6.30 | -2.33 | 0.87 | 0.47 |
| Romania | -3.16 | -4.11 | -3.60 | 1.29 | 0.83 |
| Slovakia | -3.64 | -5.56 | -2.69 | 1.16 | 0.52 |
| Slovenia | 0.24 | 0.30 | 0.55 | 0.29 | 0.18 |
| <i>Rest of OECD</i> | | | | | |
| Australia | -1.85 | -2.08 | -2.10 | 0.28 | 0.21 |
| Canada | -2.80 | -3.84 | -2.87 | 0.42 | 0.34 |
| Switzerland | 2.15 | -4.31 | 21.88 | 0.08 | 0.06 |
| Chile | -0.99 | -3.09 | 2.36 | 0.27 | 0.18 |
| Japan | 2.06 | 8.70 | -3.24 | 0.14 | 0.14 |
| Korea | 0.75 | 2.70 | -1.51 | 0.49 | 0.37 |
| Mexico | -2.40 | 0.04 | -5.52 | 0.38 | 0.29 |
| New Zealand | -0.20 | -0.58 | 0.28 | 0.27 | 0.19 |
| Turkey | 3.05 | 5.67 | -0.35 | 0.32 | 0.37 |
| United States | 0.18 | 1.44 | -1.45 | 0.27 | 0.22 |
| R.o. EFTA | -3.01 | -4.02 | -3.17 | 0.23 | 0.27 |
| <i>BRICS</i> | | | | | |
| Brazil | -0.95 | -3.03 | 2.68 | 0.23 | 0.26 |
| China | -1.95 | -3.85 | 2.08 | 1.25 | 0.96 |
| India | -2.66 | -4.40 | -0.13 | 0.76 | 0.57 |
| Russia | -4.10 | -7.76 | 5.11 | 1.59 | 1.36 |

Table C.9: Average annual growth rates of energy efficiency factor – continued on next page

Note: Data refers to energy usage for production. Sector intensity is given as energy usage by all sectors of an economy in kilogram of oil equivalent (kgoe) per unit of value added expressed in 1997 US dollars. Malta was excluded because of zero reported energy usage in some years. Rest of EFTA refers to the composite region including Norway, Iceland, and Liechtenstein. R.o. SACU refers to Southern African Customs Union. South Africa is not included in the BRICS group because is part of the composite region Rest of SACU. Israel is not included in the OECD group because it is part of the composite region Rest of Middle East. For details on composite regions see Table (A.4).

| Region | % Δ Energy Efficiency Factor | | | Sector Intensity | |
|------------------------------|-------------------------------------|---------|---------|------------------|-------|
| | 97 – 14 | 97 – 07 | 07 – 14 | 1997 | 2007 |
| | <i>percent</i> | | | <i>kgoe/USD</i> | |
| <i>ROW Single Countries</i> | | | | | |
| Albania | -0.55 | 0.47 | -2.05 | 0.58 | 0.20 |
| Argentina | 0.68 | -0.93 | 2.65 | 0.19 | 0.20 |
| Bangladesh | 0.10 | -0.62 | 1.01 | 0.13 | 0.14 |
| Botswana | 0.99 | -0.87 | 0.76 | 0.10 | 0.07 |
| Colombia | -4.38 | -7.73 | 0.44 | 0.35 | 0.24 |
| Hong Kong | -2.22 | -4.17 | 1.02 | 0.05 | 0.04 |
| Indonesia | -1.26 | -1.71 | -2.64 | 0.51 | 0.46 |
| Sri Lanka | -3.56 | -4.63 | -4.15 | 0.24 | 0.19 |
| Morocco | -0.92 | 2.34 | -4.48 | 0.29 | 0.21 |
| Mozambique | -3.99 | -5.84 | -1.53 | 0.67 | 0.36 |
| Malawi | 0.09 | 0.87 | -1.56 | 0.26 | 0.16 |
| Malaysia | 2.45 | 0.44 | 4.49 | 0.39 | 0.52 |
| Peru | 0.37 | -0.80 | 2.23 | 0.18 | 0.20 |
| Philippines | -1.58 | -4.22 | 4.44 | 0.49 | 0.29 |
| Singapore | -4.36 | -7.04 | -2.63 | 0.85 | 0.43 |
| Thailand | -1.74 | -4.42 | 3.72 | 0.56 | 0.58 |
| Taiwan | -2.78 | -3.19 | -3.74 | 0.26 | 0.33 |
| Tanzania | -0.12 | -0.63 | 0.58 | 0.62 | 0.55 |
| Uganda | -0.24 | -0.33 | -0.12 | 0.25 | 0.16 |
| Uruguay | -1.78 | -4.69 | 3.34 | 0.15 | 0.13 |
| Venezuela | -0.01 | -1.21 | 2.24 | 1.25 | 0.79 |
| Vietnam | -0.28 | -2.12 | 0.92 | 0.55 | 0.50 |
| Zambia | 2.49 | 4.29 | -0.91 | 1.02 | 0.65 |
| Zimbabwe | -0.43 | -0.75 | 0.32 | 0.45 | 0.74 |
| <i>ROW Composite Regions</i> | | | | | |
| R.o. Southern Africa | -2.15 | 6.93 | -6.02 | 0.71 | 0.37 |
| R.o. Andean Pact | -2.73 | -7.28 | 10.46 | 0.47 | 0.34 |
| R.o. Central America | -3.24 | -5.47 | -0.68 | 2.41 | 0.96 |
| R.o. Middle East | -3.51 | -5.74 | -1.54 | 1.10 | 0.75 |
| R.o. Northern Africa | 0.26 | -1.62 | 3.01 | 0.76 | 0.57 |
| R.o. Southern Asia | -2.40 | -4.08 | -0.07 | 0.90 | 1.03 |
| R.o. SACU | 3.32 | 2.05 | 4.82 | 0.91 | 0.63 |
| R.o. South America | -0.82 | -4.10 | 8.01 | 2.39 | 1.48 |
| R.o. Sub-Saharan Africa | 0.35 | 0.60 | -0.17 | 0.52 | 0.44 |
| R.o. Former SU | -2.40 | -4.60 | 0.95 | 2.38 | 1.51 |
| R.o. World | -1.41 | -2.21 | -0.29 | 4.60 | 11.05 |

Table C.9: – continued from last page.

C.5 Supplementary regression results

The figures and tables presented in this sections complement the difference-in-difference analysis undertaken in the main text.

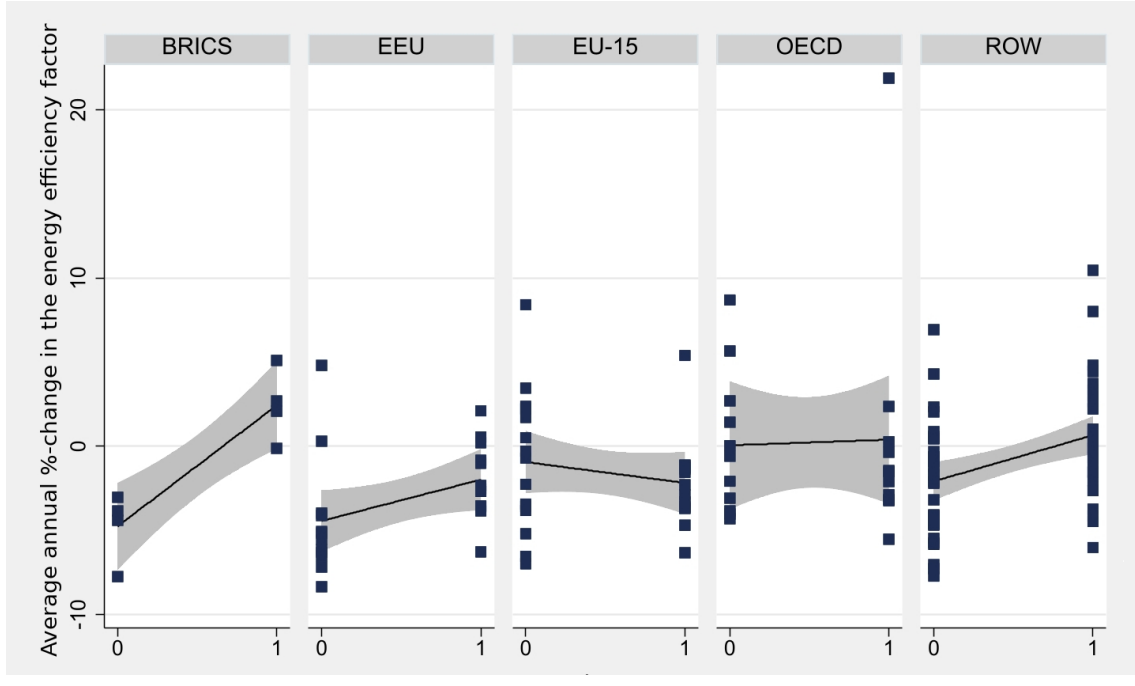


Figure C.4: Growth in the energy efficiency factor pre- and post 2007

Note: Average annual percentages changes in the energy efficiency factor for different country-groups. BRICS comprises Brazil, Russia, India and China, EEU stands for the Eastern European Union, EU-15 stands for the old EU 15 members, OECD refers to non-EU OECD countries, and ROW stands for the rest of the world. 0 refers to the period 1997–2007, 1 to the period 2007–2014. The rectangles represent individual countries. Linear fit and 95% confidence interval (grey areas) are shown.

Figure C.4 displays the evolution of the efficiency factor ($\Theta_{int}^{\omega,r}$), benchmarked to territorial production, for the periods before and after 2007 for different country groups. EU countries are grouped into the old EU 15 members and new Central and Eastern European (EEU) members that joined the EU since 2004, to account for potentially different developments across these two economically heterogeneous groups³⁴, the rest of the OECD (which includes all non-EU OECD countries in our data), and the rest of the world aggregate (ROW).³⁵

³⁴ EU 15 members were already considerably more energy efficient than EEU members at the beginning of our sample, which may impact on their potential for sectoral energy intensity improvements (see Tables C.6 and ?? in this Appendix).

³⁵ South Africa is not included in the BRICs group because it is not included as an individual country in the IO tables used in the construction of our dataset. It is grouped together with Lesotho, Namibia, and Swaziland. Israel is not included in the OECD group because it is also part of a composite region (see Table A.4 in Appendix A).

Out of the regions in Figure C.4, only the group of EU 15 countries experienced a stronger improvement in sectoral energy-intensity after 2007 compared to before. All other country-groups experienced on average smaller improvements or even increases in the sectoral energy-intensity term after 2007 as compared to the period before. However, the graph for the non-EU OECD countries seems to be influenced by an outlier (Switzerland). Excluding Switzerland from the group results in a stronger decrease in the energy-intensity term in the second period also in the non-EU OECD group.³⁶

³⁶ In Switzerland, the large increase in sectoral energy intensity between 2007 and 2014 was driven by the electricity sector, which experienced a strong decline in value added in this period. The electricity sector shows by far the largest energy usage across all Swiss sectors, thus receiving a large weight in the computation of the sectoral energy intensity factor.

| Average annual growth rate of the energy efficiency factor, production | | | | | |
|--|-----------------------|----------------------|----------------------|-----------------------|-----------------------|
| | (1) | (2) | (3) | (4) | (5) |
| Constant | -1.895*** (-2.775) | -1.819** (-2.534) | -1.433** (-2.292) | -2.217*** (-3.397) | -2.053*** (-3.274) |
| Sector Intensity | -0.262 (-1.407) | -0.202 (-1.353) | -0.193 (-1.270) | -0.176 (-1.420) | -0.178 (-1.464) |
| GDP pc | 0.000 (0.579) | 0.000 (0.262) | 0.000 (-0.634) | 0.000 (-0.002) | 0.000 (-0.589) |
| 2007–2014 | 2.488*** (3.162) | 2.524*** (3.215) | 2.140*** (2.965) | 3.191*** (4.161) | 3.246*** (4.275) |
| EU | -0.930 (-0.894) | | | | |
| EU · (2007–2014) | -2.311* (-1.814) | | | | |
| EU15 | | 0.590 (0.413) | 1.098 (0.833) | 1.317 (0.872) | 1.793 (1.270) |
| EU15 · (2007–2014) | | -3.868** (-2.508) | -3.220** (-2.267) | -4.436*** (-3.026) | -4.303*** (-2.963) |
| EEU | | -2.571** (-2.229) | -2.588** (-2.240) | -2.056* (-1.734) | -1.949* (-1.661) |
| EEU · (2007–2014) | | -0.231 (-0.153) | 0.384 (0.274) | -0.803 (-0.554) | -0.696 (-0.480) |
| R.o.OECD | | | | 2.326 (1.498) | 3.129** (2.107) |
| R.o.OECD · (2007–2014) | | | | -2.863 (-1.102) | -5.377*** (-3.261) |
| N | 154 | 154 | 152 | 154 | 152 |
| R ² | 0.121 | 0.146 | 0.146 | 0.165 | 0.206 |

Table C.10: Difference-in-differences regressions with controls – production

Note: t -statistics, based on robust standard errors, in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. R.o.OECD stands for the rest of the OECD aggregate. Regressions (3) and (5) exclude Switzerland in both periods.

C.5.1 Graphs and regressions for footprint inventories

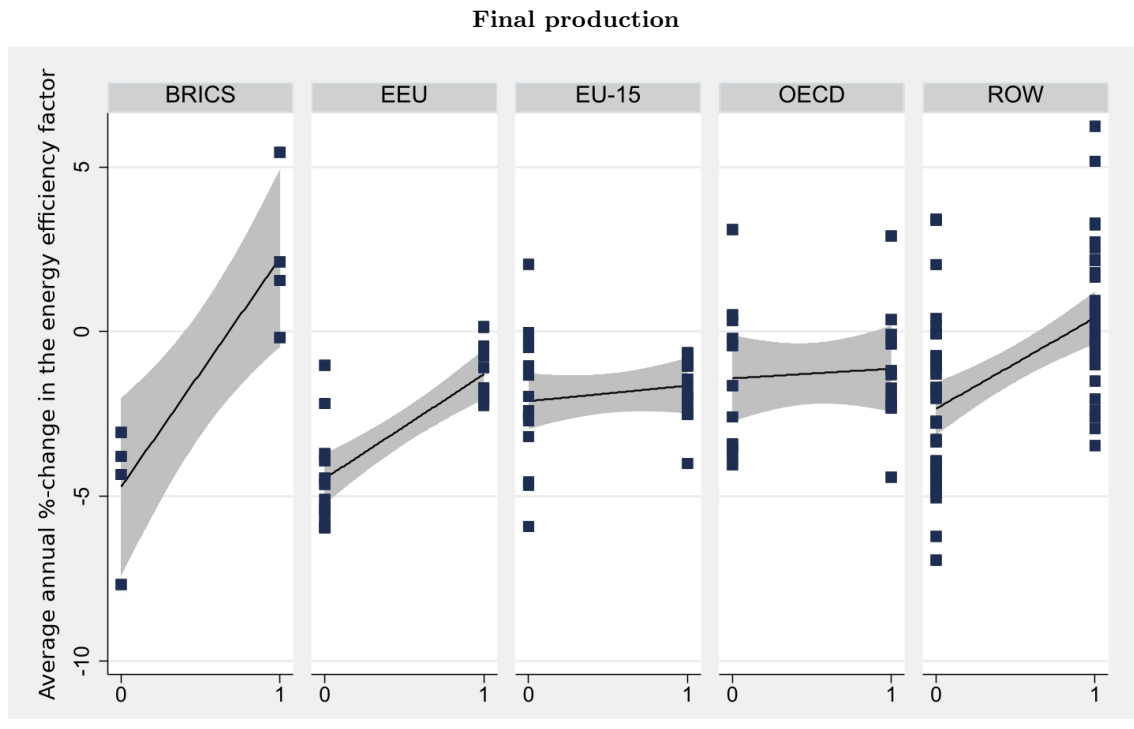


Figure C.5: Growth in the energy efficiency factor, final production
Notes as in Figure C.4.

Consumption

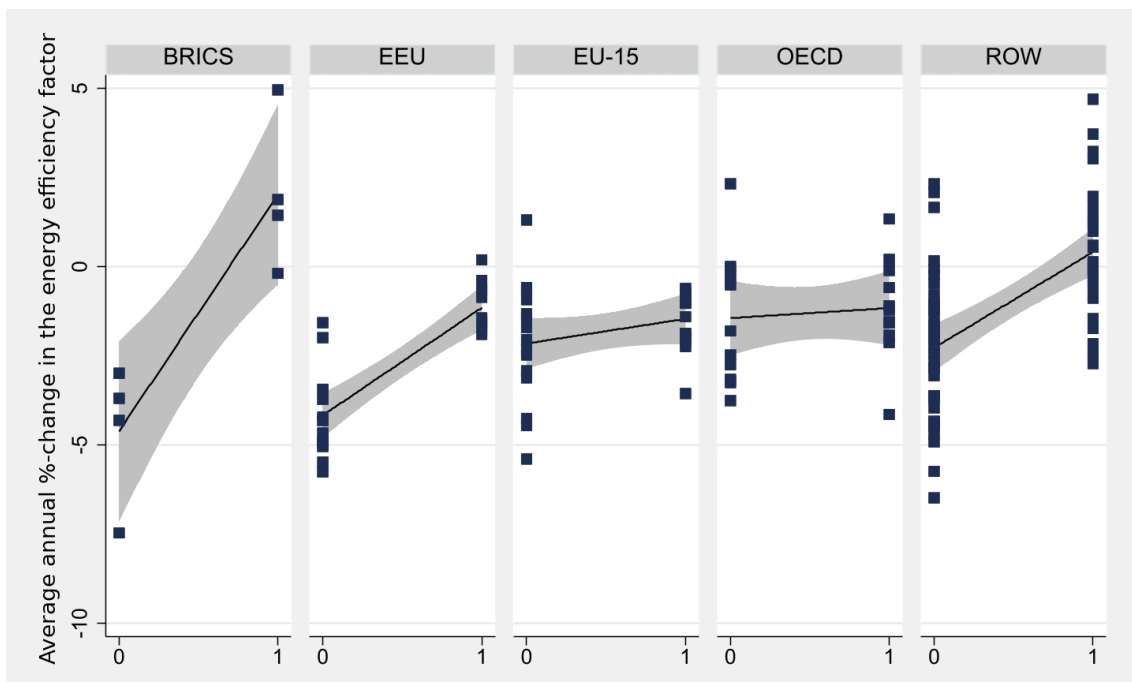


Figure C.6: Growth in the energy efficiency factor, consumption
Notes as in Figure C.4.

| Average annual growth rate of the energy efficiency factor, final production | | | | | |
|--|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | (1) | (2) | (3) | (4) | (5) |
| Constant | -2.329*** (-6.560) | -2.329*** (-6.516) | -2.307*** (-6.336) | -2.585*** (-6.290) | -2.585*** (-6.288) |
| 2007–2014 | 2.555*** (5.320) | 2.555*** (5.284) | 2.479*** (5.061) | 3.194*** (5.795) | 3.194*** (5.793) |
| EU | -0.828 (-1.518) | | | | |
| EU · (2007–2014) | -0.887 (-1.349) | | | | |
| EU15 | | 0.219 (0.347) | 0.197 (0.310) | 0.475 (0.715) | 0.475 (0.715) |
| EU15 · (2007–2014) | | -2.086*** (-2.788) | -2.010*** (-2.671) | -2.725*** (-3.421) | -2.725*** (-3.420) |
| EEU | | -2.136*** (-3.785) | -2.158*** (-3.794) | -1.879*** (-3.122) | -1.879*** (-3.121) |
| EEU · (2007–2014) | | 0.613 (0.880) | 0.689 (0.983) | -0.026 (-0.034) | -0.026 (-0.034) |
| R.o.OECD | | | | 1.166 (1.483) | 1.365* (1.670) |
| R.o.OECD · (2007–2014) | | | | -2.902*** (-2.823) | -3.502*** (-3.536) |
| N | 154 | 154 | 152 | 154 | 152 |
| R ² | 0.268 | 0.307 | 0.299 | 0.346 | 0.353 |
| P1: base | -2.329 | -2.329 | -2.307 | -2.585 | -2.585 |
| P1: EU | -3.156 | | | | |
| P1: EU 15 | | -2.110 | -2.110 | -2.110 | -2.110 |
| P1: EEU | | -4.464 | -4.464 | -4.464 | -4.464 |
| P1: R.o. OECD | | | | -1.419 | -1.221 |
| P2: base | 0.227 | 0.227 | 0.172 | 0.608 | 0.608 |
| P2: EU | -1.488 | | | | |
| P2: EU 15 | | -1.641 | -1.641 | -1.641 | -1.641 |
| P2: EEU | | -1.296 | -1.296 | -1.296 | -1.296 |
| P2: R.o. OECD | | | | -1.127 | -1.529 |
| p-value: P1 EU15 – EEU | | 0.001 | 0.001 | 0.001 | 0.001 |
| p-value: P1 EU15 – OECD | | | | 0.417 | 0.313 |
| p-value: P1 EEU – OECD | | | | 0.000 | 0.000 |
| p-value: P2 base – EU | 0.000 | | | | |
| p-value: P2 base – EU 15 | | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: P2 base – EEU | | 0.000 | 0.001 | 0.000 | 0.000 |
| p-value: P2 base – OECD | | | | 0.010 | 0.000 |
| p-value: P2 EU15 – EEU | | 0.316 | 0.317 | 0.320 | 0.320 |
| p-value: P2 EU15 – OECD | | | | 0.393 | 0.819 |
| p-value: P2 EEU – OECD | | | | 0.779 | 0.635 |
| p-value: P1-P2 base | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: P1-P2 EU | 0.000 | | | | |
| p-value: P1-P2 EU15 | | 0.413 | 0.413 | 0.416 | 0.416 |
| p-value: P1-P2 EEU | | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: P1-P2 OECD | | | | 0.737 | 0.708 |
| p-value: DID EU15 – EEU | | 0.001 | 0.001 | 0.001 | 0.001 |
| p-value: DID EU15 – OECD | | | | 0.865 | 0.440 |
| p-value: DID EEU – OECD | | | | 0.005 | 0.000 |

Table C.11: Difference-in-differences regressions: energy efficiency factor, final production
Note: t -statistics, based on robust standard errors, in parenthesis. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variables measure the average annual percentage change of the energy efficiency factor of final production. R.o.OECD stands for the rest of the OECD aggregate. The panel below the R^2 reports the average annual percentage change in the energy efficiency factor for each of the country-groups and periods. $P1$ refers to the period 1997–2007, $P2$ to the period 2007–2014. *base* stands for the base-group (i.e. non-EU countries in regressions (1)–(3), non-EU non-OECD countries in regressions (4) and (5)). The bottom panel reports a series of Wald-tests for differences across country-groups and/or periods. *DID* stands for difference-in-differences and tests for differences in the interaction-terms (i.e. differences in changes from $P1$ to $P2$ across country-groups). Regressions (3) and (5) exclude Switzerland in both periods.

| Average annual growth rate of the energy efficiency factor, final consumption | | | | | |
|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | (1) | (2) | (3) | (4) | (5) |
| Constant | -2.282*** (-7.456) | -2.282*** (-7.406) | -2.272*** (-7.229) | -2.518*** (-7.057) | -2.518*** (-7.055) |
| 2007–2014 | 2.476*** (6.052) | 2.476*** (6.011) | 2.443*** (5.822) | 3.095*** (6.603) | 3.095*** (6.601) |
| EU | -0.770* (-1.655) | | | | |
| EU · (2007–2014) | -0.751 (-1.348) | | | | |
| EU15 | | 0.126 (0.236) | 0.116 (0.216) | 0.362 (0.640) | 0.362 (0.639) |
| EU15 · (2007–2014) | | -1.785*** (-2.812) | -1.752*** (-2.738) | -2.405*** (-3.560) | -2.405*** (-3.558) |
| EEU | | -1.889*** (-3.945) | -1.899*** (-3.932) | -1.653*** (-3.220) | -1.653*** (-3.219) |
| EEU · (2007–2014) | | 0.542 (0.931) | 0.575 (0.978) | -0.077 (-0.123) | -0.077 (-0.123) |
| R.o.OECD | | | | 1.075 (1.641) | 1.206* (1.755) |
| R.o.OECD · (2007–2014) | | | | -2.814*** (-3.368) | -3.195*** (-3.801) |
| N | 154 | 154 | 152 | 154 | 152 |
| R ² | 0.109 | 0.142 | 0.140 | 0.163 | 0.200 |
| P1: base | -2.282 | -2.282 | -2.272 | -2.518 | -2.518 |
| P1: EU | -3.051 | | | | |
| P1: EU 15 | | -2.155 | -2.155 | -2.155 | -2.155 |
| P1: EEU | | -4.171 | -4.171 | -4.171 | -4.171 |
| P1: R.o. OECD | | | | -1.443 | -1.312 |
| P2: base | 0.194 | 0.194 | 0.171 | 0.577 | 0.577 |
| P2: EU | -1.327 | | | | |
| P2: EU 15 | | -1.465 | -1.465 | -1.465 | -1.465 |
| P2: EEU | | -1.153 | -1.153 | -1.153 | -1.153 |
| P2: R.o. OECD | | | | -1.163 | -1.413 |
| p-value: P1 EU15 – EEU | | 0.001 | 0.001 | 0.001 | 0.001 |
| p-value: P1 EU15 – OECD | | | | 0.313 | 0.253 |
| p-value: P1 EEU – OECD | | | | 0.000 | 0.000 |
| p-value: P2 base – EU | 0.000 | | | | |
| p-value: P2 base – EU 15 | | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: P2 base – EEU | | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: P2 base – OECD | | | | 0.001 | 0.000 |
| p-value: P2 EU15 – EEU | | 0.264 | 0.264 | 0.267 | 0.267 |
| p-value: P2 EU15 – OECD | | | | 0.520 | 0.903 |
| p-value: P2 EEU – OECD | | | | 0.983 | 0.539 |
| p-value: P1-P2 base | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: P1-P2 EU | 0.000 | | | | |
| p-value: P1-P2 EU15 | | 0.155 | 0.155 | 0.158 | 0.158 |
| p-value: P1-P2 EEU | | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: P1-P2 OECD | | | | 0.686 | 0.886 |
| p-value: DID EU15 – EEU | | 0.000 | 0.000 | 0.000 | 0.000 |
| p-value: DID EU15 – OECD | | | | 0.629 | 0.354 |
| p-value: DID EEU – OECD | | | | 0.001 | 0.000 |

Table C.12: Difference-in-differences regressions: energy efficiency factor, final consumption
Note: *t*-statistics, based on robust standard errors, in parenthesis. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variables measure the average annual percentage change in the energy efficiency factor of final consumption. R.o.OECD stands for the rest of the OECD aggregate. The panel below the R^2 reports the average annual percentage change in the energy efficiency factor for each of the country-groups and periods. *P1* refers to the period 1997–2007, *P2* to the period 2007–2014. *base* stands for the base-group (i.e. non-EU countries in regressions (1)–(3), non-EU non-OECD countries in regressions (4) and (5)). The bottom panel reports a series of Wald-tests for differences across country-groups and/or periods. *DID* stands for difference-in-differences and tests for differences in the interaction-terms (i.e. differences in changes from *P1* to *P2* across country-groups). Regressions (3) and (5) exclude Switzerland in both periods.

| | non-renewable | | | renewable | | | |
|------------------------|-----------------------|-----------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| | fossil | nuclear | other n-ren | hydro | wind | solar | other ren |
| Constant | 0.154 (1.495) | -0.014 (-1.234) | 0.004** (2.418) | 0.021 (0.554) | 0.003*** (4.569) | 0.001*** (2.624) | -0.169* (-1.868) |
| 2007–2014 | 0.266* (1.683) | 0.018 (1.435) | -0.000 (-0.152) | -0.029 (-0.601) | 0.017*** (3.789) | 0.008*** (3.561) | -0.280* (-1.865) |
| EU15 | -0.039 (-0.280) | -0.202*** (-3.682) | 0.008* (1.786) | -0.056 (-1.384) | 0.036*** (4.256) | 0.001 (1.083) | 0.252** (2.502) |
| EU15 · (2007–2014) | -0.914*** (-4.550) | 0.187** (2.561) | 0.018*** (2.767) | 0.119** (2.250) | 0.058** (2.511) | 0.051*** (3.664) | 0.482*** (2.956) |
| EEU | -0.161 (-1.034) | -0.051 (-0.504) | -0.006 (-0.765) | -0.011 (-0.274) | 0.005*** (5.570) | -0.001 (-1.301) | 0.224* (1.746) |
| EEU · (2007–2014) | -0.717** (-2.424) | -0.065 (-0.260) | 0.040*** (2.997) | 0.095* (1.728) | 0.034*** (2.832) | 0.022*** (3.398) | 0.591*** (3.135) |
| R.o.OECD | 0.011 (0.077) | -0.032 (-0.519) | 0.003 (0.637) | -0.151* (-1.901) | 0.008*** (2.744) | 0.001 (0.595) | 0.161 (1.554) |
| R.o.OECD · (2007–2014) | -0.582** (-2.323) | -0.100 (-0.695) | 0.007 (0.931) | 0.193** (2.217) | 0.022** (2.397) | 0.014*** (2.693) | 0.446** (2.312) |
| N | 152 | 152 | 152 | 152 | 152 | 152 | 152 |
| R ² | 0.220 | 0.061 | 0.322 | 0.077 | 0.506 | 0.482 | 0.233 |
| P1: base | 0.154 | -0.014 | 0.004 | 0.021 | 0.003 | 0.001 | -0.169 |
| P1: EU15 | 0.115 | -0.216 | 0.011 | -0.035 | 0.039 | 0.003 | 0.083 |
| P1: EEU | -0.007 | -0.064 | -0.003 | 0.009 | 0.008 | 0.001 | 0.055 |
| P1: R.o.OECD | 0.165 | -0.046 | 0.006 | -0.130 | 0.011 | 0.002 | -0.008 |
| P2: base | 0.420 | 0.004 | 0.003 | -0.008 | 0.020 | 0.009 | -0.448 |
| P2: EU15 | -0.533 | -0.011 | 0.029 | 0.055 | 0.114 | 0.061 | 0.285 |
| P2: EEU | -0.457 | -0.112 | 0.037 | 0.076 | 0.060 | 0.030 | 0.367 |
| P2: R.o.OECD | -0.151 | -0.128 | 0.013 | 0.033 | 0.050 | 0.025 | 0.159 |
| p-value: P1: EU15–EEU | 0.416 | 0.183 | 0.118 | 0.050 | 0.000 | 0.056 | 0.784 |
| p-value: P1: EU15–OECD | 0.710 | 0.036 | 0.343 | 0.187 | 0.002 | 0.731 | 0.174 |
| p-value: P1: EEU–OECD | 0.256 | 0.872 | 0.321 | 0.054 | 0.341 | 0.189 | 0.543 |
| p-value: P2: base–EU15 | 0.000 | 0.752 | 0.000 | 0.067 | 0.000 | 0.000 | 0.000 |
| p-value: P2: base–EEU | 0.001 | 0.615 | 0.002 | 0.024 | 0.001 | 0.001 | 0.000 |
| p-value: P2: base–OECD | 0.007 | 0.314 | 0.151 | 0.239 | 0.001 | 0.004 | 0.000 |
| p-value: P2: EU15–EEU | 0.748 | 0.669 | 0.498 | 0.429 | 0.023 | 0.040 | 0.331 |
| p-value: P2: EU15–OECD | 0.045 | 0.402 | 0.058 | 0.356 | 0.004 | 0.012 | 0.293 |
| p-value: P2: EEU–OECD | 0.274 | 0.951 | 0.062 | 0.121 | 0.472 | 0.443 | 0.113 |
| p-value: P1–P2 base | 0.094 | 0.153 | 0.880 | 0.549 | 0.000 | 0.001 | 0.064 |
| p-value: P1–P2 EU15 | 0.000 | 0.005 | 0.005 | 0.000 | 0.001 | 0.000 | 0.002 |
| p-value: P1–P2 EEU | 0.073 | 0.850 | 0.003 | 0.014 | 0.000 | 0.000 | 0.007 |
| p-value: P1–P2 OECD | 0.106 | 0.567 | 0.359 | 0.025 | 0.000 | 0.000 | 0.172 |
| p-value: DID EU15–EEU | 0.480 | 0.335 | 0.137 | 0.487 | 0.351 | 0.054 | 0.406 |
| p-value: DID EU15–OECD | 0.152 | 0.076 | 0.294 | 0.332 | 0.133 | 0.014 | 0.796 |
| p-value: DID EEU–OECD | 0.672 | 0.903 | 0.036 | 0.207 | 0.361 | 0.346 | 0.387 |

Table C.13: Difference-in-differences regressions: energy mix of final production

Note: t -statistics, based on robust standard errors, in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *other n-ren* and *other ren* stand for the group of other non-renewable energy commodities, and other renewable energy commodities, respectively. The dependent variables measure the average annual change in the share (expressed in percent) of the respective energy commodity in the total energy mix. The panel below the R^2 reports the average annual change in the share of the energy commodity for each of the country-groups and periods. *P1* refers to the period 1997–2007, *P2* to the period 2007–2014. *base* stands for the base-group of non-EU non-OECD countries. The bottom panel reports a series of Wald-tests for differences across country-groups and/or periods. *DID* stands for difference-in-differences and tests for differences in the interaction-terms (i.e. differences in changes from *P1* to *P2* across country-groups). Cyprus is excluded from the regressions.

| | non-renewable | | | renewable | | | |
|-------------------------|-----------------------|-----------------------|---------------------|----------------------|---------------------|---------------------|----------------------|
| | fossil | nuclear | other n-ren | hydro | wind | solar | other ren |
| Constant | 0.210** (2.007) | -0.014 (-1.147) | 0.004** (2.453) | 0.045* (1.663) | 0.004*** (5.624) | 0.001** (2.431) | -0.250** (-2.509) |
| 2007–2014 | 0.247 (1.569) | 0.012 (0.897) | -0.000 (-0.061) | -0.071* (-1.913) | 0.018*** (4.833) | 0.010*** (4.258) | -0.216 (-1.386) |
| EU15 | -0.127 (-1.033) | -0.194*** (-5.013) | 0.007* (1.915) | -0.075** (-2.520) | 0.032*** (4.364) | 0.001 (1.169) | 0.356*** (3.359) |
| EU15 · (2007–2014) | -0.844*** (-4.455) | 0.174*** (2.920) | 0.018*** (2.994) | 0.162*** (3.860) | 0.052*** (2.631) | 0.047*** (3.713) | 0.390** (2.364) |
| EEU | -0.221 (-1.383) | -0.072 (-0.703) | -0.005 (-0.835) | -0.025 (-0.759) | 0.006*** (6.726) | -0.001 (-0.902) | 0.317** (2.167) |
| EEU · (2007–2014) | -0.672** (-2.572) | -0.039 (-0.185) | 0.034*** (3.164) | 0.124** (2.380) | 0.031*** (3.103) | 0.020*** (3.620) | 0.502** (2.437) |
| R.o.OECD | -0.045 (-0.326) | -0.032 (-0.665) | 0.004 (0.944) | -0.156** (-2.376) | 0.007*** (2.747) | 0.001 (0.467) | 0.221** (1.990) |
| R.o.OECD · (2007–2014) | -0.522** (-2.242) | -0.080 (-0.623) | 0.007 (0.828) | 0.201*** (2.817) | 0.020*** (2.615) | 0.013*** (2.727) | 0.362* (1.932) |
| N | 152 | 152 | 152 | 152 | 152 | 152 | 152 |
| R ² | 0.243 | 0.074 | 0.325 | 0.121 | 0.544 | 0.509 | 0.236 |
| P1: base | 0.210 | -0.014 | 0.004 | 0.045 | 0.004 | 0.001 | -0.250 |
| P1: EU15 | 0.083 | -0.207 | 0.011 | -0.030 | 0.036 | 0.003 | 0.105 |
| P1: EEU | -0.011 | -0.085 | -0.001 | 0.020 | 0.010 | 0.001 | 0.067 |
| P1: R.o.OECD | 0.165 | -0.046 | 0.008 | -0.110 | 0.010 | 0.002 | -0.029 |
| P2: base | 0.457 | -0.002 | 0.004 | -0.026 | 0.022 | 0.011 | -0.466 |
| P2: EU15 | -0.514 | -0.022 | 0.028 | 0.061 | 0.106 | 0.060 | 0.280 |
| P2: EEU | -0.436 | -0.112 | 0.032 | 0.073 | 0.059 | 0.031 | 0.353 |
| P2: R.o.OECD | -0.110 | -0.115 | 0.014 | 0.020 | 0.049 | 0.024 | 0.117 |
| p-value: P1: EU15–EEU | 0.495 | 0.260 | 0.078 | 0.028 | 0.000 | 0.059 | 0.736 |
| p-value: P1: EU15–OECD | 0.458 | 0.008 | 0.612 | 0.188 | 0.001 | 0.565 | 0.029 |
| p-value: P1: EEU–OECD_p | 0.244 | 0.726 | 0.201 | 0.039 | 0.728 | 0.278 | 0.417 |
| p-value: P2: base–EU15 | 0.000 | 0.661 | 0.000 | 0.004 | 0.000 | 0.000 | 0.000 |
| p-value: P2: base–EEU | 0.000 | 0.545 | 0.001 | 0.015 | 0.000 | 0.001 | 0.000 |
| p-value: P2: base–OECD | 0.003 | 0.346 | 0.107 | 0.112 | 0.000 | 0.004 | 0.000 |
| p-value: P2: EU15–EEU | 0.680 | 0.630 | 0.673 | 0.747 | 0.021 | 0.034 | 0.425 |
| p-value: P2: EU15–OECD | 0.017 | 0.467 | 0.090 | 0.041 | 0.003 | 0.008 | 0.107 |
| p-value: P2: EEU–OECD | 0.148 | 0.991 | 0.105 | 0.117 | 0.369 | 0.319 | 0.055 |
| p-value: P1–P2 base | 0.119 | 0.371 | 0.952 | 0.058 | 0.000 | 0.000 | 0.168 |
| p-value: P1–P2 EU15 | 0.000 | 0.002 | 0.002 | 0.000 | 0.000 | 0.000 | 0.002 |
| p-value: P1–P2 EEU | 0.043 | 0.898 | 0.002 | 0.150 | 0.000 | 0.000 | 0.035 |
| p-value: P1–P2 OECD | 0.111 | 0.594 | 0.404 | 0.035 | 0.000 | 0.000 | 0.162 |
| p-value: DID EU15–EEU | 0.463 | 0.328 | 0.176 | 0.349 | 0.332 | 0.047 | 0.445 |
| p-value: DID EU15–OECD | 0.111 | 0.073 | 0.255 | 0.546 | 0.123 | 0.010 | 0.806 |
| p-value: DID EEU–OECD | 0.579 | 0.865 | 0.040 | 0.277 | 0.341 | 0.253 | 0.411 |

Table C.14: Difference-in-differences regressions: energy mix of final consumption

Note: t -statistics, based on robust standard errors, in parenthesis. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *other n-ren* and *other ren* stand for the group of other non-renewable energy commodities, and other renewable energy commodities, respectively. The dependent variables measure the average annual change in the share (expressed in percent) of the respective energy commodity in the total energy mix. The panel below the R^2 reports the average annual change in the share of the energy commodity for each of the country-groups and periods. *P1* refers to the period 1997–2007, *P2* to the period 2007–2014. *base* stands for the base-group of non-EU non-OECD countries. The bottom panel reports a series of Wald-tests for differences across country-groups and/or periods. *DID* stands for difference-in-differences and tests for differences in the interaction-terms (i.e. differences in changes from *P1* to *P2* across country-groups). Cyprus is excluded from the regressions.

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Energy footprints and the international trade network: A new dataset.
Is the European Union doing it better?

Abstract

Understanding the global energy network and the developments of energy efficiency is key to advance energy regulation and fight climate change. We develop a global panel dataset on energy usage inventories based on territorial production, final production and consumption over 1997–2014. We apply structural decomposition analysis to isolate energy efficiency changes and study the effectiveness of the European Union Energy Services Directive (2006/32/EC) on energy efficiency. High-income regions are net-importers of embodied energy and use a larger share of non-renewable energy than developing countries. The effectiveness of the Directive is mixed. The different ambition of national energy policies of the European Union members and some complementarity in supply chains underlie the different dynamics found. High-income countries share efficiency gains and changes in the mix of energy sources. These trends are not specific to the European Union. Energy policies in high-income countries are less effective for energy footprints. Our findings are indicative of energy leakage. Energy regulation should account for global supply chains and target energy footprints.

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