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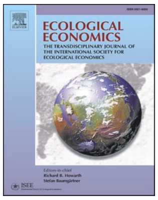

Energy footprints and the international trade network: A new dataset. Is the European Union doing it better?[☆]

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ABSTRACT

Understanding the developments of energy efficiency in the context of the global energy network is key to advance energy regulation and fight climate change. We develop a global panel dataset on energy usage accounts 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. The effectiveness of the Directive is mixed. The different dynamics found among the European Union members result from differences in the ambition of national energy policies and from the structure of their supply chains. The observed trends towards energy efficiency gains and increases in renewable energy shares are not specific to the European Union, but are common among high-income countries. 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.

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 reduce energy usage and GHG emissions without compromising economic growth. Many countries target energy efficiency in their nationally determined contributions (NDCs) to the Paris Agreement, and the United Nations emphasizes energy efficiency in the Sustainable Development Goals.

Energy policies focus primarily on energy usage of production activities within the territory and do not address energy embodied in final production and consumption (see e.g. Nieto et al., 2018; Iyer et al., 2017). 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 a country's territorial production can differ substantially from the energy required for final production and consumption. Energy policies aimed at territorial production fail to account for energy embodied in imported

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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. Policy-induced relocations of energy-intensive production underlie carbon leakage.[1]

Energy policies targeting energy efficiency should anticipate potential outsourcing of energy-intensive production and rebound (general-equilibrium) effects to ensure that the policy instruments deployed are sufficient to decrease energy usage. We analyze the effectiveness of the European Union (EU)'s Energy Services Directive to enhance energy efficiency, considering the effects of global supply chains. For that purpose, we develop a dataset of energy accounts and propose the sectoral energy intensity factor from a structural decomposition analysis (SDA) as an improved measure of energy efficiency, which we use in an econometric analysis. The contributions of this paper are threefold.

First, this paper introduces a dataset of energy usage accounts 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 accounts based on territorial production and, using multi-regional input-output (MRIO) techniques, calculate two energy footprint accounts. These two footprint accounts, associated with final production and consumption, factor in 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.[2] 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 on energy accounts and extends them in one or several dimensions.[3]

Second, this paper puts forward a proxy for energy efficiency derived from a SDA and uses it in an econometric analysis. We apply multiplicative Logarithmic Mean Divisia Index (LMDI) decomposition to energy usage and to the ratio of energy usage per unit of value added derived from the three accounts calculated. 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, covering the scale, composition, and technology effects used in the pollution–growth literature (Antweiler et al., 2001; Copeland and Taylor, 2005). 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. 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. By contrast, the SDA disentangles energy efficiency changes from other factors that affect energy per value added, and the intensity factor is weakly correlated with energy per value added. Accordingly, 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).

Finally, this paper analyzes whether the developments of energy usage in the EU from 1997 to 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, issued in 2006, aims at stronger energy efficiency improvements and introduces specific targets as compared to previous regulation (i.e. Council Directive [1993/76/EEC] to limit CO_2 emissions by improving energy efficiency). The Energy Services Directive specifies an overall national indicative, not legally enforceable, energy savings target of 9%, to be achieved from 2008 to 2016 through energy services and other energy efficiency improvements. It also specifies the need to promote the production of renewable energy, although it does not lay out specific targets on renewable energy shares. The Directive requires the EU member states to bring into force national policies by May 2008 and to progressively update Energy Efficiency Action Plans outlining national measures taken. 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 (e.g. the Energy Efficiency Directive [2012/27/EU] and the Directive on Energy Efficiency [2018/2002]), and specifies mandatory targets for renewable energy (e.g. the Renewable Energy Directive [2009/28/EC] and the Renewable Energy Directive [2018/2001/EU]).

Our energy accounts dataset 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. Through a set of regressions, we compare changes in the energy efficiency factor derived from the SDA in EU countries before and after the implementation of the Directive with 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 changes in the shares of seven energy commodities in the energy mix before and after the implementation of the Directive. The analysis is conducted for the three energy accounts calculated—territorial production-, final production-, and consumption-based energy usage. To the best of our knowledge, such an analysis is novel in the literature.

The following section reviews the related literature. Section 3 briefly describes the construction of the dataset containing the three energy accounts and the methods applied. 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. Related literature

Our research relates to four strands of literature. First, the production-based accounts in our dataset supplement existing datasets on energy accounts—such as Eora (Lenzen et al., 2012, 2013), Exiobase (Stadler et al., 2018a), Global Trade Analysis Project (GTAP; Aguiar et al., 2019; McDougall and Lee, 2006) and World Input-Output Database (WIOD; Timmer et al., 2015, 2016; Genty et al., 2012)—and extend them in one or several dimensions (sectoral disaggregation, country and time coverage, and energy usage concept and energy commodity disaggregation). The sectoral coverage of our dataset is similar to WIOD and larger than that publicly available in Eora. Exiobase and GTAP offer

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[1] Carbon leakage occurs when firms relocate their production from a country with stringent environmental policies to a country with lax environmental policies, leading to an increase in GHG emissions (see e.g. Babiker, 2005; Copeland and Taylor, 2005; Aichele and Felbermayr, 2015). Carbon dioxide (CO_2) emissions from fossil fuel combustion are the most important source of increased atmospheric concentration of CO_2 since the pre-industrial period (Solomon et al., 2007). Accordingly, policy-induced relocations of energy-intensive production, energy leakage, may account for the bulk of carbon leakage.

[2] 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).

[3] Our dataset, comprising the three energy accounts, is available upon request.

a larger sectoral disaggregation but GTAP has a shorter time coverage. WIOD, Exiobase and Eora provide few more recent years, but most of these years in Exiobase and Eora are projected. Although we present a country aggregation that keeps consistency with the available disaggregation of 1997 (GTAP 5), the country coverage is similar to GTAP and larger than that in WIOD and Exiobase. Only Eora provides a larger number of countries.

With respect to the energy usage concept, existing MRIO-based datasets offer energy extensions benchmarked to different definitions of energy usage (see Usubiaga-Liaño et al., 2021, for an overview). Eora provides gross and net energy usage, while WIOD and Exiobase offer gross- and emission-relevant energy use. Exiobase also provides net energy use and distinguishes between primary and secondary energy use. GTAP provides energy volume for the usage of fossil fuels and electricity only, although the electricity sector has been recently disaggregated to identify electricity produced from nuclear and several renewable energy sources by Peters (2016) and Chepeliev (2020). Our dataset includes gross and primary energy usage, and groups 62 energy commodities into seven energy source groups, which is beyond or at the level of detail offered by existing databases. All in all, our dataset provides a good compromise between these dimensions. Moreover, in contrast to the existing datasets, we provide energy footprint accounts for the same sector, country, time and energy coverage as for the production-based accounts.[4]

Second, our analysis relates to previous research performing index decomposition analysis (IDA-) and SDA-based decompositions of energy usage and intensity across countries.[5] This previous research concludes that factors capturing economic activity and population are the most important drivers of increasing energy usage, whereas the energy intensity factor, although contributing to decreasing energy usage, does not offset the effect of economic activity (Lan et al., 2016; Kaltenegger et al., 2017; Zhong, 2018; Kulionis and Wood, 2020). Factors capturing the structure of the economy seem to play a minor role in Zhong (2018), while Kaltenegger et al. (2017) highlight the contribution of the factor capturing global supply chains for consumption-based energy footprints, being the second largest contributor after economic activity. Changes in global supply chains increase energy footprints over 1995–2009.

The results from the analyses on energy intensities are consistent with the picture for energy usage. Decreases in energy intensity are mostly driven by efficiency gains captured by the intensity factor, whereas sectoral composition effects captured by the structure factor are less important (Mulder and de Groot, 2012; Fernández González et al., 2013; Croner and Frankovic, 2018). Also differences across European countries are largely driven by the intensity factor (Alcántara and Duarte, 2004; Guevara et al., 2021) and by the composition of final energy demand (Guevara et al., 2021), while the structure factor is less important (Alcántara and Duarte, 2004; Guevara et al., 2021). Croner and Frankovic (2018) find that the intensity factor shows a similar pattern for production- and consumption-based accounts, whereas the effects of the structure factor are larger for production- than for consumption-based accounts. International trade leads to an increase of global energy intensity for both accounts.

Third, our analysis adds to the literature on the measurement of energy efficiency improvements that can be attributed to energy efficiency policies. We propose to use the efficiency factor resulting from an SDA, instead of energy per value added, to measure energy efficiency, and use it in an econometric framework to quantify the effect of energy efficiency policies. Energy intensity, defined as energy usage divided by GDP, is commonly used to set energy and climate targets in the NDCs of the Paris Agreement, to inform climate change policies, and for cross-country comparisons (see Chang, 2014; Goh and Ang, 2020). Yet, many socio-economic, technological and environmental elements affect energy intensity. Energy efficiency factors derived from decomposition analyses isolate the effect of sector-specific energy intensity and are thus better suited to quantify policy-induced changes in energy efficiency. Some studies emphasize the use of decomposition-based factors to measure energy efficiency (Goh and Ang, 2020; for IDA-based analyses see e.g. Ang et al., 2010, Román-Collado and Economidou, 2021 and for SDA-based analyses Guevara et al., 2021), but factors resulting from IDA- and SDA-based decompositions cannot isolate policy-impacts without further analysis. This problem affects many of the studies cited above (see Bertoldi and Mosconi, 2020; Trotta, 2020; Román-Collado and Economidou, 2021, for a discussion). Nevertheless, efficiency factors from decompositions are not used in econometric applications to our knowledge (see also Wang et al., 2017).

Finally, our article relates to the literature on the effectiveness of the EU's energy policy. The findings of this literature suggest that the EU's energy policy could be the cause of lower energy usage over time,[6] and that most member states show strong progress in increasing the share of renewable electricity sources (Andreas et al., 2017; Reuter et al., 2017). The progress achieved varies considerably across EU member states, potentially on account of differences in the translation of EU directives into national legislation (see e.g. Horowitz and Bertoldi, 2015; Rosenow et al., 2016; Nabitz and Hirzel, 2019) and the presence and success of voluntary energy agreements (Cornelis, 2019). Additionally, differences in national legislation may result from heterogeneous energy-related positions (Szulecki et al., 2016), diverse stringency in energy targets (Reuter et al., 2017, 2019), and differences in initial conditions for improvement across countries (Cornillie and Frankhauser, 2004; Chan, 2014; Vehmas et al., 2018), which often reflect a divide between the old EU15 and the new Eastern European Union (EEU) member states. Yet, the findings of this literature are usually not contrasted to developments outside the EU.

Research that evaluates the impacts of the EU's Energy Services Directive [2006/32/EC] is scarce and emphasizes the challenge to measure policy-induced energy savings. In order to identify the effect of the Energy Services Directive, Horowitz and Bertoldi (2015) regress national-level energy usage on bottom-up energy-efficiency indexes and a set of situational (economic, socio-demographic and physical) factors for the period before and after the Directive enters into force. The authors find that situational factors account for a large part of national energy savings and that the savings resulting from energy policies increase in the period after the Directive applies. The authors conclude that the larger policy-induced savings stem from the household but not from the manufacturing sector.

3. Data construction and methods

This section summarizes the construction of the energy accounts and outlines the methodology used in the empirical analysis. We first

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[4] Although users can download consumption-based energy accounts based on existing MRIO-databases from the Ecology Programme of the Norwegian Institute of Science and Technology (https://environmentalfootprints.org/explorerIndustrial), the availability and benchmarks of these footprints varies by source and is restricted to total energy and to a reduced number of countries and sectors.

[5] Henriques and Kander (2010), Voigt et al. (2014), Löschel et al. (2015), and Forin et al. (2018) use IDA decompositions of production-based energy usage and intensity. Decompositions of consumption-based energy footprints using SDA for a broad set of countries can be found in Lan et al. (2016), Kaltenegger et al. (2017), and Kulionis and Wood (2020). Zhong (2018) and Croner and Frankovic (2018) implement decompositions for production- and consumption-based accounts. Alcántara and Duarte (2004) apply a cross-sectional decomposition on consumption-based energy intensity for a set of European countries, and Guevara et al. (2021) do so for energy intensities benchmarked to production- and consumption-based accounts.

[6] See Horowitz and Bertoldi (2015); Reuter et al. (2017); Román-Collado and Colinet (2018); Reuter et al. (2019); Bertoldi and Mosconi (2020); Román-Collado and Economidou (2021).

describe the construction of the production-based energy accounts and the derivation of the two energy footprint (final production- and consumption-based) accounts. After that, we briefly describe the SDA of the three energy accounts including the extraction of the efficiency factor, and the regression analysis applied. Further details are provided in Appendix B.

3.1. Construction of the energy accounts

3.1.1. Production-based energy accounts

The construction of production-based energy accounts relies on raw data from the World Energy Balances database (2018 edition) of the International Energy Agency (IEA), which provides information on the territorial usage of 62 imported and domestically produced 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 GTAP and used to calculate the footprints. Our methodology to construct the production-based accounts is based on the methods developed by Stadler et al. (2018a), Genty et al. (2012) and McDougall and Lee (2006), who compile energy satellite data for Exiobase, WIOD, and GTAP, respectively. 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.[7]

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 account for 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 used in the system of national accounts (SNA) that underlies the MRIO data. 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 (see Peters, 2008; Peters and Hertwich, 2008a; Usubiaga and Acosta-Fernández, 2015; Usubiaga-Liaño et al., 2021). Completing this step results in a database on the gross energy use of 62 energy commodities by 57 economic sectors and private households in 66 countries and 12 composite regions.

Fourth, for our empirical application, we aggregate the subset of primary energy commodities in our data to seven groups (see Table A.1 in Appendix A for the aggregation, and Appendix B.1 for further details). The seven groups comprise four renewable (hydro, wind, solar, and other renewable) and three non-renewable (fossil, nuclear, and other non-renewable) primary energy products. We aggregate all primary fossil fuels 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 and municipalities, to the category *other non-renewable energy*. For renewable primary energy, we keep separate categories for *hydro*, *solar* and *wind energy*, and assign biofuels from biomass, geothermal and tide energy to the category *other renewable energy*.

The resulting dataset comprises territorial-based usage of seven primary energy commodities disaggregated to 57 economic sectors (plus private households) in 78 regions (66 single countries and 12 composite regions) for the years 1997, 2001, 2004, 2007, 2011 and 2014. The restriction to the definition of energy usage as primary energy consumption (PEC) within the MRIO framework in our empirical application presents three advantages. First, it avoids double counting of energy. The presence of secondary fuels would lead to double counting as they are derived from primary energy products. Usubiaga-Liaño et al. (2021) find that double counting is an issue in many studies on MRIO-based energy footprints. Second, primary energy data includes losses that occur in their transformation to secondary energy. This allows us to capture energy savings from improvements in energy transformation. Third, energy extensions of MRIO datasets which are based on energy usage are better suited to assess efficiency developments at the level of industries and households compared to supply-based extensions such as extraction-based energy supply (see Owen et al., 2017; Wieland et al., 2019).

3.1.2. Footprint energy accounts

Based on the production-based energy data, we calculate two footprint-based (final production and consumption) energy accounts. These accounts measure the total energy content of final goods by accounting for energy used in their production along their whole (national and international) supply chains, using MRIO techniques, such that the responsibility for energy usage is assigned to the assembler and consumer of final goods, respectively (see e.g. Peters, 2008; Davis and Caldeira, 2010; Fernández-Amador et al., 2016, 2020).

We construct the energy footprints for each of the seven primary energy commodities and each year in our dataset as follows. First, we combine national IO tables for the regions considered and a rest of world aggregate to global MRIO tables (see Peters et al., 2011b), which we use to derive the global intermediate input requirements matrix A. This matrix collects the direct input requirements sourced from all other sectors to produce one unit of output in each sector in each region. To minimize the problem of aggregation bias, which arises in IO data from the aggregation of the economic activities of firms to a broad set of sectors (see Miller and Blair, 2009), we keep the sector and region aggregation in our dataset constant over time. For this, we aggregate all tables to the sectors and regions present in the earliest year of our dataset, 1997, with $s = 57$ sectors and $n = 78$ regions.[8]

Second, the matrix A allows us to express gross output produced by each sector, collected in a vector x, as the sum of intermediates sold to other sectors, Ax, and sales of final goods, collected in a vector y, i.e. $x = Ax + y$. We can solve for the vector of gross output as $x = (I - A)^{-1}y$, I being the identity matrix. $(I - A)^{-1}$ is the Leontief-inverse matrix, 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 global supply chains, we transform the linkages among the sectors to value added, using the matrix of sector value-added intensities, V, and re-scale the Leontief-inverse matrix with sectoral energy

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[7] The aggregation is determined by the detail of the input-output (IO) tables for 1997 sourced from GTAP and used to calculate our energy footprint measures. For consistency, we keep the same aggregation across years. A larger disaggregation is possible for the years after 1997.

[8] Aggregation bias can be especially problematic when MRIO tables are combined with physical activities, such as energy usage, if those activities are the result of a subset of firms in a sector only (see Wyckoff and Roop, 1994; Bouwmeester and Oosterhaven, 2013; Steen-Olsen et al., 2014; de Koning et al., 2015; Piñero et al., 2015; Schoer et al., 2021). Since our empirical application focuses on changes in energy efficiency over time, aggregation bias that stays constant over time does not affect our results.

intensities, E^q, for each energy commodity, q, sourced from the production-based energy account, i.e. $E^qV(I-A)^{-1}$. To derive the regional energy footprint accounts, we allocate these flows to the region where the final good is assembled (final production account) and consumed (consumption account) by multiplying the re-scaled Leontief-inverse matrix with matrices of final production, Y^o, and consumption, Y^c, respectively. This results in the regional commodity-specific energy footprint accounts $\psi^{o,\,q}$ for final production and $\psi^{c,\,q}$ for consumption

$$\begin{aligned}\psi^{o,q} &= \iota'\left[E^qV(I-A)^{-1}Y^o\right]\\ \psi^{c,q} &= \iota'\left[E^qV(I-A)^{-1}Y^c\right]\end{aligned} \tag{1}$$

with ι' being a column vector of ones.

As a last step, we add the direct usage of the seven primary energy commodities by private households, captured by the vectors ψ^q_{ehh} to the regional energy accounts, i.e. $\widetilde{\psi}^{o,q} = \psi^{o,q} + \psi^q_{ehh}$ and $\widetilde{\psi}^{c,q} = \psi^{c,q} + \psi^q_{ehh}$. These two vectors complement similar vectors for the production-based energy accounts, $\widetilde{\psi}^{v,q}$. We obtain the accounts for total energy usage by summing over all energy commodities q, and extract from these vectors the energy usage for each region r. We refer to Appendix B.2 for details.

3.2. Structural decomposition analysis of national energy usage

Let $\widetilde{\psi}^{\omega,r}$ denote the energy usage of region r benchmarked to account ω —alternatively, production, final production, and consumption. Accounts 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, $\widetilde{\theta}^{\omega,r} = \widetilde{\psi}^{\omega,r}/\phi^{\omega,r}$, and calculate indices of the relative change of regional energy usage and intensity within a given period as $\underline{\Delta}\widetilde{\psi}^{\omega,r}$ and $\underline{\Delta}\widetilde{\theta}^{\omega,r}$, respectively, such that for years 0 and t, the first and the last year of any given period, $\underline{\Delta}\widetilde{\psi}^{\omega,r} = \widetilde{\psi}^{\omega,r,t}/\widetilde{\psi}^{\omega,r,0}$ and $\underline{\Delta}\widetilde{\theta}^{\omega,r} = \widetilde{\theta}^{\omega,r,t}/\widetilde{\theta}^{\omega,r,0}$.

Energy usage and intensity, and their associated relative-change indices, are determined by economic scale, structural composition, and technology (and changes thereof). We calculate the contribution of different factors to these changes by applying SDA to the MRIO tables underlying the construction of the energy accounts (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*), 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*).

We decompose the index of the change in region r's energy usage of account ω, $\underline{\Delta}\widetilde{\psi}^{\omega,r}$, as $\underline{\Delta}\widetilde{\psi}^{\omega,r} = \prod_a \underline{\Delta}\psi^{\omega,r}_a$, and the index of the change in region r's energy intensity of account ω, $\underline{\Delta}\widetilde{\theta}^{\omega,r}$, as $\underline{\Delta}\widetilde{\theta}^{\omega,r} = \prod_a \underline{\Delta}\theta^{\omega,r}_a$, where $a = \{act, mix, int, sup, str, trd, ehh\}$. The seven sub-indices $\underline{\Delta}\psi^{\omega,r}_a$ and $\underline{\Delta}\theta^{\omega,r}_a$ report the contribution of each of these seven factors to changes in the energy index decomposed—i.e. energy usage ($\underline{\Delta}\widetilde{\psi}^{\omega,r}$) and intensity ($\underline{\Delta}\widetilde{\theta}^{\omega,r}$) for each of the three energy accounts ω—when holding all other factors constant. Like $\underline{\Delta}\widetilde{\psi}^{\omega,r}$ and $\underline{\Delta}\widetilde{\theta}^{\omega,r}$, the contributions are expressed as relative-change indices. A sub-index $\underline{\Delta}\psi^{\omega,r}_a$ and $\underline{\Delta}\theta^{\omega,r}_a$ 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 or intensity. Appendix B.3 offers a detailed explanation of the derivation of $\underline{\Delta}\widetilde{\psi}^{\omega,r}$, $\underline{\Delta}\widetilde{\theta}^{\omega,r}$, and their sub-indices, from the underlying MRIO tables.[9]

From the decomposition of $\underline{\Delta}\widetilde{\psi}^{\omega,r}$ and $\underline{\Delta}\widetilde{\theta}^{\omega,r}$ 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, the factor $\underline{\Delta}\theta^{\omega,r}_{int}$ isolates these intensity changes on the sector level from all other factors including the energy mix. It is thus a better proxy for changes in energy efficiency than the more commonly used ratio of energy per value added, energy intensity ($\underline{\Delta}\widetilde{\theta}^{\omega,r}$), 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 has the form

$$\underline{\Delta}\theta^{\omega,r}_{int} = \frac{\underline{\Delta}\psi^{\omega,r}_{int}}{\underline{\Delta}\phi^{\omega,r}_{int}} = \underline{\Delta}\psi^{\omega,r}_{int}, \tag{2}$$

where the last equality results from the fact that $\underline{\Delta}\phi^{\omega,r}_{int} = 1$ because the intensity factor does not exist in the decomposition of value added (i.e. $\Delta\phi^{\omega,r}_{int} = 0$ where the sub-indicator $\Delta\phi^{\omega,r}_{int}$ 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 calculate the efficiency factor, $\underline{\Delta}\psi^{\omega,r}_{int}$, at the most disaggregated level available in our MRIO framework and then aggregate across regions, sectors, and energy commodities to keep aggregation bias as small as possible. For this, we express region r's efficiency factor as a function of changes in energy intensities of all energy commodities, sectors and partner regions along the supply chain, which are weighted by expressions that reflect changes in region r's energy usage and bilateral flows of embodied energy between trading partners. We proceed in three steps.

First, we express region r's efficiency factor for account ω, $\underline{\Delta}\psi^{\omega,r}_{int}$, as the product of efficiency factors across all sectors ($k \in [1, s]$) and across all partner regions (p). Let u and m define, respectively, destination and origin regions ($u, m \in [1, n]$ where n is the total number of regions). For the production-based energy account, the partner regions, denoted by p, are destination regions ($p = u$) where the production of the origin region m ($r = m$) is consumed, while for the final production- and consumption-based energy accounts the partner regions are the origin regions ($p = m$) of the production used for final production or consumption in the destination region ($r = u$; see Table 1).

Thus,

$$\underline{\Delta}\psi^{\omega,r}_{int} = \prod_p^n \prod_k^s \underline{\Delta}\psi^{\omega,mu}_{int,k}, \tag{3}$$

where in production accounts $r = m$ and $p = u$, and in final production and consumption accounts $r = u$ and $p = m$.

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[9] The geographic composition of trading partners of final goods (*trd*) can only be derived for territorial production and consumption accounts, as from a final production perspective there is no trade in final goods. For the final production account, $\underline{\Delta}\psi^{\omega,r}_{trd} = \underline{\Delta}\theta^{\omega,r}_{trd} = 1$ by definition.

Table 1
Origin and destination regions for the derivation of energy accounts.

Energy account	Origin region (m)	Destination region (u)
Production	r	p
Final production & consumption	p	r

Second, we derive $\underline{\Delta}\psi_{int,k}^{\omega,mu}$, the efficiency factor for account ω in region r specific to partner p and sector k, as a function of the change in bilateral embodied energy ($\Delta\psi_{int,\,k}^{\omega,\,mu}$), scaled by a weighting function, i.e.

$$\underline{\Delta}\psi_{int,k}^{\omega,mu} = exp\left[\frac{\Delta\psi_{int,k}^{\omega,mu}}{L(\widetilde{\psi}^{\omega,r,t},\widetilde{\psi}^{\omega,r,0})}\right] , \tag{4}$$

where again in production accounts $r = m$ and $p = u$, and in final production and consumption accounts $r = u$ and $p = m$. The weighting function 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 $\widetilde{\psi}^{\omega,r,t}$ and $\widetilde{\psi}^{\omega,r,0}$ refer to the national energy usage of region r for account ω in periods t and 0. Thus, the weighting function in the denominator is the logarithmic mean of the change in national energy usage of account ω in region r.

Finally, we express $\Delta\psi_{int,\,k}^{\omega,mu}$, the change in bilateral embodied energy, as a weighted function of changes in energy intensities, $ln(e_k^{m,t}/e_k^{m,0})$, across all sectors k and origin regions m between periods t and 0 (see Table B.2 and Eq. (B.17) in Appendix B.3),

$$\Delta\psi_{int,k}^{\omega,mu} = \sum_g^n \sum_j^s \sum_q^f W_{\psi,kj}^{\omega,mgu,q}\, ln\left(\frac{e_k^{m,t}}{e_k^{m,0}}\right), \tag{5}$$

where g refers to regions and j to sectors along the supply chain between origin region m and destination region u. The weights multiplying the change in energy intensities are represented by $W_{\psi,kj}^{\omega,mgu,q} = L(v_{\psi,kj}^{\omega,mgu,q,t}, v_{\psi,kj}^{\omega,mgu,q,0})$, 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. In this way, we derive the efficiency factor, $\underline{\Delta}\psi_{int}^{\omega,r}$, from the most disaggregated level available in the MRIO framework. We refer to Appendix B.3 for further details.

3.3. Regression analysis

We carry out a set of regressions in the spirit of difference-in-difference analysis 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.[10] The econometric analysis aims at identifying policy-induced changes in the SDA-based efficiency factor. The inclusion of control groups allows to identify EU specific dynamics. The dependent variable is the average annual growth rate of the efficiency factor of region i in period t and energy account ω derived from the SDA, which we denote as $\bar{\underline{\Delta}}\psi_{int,it}^{\omega}$ 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.[11]

$$\bar{\underline{\Delta}}\psi_{int,it}^{\omega} = \alpha + \beta P_2 + \sum \gamma_g D_g + \sum \delta_g P_2 D_g + u_{it} \tag{6}$$

where P_2 is a dummy equal to 1 for the second period of analysis (2007–2014), D_g are dummies equal to 1 for the groups specified in different specifications—namely EU28, EU15, the Eastern European Union (EEU), and rest of OECD—and P_2D_g are interactions of both.[12] 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 regressions to study whether the EU's switch from fossil fuels towards renewable energy is particularly rapid relative to other regions after the implementation of the Directive. 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.

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 to 2016 through energy services and other energy efficiency improvements, and refers to the need to promote the production of renewable energy. It aims at stronger energy efficiency improvements as compared to previous regulation, and introduces specific targets for energy savings. Already the 1993 Council Directive [93/76/EEC] aims at limiting CO_2 emissions by improving energy efficiency but it does not specify quantifiable efficiency targets. Following the Energy Services Directive, EU member states must start implementing national policies by May 2008 and must prepare and periodically update Energy Efficiency Action Plans (EEAP), outlining which national measures are taken to achieve the 9% target. However, the national target is not legally enforceable and the implementation and achievements following the Directive differ across the EU member states.[13]

The Energy Services Directive does not set specific targets for the share of renewable energy in energy consumption, which is addressed in subsequent regulation. The Renewable Energy Directive [2009/28/EC], issued in 2009, introduces mandatory national targets from 2011 to 2020, amounting to a share of 20% of energy consumption from renewable sources for the EU in aggregate by 2020. It also specifies a target share of renewable energy in transport of 10% to be reached by

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[10] Difference-in-difference analysis relies on the assumption that in the absence of treatment, differences in the outcome between the treatment and the control group remain constant over time (parallel trends assumption). In our analysis, we only have one time period before and one time period after the treatment. Thus, it is not possible to assess the parallel trends assumption by visual inspection.

[11] 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, resulting in infinite growth rates of energy usage. Accordingly, Malta is excluded from the analysis.

[12] The United Kingdom is included in the group of EU28 and EU15 countries, although at the date of writing, it is not part of the EU any more.

[13] Follow-up regulation strengthens the targets for energy usage. The Energy Efficiency Directive [2012/27/EU], which repeals the Energy Services Directive, formulates an energy target of a 20% reduction in primary energy usage as compared to projections until 2020 and supplements it with targets for CO_2 emissions and renewable energy. The Directive on Energy Efficiency [2018/2002], amends the previous Energy Efficiency Directive and increases the target to a 32.5% reduction in energy usage as compared to projections until 2030. Our sample is free from the effects of these directives because their implementation and the resulting effects typically occur with a time lag.

2020. The Renewable Energy Directive of 2018 [2018/2001/EU] updates the Directive of 2009 and increases the renewable energy targets for the EU to 32%, and to 14% in transport, by 2030.[14]

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, following a change of production structures towards production in less energy intensive sectors or following technological change that reduces the energy intensity of production. The incentives to promote technological change 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 in the long run, since declines in economic activity merely lead to transitional reductions in energy usage and the relocation of energy-intensive production processes to other countries does not reduce energy usage at a global scale. Thus, to assess whether the 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.

To isolate changes in sectoral energy intensity from other factors, we apply the SDA to energy usage and to the ratio of energy usage per unit of value added (energy intensity) in Section 4.1, and analyze their factor compositions. As we show below, the efficiency factor from the SDA 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*

4.1.1. *Decomposition of energy usage*

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 overall energy usage over time, such as economic activity (*act*), sourcing patterns of intermediates (sup), sectoral composition (*str*) and trading partners (*trd*) of final goods, energy mix applied (*mix*), and energy usage by households (*ehh*). Fig. 1 presents the results of the decomposition for all three energy accounts for the EU28, its two sub-groups the EU15 and the EEU, the rest of OECD (R.o.OECD), and the rest of the world (R.o.World), composed of low and middle-income countries, between 1997 and 2014. The change in overall energy usage, $\underline{\Delta}\widetilde{\psi}^{\omega,r}$, is represented as percentage change by the black dots, while the colored bars represent the contribution of the seven factors, $\underline{\Delta}\psi_a^{\omega,r}$, where $a = \{act, int, sup, str, trd, mix, ehh\}$, to the overall change, also in percentages. The height of a given bar reflects the percentage change in $\underline{\Delta}\widetilde{\psi}^{\omega,r}$ when fixing all other factors over the period considered.[15] Four main outcomes can be highlighted from Fig. 1.

First, energy usage associated with all three accounts increases between 1997 and 2014 in all regions, with the exception of production-based energy usage in the EU28 and its two sub-groups. In the EEU, the reductions of production-based energy usage are marginally larger than in the EU15 (in line with Vehmas et al., 2018). The largest increase in energy usage occurs in the R.o.World group (see also Kaltenegger et al., 2017).[16]

Second, the development of energy usage is primarily determined 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.[17] Increasing economic activity (*act*) is the main factor contributing to higher energy usage in all regions and accounts, with the exception of production-based accounts in the EEU, where the influence of energy intensity improvements (*int*) is larger. In general, the patterns found for the EU28 closely resemble those of the EU15 because of its larger economic and demographic mass compared to the EEU.[18]

Third, energy intensity improvements (negative *int* term) reduce energy usage across all accounts and regions shown, partially counteracting the effect of increasing economic activity. The most sizable improvements are observed in the EEU, pointing to a catch-up process due to the modernization and restructuring of the former planned economies. The second largest improvements occur in the R.o.World, reflecting the stronger importance of energy intensity improvements in lower income countries (see also Zhong, 2018).

Fourth, whether reorganizations in supply-chain linkages (*sup*) contribute to higher or lower energy usage depends on the energy account and country group considered. This varying contribution is also found by Lan et al. (2016), Kaltenegger et al. (2017), and Kulionis and Wood (2020) for consumption-based accounts. 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 EEU and the R.o. World. In the EEU countries, this may result from the process of economic restructuring and their integration into the European supply chain network (see Baldwin and Lopez-Gonzalez, 2015). For the footprint-based accounts, the increasing effect (positive *sup* term) in all regions but the R.o.OECD suggests a shift in the sourcing of intermediates towards sectors and/or countries with higher energy usage.

The pattern observed for the sourcing of intermediates (*sup*) in the aggregate EU28 and the EU15 suggests outsourcing of energy-intensive intermediates to other countries. There, the production of intermediates declines and/or shifts towards sectors with lower energy usage, while the energy content of imported intermediates increases. For the production-based energy usage, this reduction in the energy content of domestically produced intermediates, together with improvements in energy-intensity, is strong enough to counterweight the influence of economic activity. Without the observed restructuring of its intermediate supply chains, the efficiency improvements in the EU28 and the EU15 alone are not strong enough to reduce energy usage for produc-

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[14] The Renewable Energy Directive [2009/28/EC] repeals Directive [2001/77/EC] on the promotion of electricity produced from renewable energy sources in the internal electricity market, and Directive [2003/30/EC] on the promotion of the use of biofuels or other renewable fuels for transport, which propose reference values for national indicative targets on the shares sourced from renewable energy sources. In contrast to the Renewable Energy Directives [2009/28/EC] and [2018/2001/EU], these previous directives do not cover energy used for heating or cooling.

[15] The product of the seven factors equals $\underline{\Delta}\widetilde{\psi}^{\omega,r}$. In Fig. 1, the heights of the bars do not add up to the black dot because of the conversion of the factors to percentage changes. Table C.1 in Appendix C.1 reports the values of the untransformed factors, such that their product equals $\underline{\Delta}\widetilde{\psi}^{\omega,r}$.

[16] Lan et al. (2016) find a similar pattern as for the *R.o.World* for consumption-based energy accounts in China and Russia between 1990 and 2010, reflecting the importance of these countries in that group.

[17] Related to the small contribution of our energy mix factor (*mix*) to changes in energy usage, Dietzenbacher et al. (2020) show in the context of renewable energy that the energy transition factor, which is related to the share of renewable energy in total energy usage, has a small effect on global production-based usage of renewable energy.

[18] Individual countries may deviate from the region-specific patterns. For example, Lan et al. (2016) and Kulionis and Wood (2020) show that in some high-income countries, large energy intensity improvements outweigh the effect economic affluence.

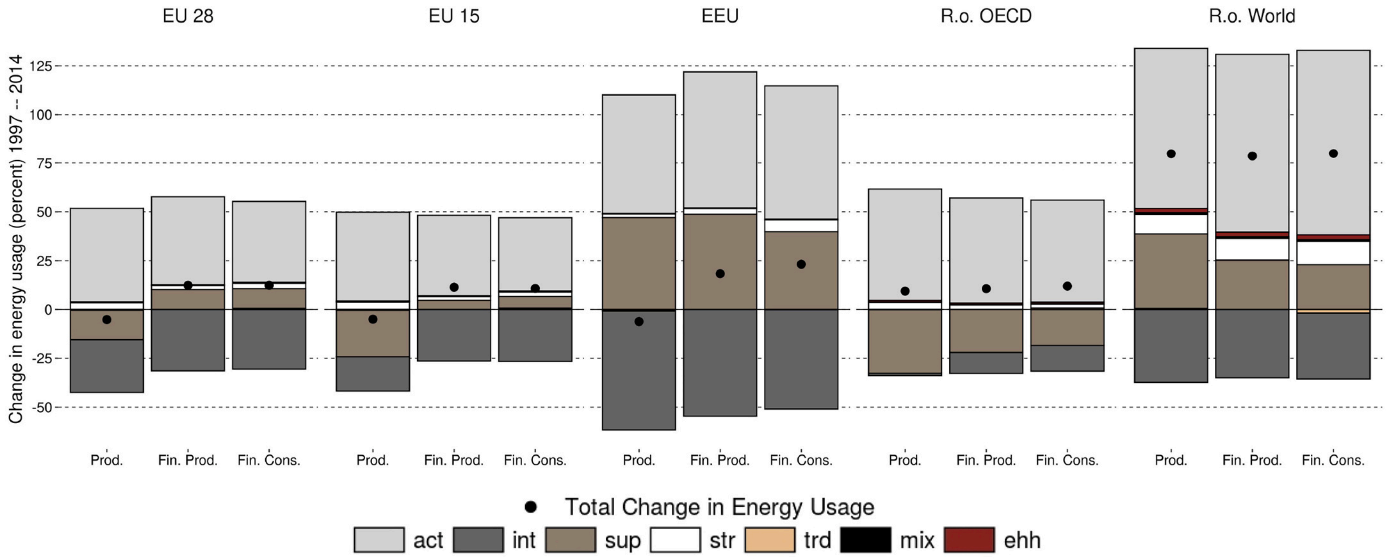

Fig. 1. Decomposition of changes in energy usage, 1997–2014.
Note: Prod. stands for production-based energy usage, Fin. Prod. and Fin. Cons. for energy embodied in final production and consumption, respectively. *Act* stands for economic activity, *int* for sectoral energy intensity, *sup* for the structure 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 the seven factors considered to the overall change in energy usage, holding all the other factors 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. The figure is based on the numerical results presented in Table C.1 in Appendix C.1.

tion. Bertoldi and Mosconi (2020) argue that the implementation of energy policies in the EU28 and Norway reduces energy usage by 12% in 2013. This finding may be reflecting such supply-chain effects, however. For the footprint-based energy accounts, the higher energy content of imported intermediates observed in our data contributes to the increase in energy footprints. The targets for outsourcing are the EEU and the R.o. World region, where the *sup* factor contributes to an increase in production-based energy usage.

4.1.2. *Decomposition of energy intensity*

As we argued above, 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. Fig. 2 displays the results of the decomposition of energy intensity. The change in energy intensity, $\underline{\Delta}\widetilde{\theta}^{\omega,r}$, is represented as percentage change by the black dots, while the colored bars represent the percentage change in energy intensity arising from a specific factor, $\underline{\Delta}\theta_a^{\omega,r}$, where $a = \{act, int, sup, str, trd, mix, ehh\}$. As explained in Section 3.2, 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 ($\underline{\Delta}\theta_{int}^{\omega,r} = \underline{\Delta}\psi_{int}^{\omega,r}$).

From Fig. 2, it is apparent that energy intensity decreases in all regions and accounts. The main factors affecting changes in energy intensity are changes in the energy efficiency factor (*int*; in line with Mulder and de Groot, 2012; Fernández González et al., 2013; Croner and Frankovic, 2018) and in the structure of supply chains for intermediates (*sup*). Unlike for energy usage, economic growth (*act*) reduces energy intensity in all regions and accounts but the production-based account in the R.o.OECD. The effects of the four other factors are much smaller.

The efficiency factor (*int*) is not always the largest contributor to energy intensity, being surpassed by the sourcing patterns of intermediates (*sup*) in some cases. Improvements in the efficiency factor (*int*) are larger than reductions in energy intensity in most cases, except for the R.o.OECD and the production-based account in the EU15. This is driven primarily by changes in the production or sourcing patterns of intermediates, which shift towards sectors with higher energy intensity (positive *sup* term) in all regions and accounts shown but the R.o.OECD and the production-based account in the EU15. Since changes in other factors also affect energy intensity, the magnitude of energy intensity improvements and the efficiency factor (*int*) can differ substantially (see e.g. the R.o.OECD). The sample correlation between energy intensity and the efficiency factor is 0.27. Therefore, using changes of energy intensity as a proxy for efficiency gains may lead to invalid conclusions about efficiency development, and the efficiency factor from the SDA is a better proxy for energy efficiency and to address the effectiveness of energy intensity policies to achieve their targets.[19]

In Fig. 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). After 2007, the contribution of the efficiency factor is much larger than the contribution of changes in supply chains for intermediates in all regions except the R.o.World, suggesting that the correlation between energy intensity and the efficiency factor is not constant over time and increases after 2007. In the EU28, production-based efficiency gains are stronger after 2007. This is driven by the developments in the EU15, while efficiency gains in the

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[19] The efficiency factor should also be isolated from the major part of the rebound effects. Thomas and Rosenow (2020) distinguish direct and indirect rebound effects resulting from cost decreases of energy induced by efficiency improvements. These cost reductions may result in higher consumption of energy services (direct rebound effect) and higher demand for other goods and services (indirect rebound effect). These rebound effects should be mostly captured by SDA-factors relating to the level of activity, the composition of global supply chains and final goods, and households energy usage. In this regard, it should be noted that a policy targeting energy efficiency could be effective in meeting its target but not so effective with respect to diminishing energy usage because of the existence of rebound effects.

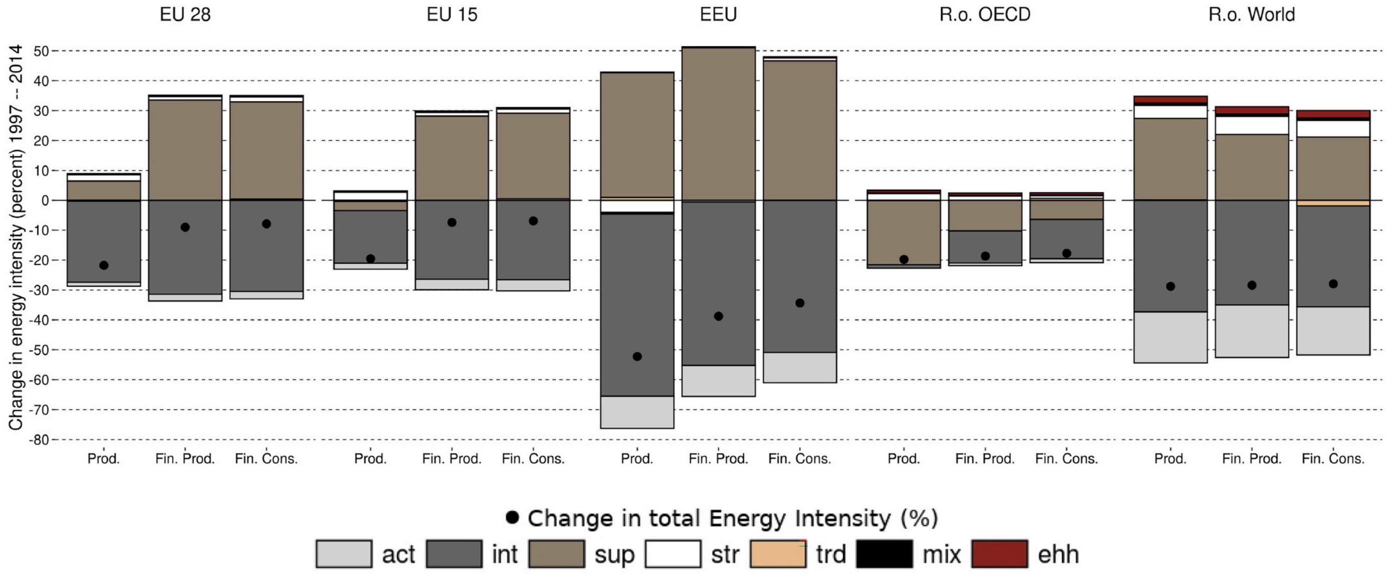

Fig. 2. Decomposition of changes in energy intensity, 1997–2014.
Note: Energy intensity is defined as energy usage divided by value added. The figure is based on the numerical results presented in Table C.2 in Appendix C.1. Other notes as in Fig. 1.

EEU decrease after 2007. Efficiency gains in the footprint-accounts decelerate after 2007 in both EU regions. In the R.o.World, the energy efficiency factor deteriorates after 2007.[20]

4.2. Regression analysis

We test whether the EU countries show significantly stronger energy efficiency improvements after the implementation of the EU Energy Services Directive and relative to other countries. For that purpose, we use average annual growth rates of the efficiency factor from the SDA from the three energy accounts as dependent variable disaggregated at the level of 77 individual countries and regions, for the sub-periods 1997–2007 and 2007–2014.

4.2.1. Energy intensity in production-based accounts

The EU Energy Services Directive targets energy intensity improvements within the territorial boundaries of the EU. Table 2 presents the regressions for the production-based energy account 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 the rest of OECD countries from all remaining countries (the base group). This specification adds a dummy for the group of OECD countries that do not form part of the EU 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.[21] The top panel in Table 2 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.

The results in column 1 point to a better performance of the EU relative to the base group (non-EU countries) after 2007. The efficiency factor decreases in EU countries before and after 2007, whereas in the base group it decreases before 2007 but increases afterward. Energy efficiency improvements do not significantly differ across the two periods in the EU.[22] The difference between the annual reductions in the EU countries (−2.50%) and the base group (−1.83%) is not statistically

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[20] 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 the efficiency factor of production for individual countries is available in Appendix C.4.

[21] In Switzerland, the increase in the energy efficiency factor is exceptionally large between 2007 and 2014 due to the large influence of the electricity sector, which experiences a sharp decline in value added over this period. We ran several specifications. We included sector energy intensity and GDP per capita (ppp-adjusted) at the beginning of the periods as control variables in the regressions, but both are statistically insignificant (see Table C.10 in Appendix C.5). We also interacted GDP per capita with the period-dummy, but this interaction is also insignificant at conventional levels. Thus, we report the regressions without additional controls.

[22] Horowitz and Bertoldi (2015) find larger reductions in energy use from the household sector but not the manufacturing sector after the implementation of the Energy Services Directive. In our regression analysis, the effect from household demand has been isolated by separating the household factor. The decomposition in Fig. 3 shows that the household factor decreased energy intensity in the EU15 over 2007–2014.

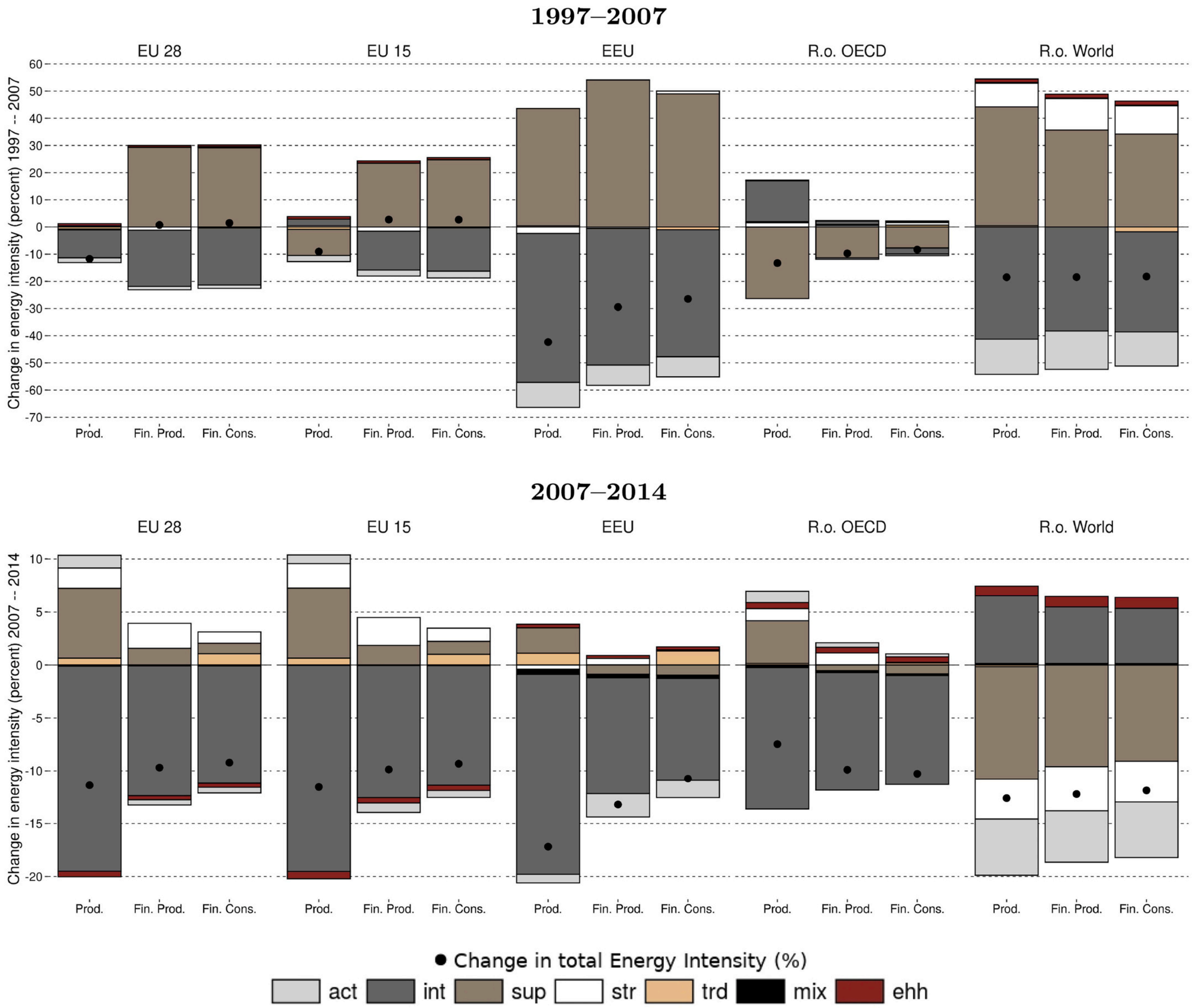

Fig. 3. Decomposition of changes in energy intensity, sub-periods.
Note: Decompositions of changes in energy intensity between 1997 and 2007 (upper graph) and between 2007 and 2014 (lower graph). The figure is based on the numerical results presented in Tables C.3 and C.4 in Appendix C.1. Other notes as in Fig. 1.

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).[23] Therefore, the difference in the growth rates of the efficiency factor between EU and the non-EU countries 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 remains 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). This contrasts with the larger potential for improvement in many EEU

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[23] 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 2. The *p*-value for the difference between the growth rates is based on a Wald test reported in the lower panel.

Table 2
Regression results: energy efficiency factor—production.

Average annual growth rate of the energy efficiency factor for production					
	(1)	(2)	(3)	(4)	(5)
Constant	−1.828***	−1.828***	−1.778***	−2.360***	−2.360***
2007−2014	2.566***	2.566***	2.084***	3.196***	3.196***
EU	−0.668				
EU · (2007–2014)	−2.162*				
EU15		0.888	0.838	1.419	1.419
EU15 (2007–2014)		−3.806**	−3.324**	−4.435***	−4.435***
EEU		−2.613**	−2.664**	−2.082*	−2.082*
EEU · (2007–2014)		−0.107	0.375	−0.736	−0.736
R.o.OECD				2.415*	2.852**
R.o.OECD · (2007–2014)				−2.860	−5.445***
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		**	**	**	**
p-value: P1 EU15 – OECD				·	·
p-value: P1 EEU – OECD				***	***
p-value: P2 base – EU	***				
p-value: P2 base – EU15		***	***	***	***
p-value: P2 base – EEU		***	***	***	***
p-value: P2 base – OECD				·	***
p-value: P2 EU15 – EEU		·	·	·	·
p-value: P2 EU15 – OECD				·	·
p-value: P2 EEU – OECD				·	·
p-value: P1-P2 base	***	***	***	***	***
p-value: P1-P2 EU	·				
p-value: P1-P2 EU15		·	·	·	·
p-value: P1-P2 EEU		**	**	**	**
p-value: P1-P2 OECD				·	·
p-value: DID EU15 – EEU		**	**	**	**
p-value: DID EU15 – OECD				·	·
p-value: DID EEU – OECD				·	**

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
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. · stands for not statistically significant at the 10% level. *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.

countries found by Chan (2014) in an efficiency frontier analysis of energy intensities in the EU in the period 2006–2010.[24] Additionally, this suggests that voluntary agreements on industrial energy efficiency, which existed in the EU15 already since the 1990s but emerged in the EEU only after 2009 (see Cornelis, 2019), are not enough to induce large energy efficiency improvements. These results are robust to the exclusion of Switzerland from the regression (column 3).

The different dynamics detected in the EU15 and the EEU find their underpinning in the different implementation of the Directive by the EU member states (see European Commission, 2014, for an overview of the national policies implemented). 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, and 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 period 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 CO_2 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 CO_2 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

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[24] Related to the larger room for improvement in EEU countries, Cornillie and Frankhauser (2004) and Vehmas et al. (2018) show that energy intensity in these countries tends to be above the EU average.

the periods (*p*-values P1 EU15-OECD and P2 EU15-OECD). From 1997 to 2007, the differences between the EEU and these two groups are significant (p-values P1 EU15-EEU and P1 EEU-OECD), whereas from 2007 to 2014 they are not (p-values P2 EU15-EEU, and P2 EEU-OECD). Also, the differentials 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). However, some patterns change for the OECD group. The stronger decrease of the efficiency factors of 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). Similar to before, the difference between the EU15 and other OECD countries is not significant (*p*-value DID EU15-OECD).

4.2.2. *Energy intensity in footprint-based accounts*

Although the EU Energy Services Directive does not target footprint-based energy measures, it can have two indirect effects on the energy intensity of suppliers of intermediates, which affect the energy footprint of EU countries. 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 as a result of the EU Directive 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. The net outcome of these two effects is ambiguous, however. Besides, the difference between the results for footprint-based energy intensity and for production-based energy intensity may be relatively small, because 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. Accordingly, we compare the results of regressions for production- and footprint-based accounts. Table 3 reports the main results for the country groups and the two periods considered. We highlight the following findings.

Table 3
Comparison of production- and footprint-based results.

	P1 (1997–2007)	P2 (2007–2014)	Difference (P2−P1)
	Production-based energy efficiency factor		
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
	Final production-based energy efficiency factor		
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
	Consumption-based energy efficiency factor		
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

Note: Results from the regressions analyzing the average annual percentage change in the efficiency factor from the SDA for the respective energy account (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 accounts. *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 regression results including Wald-tests for significant differences across country-groups and periods are reported in Tables 2, 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 regression tables: The regressions exclude Switzerland in both periods.

First, the estimates for the footprint accounts reflect the different sourcing patterns of intermediates. The differences in the efficiency factor across country-groups are less pronounced for the footprint accounts than for the production-based account. This may indicate that energy-efficient countries, EU15 and other OECD countries, source energy-intensive intermediates from less efficient countries, EEU and the base group (non-EU non-OECD countries). The dynamics observed are consistent with this reading. Before 2007, the EU15 and the group of other OECD countries show larger efficiency gains in footprint-based than in production-based accounts, 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. Although the footprint-based efficiency factor decreases in the other OECD countries, their production-based efficiency factor increases, such that the energy-efficiency improvements of suppliers of embodied intermediates are 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. In this period, the energy-efficiency of footprints in EU15 and other OECD countries improves less than production-based energy efficiency.

Second, the comparison of the efficiency gains between footprint- and production-based accounts suggests that the EU15 relies more heavily on imports of embodied intermediates with less efficiency gains than the rest of OECD 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 in the EU15 and the OECD (excluding Switzerland) are larger after 2007 for production-based accounts, for footprint accounts this is the case only in the OECD (see difference P2–P1). Nevertheless, 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 (see Tables C.11 and C.12 for details). However, after 2007, the footprint-based efficiency gains are slightly larger in the EU15 than in the EEU and the rest of the OECD (the difference being statistically insignificant).

All in all, EU15 and OECD countries experience stronger efficiency gains in production- based energy accounts after 2007 as compared to before. Yet, the estimated dynamics of production- and footprint-based estimates are indicative of a shift of energy-intensive production from EU15 and OECD countries towards countries in the EEU and non-EU, non-OECD countries. This is in line with findings supporting the existence of carbon leakage provided by e.g. Aichele and Felbermayr (2015) and Fernández-Amador et al. (2016). Given the analogous dynamics estimated for EU15 and OECD countries, it is unlikely that the EU Energy Services Directive constitutes 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 energy leakage that our results indicate may offset the potential of energy intensity policies in high-income countries to contribute to a reduction of consumption-based energy usage. In this case, the trend towards more energy efficiency does not translate into lower energy footprints in high-income countries.

4.2.3. *Changes in the energy mix*

From the dataset elaborated, it can be observed that the EU's switch from fossil fuels towards wind and solar energy is faster than in other regions over 1997–2014 (see also Dietzenbacher et al., 2020). Although

Table 4
Regression results: energy mix of production.

	Non-renewable			Renewable			
	Fossil	Nuclear	Other n-ren	Hydro	Wind	Solar	Other ren
Constant	0.213**	−0.008	0.003*	0.031	0.002**	0.003	−0.243**
2007–2014	−0.065	0.016	0.000	−0.039	0.016**	0.005	0.065
EU15	−0.458***	−0.050	0.028***	−0.070	0.068***	0.004	0.479***
EU15 · (2007–2014)	−0.501**	0.053	0.016	0.142*	0.089*	0.076***	0.125
EEU	−0.406**	0.085	−0.006	−0.054	0.003*	−0.002	0.380***
EEU · (2007–2014)	−0.668	−0.133	0.076**	0.234*	0.050**	0.032***	0.410**
R.o.OECD	−0.219	0.029	0.012	−0.111*	0.009**	0.001	0.279**
R.o.OECD · (2007–2014)	−0.053	−0.240	−0.002	0.121	0.026*	0.021**	0.126
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	·	·	**	·	***	***	·
p-value: P1: EU15–OECD	*	·	·	·	***	·	**
p-value: P1: EEU–OECD	·	·	·	·	·	·	·
p-value: P2: base–EU15	***	·	***	·	***	***	***
p-value: P2: base–EEU	**	·	**	·	**	**	***
p-value: P2: base–OECD	·	·	·	·	***	***	**
p-value: P2: EU15–EEU	·	·	·	·	**	*	·
p-value: P2: EU15–OECD	***	·	**	·	***	**	·
p-value: P2: EEU–OECD	*	·	**	·	·	·	**
p-value: P1–P2 base	·	·	·	·	**	·	·
p-value: P1–P2 EU15	***	·	·	***	**	***	**
p-value: P1–P2 EEU	*	·	**	*	***	***	***
p-value: P1–P2 OECD	·	·	·	*	***	***	·
p-value: DID EU15–EEU	·	·	*	·	·	*	*
p-value: DID EU15–OECD	·	·	·	·	·	**	·
p-value: DID EEU–OECD	·	·	**	·	·	·	·

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *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. · stands for not statistically significant at the 10% level. *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.

the Energy Services Directive does not formulate specific targets on renewable energy, faster improvements in the shares of renewable energy in EU countries over 2007–2014 may result from the mandatory renewable energy targets for 2011–2020 specified in the Renewable Energy Directive [2009/28/EC]. To test for this observation, we run regressions using the average annual change in the share of the seven energy commodities in the energy mix as dependent variables.[25] Table 4 reports the results for production-based accounts. From these results, we conclude that the transition from fossil fuels to renewable energy sources is faster in the EU than in other OECD countries after 2007, but also before. This suggests that the increase in speed of the transition is not specific to the EU but similar to the developments in other high-income countries. Two findings support our conclusion.

First, in both the EU15 and the EEU, the reduction in the share of fossil fuels and the increase in the shares of the renewable energy categories are larger after 2007. The reduction in the share of fossil fuels in the EU15 is significantly different from the reduction in the rest of OECD countries for the same period (p-value P2 EU15-OECD). The shares of hydro, wind, and solar energy also increase faster after 2007 compared to before in other OECD countries (see *p*-values P1-P2). However, wind and solar energy expand significantly stronger in the EU15 compared to the EEU and the rest of OECD countries in both time-periods. This contrasts to the non-significant difference between wealthy and less wealthy EU countries in the transition to renewable energy after 2008 documented by Andreas et al. (2017). Since Andreas et al. do not distinguish between renewable energy sources, their finding may be explained by the stronger increase in hydro and other non-renewable energy in the EEU compared to the EU15 after 2007, although these differences between EU15 and EEU are statistically insignificant in our case.

Second, the change in the expansion rates across periods in most energy sources differs between EU countries and the base group (non-EU non-OECD countries) but is not significantly different from that in the other OECD countries. 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 the increase in the growth rate of renewables is significantly stronger only in the EU15 for solar energy (p-value DID EU15-OECD). The faster reduction in the share of fossil fuels in the EU15 after 2007 is similar to the rest of the OECD (the differential is marginally insignificant; p-value DID EU15-OECD). The EEU increases the share of other non-renewable energy after 2007 faster than the OECD (p-value DID EEU-OECD). For the energy mix of footprint accounts, our findings are qualitatively similar to the ones described for

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[25] An outlier, Cyprus, is excluded from the regressions: 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 production-based energy mix (see Tables C.13 and C.14 in Appendix C).

5. Conclusion

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 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.

In this paper, we study the effects of the EU Energy Services Directive [2006/32/EC] on energy efficiency of production, final production and consumption to account for the effects of global supply chains on the effectiveness of the Directive. We construct a dataset of national energy accounts and propose the sector energy efficiency factor from an SDA as an improved measure of energy efficiency. The energy efficiency factor is used in a regression analysis, where we compare changes in energy efficiency in EU countries with changes observed in other countries over the periods before and after 2007 for the three energy accounts calculated, and analyze changes in the energy source mix over the same periods.

Our results indicate that the EU Energy Services Directive may have triggered policies that lead to stronger energy efficiency gains in production in the EU15 after 2007, as targeted by the Directive, but not in final production and consumption. 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 production-based energy usage of EU15 and OECD countries relative to non-high-income countries increases after 2007. Also, the faster 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 policy 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 towards more energy-intensive imports from non-high-income countries after 2007, and their better efficiency for production-based energy usage relative to non-high-income countries does not extend to footprint inventories. EU15 members reduce their energy usage for production from 1997 to 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, which usually targets production-based energy, 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 for final production and consumption. Energy regulation should account for global supply chains to ensure that energy efficiency gains imply reducing 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. Furthermore, the design of energy efficiency policies should also account for potential rebound effects. In this regard, a general-equilibrium approach can identify and incorporate the role of global supply chains and rebound effects into ex-ante policy assessments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107635.

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