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Is decoupling a red herring? The role of structural effects and energy policies in Europe

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ABSTRACT

Decoupling energy consumption and carbon emissions from economic growth is at the core of the climate change debate: successful decoupling is evidence that efficiency measures can be economically sustainable. In this article, the authors analyze the underlying nature of this decoupling in the European Union from 1990 to 2014. The objective is to quantify the role of structural changes and the effectiveness of energy efficiency measures in lowering energy consumption. We decompose final energy consumption per sector, including households and transportation into three key drivers: economic growth, economic structure and energy intensity. Our results show that a significant part of the reduction in energy consumption can be attributed to structural changes, such as deindustrialization, while an equally significant part can be attributed to energy efficiency. This further corroborates the idea that much of the observed decoupling is virtual; largely due to outsourcing of energy intensive activities. Energy is then imported in the form of embodied energy in goods and services. The dynamics of these effects suggest that a shift in our understanding of decoupling is necessary. The implementation of effective energy efficiency policies, accounting for embodied energy, remain of high priority.

1. Introduction

The decoupling of energy consumption from economic growth is widely advertised by many countries as a great achievement towards the fight against climate change and other environmental impacts (EEA, 2016). The ratio between energy use and economic output (gross domestic product or GDP), also known as "energy intensity", is the indicator used to assess the depth and rate of decoupling of final energy consumption and economic growth. A report from the International Energy Agency (IEA) indicated that a declining trend for energy intensity was observed across most of the globe between 1990 and 2004 (IEA, 2008). The decoupling of any natural resource, such as energy, and GDP is observed in two ways: (i) relative decoupling, when the growth rate of energy consumption is positive but less than that of economic growth, or (ii) absolute decoupling, when energy consumption is stable or declining while the economy is growing (UNEP, 2011). In the particular case of the European Union (EU), data from the European Environment Agency (EEA) shows that this decoupling was relative until approximately 2005, after which it became absolute (EEA, 2016).

However, this decoupling can also be distinguished between real and virtual (Moreau and Vuille, 2018); real decoupling occurs due to effective reduction in energy consumption or energy efficiency measures in economic activities and households. Virtual decoupling, on the other hand, is an apparent reduction in energy intensity due to changes in economic structure, such as increased reliance on imports, which reduce domestic energy consumption by exporting it abroad. Understanding what are the drivers behind this decoupling is important to analyze the effectiveness of different energy policies and to understand the problem on a global level. As such, it is important to understand just how much of the decoupling claimed can be attributed to global, regional or national changes in economic structure, especially at the level of economic activities, and how much can be credited to energy efficiency measures and innovations. Therefore, the authors decomposed the evolution of energy consumption in the EU into three main drivers: scale effect (economic growth), structural effect (deindustrialization and tertiarization) and intensity effect (energy efficiency). The objective is to understand what are the underlying causes of the decline in energy intensity in the EU, and to what extent decoupling may be virtual rather than real, in other words a red herring.

The increasingly large role of international trade has spurred drastic structural changes across the globe, with major industry sectors moving manufacturing away from their domestic markets in search of increased competitiveness. World Bank data shows that international trade

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(measured as percentage of GDP) has steadily grown since approximately the 1970s. A similar trend can also be observed with physical trade indicators in Europe over the past 17 years (World Bank, 2017). This reshuffling of global manufacturing left many developed countries in a state of deindustrialization, in which industries moved where production and labor costs were lower. By deindustrialization we mean either an absolute (relative) decline in manufacturing employment or output (with respect to services) or a decline in the trade of manufactured goods (Lever, 1991). With services being less energy intensive than primary (e.g. mining) and industry (e.g. manufacturing) sectors, many developed countries have seen their domestic energy intensity decline or at least stabilize. However, the energy savings due to deindustrialization are only apparent, as energy is still being consumed elsewhere to manufacture the goods lost domestically. That energy is then imported as embodied energy in products (goods and services), but accounted for in the country of manufacturing. Understanding how much globalization plays a role in the national and regional decoupling trends can help us understand how far we are from achieving real global or regional decoupling, and thus support future policies to avoid energy or emission leakages.

Despite this ubiquitous effect of trade, it is important to note that the EU is mostly trading internally amongst member states. From 1999 to 2005, about 68% of EU trade in monetary terms came from other EU countries. Since 2007 this proportion has been declining, but the EU still constitutes a major destination of its own production (WTO, 2017). This means that within the EU, member states can offset one another's deindustrialization as shown in Fig. 1 where Europe's trade balance has improved over recent years. In other words, the energy (or emissions) terms of trade are more equitable among EU member states than between the EU and other regions. For example, when factories move from western to eastern member states, the EU's trade balance with the rest of the world remains unchanged. Conversely, trade balances have become increasingly negative in North America, with a steeper decrease starting in the late 1990s. Fig. 1 also illustrates an increasingly positive trade balance for Asia (and the Middle East when the price of Oil was high), starting around the same time when the World Trade Organization (WTO) was established to champion international trade.

Although Europe is increasingly dependent on the world for imports, it remains highly industrialized, with ratios of imports to exports hovering around 100%.

In energy terms, data from the IEA shows a clear upward trend in the number of energy policies implemented by year in the EU (IEA, 2017), starting in the early 2000s. This is especially true in households and services, which contributed to the decline in energy intensity. The extent to which countries pass energy policies varies significantly among EU members, with Germany being on the forefront and Eastern Europe contributing less to the total count.

Thus, we test the hypothesis that structural effects, namely deindustrialization and tertiarization, contribute significantly to changes in energy consumption in Europe, more so than energy efficiency measures. In other words, the decoupling observed is largely virtual rather than actual.

We do so by analyzing energy consumption at three levels, the EU-28 member states, further clustered into four EU regions, and finally we focus on two cases which, according to our results, are representative of two these clusters, namely Germany and Poland. Few authors have applied different decomposition analysis methods to understand the drivers and trends of energy consumption and energy intensity in Europe specifically. Lan et al. (2016) applied spatial Structural Decomposition Analysis to estimate global energy footprints for 186 countries between 1990 and 2010. They found a clear connection between a country's GDP per capita and a concentration of energy footprints on their imports, thus supporting our hypothesis that decoupling is virtual, and largely offset by energy embodied in imports. When looking at worldwide energy footprints, the authors found that the main drivers behind the energy consumption increase was affluence, while structural effects had a low impact. They also found that the affluence effect is offset by efficiency improvements, especially in industry, while structural effects were country dependent. Fernández Gonzàlez et al. (2014) found similar results by decomposing the energy consumption of

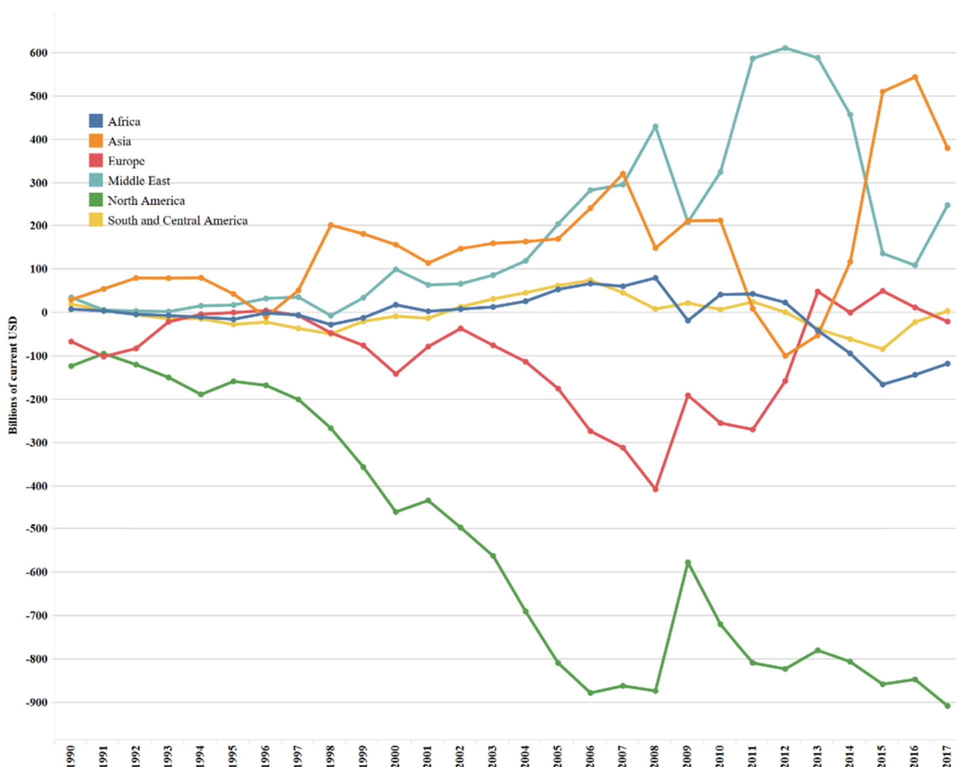


Fig. 1. Trade Balances of Main World Regions (Source: own calculation based on WTO data).

EU-27 member states between 2001 and 2008. Structural effects also exhibited variability across member states. The authors partially explain this through economics, migration and policies. Using the same methodology, Marrero and Ramos-Real (2013) decomposed the energy intensity of the main economic activities in the EU-15 between 1991 and 2005. Yet, this study excluded the transport and household sectors, and provided only a partial picture of the effects underpinning energy intensity at the national level. More relevant in our case, Reuter et al. (2017) analyzed the primary energy consumption and energy conversion in particular in the EU-28, with case studies on Germany and Poland as well. Their goal was to evaluate the distance to energy efficiency targets by decomposing primary energy into three components: electricity consumption, electricity mix (renewables, nuclear, coal, gas etc.) and level of efficiency in the electricity system. They concluded that final energy consumption is one of the main drivers of primary energy decoupling, and as such, the authors recommend an in-depth study of final energy consumption and its drivers, such as socio-economic and technological factors.

Hence the research presented in this article where we go a step further by decomposing the final energy consumption of economic activities as well as households and transportation, measured in physical terms (space heated and km traveled). This allows us to distinguish clearly how structural changes and energy efficiency in the industry and services have fared compared to household consumption of energy services. We also expand the previous EU studies to capture the large changes which occurred in the 1990s with German reunification and the WTO. To underline the trends and evaluate the contribution of energy policies, we look at five year increments, from 1990 to 2014. We therefore fill a gap in the analysis of final energy consumption in the EU to include early changes in structural effects and later changes in efficiency. EU member states are then clustered according to structural and intensity effects and we analyze in detail the archetypical cases of two clusters.

In the following sections the authors further explain the methodology applied, present the results, and finally, discuss the results and their implications from an energy policy standpoint to evaluate what are the main drivers of decoupling in the EU, and what, if any, are the policy implications.

2. Methodology

Index decomposition analysis (IDA) was chosen here for two main reasons: (1) it is more commonly used in decoupling research and the results can be easily interpreted (Su and Ang, 2012) and (2) due to fewer data requirements. IDA allows for the analysis of more recent periods, which Structural Data Analysis (SDA), although superior in detail, cannot do due to the limited availability of up-to-date Input Output Tables (IOTs). Comparisons between the two methods remain scarce (e.g. Hoekstra and van den Bergh, 2003).

Within IDA, several methods exist, all falling within two categories: Laspeyres Index and Divisia Index. Additionally, the decomposition can be additive (studying the difference in an indicator between two periods), or multiplicative (studying the ratio between two periods). Based on the comprehensive comparative study developed by Ang (2004), the additive Log Mean Divisia Index (LMDI) method was used in this study.

2.1. Application

Additive decomposition was done as proposed by Ang (2005), with the following identity equation:

$$E = \sum_i E_i = \sum_i Q\frac{Q_i E_i}{QQ_i} = \sum_i QS_i I_i \quad (1)$$

where E is the total final energy consumption in an economy, E_i the energy consumption of the ith economic activity (e.g. mining or manufacturing), Q is the total economic output (GDP) of the economy, and Q_i is the value added of the ith activity. As such, Q is the scale effect (economic growth). The ratio of Q_i over Q also written S_i is the structural effect, measuring how the output of activity i changes with respect to GDP. The intensity effect, or the energy consumption per unit of economic output I_i is given by the ratio of E_i and Q_i for the ith activity.

A few adjustments must be detailed here: since we included two final consumption sectors, household residential energy consumption and transportation, their share of the effects in Eq. (1) was computed in physical rather than monetary terms. While for industry and services value added is used, the effects from residential energy consumption and passenger (freight) transportation were measured in average floor area of dwellings and passenger-km (ton-km) traveled respectively. The effects of each of these proposed drivers (scale, structure and intensity effects) on the overall changes in energy consumption are measured through the equation:

$$\Delta E = \Delta Q + \Delta S + \Delta I \quad (2)$$

where

$$\Delta Q = \sum_i \frac{E_i^T - E_i^0}{lnE_i^T - lnE_i^0} ln\left(\frac{Q^T}{Q^0}\right) \quad (3)$$

$$\Delta S = \sum_i \frac{E_i^T - E_i^0}{lnE_i^T - lnE_i^0} ln\left(\frac{S_i^T}{S_i^0}\right) \quad (4)$$

and

$$\Delta I = \sum_i \frac{E_i^T - E_i^0}{lnE_i^T - lnE_i^0} ln\left(\frac{I_i^T}{I_i^0}\right) \quad (5)$$

where superscripts denote the initial year (0) in the time period and (T) the final year. The advantage of additive LMDI lies in the interpretation of the results and is more adequate for changes that are more linear rather than exponential. The disadvantage is that it makes country comparisons harder since the results are given in absolute terms. To understand the comparison, we normalized with the total energy consumption for all countries. Thus, instead of reporting the absolute values calculated from additive LMDI, the results are reported in terms of percentage change from the first year of each period, following the equation:

$$\frac{\Delta E}{E^0} = \frac{\Delta Q}{E^0} + \frac{\Delta S}{E^0} + \frac{\Delta I}{E^0} \quad (6)$$

First, this allows us to gauge how relevant the changes are. For example, a change of 50,000 TJ in absolute terms is much larger for Spain than it is for Germany, because Germany consumes much more energy than Spain. Second, by reporting all numbers in terms of a percentage change, it becomes easy to compare across countries and measure how their efforts in energy efficiency have paid off.

2.2. Data

Data for the IDA analysis primarily came from the ODYSSEE-MURE database, with detailed sectorial data available from 1990 until 2014 for most countries (ODYSSE MURE, 2017). While the primary source of data in ODYSSEE is Eurostat, it conveniently combines industry data with transportation and households. The long time series was further divided into five intervals, 1990–1995, 1995–2000, 2000–2005, 2005–2010, 2010–2014. This division allowed for the observation of underlying trends from 1990 to 2014. However, the database is not complete, and for several countries and/or periods, part of the data came from the World Input Output Database (WIOD) (Timmer et al., 2015). All monetary flows were adjusted to constant EUR 2005 using GDP deflators from the World Bank,[1] annual exchange rates from the

[1] Inflation, GDP Deflator (Annual %). *World Bank*, data.worldbank.org/

WIOD and 1998 exchange rates from the European Central Bank (ECB)[2] for countries that switched to EUR in 1999. Additionally, since some of the WIOD data starts only in 1995 and ends in 2009, part of the missing data was extrapolated. Nevertheless, across all years at least 94% of the data was extracted from the ODYSSEE MURE database, ensuring a high consistency in the results. Finally, data on energy efficiency policies came from the International Energy Agency's Policies and Measures Database (IEA, 2017), as well as data from the World Trade Organization on national and regional trade flows (WTO, 2017).

3. Results

The results are presented for the EU as a whole, followed by the analysis of clusters of EU member states which experienced similar development before we dive into two representative case studies. All the results for individual EU member states can be found in Supplementary data.

3.1. European Union

Fig. 2(a) shows the percentage change in energy consumption from 1990 to 2014, broken down into the key drivers: scale effect (economic growth), structural effect (deindustrialization, tertiarization) and intensity effects (energy efficiency). Fig. 2(b) illustrates final energy consumption in absolute terms as well as the difference between energy embodied in imports and exports, or energy trade balance. The results for scale and structural effects are almost mirror images of each other. The large negative structural effects in the 1990s indicate that the EU experienced a period of high deindustrialization even as the economy was growing rapidly. This initially lowered energy intensity which started decreasing again in the year 2000. The increasingly negative intensity effects thereafter, suggest a more prominent role of energy efficiency measures. Note that many of the effects are relatively small (less than 5% over 5 years). This can either be because the EU experienced small homogeneous effects, or because variations between countries average each other out on a regional level.

A comparison between Fig. 2(a) and (b) shows that there is a lag between changes in final energy consumption due to structural effects and a rise in energy embodied in trade. Variations in energy consumption differ significantly at the level of economic activities. The EU wide results in Table 1 show that the 1990s and 2000s saw large negative structural effects in both the primary and secondary sectors. Thus, much of the deindustrialization observed occurred in the 1990s, yet these changes were not uniform across member states, as the cluster analysis below shows. Internal trade in the EU might have compensated for structural changes in some member states. The effects at the EU level are therefore smaller than that observed in many individual member states.

Although negative intensity effects were pervasive in the primary sector, they were much less noticeable in the secondary, suggesting a larger role in the modernization of agriculture than in the industry. It is only in the latest period that intensity effects become dominant in the secondary sector. The service sector saw minimal structural effects and small negative intensity effects in most periods. Households exhibit a similar profile as the service sector except for significant negative structural effects in the late 1990s and early 2000s as heated space per capita decreases with densification.

3.2. Regional analysis

Across Europe, countries differ significantly in terms of climate, energy policies, economic structure and other factors. These differences observed in our results can be approximately clustered based on regional lines, with Eastern Europe gradually entering the EU and the global market since 1990. Southern Europe has milder climates, and the West and North developed large industrial and trade infrastructures, for instance. As such, it is expected that decomposition would yield different results across these geopolitical regions. In this section we show that regional differences make more in depth investigation worthwhile to understand their political, economic and historical drivers. The figures shown exclude Luxembourg and Malta for lack of complete data. All the plots including individual countries can be found in Supplementary data. Information on total goods transported is not included for the secondary sector in the following countries due to data unavailability: Belgium, Bulgaria, Estonia, Hungary, Lithuania, and Slovakia.

We focus on structural and intensity effects as they play out in the secondary and tertiary sectors. The primary sector represent a very small portion of energy use in Europe and are not shown and less relevant for comparative purposes and when analyzing the underlying trends in energy consumption. Table 2 shows how the four main regions of Europe fare in terms of structural and intensity effects in industry and services. The average of each region is weighted based on the average total final energy consumption of each country per time period and is shown as a percentage change relative to the first year of each period shown.

This shows that structural effects across Europe were overwhelmingly negative on the secondary sector and mostly positive in services. However, the results on the tertiary sector were significantly smaller in magnitude, reaching no more than 5% change in energy use over 5 years, in a sector that is already typically smaller than the secondary sector in terms of energy consumption. This indicates that a decline in the energy consumption of industry is not offset by an increase in that of services. While industry and services might compensate changes in each other's economic output, there's little reason to believe services would use more energy than industry per unit of output. In other words, energy intensities differ significantly across economic activities. In addition, while there is some variability between the regions in the magnitude of these effects, there are few discernible patterns. One thing that can be observed is that Eastern Europe shows significant tertiarization in the 1990s, while the effects in its secondary sector remained similar to the rest of the EU. This indicates the small extent of deindustrialization in Eastern Europe as well as an uptake of services after the collapse of the Soviet Union.

While structural effects do not seem to clearly differentiate these four regions, intensity effect tells a different and clearer story. The first conclusion is that Eastern Europe exhibits a significant increase in energy efficiency in the secondary sector, more so than in any other regions. This explain why industry in Eastern Europe started to modernize and catch up to Western European standards. In addition to the service sector, Southern Europe experienced a decline in energy efficiency, which slowed over time. Overall, both in terms of intensity and structural effects, Northern and Western Europe behave quite similarly, an expected result given these are the most developed regions. This sets the stage for a more in depth analysis of individual countries representing the two most interesting of these regions, East and West, which contrast quite clearly as explained below.

3.3. Case studies

Germany and Poland were chosen as case studies to perform a more in-depth analysis, not only as representatives of Western and Eastern Europe, but also as two opposite pathways towards deindustrialization. Germany has grown the EU's largest trade surplus in monetary terms

(*footnote continued*)
indicator/NY.GDP.DEFL.KD.ZG.

[2] Determination of the Euro Conversion Rates, *European Central Bank*, 31 Dec. 1998, www.ecb.europa.eu/press/pr/date/1998/html/pr981231_2.en.html.

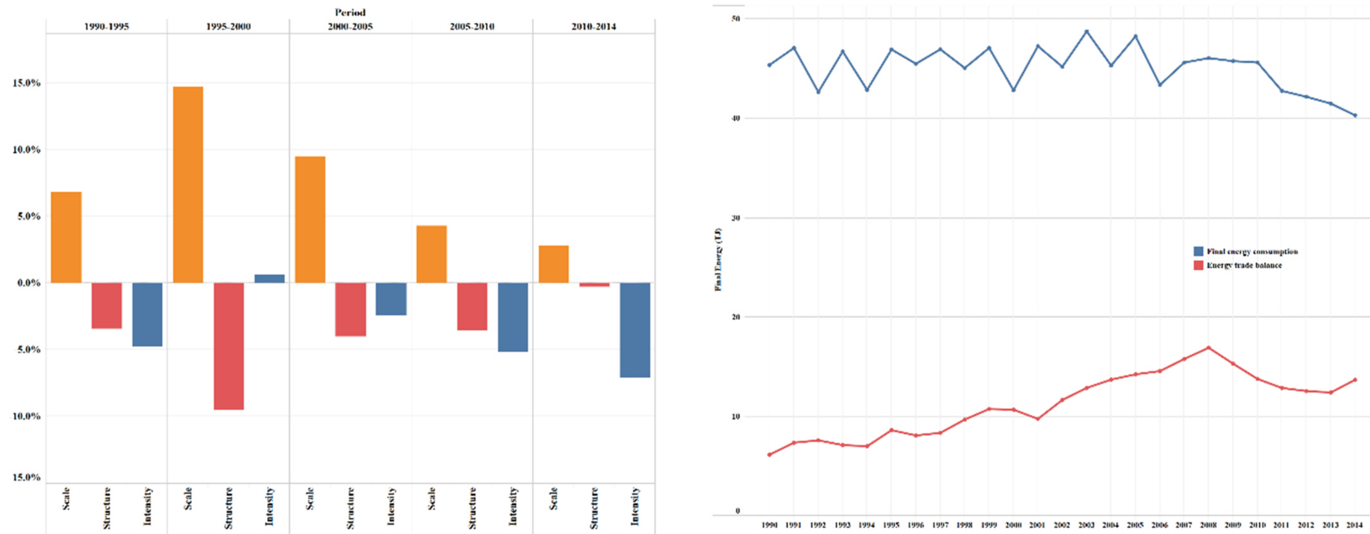


Fig. 2. Decomposition of final energy consumption in the EU-28, broken down into Scale, Structure and Intensity Effects (a) (source: own calculation), and the EU-28 final energy consumption and energy trade balance (b) (source: Eora and own calculation).

Table 1
Sector level results for the EU in terms of Scale, Structural and Intensity Effects for all five periods of time (positive changes are shown in blue and negative changes in red).

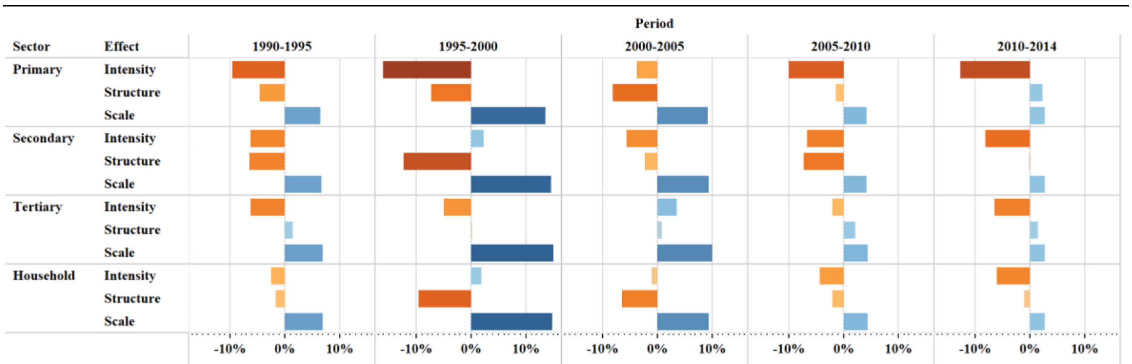
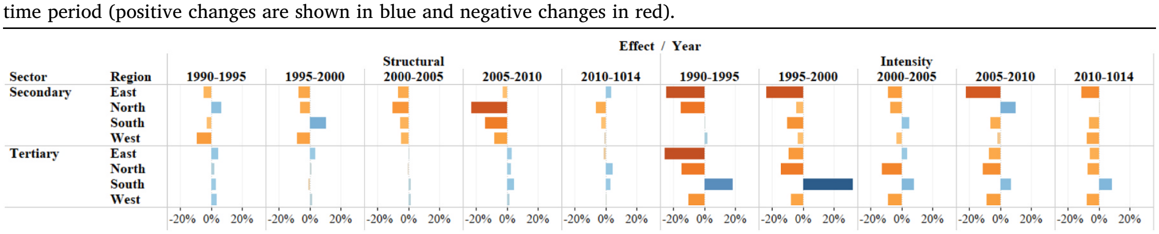


Table 2
Sector level results for the four main European regions in terms of Structural and Intensity Effects in the secondary and tertiary sectors per time period (positive changes are shown in blue and negative changes in red).



while Poland went from the EU's lowest trade surplus in energy terms in 1990 to an energy trade deficit. Such changes exemplify very different patterns of economic structure and energy use, seldom found elsewhere.

3.3.1. Germany

Germany experienced negative structural effects since 1990, averaging 3% every 5 years, indicative of deindustrialization, as shown in Fig. 3(a). For reference purposes, the evolution of final energy consumption and the energy embodied in German trade are also shown in absolute terms (b). Intensity effects are also negative from 1990 to 2014, becoming increasingly large in recent years, which reflects a growing effort in implementing energy policies and efficiency measures in particular.

While final energy consumption has declined, it plateaued since 2006 and so did embodied energy in trade since 2000. This shows that the effects of structure and intensity might have reached their limit.

Table 3 shows the results per sector as a percentage change with respect to the first year of each time period. The primary sector saw some of the largest percentage change in energy consumption in Germany, reaching almost 60% for structural effects in the first period. However, while these changes were large within the primary sector, they played a minimal role in the overall change in energy consumption, since agriculture is the least energy intensive, in all regions.

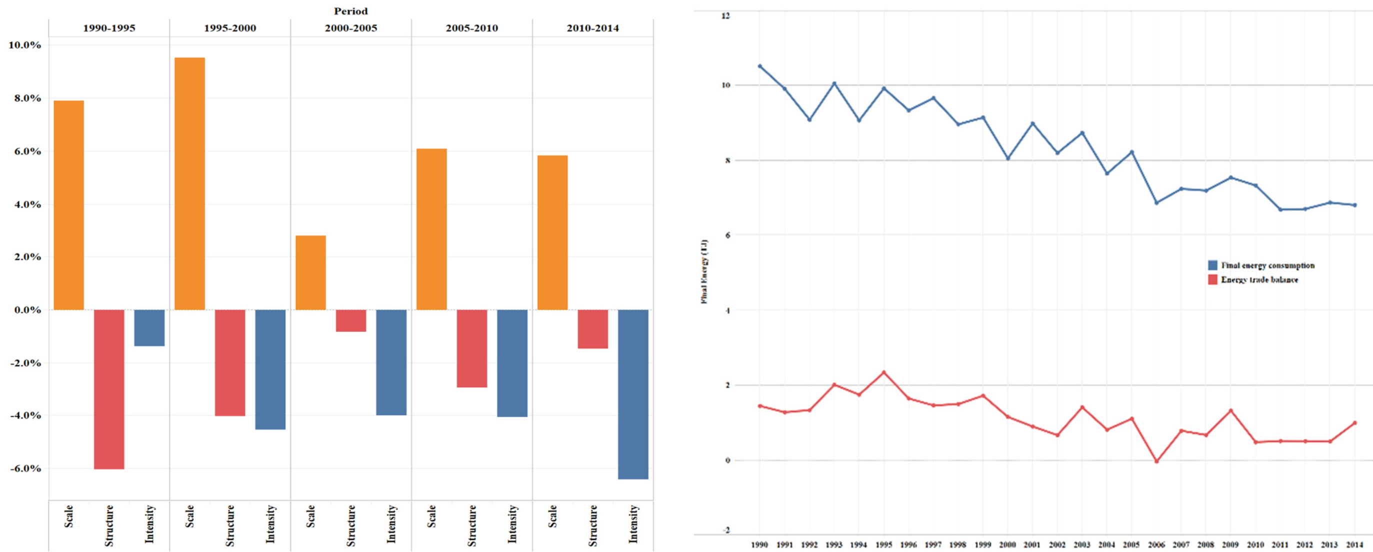


Fig. 3. Decomposition of Germany's final energy consumption, broken down into its key drivers (a) (source: own calculation), and final energy consumption and energy trade balance (b) (source: Eora and own calculation).

Structural effects were consistently negative, indicating a decline in agricultural and mining activities. In the secondary sector, these effects are not as low, reaching −10% at most. However, since the secondary sector is responsible for much of Germany's output, even small changes can have large national and regional impacts. The results suggest a period of stronger deindustrialization in the early 1990s, followed by a more stable period and reindustrialization. It also shows that intensity effects have played a role in reducing energy consumption in the industry, particularly after 2010. These small changes are in line with evidence from German trade balances, which suggest that Germany remained industrialized throughout the 1990s and 2000s, and is now experiencing an even greater trade surplus (WTO, 2017).

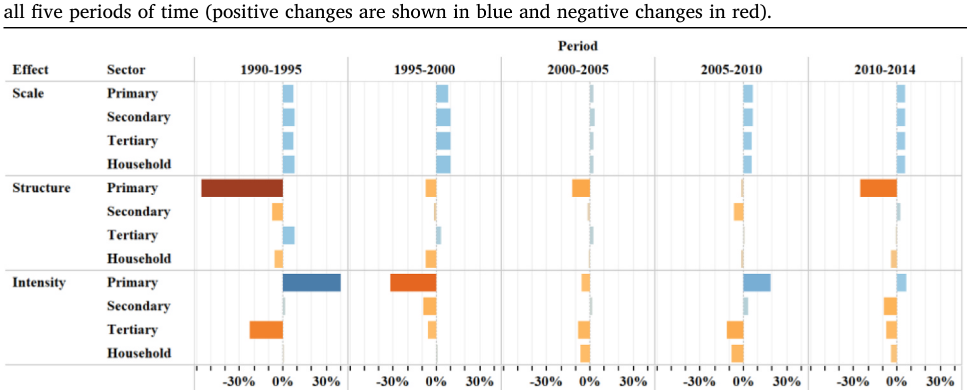
The service sector experienced relatively large percentage change from individual effects, with some reaching over 20%. These changes were predominantly due to intensity effects, which were consistently negative. Additionally, the sector experienced small but consistent positive structural effects, explaining the growth in the service sector's output. The consistent intensity effects indicate the effective implementation of energy efficiency measures. Finally, we observe that during the 1990s, households underwent significant negative structural effects, substituted by significant negative intensity effects after 2000. Given that energy use for heating is corrected for climatic conditions, negative structural changes mean less square meters of heated space per capita as with urban densification. While the percentage changes for households are small, no more than 7%, their consumption accounts for a large share of final energy use. These results illustrate a trajectory of moderate deindustrialization and strong energy policy that Germany implemented since reunification. It kept an industrialization levels high and remains one of Europe's main exporters as shown by small negative structural effects in the decomposition results and a practically constant energy trade balance since 2000. In addition, the results in terms of intensity effects, a proxy for energy efficiency, concur with a significant increase in energy policies passed in the late 2000s (IEA, 2017).

These results are in line with previous work which also showed negative structural effects in Germany, and increasingly negative intensity effects throughout the late 1990s and early 2000s (Marrero and Ramos-Real, 2013). Similarly, Fernández Gonzàlez et al. (2014) found that both structure and intensity effects were negative in Germany between 2001 and 2008, with intensity dominating, a finding they attribute to the decreasing importance of industry in the economy. Thus our results support the hypothesis of virtual decoupling for Germany over the entire period by substituting outsourcing of energy intensive industry abroad for final energy. However, intensity gains cannot be overlooked, as they are significant, and their timing coincides with effective energy policy.

3.3.2. Poland

As seen in Fig. 4(a), intensity effects were negative across all periods

Table 3
Relative evolution of final energy demand in Germany broken down into Scale, Structural and Intensity effects for all five periods of time (positive changes are shown in blue and negative changes in red).



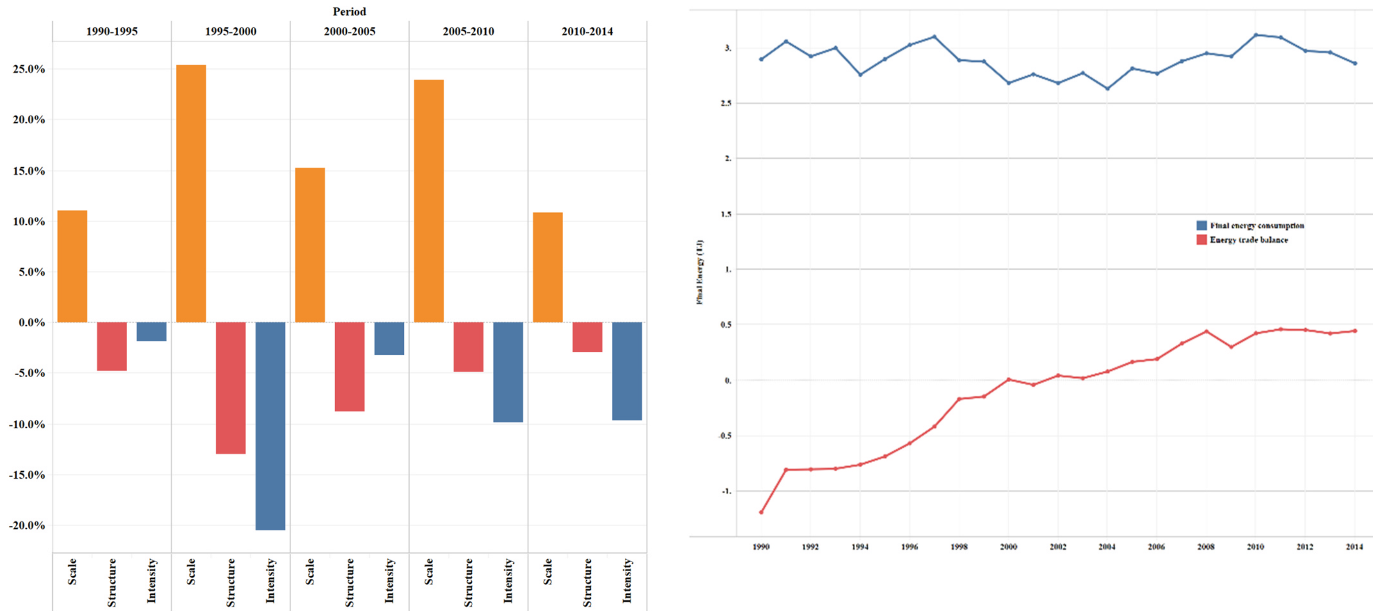


Fig. 4. Decomposition of Poland's final energy consumption, broken down into its key drivers (a) (Source: own calculation), and final energy consumption and energy trade balance (b) (source: Eora and own calculation).

in Poland, an interesting finding considering Poland's lenient energy policy setting. Structural effects, as expected, were also negative throughout, and particularly significant in the late 1990s, in the aftermath of Poland's capitalist debut. These effects eventually tapered off in the 2000s when Poland became a net energy importer as shown in Fig. 4(b).

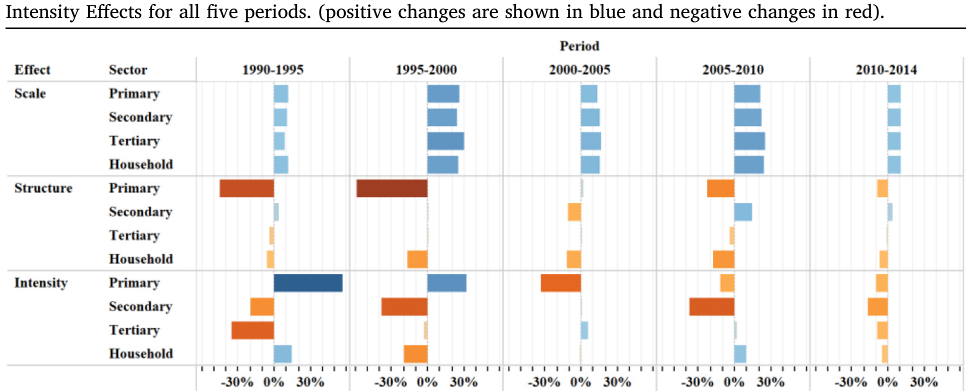
The results of decomposition can be interpreted in light of Poland's recent history. It was not until 1990 that the country started radical wholesale economic reforms after years of centralized planning. This largely explains the significant effects observed in the 1990s. Although Poland's energy policies remained permissive, it did not seem to have stopped it from achieving great intensity decline over the last 25 years, raising the question as to whether those gains are mostly market driven. To understand Poland's trends better, we must look at the sector level disaggregation, which effects are shown in Table 4. The primary sector saw the biggest percentage change in energy consumption, reaching close to 60% for structural effects over five years. This exemplifies the declining role of agriculture and the opening of the Polish market to competition. Eventually the primary sector also starts to see negative intensity effects, which signal a modernization of agriculture and mining.

The secondary sector shows smaller structural effects than the primary sector, meaning little changes in industrial activities. We see positive structural effect in the industry from the late 2000s onwards. This coincides with an increase in exported goods and services as well and imported energy. Finally, negative intensity effects prevailed over most periods, indicating a modernization of industry.

The service sector results show that structural effects played virtually no role in energy consumption changes: the main changes came from the effect of scale, with the exception of the early 1990s, when large negative intensity effects can be seen. These results are counter-intuitive when considering Poland's history and the boom in services at the end of the soviet era. According to our results, the scale factor for the service sector evolved at the same rate as the other sectors. Hence the contribution of imports, including for services as shown in Fig. 4(b). Finally, households show a consistent but small negative structural effect, and oscillating intensity effects. This is not entirely surprising, as Poland has passed very few energy policies targeting households. Although Poland shows some signs of structural changes, in particular in agriculture and mining activities, 2 digit changes in scale over all periods has dwarfed other effects. Therefore, the case of Poland provides little support to our hypothesis on decoupling except that it was one of the last net energy exporter within the EU 28 member states.

The period-by-period observation of the sectorial decomposition of

Table 4
Relative evolution of final energy demand in Poland broken down into the Scale Effects, Structural Effects and Intensity Effects for all five periods. (positive changes are shown in blue and negative changes in red).



Poland shows stark contrasts with Germany. First, few effects of deindustrialization can be observed in the secondary sector, as expected given the economic context in Poland in the 1990s. This can be at least partially attributed to the level of aggregation used. The results tell a slightly different story when looking at economic activities (see Supplementary data): some industrial activities saw significant positive structural effects throughout the 1990s, which subsided in the late 2000s, particularly machinery, food and non-metallic minerals. However, the primary metal manufacturing industry, a notoriously energy intensive industry, saw large negative structural effects (Mayer and Flachmann, 2011). However, these negative effects were offset by energy consumption gains from industries that flourished in the post-communist era, driven by higher living standards (more cement and food needed, for instance) and by the need to upgrade factories (machinery). Intensity effects were clearly dominated by the secondary sector, with both gains and losses observed in other sectors. While very few energy policies were implemented targeting households and services, there were market incentives to increase energy efficiency in the industry, as it increases competitiveness. Thus, this might be one reason why Poland saw significant efficiency gains without corresponding policy efforts. Moreover, a sharp increase in enacting energy policies in Poland corresponds to accession to the EU in 2004. When comparing these findings with previous work, structural effects had a more positive impact on Polish energy consumption, and intensity effects were largely negative between 2001 and 2008 (Fernández González et al., 2014). This is partly in line with our results, which show positive structural effects in the secondary sector between 2005 and 2010.

4. Discussion

4.1. Virtual decoupling

We have shown that negative structural changes, or deindustrialization, played a significant role in reducing final energy consumption in the secondary sector for all EU member states. These effects were predominant in the 1990s and early 2000s, after which they mostly subsided while negative intensity effects increased. This confirms our hypothesis that deindustrialization has contributed to a significant decline in energy consumption and that decoupling is equally real and virtual. Overall, structural changes reduced energy consumption by 21% in the EU from 1990 to 2014 while energy efficiency measures as hypothesize with decline intensity reduced energy consumption by 19%. This virtual decoupling was strongest in the late 1990s in the EU, which casts doubts on the real potential of energy efficiency. Both effects were almost entirely counterbalanced by economic growth.

Yet the underlying reasons for the evolution of energy consumption in Europe vary across countries and regions. While Eastern and Western Europe have experienced deindustrialization in all activities consistently from 1990 to 2015, structural changes are not as sustained in other regions. This makes sense when viewed from an international trade perspective. Much of EU trade is internal, which means that one country's deindustrialization can be compensated by other EU member states. In other words, the loss of manufactured goods in one EU state becomes a gain for manufacturing in another. This means that Western EU countries have experienced a much stronger virtual decoupling than others, which have experienced little to no effects. From 1990 to 2014, structural changes have contributed to a reduction in energy consumption by 15% and 34% in Germany and Poland, less than the 20% and 45% reduction in energy intensity, respectively. The resulting decline in energy intensity is partially imported in the form of embodied energy in manufactured goods. We can even extend this to the tertiary sector and argue that Europe imports embodied energy in services, as digitalization has enabled a range of outsourcing for services (CBI, 2015). As such, Europe imports products (goods and services) from countries with low efficiency standards, bringing in more embodied energy than if they had been produced domestically. This also applies to intra-EU trade, since there is no uniform energy efficiency standard among EU members yet.

In addition, most of the structural effects occurred in sectors such as primary metals and non-metallic minerals manufacturing, two industries with low value added typically found upstream in the value chain. Current trade patterns, where EU countries exports high value added products and import low value added products, show that this can be extended to other production consumption chains (Timmer et al., 2015). Such terms of trade essentially lead to negative energy trade balances, with more embodied energy being imported than exported (Clift and Wright, 2000). For example, the final energy consumption of primary metal manufacturing (22.8% of Germany's industrial energy use in 2015) differs significantly from that of the automotive industry, with only 3% of Germany's industrial energy consumption in 2015 (DEStatis, 2017). This again supports the conclusion that Europe is virtually decoupling. The role of embodied energy in trade is relevant here as well as reindustrialization, a concept that has been put forward by the EU, in the context of Industry 4.0 (EC, 2017).

The European Commission has a mandate to improve energy efficiency within its borders such that consumption based energy accounts also become relevant in the face of a fractured EU. Two cases could result in an increase in embodied energy in trade: (1) a decline in energy efficiency standards in former EU member states which remain strong trade partners (Fredriksson et al., 2017) (2) a reshuffling of trade to other world regions with lower energy efficiency standards.

4.2. Energy efficiency

Finally, while deindustrialization has contributed significantly to the reduction of energy consumption in Europe, so were intensity effects which act as proxies to the implementation of energy efficiency measures. The overwhelmingly negative effects paint a bright picture: many European countries are making significant energy efficiency improvements, particularly in the last decade analyzed. A direct correlation can be observed between the number of energy policies introduced and the magnitude of these negative intensity effects. Eastern European countries have passed an average of 9 energy policies per country since 1990, while Western European countries passed an average of 58 with Germany passing most of them, and reaping the benefits, while Poland passed few policies yet improved somewhat. In fact, most of Poland's energy policies were only conceived after becoming an EU member (Fig. 5). Although intensity effects tend to dominate after 2010, the magnitude of these effects is smaller than that of other effects in the 1990s.

Thus, deindustrialization and improvement in energy efficiency stabilized in recent years, a sign that the "low hanging fruits" of energy consumption reduction have already been picked, and future efforts to reduce energy consumption will have to be greater. Moreover, the efficiency measures with the largest impact apply primarily to energy intensive sectors, precisely the ones being outsourced.

Note that most of the energy policies introduced pertained to households, businesses and transport, with few dealing with industry (IEA, 2017). Despite that, both primary and secondary sectors saw significant negative intensity effects throughout most examined periods, demonstrating that perhaps the market provides a large enough incentive for energy efficiency measures within internationally competitive sectors.

5. Conclusions & policy implications

The results confirm the widespread impact of deindustrialization in the reduction of energy consumption in Europe and some of its individual member states since 1990. Although the magnitude of structural changes varies across time and place, the main conclusion is that

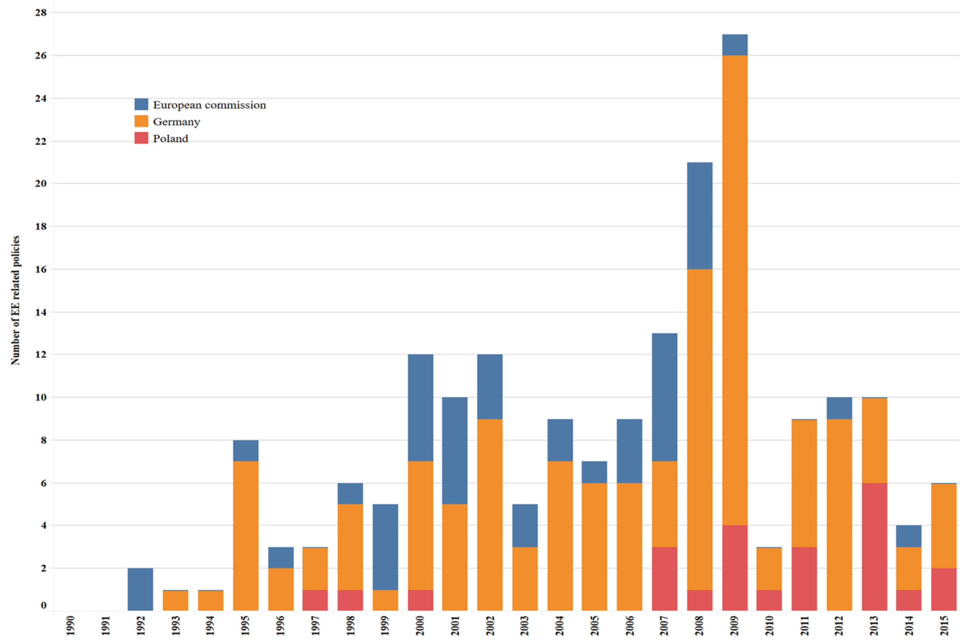


Fig. 5. Timeline of Energy Efficiency Policies (Source: own calculation based on IEA data (IEA, 2017)).

such changes have been as significant as energy efficiency measures in curbing energy consumption. All sectors are influenced, especially agriculture, mining and industrial activities as well as households. Therefore, virtual decoupling has in fact contributed to the artificial lowering of the EU's energy consumption by substituting embodied energy for final energy. Energy efficiency measures (intensity effects) are equally important, and more so in the last decade, when deindustrialization has slowed. Nevertheless, the marginal contribution of energy efficiency has started to decline which signals potentially more virtual than real decoupling in the future.

Two thirds of EU member states' international trade happen within the EU, such that goods manufactured in one state can compensated for manufacturing losses in another. Yet, a decline in the share of intra-EU trade might further impact the EU's total energy consumption in the short term. Trade deficits in monetary terms can be compensated internally, whereas trade deficits in energy terms result from production and consumption chain and infrastructure changes over the long term. In addition, results at the level of regions and sectors, show how policies can be designed, implemented and monitored to maximize real or virtual decoupling between energy consumption and economic growth. The relationship between energy, industrial and trade policies is therefore of utmost importance.

With little political commitments and a tight time line on climate change mitigation, understanding how Europe can account for and mitigate the effects of virtual decoupling is essential. This research contributes to more transparency in how EU members use energy, extending their responsibility to countries which must bear the additional energy consumption.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2018.12.028.

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