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Environmental analysis of structural and technological change in a context of trade expansion: Lessons from the EU enlargement

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ABSTRACT

The enlargement of the EU towards Central and Eastern Europe started in 2004 and represented a significant challenge for European political and economic agendas. Fifteen years later, Central and Eastern European (CEE) countries have experienced a significant economic growth, mostly based upon industrial development and trade expansion, displaying a strong integration in EU global value chains.

In this paper, we aim to analyse if this process of economic and commercial integration has also triggered the externalization of environmental pressures towards Central and Eastern Europe or, on the contrary, trade expansion has been accompanied with a significant technological and structural change in these countries, offsetting the potential scale effects associated to the export growth.

To that aim, we use an environmentally extended multi-regional input-output (MRIO) model with information from 2000 to 2016 that will allow us to quantify the PM2.5 emissions embodied in intra-European trade flows. As a second step, we develop a Structural Decomposition Analysis to evaluate the factors driving emissions embodied in exports from CEE to Western EU countries.

1. Introduction

The enlargement of the European Union (EU) towards Central and Eastern Europe (CEE) represented one of the most challenging issues in its recent history. Although the main drivers for this enlargement have their origin in the economic and political spheres, its environmental consequences focused the main debates during the accession process (Baker, 2000; Kulessa, 2002) and continues nowadays. The so-called *environmental acquis*, promoting domestic legislation to comply with international environmental regulation, was central in the requirements for accessing to the EU "*Acquis Communitaire*". The domestic legislative efforts for compliance with the new requirements were accompanied by huge investments to improve energy efficiency and replace coal energy. These developments were funded by EU programs and joint initiatives as, for instance, Phare, SAPARD or ISPA (Danish Ministry of the Environment, 2001).

A central issue in the debate on the environmental effects of the EU enlargement was the role that, technological and structural change and, especially, trade expansion would play (Kulessa, 2002). The complete integration of the countries in the EU would favour their economic growth, enhancing productive specialization and trade openness as centrepieces of this process. The economic literature has provided mixed results on the effects of economic growth and trade intensification on the environment. On the one hand, the effects of increased interregional and international transport, linked to trade, represent an important source of environmental pressure, particularly of atmospheric emissions (Cristea et al., 2013; Zhang et al., 2017). In addition, the increased energy efficiency associated to economic growth can lead to a greater resource consumption, involving rebound effects (Freire-González, 2017; Vélez-Henao et al., 2019; Wei and Liu, 2017). Further, in the case at hand, if CEE economies did not finally adopt all environmental standards, their lax regulation could trigger a scenario of reallocation of the dirty industries, giving rise to the well-known Pollution Haven Hypothesis (PHH) (Martínez-Zarzoso et al., 2017).

On the positive side, economic growth would make it possible to devote more resources for the adoption of cleaner technologies (Bumpus and Comello, 2017), as well as technological learning processes in neighbouring economies. A structural change was to be expected with a profound transformation of heavy industry and a shift towards a more outsourced economy, based on less resource-intensive industries.

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Moreover, modernisation associated to economic development and globalization in the framework of the EU would increase environmental awareness (Inglehardt, 1997). The question, therefore, was to what extent the negative impacts associated with economic growth and internationalization would offset the positive effects in the medium and long term.

Fifteen years later, CEE countries have experienced a significant economic growth, mostly based upon industrial development and trade expansion, with a strong integration in the European global value chains. Intra-EU trade represents an important engine in the generation of income and employment (Bolea et al., 2019) and extra-EU exports have increased. Therefore, the first years of the 21st century provide an adequate timeframe to evaluate the evolution of CEE environmental emissions associated with international trade, as well as to re-examine the role that structural and technological factors have played in this globalizing process. More specifically, with a focus on PM2.5 emissions, we use Structural Decomposition Analysis (SDA) to evaluate the factors driving the emissions embodied in exports from CEE to Western EU between 2000 and 2016. This period is of particular interest for CEE economies. It includes the pre-accession years when the environmental acquis applied, the effective implementation of the enlargement and the resulting intensification of trade flows with Western EU countries, as well as the global economic crisis and its subsequent years. In this framework, this analysis will allow us to approximate how the internationalization of CEE economies in the context of the EU affected PM2.5 emissions, modifying their position as pollution havens.

Air pollution is a major cause of premature death and disease in Europe. According to WHO (2016) ambient air pollution is responsible for 3 million deaths in the world. In this paper we focus on fine particulate emissions (PM2.5), recommended as the reference indicator for air particle concentration by WHO (2006). Exposure to PM2.5 is associated with an increase in cardiovascular and respiratory morbidity (Annesi-Maesano et al., 2007) that involve mortality, life-years lost and important medical costs (Deryugina et al., 2019). The European Environment Agency (2019) estimated in 374,000 the number of premature deaths in the EU attributable to PM25 exposure for 2016.

Very few papers have analysed the relationship between PM2.5 emissions and its economic determinants (Guan et al., 2014; Lin et al., 2014; Meng et al, 2015, 2019; Zhang et al., 2017). The evaluation of environmental impacts along global production chains is necessary for the definition of policies that consider productive structures and the complex network of inter-sectoral and international flows. Indirect emissions, that is, those embodied in traded goods among sectors and countries through global supply chains, can be far more meaningful than the direct ones. Multiregional-multisectoral environmentally extended input-output models have been widely used to study environmental pressures on air, water or land resources through global value chains (Hoekstra and Wiedmann, 2014; Lin et al., 2014; Meng et al., 2019; Zhang et al., 2019). Zhang et al. (2017) evaluate the impact that international trade and transport exert on health due to emissions at the global level. They conclude that around 22% of premature deaths in the world in 2007 were related to emissions generated in the production of goods and services that were consumed in another region.

At the best of our knowledge, this is the first paper analysing the evolution of PM2.5 emissions in CEE countries and their linkages with trade expansion in recent decades. The results of this study can offer a comprehensive vision on the environmental path of the integration of CEE countries in the EU and the role of structural and technological change moderating emissions in a context of trade expansion. This is particularly relevant for the development of strategies and regulations that foster a European co-operation towards sustainable economies.

The rest of the paper is organised as follows. The next section explains the main details of the methods and data used. Section 3 goes into the trajectory followed by CEE emissions embodied in exports (Section 3.1) and the quantification of its determinants (Section 3.2). Finally, the paper closes with the main conclusions.

2. Methodology

In this paper we use environmentally extended multiregional input-output modelling to take into account the internal structure of countries and the sectoral within and cross-country linkages. Input-output models are powerful tools to track direct and indirect economic interrelations worldwide, being increasingly used to study global supply chains. Basic references for this framework are Isard (1951) and Miller and Blair (2009).

The equilibrium equation for the world economy in this multiregional context formed of m countries and n sectors is represented in (1).[1] $\mathbf{x}$ denotes the total output, $\mathbf{Z}$ is the matrix of multiregional intermediate flows, $\mathbf{y}$ is the vector of total final demand of countries and $\mathbf{e}$ a unitary vector.

$$\mathbf{x} = \mathbf{Z}\mathbf{e} + \mathbf{y} \tag{1}$$

Let us denote by $\mathbf{A}$ the matrix of technical coefficients in the multiregional framework. Each element (a_{ij}^{rs}) shows the volume of intermediate input i of a country r that is needed to produce a unit of output j in country s. Equation (1) can be expressed on the basis of $\mathbf{A}$ and in terms of the Leontief inverse $\mathbf{L}$ for the whole multiregional economy.

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{L}\mathbf{y} \tag{2}$$

Each element in $\mathbf{L}$ shows all the production generated in sector i and country r to fulfil the demands of inputs incorporated in all the steps of the production chain and ending in the final demand of sector j in country s. In this regard, the elements in $\mathbf{L}$ capture the production embodied in all the economic flows linking sectors i and j, and countries r and s through international supply chains. We work within this multi-sectoral and multi-regional input-output model, and we focus on the domestic EU production and interchanges among the EU countries.

Pre-multiplying equation (2) by a diagonalized vector of fine particulate matter $(\widehat{\mathbf{p}})$ emission intensities (direct emissions per unit of output), and following Cazcarro et al. (2012) that apply a breakdown of final demands consisting of block sectoral diagonal matrices of countries $(\mathbf{Y})$, we obtain matrix $\mathbf{P}$ as:

$$\mathbf{P} = \widehat{\mathbf{p}}\mathbf{L}\mathbf{Y} \tag{3}$$

$\mathbf{P}$ captures all emission flows in the global economy associated with the production of the commodities traded among countries, as well as for country's domestic consumption. Matrix $\mathbf{P}$ is composed of block matrices $(\mathbf{P^{rs}})$, with each representative element p_{ij}^{rs} showing the PM2.5 emissions generated in sector i of region r to meet the final demand of sector j in country s. Therefore, as a first step, we apply multi-regional input-output modelling to obtain $\mathbf{P}$ matrix, representing the world economy. Then, we focus on PM2.5 emissions embodied in exports from CEE to Western EU countries (p_t^{rs}). That is, all the emissions generated in CEE countries in the production of the intermediate inputs and final goods ending in Western EU countries, which can be obtained as in equation (4):

$$p_t^{rs} = \sum_{s \neq r} \mathbf{e}' \mathbf{P^{rs}} \mathbf{e} \tag{4}$$

in which r are CEE countries,[2] s Western EU countries and t the reference period.

Secondly, we apply SDA to $\mathbf{P}$ matrix. SDA is a technique often used in

[1] Note on the operators: Matrices are in bold capital letters, vectors are in bold lower case letters and scalars are in italicized letters A circumflex is used for diagonal matrices and transposition is indicated with an apostrophe. ⊗ is the Hadamard product, indicating the element wise multiplication of matrices.

[2] We consider as EU eastern countries: Bulgaria, Czech Republic, Croatia, Estonia, Hungary, Latvia, Lithuania, Slovak Republic, Slovenia, Poland and Romania.

the sectoral input-output framework to disentangle the observed changes in a variable on a group of factors which may act as accelerators or retardants (Dietzenbacher and Los, 1998; Rose and Casler, 1996). Inspired in growth accounting specifications, SDA accounts for the contribution of different relevant factors to the total changes in a target variable. Once we have obtained the changes in matrix **P** through SDA, we focus on the structural, technological and demand factors influencing emissions embodied in trade flows between CEE and Western European countries.

More specifically, considering the changes in emissions between two periods, t_0 and t_1, we can decompose this change, in an additive form, on the basis of the variations in the emissions intensity per unit of output ($\widehat{\mathbf{p}}$), changes in the Leontief inverse (**L**), and changes in the final demand (**y**).

$$\Delta \mathbf{P} = \widehat{\mathbf{p}}_1 \mathbf{L}_1 \mathbf{Y}_1 - \widehat{\mathbf{p}}_0 \mathbf{L}_0 \mathbf{Y}_0 \tag{5}$$

We can go further into the decomposition of **L** and **Y** components. Note that the Leontief inverse in this MRIO framework captures the regional and sectoral shares of intermediate inputs along the full supply chain. Thus, we can isolate the changes in **L** due to variations of the sectoral and regional shares in this supply chain. Additionally, we can identify different factors driving final demands (**Y**), particularly scale, product composition and regional composition.

In a discrete framework, in order to operationalize the changes above, Dietzenbacher and Los (1998) show that the simple average of the two polar solutions is a good approximation to the average of all the n! possible decomposition forms (being n the number of explicative factors). Likewise, we follow Oosterhaven and Van der Linden (1997) and Dietzenbacher et al. (2020) for the decomposition of the changes in **L** matrix.[3] The first polar decomposition can be expressed as:

$$\Delta \mathbf{P} = \Delta \widehat{\mathbf{p}} \mathbf{L}_0 \mathbf{Y}_0 + \mathbf{p}_1 \Delta \mathbf{L} \mathbf{Y}_0 + \mathbf{p}_1 \mathbf{L}_1 \Delta \mathbf{Y} = \Delta \widehat{\mathbf{p}} \mathbf{L}_0 \mathbf{Y}_0 + \widehat{\mathbf{p}}_1 \mathbf{L}_1 \otimes (\mathbf{H}_1 \otimes \Delta \mathbf{B} + \mathbf{B}_0 \otimes \Delta \mathbf{H}) \otimes \mathbf{L}_0 \mathbf{Y}_0 + \widehat{\mathbf{p}}_1 \mathbf{L}_1 (\Delta \mathbf{Q} \otimes \mathbf{G}_1 \otimes \mathbf{T}_1 + \mathbf{Q}_0 \otimes \Delta \mathbf{G} \otimes \mathbf{T}_1 + \mathbf{Q}_0 \mathbf{G}_0 \otimes \Delta \mathbf{T})$$

Similarly, the second polar decomposition is:

$$\Delta \mathbf{P} = \Delta \widehat{\mathbf{p}} \mathbf{L}_1 \mathbf{Y}_1 + \mathbf{p}_0 \Delta \mathbf{L} \mathbf{Y}_1 + \mathbf{p}_0 \mathbf{L}_0 \Delta \mathbf{Y} = \Delta \widehat{\mathbf{p}} \mathbf{L}_1 \mathbf{Y}_1 + \widehat{\mathbf{p}}_0 \mathbf{L}_0 \otimes (\mathbf{H}_0 \otimes \Delta \mathbf{B} + \mathbf{B}_1 \otimes \Delta \mathbf{H}) \otimes \mathbf{L}_1 \mathbf{Y}_1 + \widehat{\mathbf{p}}_0 \mathbf{L}_0 (\Delta \mathbf{Q} \otimes \mathbf{G}_0 \otimes \mathbf{T}_0 + \mathbf{Q}_1 \otimes \Delta \mathbf{G} \otimes \mathbf{T}_0 + \mathbf{Q}_1 \otimes \mathbf{G}_1 \otimes \Delta \mathbf{T})$$

For the decomposition of **L** we use matrix **H** that quantifies the share that input i from country r represents on the total output of sector j and country s, with each representative element being $h_{ij}^{rs} = a_{ij}^{rs} \Big/ \sum_r \sum_i a_{ij}^{rs}$, and matrix **B** whose elements $b_j^S = \sum_r \sum_i a_{ij}^{rs}$ indicate the share of each input j on the total output of country s, regardless the origin of this input. Besides, we decompose **Y** into matrix **T** formed of block diagonal matrices with each element of the main diagonal ($t^r = \sum_s \sum_i \sum_j y_{ij}^{rs}$) reflecting the total final demand of country r, matrix **G** with each representative element of the main diagonal of its block matrices $\left(g_i^r = \sum_s \sum_j y_{ij}^{rs} \Big/ t^r \right)$ indicating the share that each industry i represents in the total final demand of country r, and matrix **Q**, also composed of block diagonal matrices in which each representative element of the main diagonal $\left(q_{ij}^{rs} = \left(y_{ij}^{rs} \Big/ \sum_s \sum_j y_{ij}^{rs} \right) \right.$ reflects the country export share, that is, how much of the final demand of sector i in country r is going to sector j in country s.

In summary, changes in the PM2.5 emissions embodied in exports can be broken down into the components (8) to (13), which can be interpreted as:

- Intensity changes that consider the change in the direct PM2.5 emissions per unit of output in each sector and country. This effect could be associated to technological changes, particularly to efficiency improvements.

$$\mathbf{INT} = 0.5 * (\Delta \widehat{\mathbf{p}} \mathbf{L}_0 \mathbf{Y}_0 + \Delta \widehat{\mathbf{p}} \mathbf{L}_1 \mathbf{Y}_1) \tag{8}$$

- Changes in the input share, which refer to the change in the mix of intermediate inputs used per unit of output in the different steps of the full production chain. This determinant would be related to technological developments due to changes in the economic structure of production.

$$\mathbf{ISH} = 0.25 * \left(\widehat{\mathbf{p}}_1 \mathbf{L}_1 (\mathbf{B}_0 \otimes \Delta \mathbf{H}) \mathbf{L}_0 \mathbf{Y}_0 + \widehat{\mathbf{p}}_0 \mathbf{L}_0 (\mathbf{B}_1 \otimes \Delta \mathbf{H}) \mathbf{L}_1 \mathbf{Y}_1 \right) \tag{9}$$

- Variations in the origin of inputs that explain the change in the import share of intermediate goods. This driver could approximate the externalization and offshoring of polluting activities related to intermediates.

$$\mathbf{IOR} = 0.25 * \left(\widehat{\mathbf{p}}_1 \mathbf{L}_1 (\mathbf{H}_1 \otimes \Delta \mathbf{B}) \mathbf{L}_0 \mathbf{Y}_0 + \widehat{\mathbf{p}}_0 \mathbf{L}_0 (\mathbf{H}_0 \otimes \Delta \mathbf{B}) \mathbf{L}_1 \mathbf{Y}_1 \right) \tag{10}$$

- Changes in the scale of demand, revealing the variation in the volume of final exports. From this factor we could ascertain the existence of decoupling.

$$\mathbf{DS} = 0.25 * \left(\widehat{\mathbf{p}}_0 \mathbf{L}_0 (\mathbf{Q}_1 \otimes \mathbf{G}_1 \otimes \Delta \mathbf{T}) + \widehat{\mathbf{p}}_1 \mathbf{L}_1 (\mathbf{Q}_0 \otimes \mathbf{G}_0 \otimes \Delta \mathbf{T}) \right) \tag{11}$$

- Changes in the destination of exports, displaying the changes in the relative weight of each trading partner on total exports.[4] It would be an indicator of commercial integration, showing if trade between two countries or regions is strengthening or weakening.

$$\mathbf{DD} = 0.25 * \left(\widehat{\mathbf{p}}_0 \mathbf{L}_0 (\Delta \mathbf{Q} \otimes \mathbf{G}_0 \otimes \mathbf{T}_0) + \widehat{\mathbf{p}}_1 \mathbf{L}_1 (\Delta \mathbf{Q} \otimes \mathbf{G}_1 \otimes \mathbf{T}_1) \right) \tag{12}$$

- Changes in the export final product mix, which shows the changes in the export shares of final goods and services. This effect could measure the commercial specialization of countries by products.

$$\mathbf{DSH} = 0.25 * \left(\widehat{\mathbf{p}}_0 \mathbf{L}_0 (\mathbf{Q}_1 \otimes \Delta \mathbf{G} \otimes \mathbf{T}_0) + \widehat{\mathbf{p}}_1 \mathbf{L}_1 (\mathbf{Q}_0 \otimes \Delta \mathbf{G} \otimes \mathbf{T}_1) \right) \tag{13}$$

$$\Delta \mathbf{P} = \mathbf{INT} + \mathbf{ISH} + \mathbf{IOR} + \mathbf{DS} + \mathbf{DD} + \mathbf{DSH} \tag{14}$$

We use EXIOBASE version 3.7 database (Stadler et al., 2018) to develop our analysis. It provides industry by industry multi-regional input-output tables (MRIO) for the period considered in this study (2000–2016)[5] as well as its corresponding environmental harmonised data (PM2.5 emissions, in this case). They include 43 countries (with all EU countries) plus 5 rest of the world (RoW) regions and 163 industries. The MRIO tables from EXIOBASE are provided in current prices. In order to avoid the effects of price changes, we have deflated the tables by using

[3] See the Supplementary Information for more detail on the components and matrices of the decomposition. SI includes Table SI 1 with information of all the elements included in the analysis.

[4] Note that this effect is zero when considering the whole **P** matrix, but can be positive or negative when focusing on exports. If it is larger than zero it would mean that commercial relationships between CEE and western EU countries have grown, leading to an increase in emissions embodied in exports.

[5] Note that EXIOBASE also offers information between 1995 and 1999. Although we have applied the SDA for this period, we have not included it in this study for two reasons. First, we are interested in the period 2000–2016, once the EU requirements were established. Second, the high inflation in Eastern countries during these years could bias the results.

the country GDP deflator[6] from the World Development Indicators database (World Bank, 2020), therefore expressing the tables at 2010 constant prices. We have calculated the annual change for all the years and chained the results (by summing the annual variations) to obtain the total change for the period 2000–2016.

3. Results

3.1. Analysis of the trends and patterns of PM2.5 emissions embodied in exports

Using the model described above, we first study the main trends in PM2.5 emissions embodied in exports from CEE to Western EU countries. As we observe in Fig. 1, they decreased from 2000 to 2016, falling at 2.7% yearly, on average. This decline was sharper between 2000 and 2005 (−7.1%), less severe from 2005 to 2012 (−3.2%), whereas the falling trend seems to reverse from 2012 onwards, annually growing at 5%, on average. The tendency of emissions does not coincide with the trajectory of embodied monetary exports, which shows peaks and slumps around its initial level, slightly increasing until 2011, and depicting a continued strong growth (11% yearly, on average) during the period 2012–2016. If the share of exports to Western EU countries on total output moved from 15% to 19% between 2000 and 2016, it remained around 18% in the case of PM2.5 emissions. Similarly, whereas the growth in exports to Western European countries represented over 25% of the increase in CEE total output, the fall in emissions embodied in exports to Western EU areas explained around 16% of the decline in emissions embodied in the total CEE production.

High levels of fine particulate matter have been associated with rapid industrialization and urbanization, with fossil fuel combustion and heavy industrial production as major direct contributions to direct PM2.5 emissions (Yang et al., 2018). Therefore, the behaviour of PM2.5 embodied in exports until 2012 is compatible with the significant structural transformation and technological change of CEE countries in the first years after their accession to the EU. The share of agriculture declined from the beginning of the transition, there was a sharp decline of the traditional carbon-intensive industries, and CEE economies shifted towards a higher weight of the service sectors. Moreover, as noted in Skjærseth and Wettestad (2007), large export-oriented companies adopted more proactive environmental strategies due to their higher exposure to international markets and public opinion. However, as Ćetković and Buzogány (2019) acknowledge, CEE countries have increasingly objected to the adoption of EU environmental legislation in recent years, particularly concerning energy policy. These dissenting votes have not been homogeneous, but rather diverge depending on national interests.

In the light of the former results, our first significant finding is the relative decoupling for PM 2.5 emissions embodied in exports from CEE to Western EU countries. The dotted grey line shows a deep descent in the PM2.5 intensity of exports, meaning that each € exported by CEE economies gradually generated less emissions during the period 2000–2016. This would point at a "weak" decoupling of exports. Besides, we have seen that CEE countries reduced their PM 2.5 emissions embodied in exports while increasing sales to the EU until 2012. This would suggest the existence of a "strong" or absolute decoupling. Nevertheless, although at a slower rate compared to monetary exports, PM2.5 emissions embodied in exports grew between 2012 and 2016, breaking the positive trajectory seen for the previous years. These results go in line with the convergence of intensity found within the EU for other environmental pressures as CO_2 emissions (Padilla and Duro, 2013) or energy consumption (Mussini, 2020) that, nevertheless, slowed down once the enlargement process was completed.

By countries, we find three different patterns (Fig. 2). First, there are areas where emissions embodied in exports decreased, with two different groups in terms of the deceleration pace. On the one hand, in some regions emissions embodied in exports plummeted (panel a countries). Romania contributed the most to the fall, accounting for 36% of the total decline. As a result, whereas in 2000 it represented around 20% of total PM 2.5 emitted by Eastern countries, it reached 12% in 2016. Hungary followed a comparable pattern, i.e., emissions embodied in exports fell by 6.6% every year on average, explaining 36% of the change. Thus, only two countries, Romania and Hungary, were responsible for more than 70% of the fall of embodied emissions in exports. In these two countries, only two sectors,[7] "Manufacture of basic iron and steel" and "Production of electricity by coal" explain over 65% of the drop. This is a clear sign of the structural change from coal to other energy sources and from basic carbon-intensive industry to other manufacturing and services branches. Similarly, Bulgaria displays a significant decrease of 4.4% every year, accounting for only 4% of total

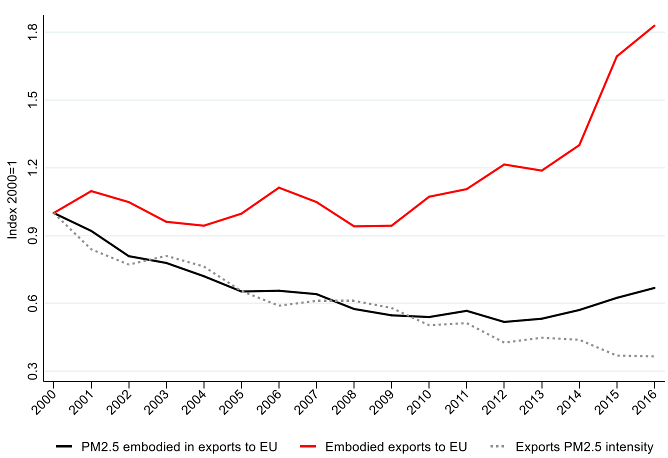

Fig. 1. Trends of embodied exports (2010 constant prices), PM2.5 embodied in exports and PM2.5 intensity of exports between East and Western EU countries. Source: own elaboration based on EXIOBASE version 3.7 database.

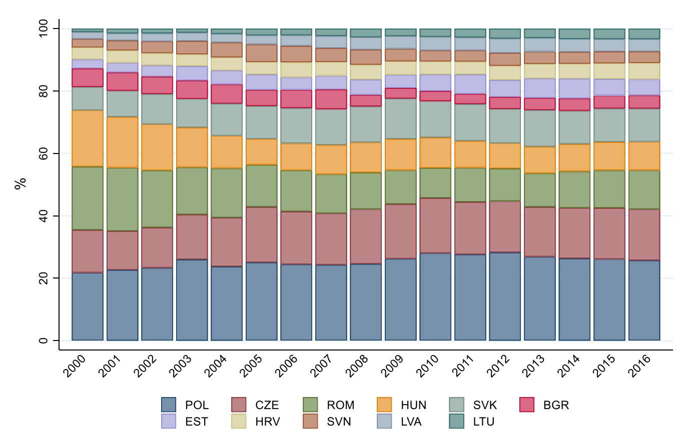

Fig. 2. Country composition of PM2.5 embodied in exports, 2000–2016. Source: own elaboration based on EXIOBASE version 3.7 database

[6] As the GDP deflator is at the country level, we apply the same deflator for all the industries in a country, which could introduce uncertainty in the deflating process.

[7] Figure SI1 in the SI shows the share of each industry to the fall of emissions embodied in exports.

emissions embodied in exports by 2016. The PM2.5 exports of these three countries mainly went to Italy and Germany, which are the flows that fell sharply.

On the other hand, we find economies with a much lighter reduction (panel b countries). The Polish emissions embodied in exports were approximately the same as the Romanian in 2000, but they were 2.1 times larger by 2016. This is due to a more modest decrease in emissions embodied in exports that fell 1.5% annually and represented 14% of the total decline. Consequently, in 2016 Poland had the largest emissions in exports in our sample, reaching 26% of the total (see Fig. 2). Poland was the country with stronger, and more stable trade relationships with the Western EU countries in the pre-adhesion period. Important advances in environmental protection took place in the nineties and the first years of the 2000s (Cole, 1995; Jankowski, 2007), hand by hand with environmental activism and institutional changes. However, recently, Poland has been one of the main regions vetoing EU environmental policies (Jankowska, 2016). The industries that were behind this fall were the "Manufacture of coke oven products" with a contribution of 85%, followed by the "Mining of coal, lignite and copper ores" and "Manufacture of basic iron and steel". In the same line, the Czech Republic emissions embodied in exports fell at 1.4% yearly, contributing 8% to the total variation. Thus, whereas the country represented around 14% of total emissions in exports by 2000, it increased to about 16.5% by 2016. In the Czech Republic, the "Manufacture of basic iron and steel", with a share of more than 50%, was the main industry explaining the decrease in emissions embodied in exports, followed by the "Chemicals" or the "Production of electricity by coal" sectors. Both Poland and Czech Republic have a strong integration with Germany, a commercial partner that explains 86% of their fall of emissions embodied in exports.

Finally, the Baltic Republics (Estonia, Lithuania and Latvia or panel c countries) show increasing emissions embodied in exports (Fig. 2), and we cannot confirm the existence of absolute decoupling. They had negligible weights in total emissions embodied in exports by 2000, ranging between 1% of Lithuania and 3.9% of Estonia. However, these shares tended to rise in 2016 (up to 5% of Estonia and 4% of Latvia), given its growing emissions embodied in exports. By industries, the "Manufacture of basic iron and steel" and "Manufacture of cement, lime and plaster" explain their increase in emissions embodied in exports. We observe that the intensification of the PM2.5 emissions embodied in exports is determined by the strong integration with their neighbours, Finland and Sweden, and with other areas as France, Germany or United Kingdom.

In summary, we can identify three geographical areas with different trends. The first group is formed of those economies with a deep transformation process in the manufacturing sector that experienced an intense fall in emissions. Secondly, we find the countries with a strong interregional integration with Western regions at the beginning of the period, where the decline in emissions was smoother. Finally, the Baltic Republics, small and traditionally opened economies, show an increase in emissions linked to their exports, revealing no significant changes in their industrial structure.

3.2. Factors driving the fall of PM2.5 emissions embodied in exports

Fig. 3 and Table 1 depict the accumulated change in PM2.5 emissions embodied in exports (Total) from CEE to Western European countries and its associated driving factors during 2000–2016. Until the Great recession, two effects, the change in the PM2.5 intensity of exports (INT) and in the composition of the inputs used (ISH) were essential to explain the decrease in embodied emissions in exports. However, whereas the fall of intensity kept encouraging the decline in emissions between 2009 and 2016, the change in the input mix behaved the opposite. For the case CO_2, Araújo et al. (2020) also found that the fall of intensity and the structural change, particularly of the electricity sector, were behind the decline in total CEE emissions until 2007.

First, the decreasing intensity effect indicates that the goods and

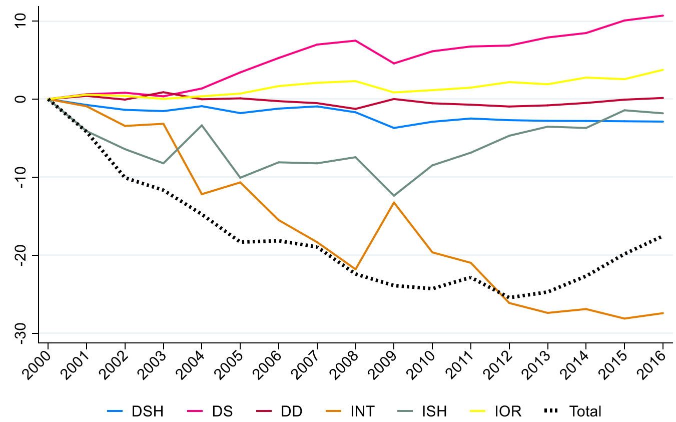

Fig. 3. Trends of change in PM2.5 emissions embodied in CEE to Western EU exports and its determinants (Gg), 2000–2016.
Source: own elaboration based on EXIOBASE version 3.7 database.

services from CEE countries embody less PM.25 emissions per € exported. Poland, Hungary, and Czech Republic are the countries that contribute the most to this fall. The largest improvement in intensity happened in industries as the "Manufacture of basic iron, steel and coke products", the "Production of electricity by coal" and the "Mining of coke oven products". All together add more than 50% of the fall. Intensity also fell in the "Coastal transport" or the "Re-processing of secondary steel" sectors. In the case of steel, there has been important efficiency improvements as a response to EU climate policy, but the potential for further development seems limited, given that low-emissions steel is not cost-competitive and most technologies are under development (Vogl et al., 2020). As for the production of electricity, the energy efficiency increased driven by the EU climate policy, which reduced emissions (Bae et al., 2017).

Second, the change in the input mix suggests that, until 2009, the use of "dirty" inputs in the production processes of CEE economies was being substituted by cleaner production factors, *ceteris paribus* the other drivers. This effect was the most relevant factor explaining the fall in emissions embodied in exports up to 2003 (Fig. 3). This was triggered by sectors as the "Manufacture of iron and steel" in Bulgaria and Romania or the "Sea transport" in Bulgaria. From 2009 the change in the composition of inputs of production processes in CEE economies contributed to the slowdown and further increase (2012–2016) of emissions embodied in exports. Despite there were notable reductions of primary sectors as the mining of different ores, other industries as the "Production of electricity by coal" and the "Manufacture of steel" were behind the reversal of the input share effect. This mainly happened in Romania. In the case of steel, the EU policy encouraged efficiency improvements rather that systemic changes, and producers oriented to foreign markets received free allocation of emissions allowances (Vogl et al., 2020). As for the production of energy, the overreliance on coal in many CEE countries as Poland also limited a more in-depth structural change (Ćetković and Buzogány, 2019).

Although less important, the change in the composition of the final goods exported (DSH) also contributed to the fall in emissions embodied in exports. Bulgaria and Hungary were key for this effect, being the "Manufacture of iron and steel" the sector that experienced the largest relative fall in the composition of final demand. Nevertheless, this sector still shows a very high scale effect, meaning that keeps growing in absolute terms. In fact, the growing volume of final exports from CEE to Western EU countries, i.e., the demand-scale factor (DS) increases during all the period, contributing to a slowdown in the fall of PM 2.5 emissions in exports (Fig. 3). This is explained to a large extent by Poland, Czech Republic and Slovak Republic, particularly after their accession into the EU in 2004.

In the same line, the change in the input composition regarding its

Table 1
Results of the SDA analysis. Change in PM2.5 emissions 2000–2016.

		DSH	DS	DD	INT	ISH	IOR	Total
Total	Gg	−2.88	10.69	0.14	−27.42	−1.82	3.75	−17.54
	%	16	−61	−1	156	10	−21	100
Group 1	Gg	−1.56	2.54	−0.39	−5.78	−9.72	0.69	−14.23
	%	11	−18	3	41	68	−5	100
Group 2	Gg	−1.07	7.09	0.55	−20.77	7.08	2.71	−4.40
	%	24	−161	−13	472	−161	−62	100
Group 3	Gg	−0.25	1.07	−0.02	−0.87	0.82	0.34	1.09
	%	−23	98	−1	−79	75	32	100

Source: own elaboration based on EXIOBASE version 3.7 database. Panel a: countries with an intense decrease (Bulgaria, Hungary and Romania). Panel b: countries with a smooth deceleration (Czech Republic, Croatia, Poland, Slovak Republic and Slovenia). Panel c: countries with growing emissions embodied in exports (Estonia, Latvia, Lithuania).

geographical origin (IOR) would be avoiding a larger decrease in emissions embodied in exports. This would mean that CEE countries are growingly importing inputs, that are later embodied in their final exports, from dirtier areas. Poland and Czech Republic that mostly imported from Russia, other European areas outside the EU and China, would be the main areas behind this driver. This confirms the tendency found in literature towards outsourcing pollution to areas with lower income or less stringent environmental standards (Hoekstra et al., 2016; Vale et al., 2018). Finally, the effect of the destination of final exports is smooth and erratic. It slightly contributed to the increase in emissions embodied in exports until 2005, meaning a commercial reorientation to Western EU areas. Then, once the commercial relationships between CEE and Western EU areas were established, this effect encouraged the deceleration of emissions embodied in exports until 2012, when the trend reversed. This pattern would be mostly related to the linkages with Germany.

In sum, for the whole region, we find a decoupling of emissions embodied in exports from CEE to Western EU countries until 2012, when they depict a turning point and begin to grow. Technological and demand determinants behaved the opposite. Within the technological drivers, there was a temporal shift between intensity and structural change. In the first years of the period (2000–2003), structural factors explained more than 60% of the total reduction in PM2.5 emissions, while intensity determined around 30%. The industrial restructuring towards less emission-intensive sectors[8] through the supply chain was even more relevant than the, also important, reductions in intensity emissions. Then, intensity became the most relevant determinant explaining the decrease of emissions embodied in exports until 2012. From the Great Recession intensity kept contributing to the slowdown of emissions embodied in exports, but the input share effect showed a changing pattern, encouraging its increase. Literature points at the new economic framework emerged from the 2008 financial crisis as a cause for the reduced ambition in EU environmental policy (Bocquillon and Maltby, 2017). Domestic interests and the capacity of national stakeholders to obtain benefits from the EU climate and energy legislation would also play a part (Ćetković and Buzogány, 2019). Additionally, CEE countries tended to incorporate inputs from comparatively dirtier regions, boosting emissions embodied in exports. Thus, the reversal of the input-mix effect, together with a continued push of the input origin and scale effects induced the growth in emissions embodied in exports from 2012 to 2016. Our findings suggest a “cleaning” process affecting the whole supply chain of exported inputs that vanished from 2012. It would be based on a significant structural change until 2008 and on gradual reductions in emission intensities.

These general trends hide an important heterogeneity, so we apply the SDA to the three country blocs. Fig. 4 and Table 1 show the determinants of PM2.5 emissions embodied in exports for the countries that experienced an intense decrease (Panel a including: Bulgaria, Hungary and Romania), a smooth deceleration (Panel b including: Czech Republic, Croatia, Poland, Slovak Republic and Slovenia) and for those where emissions embodied in exports grew between 2000 and

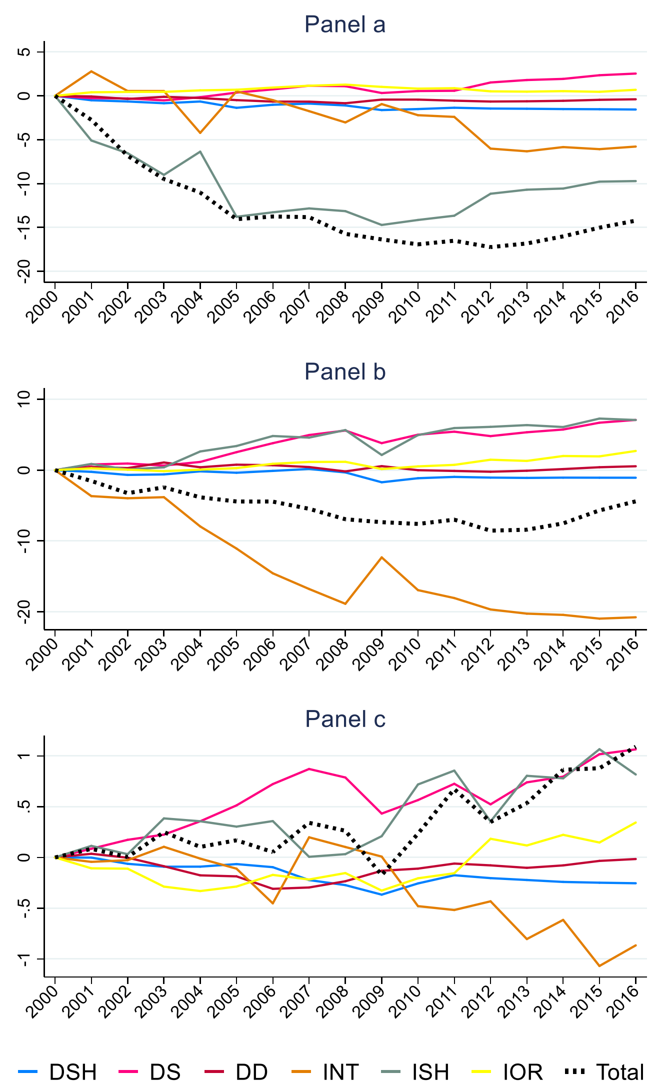

Fig. 4. Trends of change in PM2.5 emissions embodied in CEE to Western EU exports and its determinants (Gg) by groups of countries, 2000–2016.
Source: own elaboration based on EXIOBASE version 3.7 database. Panel a: countries with an intense decrease (Bulgaria, Hungary and Romania). Panel b: countries with a smooth deceleration (Czech Republic, Croatia, Poland, Slovak Republic and Slovenia). Panel c: countries with growing emissions embodied in exports (Estonia, Latvia, Lithuania).

8 We have seen an important decline of the steal and production of electricity by coal industries.

2016 (Panel c including: Estonia, Latvia, Lithuania).

Our calculations based on Table 1 show that the great fall in emissions embodied in exports in Romania, Bulgaria and Hungary (panel a countries) accounted for around 80% of the total drop in CEE emissions between 2000 and 2016. Throughout the period, these countries underwent a total reduction in emissions linked to exports of 14.2 Gg (Table 1), of which 44.2% and 44.4% are explained by Romania and Hungary, respectively, and 11% by Bulgaria (see Table SI 2). The results point to the change in the input mix as the main driver of the sharp reduction in emissions embodied in exports, which accounts for 68% of the total change (Table 1). However, as Fig. 4 shows, the compositional change towards the use of cleaner inputs in the production processes was limited to the period 2000–2009 in panel a countries. These changes in the input mix mostly happened in Bulgaria and Romania related to the decreasing share of the "Basic iron and steel industry", the "Steam and hot water supply" and the "Production of electricity by coal". Despite the input share effect kept decreasing in Bulgaria and Hungary until 2016, it reversed in Romania given the increasing share of industries as "Production of electricity by coal" and the "Basic and secondary manufacture of steel". The moderate economic development, which affected emission standards and energy prices, together with the role of foreign companies, could have favoured the structural change in Romania and Bulgaria (Ćetković and Buzogány, 2019). As for Hungary, its capacity to undertake this structural change towards less pollutant inputs could be related to the importance of hydropower and nuclear in the energy mix (Moro and Lonza, 2018).

Additionally, the change in energy intensity accounts for 41% of the total change (Table 1), contributing to the decrease in emissions embodied in exports, mostly from 2005. This effect remained rather unchanged from 2012 to 2016. Behind the intensity effect there is an important heterogeneity. In Hungary intensity decreased notably until 2005, mostly driven by the "Manufacture of iron and steel". The emission intensity of exports declined slightly in Romania from 2005 and kept constant between 2012 and 2016. However, it growingly contributed to the increase in emissions embodied in exports in Bulgaria. As opposed to technological factors, the scale effect, that is, the growing exports of these countries, pushed the emissions embodied in exports up, chiefly in Hungary and Bulgaria, and also in Romania from 2011. Similarly, the change in the origin of the inputs used to produce the final goods and services exported (IOR), mostly imported from Russia and other European areas outside the EU, partially offset the fall in emissions embodied in exports, mainly in Hungary and Romania.

In sum, these findings suggest a transformation in the chains and industries of panel a countries, with increasingly higher value-added inputs instead of primary intermediates. This structural change moderated from 2009, mainly in Romania, countering the fall in emissions embodied in exports.

Panel b (Fig. 4 and Table 1) depicts different patterns, not only in terms of the gradual and softer deceleration in emissions linked to international trade with the EU, but also regarding the main explanatory factors. Over the period 2000–2016, emissions in these countries were reduced by 4.4 Gg (Table 1). They represented around 37% of the total reduction in emissions at the beginning of the period, but this percentage was over 25% by 2016. Poland and Czech Republic account for more than 87% of the bloc's emission reduction (see Table SI 2). Compared to panel a, in this case it was the deep and sustained downturn in intensity (INT) that explains the total change in PM2.5 emissions embodied in exports. This fall was mostly due to the intensity decline of Polish and Czech "Manufacture of coke products" and the "Mining of copper ores". However, the structural change relative to the origin of inputs and, fundamentally, the type of inputs incorporated in exports, greatly limited this reduction, mainly from 2004. This was mostly driven by the "Manufacture of coke oven products" that were used as primary inputs in the Polish production processes. Poland, which generates 80% of its electricity from coal, has shown a high resistance to change, given the power of coal corporations, unions and the government that controls a notable share of the energy markets. Energy security issues, and the concern on energy prices also limit the possibility of structural change (Brauers and Oei, 2020; Ćetković and Buzogány, 2019). Likewise, the SDA results show the pull of emissions associated with the increase in demand (DS). Poland and the Czech Republic explain a large share of the increase in exports to Western EU countries. The most important sectors driving this scale effect were the "Mining of copper ores" and the "Manufacture of coke over products and of iron and steel", and the "Chemicals" in the Czech Republic. These growing exports were designed to a large extent to Germany, France, Italy and Austria.

Finally, a more erratic behaviour is observed in the Baltic economies (Panel c in Fig. 4 and Table 1). Over the period, these countries slightly increased the crystallized emissions in their exports to Western EU in 1.09 Gg (Table 1). This rising trend is mainly explained by two factors. First, the structural change, which led to the incorporation of primary inputs and energy sources with a higher polluting content (ISH). This happened intensively in the three countries from the economic crisis of 2008, and was largely determined by the intense use of coal in the production of electricity as well as by the role of coastal and railway transport. The "dirty" input mix change occurred despite the processes of technological improvement to reduce emissions per unit of output in sectors as the "Sea transport", the "Production of electricity by coal" or the "Extraction of natural gas". The second force acting as an accelerant of emissions embodied in exports was the scale effect (DS), especially intense in Estonia, and relevant due to the strong commercial relations with neighbouring countries as Sweden and Finland.

4. Conclusions and policy implications

Over the last decades CEE countries effectively integrated into European value chains. The process of integration into the EU represented an unprecedented opportunity for CEE economies to expand trade flows –with the EU as their main partner– and to develop technological and structural change from legacy production structures based on primary industry and highly polluting technologies towards higher value-added sectors. The requirements for the European integration and the significant technological investment accelerated this process. In this context of important technological and structural change, our paper has addressed the role of CEE commercial expansion in emissions. Concretely, we focus on fine particulate matter, an extremely harmful pollutant to human and environmental health. PM2.5 emissions are associated with the heavy industry, energy and transport, and have been hardly considered in the economic-environmental literature.

MRIO modelling has allowed us to evaluate the role of technological factors and those of demand, as well as the transmission of technical improvements through global value chains in an integrated way. Besides, using a SDA we have isolated the effects of technological (change in direct intensities, in the input mix and in the geographical origin of inputs) and demand factors (increase in scale, change in the composition of the exported final products and in the export destinations). As far as we know, this is the first MRIO analysis, focused on CEE economies and on a pollutant responsible for a significant number of deaths in Europe (European Environment Agency, 2019).

Considering CEE countries as a whole, the results point to a process of commercial expansion compatible with the reduction of emissions embodied in exports until 2012. Then, they grew coupled with sales to the EU. Our findings indicate that this process was fuelled by a clear reduction in direct emissions per unit of output throughout all the period. Improvements in energy efficiency and the replacement of polluting energy sources as coal have been crucial over a significant part of the period under study. The largest reduction in emissions intensity was explained by the transformation of the basic industry, the mining sector and the production of electricity by coal, which accounted for more than 50% of the fall. In the case of electricity production, the increased energy intensity allowed reducing emissions, fulfilling the requirements of the EU climate policy. Also, until the Great Recession, a significant structural change in the production chains happened, since the goods and services exported to Europe tended to incorporate less polluting inputs. Then, between 2009 and 2016 the change in the input mix contributed to curb emissions embodied in exports.

The results also display a significant heterogeneity among countries. We have identified three large regional blocs, with different technological and structural patterns. The countries with the greatest reduction in emissions strongly transformed their productive structure, reducing their traditional dependence on coal as an energy source. The structural change would be the main explanatory factor. However, within this cluster, there was a worrisome trend towards the incorporation of dirty inputs in the Romanian exports, underpinning a steady increase in their emissions embodied in exports since the Great Recession. A second group of countries, having a prior commercial integration with their Western European neighbours, exhibited a more moderate drop in emissions over the period. This would be due to direct sectoral technological improvements rather than a clear process of industrial conversion. Finally, a group of smaller and open countries, the Baltic economies, increased their emissions linked to exports, with negligible technological and structural improvements. Although the profound sectoral transformations along the production chain offset the increases in emissions linked to the strong growth in exports in the first two blocs, demand factors determine the relationship in the latter case, giving rise to emissions.

From the point of view of policy implications, the results show the importance of considering both demand and technological changes for an effective formulation of environmental policy at the global level. In this sense, most environmental policies are intended to reduce direct emissions from productive activities, without considering the international factors that underlie the configuration of current global supply chains. The measures for the reinforcement of low-emission technologies carried out in Europe must also be accompanied by a review of global production processes, which could hide the outsourcing of pollution through the incorporation of inputs from less stringent environmental countries. This would be increasingly the case of large CEE economies as Romania and Poland that import pollution-intensive intermediates from Russia and China. Likewise, the results show a great progress of technological and structural change until the EU enlargement. However, this process came to a halt in recent years, given the containment of direct technological improvements and the turnaround of the input specialization of supply chains. This is a worrying phenomenon as it would indicate that the chances for improvement through technological change are running out. Cost-competitive choices and the underdevelopment of some technologies appear as potential bottlenecks for further improvements in energy systems. Recently, these technological barriers coincide with a greater reluctance of some CEE countries to advance towards more ambitious energy policies focused on low-carbon societies. In line with Fedajev et al. (2019), CEE economies are called to review energy and industrial policies, targeting medium and high manufacturing technologies for further upgrading in global value chains and replacing coal with alternative clean energy sources. As we have seen, this transformation would entail environmental positive effects given the predominance of the structural component to explain emission trends.

We should note some of the main limitations of the analysis. First, SDA is a comparative-static technique which relates the emissions exchanges within the EU with the main variations in economic variables and their contribution to total change. More specific studies should be undertaken to understand the causal relationships between the variables. Second, one should consider that, as indicated in Section 2, the input-output tables have been updated using national deflators that do not distinguish price differences among sectors. Third, the study could be expanded to include some other pollutants in order to provide a wider picture on the drivers of pollution displacements through global supply chains. This work also opens the way to the study of ecological unequal exchange. It seems to have occurred between CEE and Western European countries, narrowing over time. Nevertheless, the imbalance with other world regions subject to lower environmental standards as Africa, Asia and other non-EU countries in Europe, is intensifying. The study of these trends, their determining factors and their impacts on different resources, is a clear extension of this work. Eventually, the assessment of countries' reaction to exogenous shocks and the potential displacement of environmental burdens related to these disruptions could further enhance this line of research.

CRediT authorship contribution statement

Rosa Duarte: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Ana Serrano:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing.

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.

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Appendix A. Supplementary data

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