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Decoupling and EKC in European Union countries: A shift-share decomposition of air emissions

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Abstract

This paper examines the non-linear effect of per capita GDP growth rate, trade openness, physical and human capital endowments on air pollution in the EU region over the period 2008-2016 by decomposing air emissions into scale, composition and technique effects. Results show a negative non-linear relationship between greenhouse and acidifying gases emissions and per capita GDP growth rate, with more open economies tending to reduce emissions both directly and indirectly through investment in physical capital. The determinants mainly affect the scale component, although the environmental improvement due to capital investment works through the technique component. There are heterogeneous effects across countries, with more pronounced environmental benefits for countries in the higher deciles of GDP and trade growth rates.

Keywords: EKC, air emissions, trade openness, factors endowments, decoupling, non-linear estimation

Introduction

In recent decades, environmental issues have become a global concern, prompting countries to implement green policies aimed at conserving resources and biodiversity through sustainable development. In this context, several key aspects have been emphasised.

Firstly, air pollution has become a priority for nations due to its detrimental impact on human health and society. In this regard, the United Nations Environment Programme (UNEP) recommended in 2018 that global greenhouse gas (GHG) emissions be reduced by at least 25% below 2017 levels by 2030 to meet the targets outlined in the Paris Agreement. The effects of air pollution are particularly harmful in regions where significant quantities of GHGs and acidifying gases (AGs) are emitted. Consequently, numerous environmental policies aim to mitigate emissions of these pollutants.

Secondly, the European Union (EU) has played a pivotal role in raising awareness of global emissions. Since 1973, with the launch of the first European Environmental Action Programme, the EU has developed a comprehensive environmental policy framework through the implementation of numerous directives, thereby gaining global influence in the sustainability process. Among the most recent and significant initiatives are the European Green Deal of 2019, the Fit for 55 initiative, the expansion of the Emissions Trading System, and the Renewable Energy Directive. Through these directives, the European Commission has proposed measures to align the EU's climate, energy, transport, and tax policies with the objective of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels, with the ultimate goal of achieving net-zero emissions by 2050. Furthermore, these policies, particularly the EU Green Deal, aim to decouple economic growth from resource use, fostering socio-economic well-being while protecting, conserving, and enhancing the EU’s natural capital, as well as boosting technological skills and innovation.

Given this context, this paper seeks to examine the role of various economic factors associated with globalised economies, such as GDP growth, trade openness, and physical and human capital endowments, in influencing GHG and AG emissions intensity. It also investigates the scale, composition, and technique effects that characterise the relationship between economic growth and environmental degradation in EU countries during the period 2008–2016. Additionally, our analysis offers insights into the EU countries' decoupling trajectories.

Regarding existing literature, it has highlighted that environmental degradation, in terms of increasing air pollution, has diverse causes. Research begins with the recognition of an inverted U-shaped relationship between per capita income and CO2 emissions, commonly known as the Environmental Kuznets Curve (EKC). Since 1991, economists have conducted numerous studies on the potential drivers of this relationship, finding that changes in emissions depend on several economic factors tied to a country's level of development, such as trade openness, innovation, and environmental regulation [Shafik and Bandyopadhyay (1992); Selden and Song (1994); Andreoni and Levinson (2001)]. During the same period, Grossman and Krueger (1991) decomposed total emissions into three effects: scale, composition, and technique. The scale effect pertains to a country's economic activity; as economic output increases, emissions tend to rise, all else being equal, a trend exacerbated by free international trade. The composition effect relates to shifts in sectoral composition; increased economic activity can lead to specialisation in advanced, greener sectors, with the net impact on emissions being contingent on the sources of comparative advantage driving trade. For example, under the Pollution Haven Hypothesis (PHH), countries with stringent environmental regulations may specialise in less polluting sectors, exporting pollution-intensive production to nations with weaker regulations, thereby reducing domestic emissions. Conversely, capital-rich countries tend to specialise in capital-intensive, more polluting sectors, while labour-rich nations gravitate towards less polluting, labour-intensive industries. Lastly, the technique effect concerns technological progress; countries with sustained economic growth are more likely to invest in cleaner technologies, a process further encouraged by higher living standards and trade liberalisation. Increased demand for green products, driven by wealthier populations and trade, often translates into stronger political will for stringent environmental policies, thereby accelerating the adoption of abatement technologies.

The shape of the EKC is closely tied to stages of economic growth, particularly changes in industrial structure and economic development [Baldwin (1995)]. During the initial phase of industrialisation (transitioning from agriculture to industry), environmental degradation intensifies, driven by scale and composition effects. However, as growth advances, technological development (shifting from industry to services) begins to mitigate environmental harm, lowering emissions through composition and technique effects.

Quantitative methods, such as the Log Mean Divisia Index (LMDI), have been used to decompose emissions for various countries. De Bruyn (1997) analysed data from the Netherlands and West Germany; Viguier (1999) studied Eastern European countries (Hungary, Poland, and Russia) alongside France and the United Kingdom; and Bruvoll and Medin (2003) focused on Norway. These studies largely agree on the critical interplay between technology adoption and economic growth in shaping emission levels.

On the other hand, the seminal publication *The Limits to Growth* (1972) by Meadows et al. argued that finite natural resources cannot sustain unchecked economic and population growth. UNEP (2011) and the European Parliament stress the importance of technological innovation, integrated urban infrastructure, and systemic changes in production, consumption, and trade to improve resource productivity and reduce material intensity. UNEP further correlates the EKC's stages with decoupling levels: emissions increase during the EKC's upward trajectory, weak decoupling occurs at the turning point, and strong decoupling is observed during the decline.

Many studies, including those by Jiang et al. (2019), Naqvi (2021), Wang and Lv (2022), and Caporin et al. (2024), have explored these dynamics. This paper contributes to the literature by employing innovative methodologies, such as LMDI Method II and Non-Linear Least Squares (NLLS) estimation, to analyse the drivers of the EKC's components (scale, composition, technique effects) and test for decoupling. We further consider heterogeneous coefficients to assess the variability in factors driving emissions. Our findings underscore the significant influence of GDP per capita growth, trade openness, and capital endowments on total emissions, identifying these variables as critical drivers of scale, composition, and technology effects. Given the study's 2008–2016-time frame, we also explore how the 2008 international financial crisis impacted the interplay between emissions and economic factors, noting that emission declines in EU countries are largely attributed to the technique effect, particularly in highly globalised nations investing in green technologies.

Finally, much of the existing research on the EKC and decoupling focuses on China [e.g., Jiang et al. (2019); Zhao et al. (2017); Wang and Lv (2022); Wang and Kim (2024)], with other studies targeting specific regions such as Central Asia [Caporin et al. (2024)] or the United States [Wang and Kim (2024)]. Relatively few articles, including ours, address these mechanisms within the EU, employing diverse methodologies [e.g., Naqvi (2021); Sanyé-Mengual et al. (2019); Papież et al. (2022); Bianco et al. (2024)].

The paper is structured as follows. Section 2 presents the decomposition methodology. Section 3 provides a detailed analysis of results about air emissions decomposition. Section 4 describes the econometric framework for the analysis of scale, composition and technique effects and data description. Section 5 reports the results. Section 6 provides a discussion of the results and Section 7 concludes.

2. Decomposition Methodology

Total emissions can be decomposed into scale, composition and technique effects using the Index Decomposition Analysis (IDA). Due to the nature of our data and the objective of the research, we have implemented the LMDI Method II with the multiplicative decomposition proposed by Ang and

Choi (1997)[1] (2015). We have opted for this kind of methodology given that the weights in the formulae summed to unity which is a desirable property in index construction. The basic idea of this approach is to decompose the change in emissions into three different drivers: economies of scale, sector composition and technological differences. The LMDI has three important properties that make it a suitable decomposition method. First, it satisfies the factor reversal test, i.e. the index gives a decomposition without residuals, so the interpretation of results is not biased. Second, it also satisfies the time reversal test: given two periods, the result does not change whether the index is measured forward or backward. Third, LMDI allows for zero values in the dataset. As suggested by Ang and Choi (1997), zeros are replaced by a small positive number[2].

In practice, a difference that one will encounter is in result presentation, since the decomposition results are given in a physical unit in the additive case while in indexes in the multiplicative case. In the end, the decision is arbitrary.

The method is constructed by considering the following set of variables:

Y_{it}	Real Gross Value Added (GVA) in country *i* in year *t*
Y_{ijt}	Real GVA in country *i* in sector *j* in year *t*
E_{it}	Total volume of emissions in country *i* in year *t*
E_{ijt}	Volume of emissions in country *i* in sector *j* in year *t*
$S_{ijt} = \frac{Y_{ijt}}{Y_{it}}$	Share of sector *j* real GVA on total real GVA in country *i* in year *t*
$I_{it} = \frac{E_{it}}{Y_{it}} = \sum_j \frac{E_{ijt}}{Y_{it}}$	Total emissions intensity in country *i* in year *t*
$I_{ijt} = \frac{E_{ijt}}{Y_{ijt}}$	Emissions intensity in country *i* in sector *j* in year *t*

Changes in total emissions between base period $t = 0$ and any period t in country *i* are calculated using the following multiplicative form:

$$\frac{E_{it}}{E_{i0}} = Scale_{it} * Composition_{it} * Technique_{it} \tag{1}$$

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[1] For a complete guide for implementation of LMDI, see Ang (2015).

[2] In our dataset, zero values for some sectoral emissions are replaced by 0.01 if the observation is equal to 0 every year, by the average of the previous and following year's values, and by the average of the last three years if the zero value refers to the last year of the analysis.

where $Scale_{it}$ is the scale effect in year *t* in country *i*, which describes a *ceteris paribus* variation in economic activity, holding all the other factors constant. $Composition_{it}$ identifies the composition effect in year *t* in country *i*. This variable isolates the effect of changes in the economic weight of the sector on environmental emissions, holding all other factors constant. Finally, $Technique_{it}$ measures the technique effect in year *t* in country *i* as the change in emissions when the real GVA and sector economic weight are held constant at their initial values [EC (2016)]. The multiplicative decomposition approach allows to express the emissions change ratio as an index; moreover, since we have implemented a panel dataset, which has a time-series component, multiplicative procedure is more suited[3].

The three terms in equation (1) can be expressed as follow:

$$(2) \qquad Scale_i = \exp\left\{\sum_j \alpha_{ijt}\, ln\frac{Y_T}{Y_0}\right\}$$

$$(3) \qquad Composition_i = exp\left\{\sum_j \alpha_{ijt}\, ln\frac{S_{ijT}}{S_{ijo}}\right\}$$

$$(4) \qquad Technique_i = exp\left\{\sum_j \alpha_{ijt}\, ln\frac{I_{ijT}}{I_{ijo}}\right\}$$

where $\alpha_{ijt} = \frac{(E_{ijt}-E_{ijo})/(lnE_{ijt}-lnE_{ijo})}{(E_{it}-E_{io})/(lnE_{it}-lnE_{io})}$ is the log average rate of change of sector emissions.

3. Empirical decomposition of air pollutants

We use Eurostat data for EU countries from 2008 to 2016 to examine the contribution of scale, composition and technique effects to the overall variation in air emissions[4,5]. The data cover 19 NACE Rev. 2 manufacturing industries at the 2-digit level[6]. Focusing on emissions of air pollutants, the decomposition analysis is carried out for two pollutants: the total volume of GHG (carbon dioxide (CO2), methane and nitrous oxide) and AG (sulphur dioxide (SO2), nitrous oxide and ammonia) in thousand tonnes[7]. GHG

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[3] Using an additive approach is more informative if quantity indicator is applied.

[4] Excluded countries due to several missing observations in the period analysed are Cyprus, Czech Republic, Ireland, Luxembourg and Malta.

[5] Given Eurostat data on GHG and AG emissions, in 2008, GHG from manufacturing sectors are responsible for the 27.64% of total GHG emissions in EU. This share slightly decreases to 26.19% in 2016. Considering the share of manufacturing AG emissions in the same periods and area, 11.89% and 10.08% respectively.

[6] See Table A1 in Appendix for a detailed description of the sectors.

[7] Data on emissions are from Eurostat "Air emissions accounts by NACE Rev. 2 activity".

emissions are expressed in CO2 equivalents, while AG emissions are expressed in SO2 equivalents.

Real GVA has been obtained as the ratio of nominal GVA at current prices to the implicit price deflator by the Nace Rev.2 sector in 2010[8].

We first describe the overall change in GHG and AG in the post-crisis period (2008–2016). Figure 1 shows that the level of EU emissions, represented by the solid line, has decreased for both GHG and AG. The most drastic decrease in emissions was concentrated in 2009 for all countries, which is probably related to the 2008 recession. There was a limited increase in air pollution in 2010, but then the data show a decreasing trend since 2014. This result is in line with EC (2016), who performed a similar analysis for a shorter period (2008–2012).

Looking at the three components obtained by the decomposition described in Section 2, we can see that for GHGs, the scale effect caused a decrease in total air emissions immediately after the crisis, after which a new increase started. The composition effect caused an increase in emissions between 2008 and 2009 and then a decrease until 2012. In addition, as suggested by the literature, the technique effect contributed to the reduction in GHG emissions. Similar trends are also observed for AG. As the decomposition results are presented in the form of indices, we cannot make a direct comparison between countries but can only describe each country's contribution to emissions in terms of variation. Looking at the ranking results, there are differences between countries in the total emissions of GHG and AG. Table 1 shows that for GHG, the lowest variation in total effect is for Lithuania in 2010 (0.480), while the highest is for Latvia in the same year (1.122). For AG, these values are 0.416 for Greece in 2016 and 1.094 for Bulgaria in 2011. In terms of GHG, the EU countries can be divided into three groups when looking at the time trends. As can be seen from the ranking in Table 1, a first group includes those countries that show a low overall impact throughout the period, such as Bulgaria, Croatia, and Lithuania; a second group shows a decrease in this value, such as Finland, France, Italy, Spain, and the United Kingdom. A third group worsened their situation in terms of emissions: Estonia, Greece, Hungary, and Poland. The other countries are still the most polluting in the EU or show an irregular trend in emissions. Focusing on AG, only Italy and the United Kingdom showed a decrease in total emissions, while the other EU countries are similarly ranked.

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[8] Data on Nominal GVA and prices come from Eurostat "National accounts aggregate by industry (up to NACE A*64)". Eurostat defines GVA as the "*output (at basic prices) minus intermediate consumption (at purchaser prices); it is the balancing item of the national accounts' production account. The sum of GVA over all industries or sectors plus taxes on products minus subsidies on products gives Gross Domestic Product*".

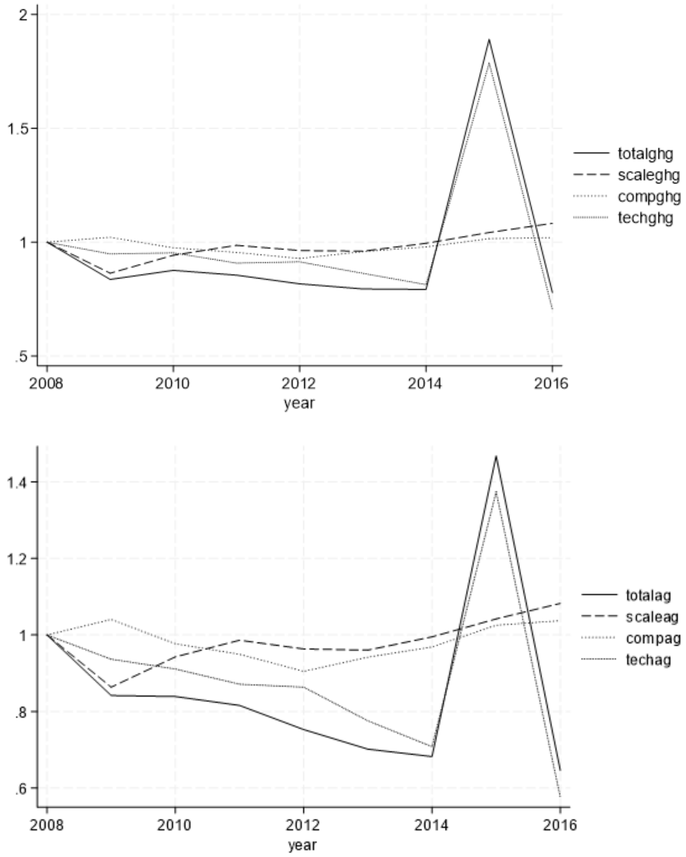


Figure 1. GHG and AG emissions decomposition for EU28, 2008-2016

By analysing the three components, some important conclusions can be drawn. Regarding the scale effect on GHG emissions, all countries showed a decrease between 2008 and 2009 due to the economic crisis, but from 2010 to 2016, the countries behaved differently. Austria, Belgium, Denmark, Estonia, Lithuania, and Poland show a steady increase in emissions due to the crisis. This result is in line with empirical evidence showing that an increase in economic activity in a country is associated with an increase in emissions, ceteris paribus. Greece and Spain show a decrease in emissions. The economies of scale of the remaining group of countries do not show a constant trend over the period, but all of them recorded a decrease in GHG emissions between 2011 and 2013. This is also confirmed for AG emissions.

A second result concerns the composition effect. GHG emissions depend strongly on the sectoral composition of GHG emissions, and the composition effect shown in the figure increases in the first year. This pattern is mainly due to an increase in the economic weight of capital-intensive sectors (manufacture of basic metals, coke, and refined petroleum products), which have contributed to an increase in total emissions. For some countries, a decreasing composition effect is observed for the whole period (Hungary and Slovenia) or for a large part of it (Estonia and Portugal). . The results are quite similar for AG emissions.

Finally, some conclusions can be drawn about the technique effect. For GHG emissions, many countries show a decreasing trend (Belgium, France, Finland, Italy, Bulgaria, and Lithuania). This may be due to the introduction of new or improved environmentally friendly technologies. Other European countries (Greece, Hungary, Germany, Portugal, and Spain) show a negative trend in the technique effect. This increase in emissions depends on the higher emission intensity of some sectors.

Concerning the technique effect on GHG emissions, some differences can be observed. Some of the above-mentioned countries show an irregular trend between 2008 and 2016, with only the Netherlands and Croatia showing a constant decrease in GHG emissions. These patterns seem to be related to the economic activity of some sectors; in fact, some polluting industries (basic metals, motor vehicles, trailers, and machinery) have increased their GVA level.

In order to quantitatively identify the main drivers of the three effects, we carry out an econometric analysis in the following sections.

Table 1. Ranking of countries by overall effect, GHG and AG emissions 2009-2016

	GHG								AG							
	2009	2010	2011	2012	2013	2014	2015	2016	2009	2010	2011	2012	2013	2014	2015	2016
Austria	20	21	21	21	23	21	23	21	19	23	21	21	21	21	20	20
Belgium	5	13	1	10	9	9	11	12	4	4	4	4	6	6	6	7
Bulgaria	2	3	1	1	1	6	2	6	22	19	23	22	23	22	23	23
Croatia	9	7	6	4	3	3	5	2	8	3	2	3	3	1	3	3
Denmark	13	9	16	16	16	13	15	17	5	9	6	5	4	4	5	5
Estonia	3	2	3	6	11	23	22	23	3	5	15	18	20	19	21	21
Finland	8	10	14	8	7	4	3	4	9	14	13	10	11	11	11	11
France	18	15	13	12	10	10	8	9	14	10	11	8	8	8	7	8
Germany	21	19	18	19	20	17	18	18	15	20	18	17	16	17	18	19
Greece	14	6	2	5	17	19	12	16	1	1	1	1	1	2	1	1
Hungary	12	8	15	14	12	16	19	20	13	16	17	16	13	14	15	15
Italy	11	11	12	7	4	2	4	3	12	15	10	6	5	5	4	4
Latvia	10	23	23	23	13	18	16	10	23	6	5	15	19	16	16	14
Lithuania	1	1	4	2	2	1	1	1	21	13	22	23	22	23	22	22
Netherland	23	22	22	20	22	20	21	22	6	7	7	9	7	7	8	9
Poland	15	17	20	22	21	22	20	19	18	18	20	20	18	20	19	17
Portugal	16	16	8	11	18	14	17	13	11	12	8	7	9	9	10	10
Romania	4	4	7	9	5	5	6	5	2	2	3	2	2	3	2	2
Slovakia	22	18	19	17	19	15	13	15	10	8	9	12	12	13	13	16
Slovenia	7	5	5	3	6	7	7	7	7	11	14	13	15	15	12	12
Spain	19	14	10	15	8	8	10	11	17	17	12	11	10	10	14	13
Sweden	6	20	17	18	15	12	14	14	20	21	19	19	17	18	17	18
United Kingdom	17	12	9	13	14	11	9	8	16	22	16	14	14	12	9	6

Note: Countries are ranked from the lowest to the highest overall effect. The year 2008 has been removed from the table as it is the reference period.

4. Econometric Methodology

A large body of literature shows that the relationship between economic growth and environmental degradation is generally represented by the EKC inverted U-shaped curve.

As highlighted by existing studies, the shape of the EKC can be influenced by many factors that affect the scale, composition and technique effects; by allowing heterogeneous coefficients we can improve our knowledge of the forces behind GHG and AG emissions over time. By testing econometrically these effects allows to overcome a limit of the use of decomposition analysis. Specifically, since we have expressed emissions in terms of index, a change in these values, sometimes, is hard to understand due to results which are cumbersome to interpret; the econometric analysis helps in this direction.

The econometric analysis is carried out in two steps. In the first step, we estimate the EKC model expressed in terms of rates of change as follows:

$$(5) \qquad g_{it}^{E} = \gamma + f(\boldsymbol{X_{it}\beta}) + \theta_{it}$$

where $\boldsymbol{X}_{it}$ is the vector of a vector of panel type independent variables and γ is the time trend coefficient of the EKC model in levels. Estimates are obtained using an OLS estimator for a linear specification of the function $f(X_{it}\beta)$ and a NLLS estimator when $f(X_{it}\beta)$ is a non-linear function of regressors. Non-linear effects have been found in the previous literature on EKC (Davidson and MacKinnon, 1993; Churchill et at., 2018).

In the second step, we estimate the decomposed model by emission components (scale, composition and technique effects). Since emissions in country *i* in year *t* can be written in terms of the decomposition equation (1), $lnE_{it} - lnE_{i0}$ corresponds to the sum of the logarithms of each component, so it can be written as $lnE_{it} - lnE_{i0} = lnScale_{it} + lnComposition_{it} + lnTechnique_{it}$. All effects (overall, scale, composition and technique) are expressed in terms of indices. Therefore, direct comparisons between countries are not possible, so by taking the natural logs and time differences of (1), we obtain the identity of emissions expressed in terms of rates of change:

$$(6) \qquad g_{it}^{E} = g_{it}^{s} + g_{it}^{c} + g_{it}^{T}$$

where $g_{it}^{k} = \ln k_{it} - \ln k_{it-1}$ is the time difference between period *t-1* and *t* for each component, with

$$k_{it} = \{EmissionTot_{it}, Scale_{it}, Composition_{it}, Technique_{it}\}.$$

Given the EKC model expressed in terms of change rates (5) and the identity (6), we also estimate the following three-equation model where dependent variables are the change rates of all components:

$$g_{it}^{S} = \gamma_1 + f(\boldsymbol{X_{it}\beta_1}) + \varepsilon_{1it} \tag{7}$$
$$g_{it}^{C} = \gamma_2 + f(\boldsymbol{X_{it}\beta_2}) + \varepsilon_{2it} \tag{8}$$
$$g_{it}^{T} = \gamma_3 + f(\boldsymbol{X_{it}\beta_3}) + \varepsilon_{3it} \tag{9}$$

$\gamma_1, \gamma_2, \gamma_3$ are time trend components (of emissions in levels); $\gamma_1 + \gamma_2 + \gamma_3 = \gamma$. $\boldsymbol{X}_{it}$ is the vector of regressors corresponding to the set of panel-type variables included in (5); $\boldsymbol{\beta_1}, \boldsymbol{\beta_2}$ and $\boldsymbol{\beta_3}$ are the vectors of estimated coefficients that are component-specific; $\varepsilon_{1it}, \varepsilon_{2it}$ and ε_{3it} are cluster robust disturbances at country level. We implement a Non-Linear Seemingly Unrelated Regression (NLSUR) estimator proposed by Gallant (1975).

4.1 Data Description

Our sample covers 23 EU countries and 8 years from 2008 to 2016. GHG and AG emissions data were obtained from Eurostat. The corresponding change rates in terms of overall, scale, composition and technique effects have been obtained following the methodology presented in Section 2. Explanatory variables are taken from the Penn World Table and is expressed in logs and first differences: GDP per capita (GDPpc), physical capital endowment (K/L), human capital index (H), share of total imports and exports on GDP (Trade). We use the two-year lagged rate of change in real GDPpc ($\Delta GDPpc_{t-2}$), so the estimates cover the period 2009-2016, while other variables are taken at *t-1*. To allow for a non-linear relationship between income and emissions, the squared and cubic terms of the GDPpc growth rate are also included. As regards factor endowments, we introduce the K/L ratio using data on capital stocks and the number of persons employed, and the H index based on years of schooling and returns to education. As far as international trade is concerned, it is important to assess the effect of trade openness, measured as the sum of the export and import shares of goods in real GDP at current purchasing power parity. See Table A2 in Appendix for a detailed description of variables.

The main variable of interest in this paper is trade. According to Antweiler et al. (2001), the impact of trade on EKC is twofold. On the one hand, it increases emissions through the scale effect, because it expands a country's economic activity, which in turn increases pollution. On the other hand, trade has a positive impact on the environment through the technique effect. As incomes rise, consumers are more likely to pay attention to environmental issues, so governments have a greater incentive to introduce stricter regulations, which in turn encourage producers to adopt cleaner technologies. The introduction of environmental policies could also positively affect the EKC through the composition effect. The composition effect captures the reduction in emissions associated with the relocation of production from more polluting sectors to countries with lax policies. This mechanism usually reduces emissions, but the net effect of trade on pollution also depends on other factors of comparative advantage that could contribute negatively to pollution [Grossman and Krueger (1993), Copeland and Taylor (1994), Cole and Elliott (2003)]. Since trade could have an indirect effect on pollution through endowments on scale, composition and technique components (trade-induced effects), two interaction terms have been included by multiplying the trade variable by those for human and physical capital.

5. Results

We first test the impact of all EKC drivers on the rates of change of total GHG and AG emissions change rates using the econometric model (5). We have estimated two model specifications. The first model (M1) is a linear model using first differences for both the dependent and independent variables and is estimated by including $\Delta GDPpc_{t-2}$,$\Delta K/L_{t-1}$,$\Delta H_{t-1}$and $\Delta Trade_{t-1}$. A second model (M2) is estimated by adding squared and cubic $\Delta GDPpc_{t-2}$ to account for non-linearities in the spirit of the EKC model, and trade interaction variables with physical and human capital.

The two sets of explanatory variables are also used to estimate a three-equation model of emission change rates related to scale, composition and technique effects.

Overall Effect: Taking the total emissions change rate as the dependent variable, OLS and NLLS estimates are reported in Table 2. As we can see from columns GHG-M1 and AG-M1, all economic variables have a significant and negative effect on the emissions change rate, leading to environmental improvements. The constant coefficient is positive (GHG) and negative (AG) but not statistically significant, so there is no time trend in emissions levels. Regarding the M2 model, the columns GHG-M2 and AG-M2 show non-linear effects of GDPpc growth and interactions between factor endowments and trade only for GHG emissions. For a better interpretation of the results, Figures 1-8 show the marginal effects at different deciles of the reported variables with confidence intervals. A negative non-linear relationship between the rate of change of total GHG emissions and GDPpc growth is highlighted in Figure 1 (top left graph) in terms of marginal effects. This implies that economic growth has a negative effect on emissions for all countries, which is stronger for higher deciles of GDP growth. Regarding trade determinants, we can identify both indirect effects of international trade, related to variations in factor endowments, and direct effects, through changes in export and import flows. The indirect effect is negative, so that a unit increase in physical (or human) capital tends to reduce air pollution. Physical capital investment reduces emissions in countries with trade change rates in the high deciles (Figure 2, top left graph), while human capital leads to environmental improvements in countries with trade change rates in the low deciles (Figure 3, top left graph). As for the direct effect of international trade (Figure 4, top panels), countries with large differences in openness tend to emit less, especially those with factor endowments in the higher deciles. This evidence is consistent with recent literature suggesting that a growing economy invests more in environmentally friendly sectors, for example, through investment in green technologies. This could imply that the declining phase of the EKC is mostly related to the technology effect, so the existence of decoupling cannot be rejected. Most of the results are also verified for AG emissions (Figures 6 to 10).

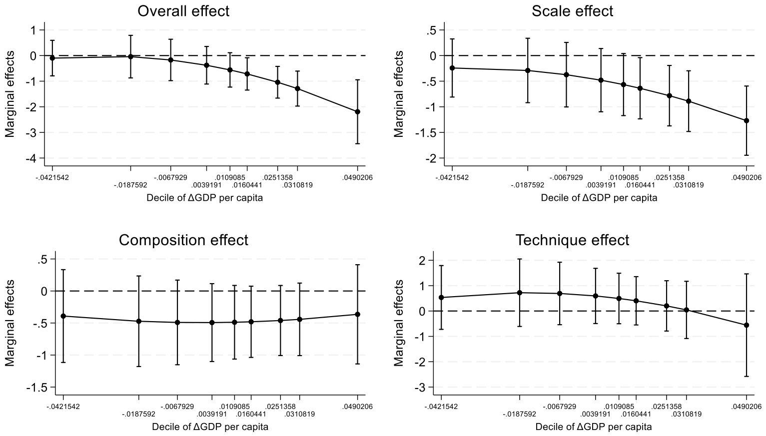
Table 2: OLS and NLLS estimates of EKC, overall effect.

	GHG-M1	**GHG-M2**	**AG-M1**	**AG-M2**
$\Delta GDPpc_{t-2}$	-1.32***	-0.29	-0.52 ***	-0.21
	(0.370)	(0.390)	(0.147)	(0.253)
$\Delta K/L_{t-1}$	-0.54***	-0.63***	-0.59***	-0.70***
	(0.180)	(0.220)	(0.089)	(0.144)
ΔH_{t-1}	-5.99**	-3.720	-5.54*	-4.02
	(2.280)	(2.260)	(2.625)	(2.582)
$\Delta Trade_{t-1}$	-0.4***	-0.29**	-0.12	0.02
	(0.060)	(0.140)	(0.074)	(0.245)
${\Delta GDPpc_{t-2}}^2$		-10.19**		0.225
		(4.290)		(2.401)
${\Delta GDPpc_{t-2}}^3$		-124.85*		-25.77
		(66.150)		(21.240)
$\Delta Trade_{t-1} * \Delta H_{t-1}$		14.380		-6.27
		(19.560)		(29.730)
$\Delta Trade_{t-1} * \Delta K/L_{t-1}$		-5.27*		-3.94
		(2.750)		(3.330)
constant	0.020	0.010	-0.011	-0.016
	(0.010)	(0.010)	(0.017)	(0.016)
R-squared	0.341	0.432	0.166	0.188
Obs	184	184	184	184

*Note. Standard errors in brackets. Significance level: *** 0.01, ** 0.05, * 0.1*

The analysis is repeated for the three emission components. Looking at the decomposed effects (Appendix, Table A3), there is a positive time trend in the scale component for GHG and AG emissions and a negative time trend in the technique effect for AG emissions, both of which are statistically significant. For M2, the negative trend in the technique equation for AG emissions is the only common result with the previous specification. For the other estimates, the null hypothesis is not rejected.

Figure 1: Marginal effects of GDP growth, GHG emissions



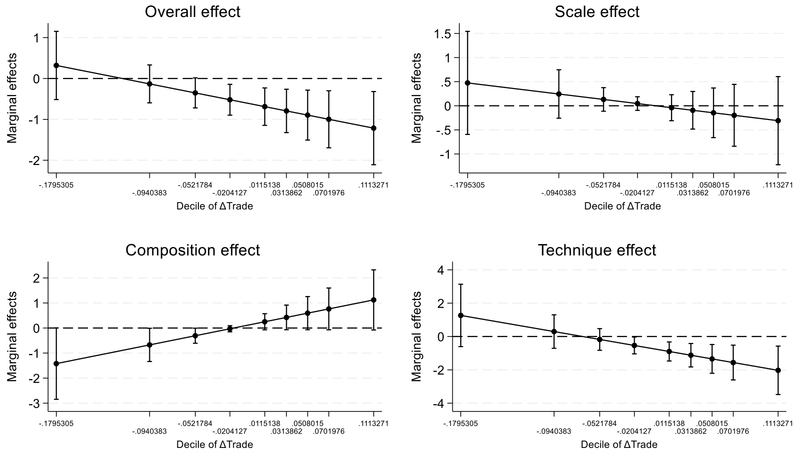
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Scale Effect: The linear SUR estimates (GHG-M1 and AG-M1 columns of Table A3) show that economic growth and trade appear to have a negative effect on emissions, leading to environmental improvements. This is confirmed for both types of air pollutants, but the results are only statistically significant for GHG. We cannot reject the null hypothesis for physical and human capital. When analysing model M2, i.e. the NLSUR estimates, most of the comments reported for the rate of change of total emissions are confirmed for the scale effect. See Figure 1 (top right graph) for the effect on GDP growth and Figure 4 (bottom graphs) for the direct effect of trade on GHG emissions. Figure 6 (top right graph) and Figure 9 (bottom graphs) show similar results for AG emissions. Note that, in contrast to the overall estimates, for countries in the lower deciles of investment in physical and human capital, the rate of change in trade reduces emissions in terms of both GHG and AG, so that being more open to trade *per se* is not sufficient to achieve lower emissions through the scale effect.

Composition Effect: Focusing on the composition effect, the M1 results suggest that there is no relationship between ΔGDPpc and changes in GHG emissions, and no trade-related variables (except physical capital) have a statistically significant effect. However, when examining the marginal effects of the M2 specification, we find a (statistically significant) negative relationship between the rate of change in GHG emissions and ΔGDPpc for countries in the lower deciles of GDP growth rate (Figure 2, top left panel). As for the trade-related determinants, there is no direct effect of international trade on the composition component, as shown in Figure 5 (upper panels). This result contradicts the PHH. The trade-induced effect of factor endowments is partly negative. A unit increase in physical capital reduces air pollution in response to trade in countries in the lower deciles of the openness change rate (Figure 2, top middle panel), but this effect is not verified for human capital investment. This evidence suggests that sectors investing in physical (green) capital improve the environment. For AG emissions, there are no statistically significant effects on the composition component (Figures 6-10).

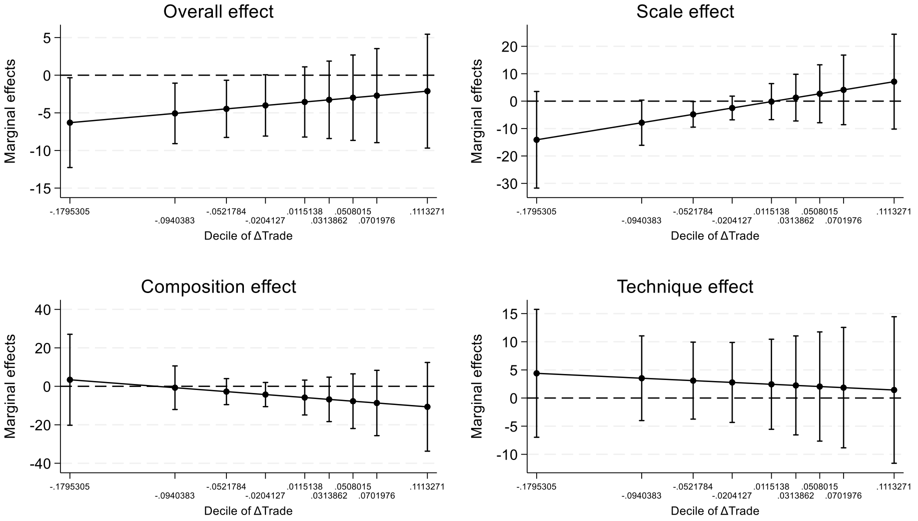
Technique Effect: Analysing the M1 results on the technique effect, we can see from Table A3 that no variables have a significant effect, except for physical capital, which has a negative coefficient. Regarding the M2 marginal effects, we find a statistically insignificant negative relationship between the rate of change of GHG emissions and the rate of GDP growth (Figure 1, bottom right-hand panel), so that GDP growth does not affect the technology effect and consequently the reduction of emissions. Regarding the direct effect of trade, we find that more open countries tend to emit less in higher deciles of investment in human and physical capital, as shown in Figure 5 (bottom panels). The indirect effect of trade through factor endowments is negative only for physical capital, so that a unit increase in physical capital reduces air pollution in response to trade in countries in higher deciles of trade change rates (Figure 2, bottom right graph). The marginal changes in human capital are not statistically significant. All results for GHG emissions are partially verified for AG emissions (see Figures 6-10). The indirect effect of physical capital investment is confirmed for AG emissions, while the relationship between the rate of change of AG emissions and the rate of GDP growth for countries is positive (and not negative) at higher deciles of GDP growth. All other effects are not statistically significant.

Figure 2: Marginal effects of investment in physical capital, GHG emissions



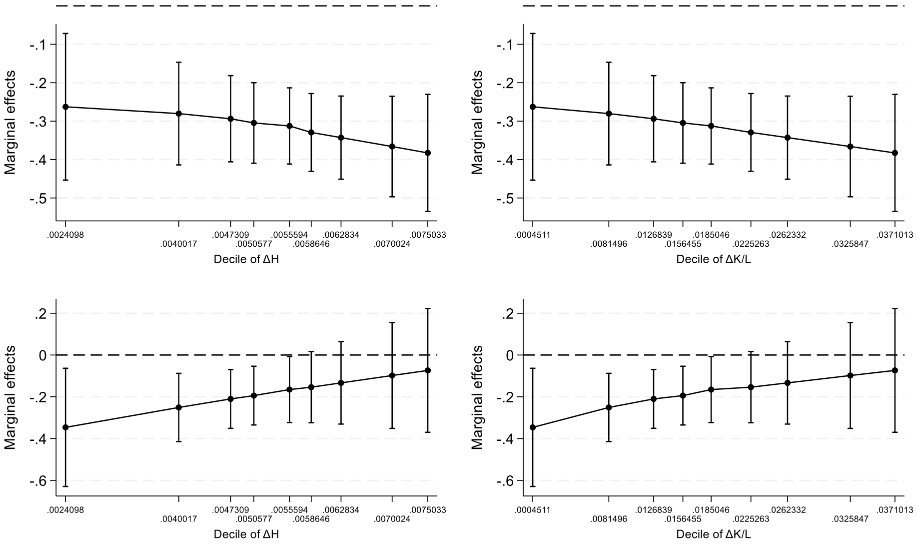
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 3: Marginal effects of investment in human capital, GHG emissions



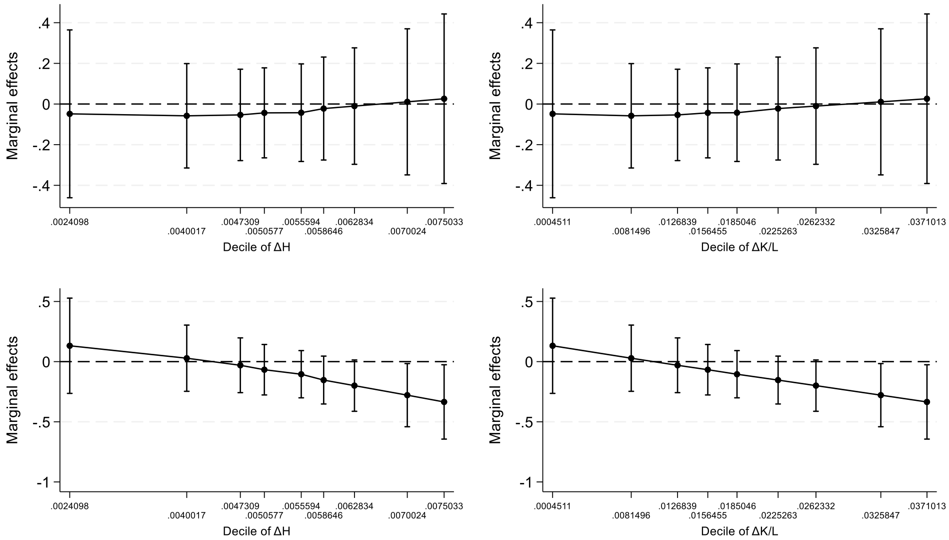
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 4: Direct effects of trade openness, overall (top graphs) and scale (bottom graphs) GHG components



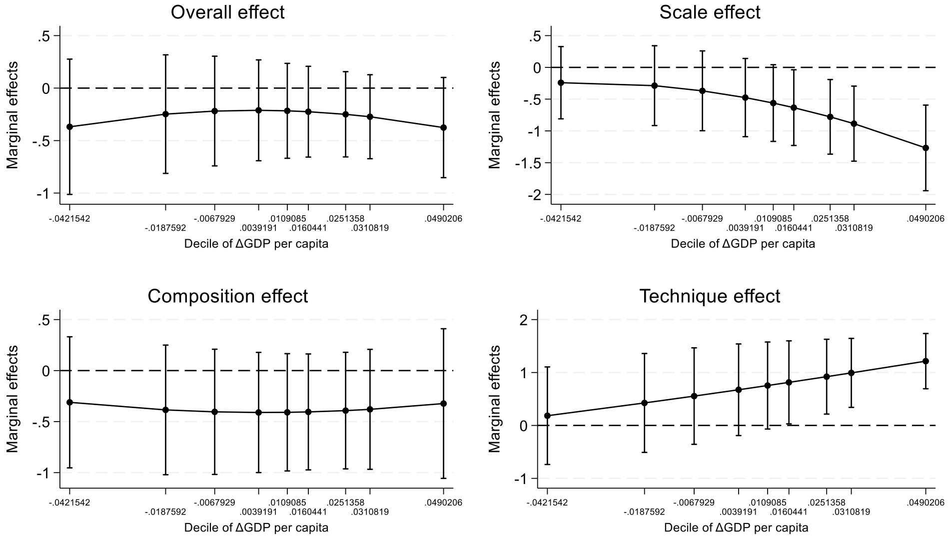
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 5: Direct effects of trade openness, composition (top graphs) and technique (bottom graphs) GHG components



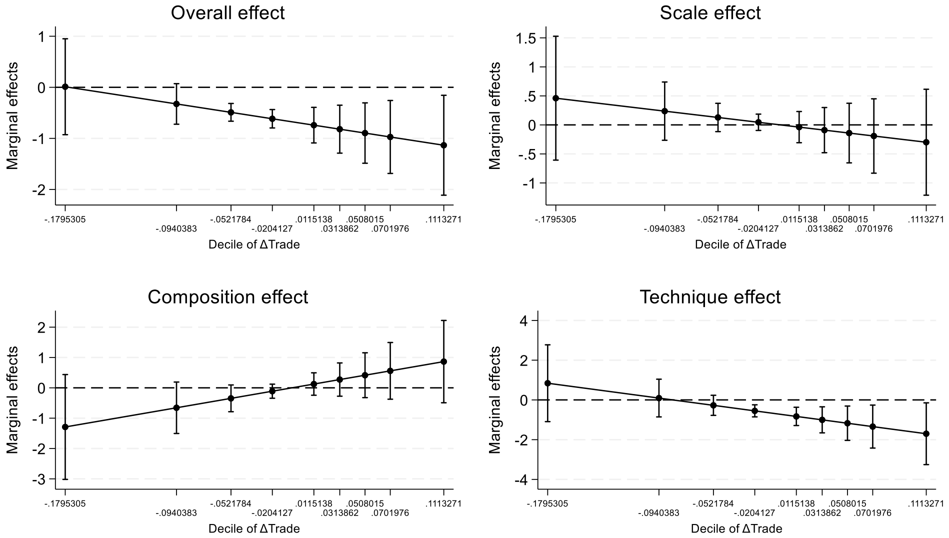
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 6: Marginal effects of GDP growth, AG emissions



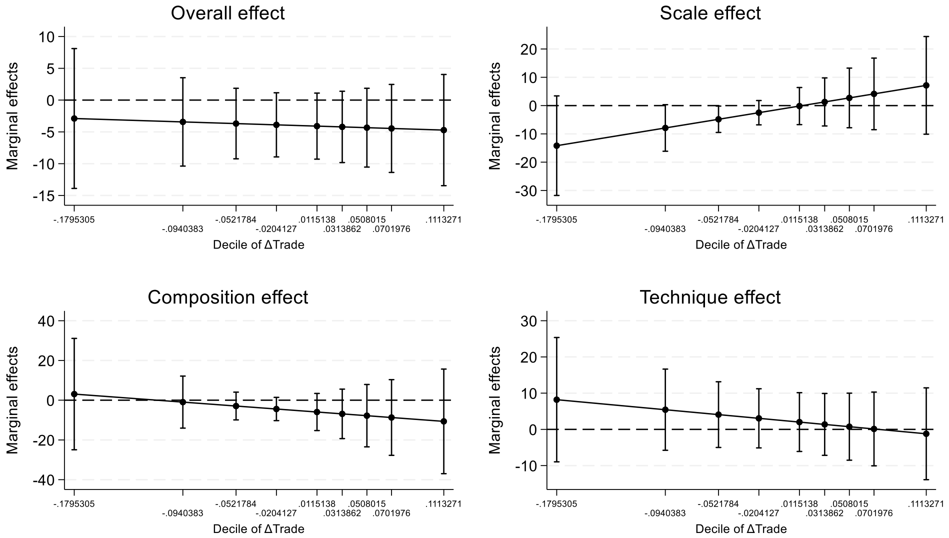
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 7: Marginal effects of investment in physical capital, AG emissions



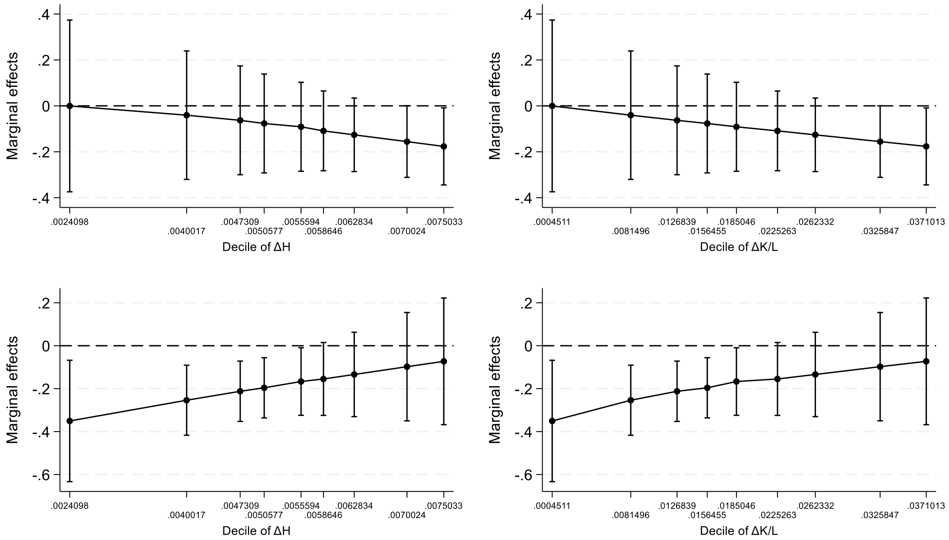
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 8: Marginal effects of investment in human capital, AG emissions



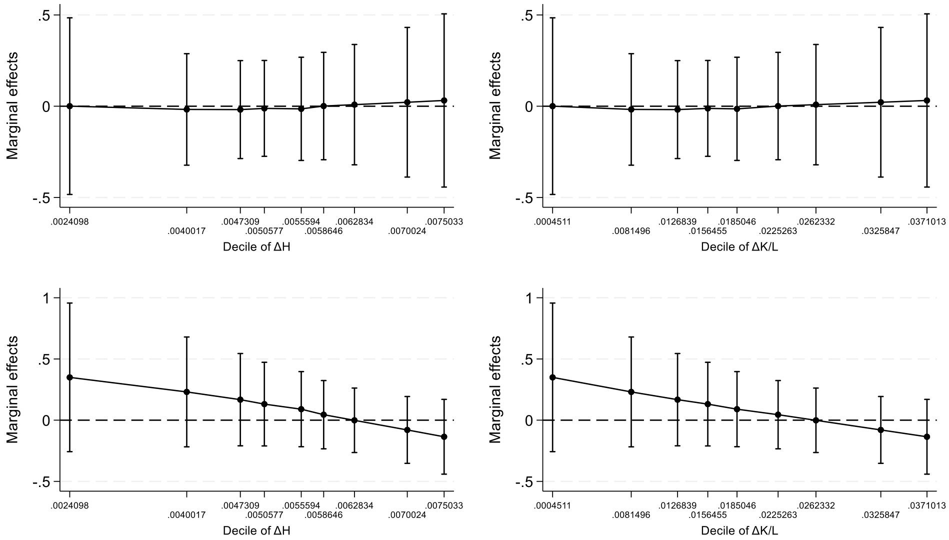
Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 9: Direct effects of trade openness, overall (top graphs) and scale (bottom graphs) AG components



Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

Figure 10: Direct effects of trade openness, composition (top graphs) and technique (bottom graphs) AG components



Note: Marginal effects at each decile of the reported variable on the x-axis from M2 model estimated by NLLS

6. Discussion

The LMDI decomposition of GHG and AG emissions for EU countries for the period 2008-2016 showed that the overall level of emissions in the EU countries stays constant, but heterogeneous effects are recorded. Some of them reported a decrease in air pollution, while others showed an increase in air pollutants emissions. The common decrease recorded between 2008 and 2010 is likely linked to the economic crisis of 2008, which led to a decline in the real GVA of countries. Regarding the three effects, emissions generally increased due to the scale effect and decreased due to the technique effect. The composition effect behaved differently from country to country.

The results on the EKC underlined that GHG and AG emissions are driven in a non-linear way by GDP per capita growth and trade, both directly and indirectly through the interaction with factor endowments.

Table 3. Emissions (GHGs and AGs) and GDPpc growth by country and median value

		ΔGDPpc	
		High growth countries	*Low growth countries*
ΔGHG	*High Polluter*	Bulgaria, Estonia, Hungary, Lithuania, Netherland, Poland, Slovakia	Austria, Belgium, Denmark, Germany, Greece
	Less polluter	Latvia, Romania, Sweden	Croatia, Finland, France, Italy, Portugal, Slovenia, Spain, United Kingdom
ΔAG	*High Polluter*	Bulgaria, Estonia, Hungary, Lithuania, Netherland, Poland	Austria, Belgium, Denmark, Germany, Greece
	Less Polluter	Latvia, Romania, Slovakia, Sweden	Croatia, Finland, France, Italy, Portugal, Slovenia, Spain, United Kingdom

Through our empirical analysis on the overall effect, we have not rejected the hypothesis that a decoupling exists. To support this result, we have constructed Table 3. It is obtained by calculating the median values of emissions and growth rates for each country and of the all sample. If the country median values of ΔGHG (ΔAG) is higher than the sample median, the country is classified as “High Polluter” otherwise it is a “Less Polluter”. Referring to ΔGDPpc, if the median value of the country is higher than the sample median value, the country lies among the “High growth countries” otherwise among the “Less growth countries”. Table 3 shows that the decoupling results are related to less polluter country with a high growth rate, so Latvia, Romania and Sweden, in terms of GHGs, and Latvia, Romania, Slovakia and Sweden, concerning AGs.

By combining the results on the three effects, some important conclusions can be drawn. First, the estimates have shown that economic factors have different impacts on each component and that the results are qualitatively similar across air pollutants. Second, the scale effect appears to be significantly driven by the growth rate of GDP per capita through a non-linear relationship, but the effect is opposite to that found in the literature. This could be explained by the fact that EU countries are advanced economies linked by a common trade market and can be interpreted as evidence in favour of decoupling. This result is confirmed by the evidence that countries that are highly dynamic in international trade reduce emissions. Moreover, the composition effect does not seem to be very relevant, except when countries make investments in physical capital that contribute to reducing GHG and AG emissions. Third, estimates of the technique component suggest that investment in physical capital can play a key role in achieving environmental improvements. However, more effort is needed in terms of resources invested to offset the scale effect.

Conclusions

Given the increasing importance of environmental issues and their impact on human health and natural degradation, researchers have examined some economic factors such as GDP, energy consumption and trade-related determinants of air emissions to find possible solutions for sustainable development. As emissions can be decomposed into three specific effects - scale, composition and technique - this paper has qualitatively and quantitatively analysed the impact of GDP growth, trade openness and factor endowments on these effects separately. Emissions were driven by GDP per capita growth in a non-linear way and by trade openness, both directly and indirectly through the interaction with factor endowments. The determinants of the scale component mainly influenced the rate of change of total emissions, but physical capital investment played a key role in reducing emissions mainly through the technique component.

From a policy point of view, institutions should manage air pollutants by concentrating resources on new investment in physical capital to expand the composition and technique effects with respect to the scale component and to consider the heterogeneous impact of investments on them. This is also in line with a decoupling pattern. Policies should encourage a rethinking of the sectoral composition by promoting investments in green capital and pay more attention to eco-innovation and technological progress with the aim of reducing emissions through a lower dependence on raw materials and the environment in general. Furthermore, concerning resource decoupling, EU, since the enacting of the European Green Deal and following corollary directives, is fostering a just and inclusive ecological and digital transition but challenges due to economic, structural, and social disparities among Member States make the adoption difficult. Different transposition times lead wealthier countries to adapt more easily, while less developed states reliant on resource-intensive industries must bear higher costs, risking competitiveness and regional inequalities. Different absorption capacity, public support, economic structures and uneven access to green technologies make transitioning harder for some nations. Administrative gaps and limited monitoring capacity hinder consistent enforcement. Finally, having diverse environmental baselines make uniform targets harder to achieve so higher flexibility is required. Not to be underestimated cross-border effects risk, which implies a shift of environmental pressures between countries. Towards solving these problems, possible solutions could refer to EU funding, differentiated timelines (short-term and long-term), collaboration among countries, which can also help ensure equity and cohesion while advancing decoupling goals.

Further research could be undertaken. First, a longer time horizon should be considered, as the implementation of an environmental regulation and the adoption of new green technologies require a longer-term perspective to allow for a complete structural change of the economy. Second, a robustness analysis of the results could be carried out by allowing for the existence of zero emissions at the sectoral level (Wood and Lenzen, 2006). Third, as there are many differences between pollutants, further studies could be carried out by applying the same analysis to other types of pollutants, such as water pollutants. Finally, it might be useful to find an appropriate variable to measure environmental regulation to capture the direct impact of specific policies on emissions.

Despite our work could contribute to the current discussion about possible drivers of emissions and insights to policymakers, it is not spurious by limitations that could be treated in further researchers. Firstly, the adoption of a LMDI II approach requires that the involved variables have constant elasticities, so the relationships between these measures and their respective outcomes remain unchanged over time. In other terms, it has been assumed that these relationships are not likely to evolve due to technological progress, changes in economic conditions or policy shift (Ang, 2004). Furthermore, since we are dealing with data that varies across countries, sectors, or time periods, LMDI II treats the changes in factors as though they have the same influence regardless of the context (Ang and Wang, 2000).

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Data Availability: All data are included in the content of the paper.

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Appendix A

Table A1. Manufacturing sectors by Nace Rev. 2 classification

Nace Code	Description
C10_C12	Manufacture of goods, products, beverage, tobacco products
C13_C15	Manufacture of textile, wearing apparel, leather and related products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31_C32	Manufacture of furniture and other manufacture
C33	Repair and installation of machinery and equipment

Table A2. Data Description

Variable	Description
Dependent Variables	
g_{it}^{E}	Total emission change rate
g_{it}^{s}	Emission change rate due to the scale effect (scale component)
g_{it}^{c}	Emission change rate due to the composition effect (composition component)
g_{it}^{T}	Emission change rate due to the technique effect (technique component)
Independent Variables (in logs and first differences)	
$\Delta GDPpc_{t-2}$	Expenditure-side real GDP per capita
$\Delta K/L_{t-1}$	Ratio of capital stock to number of engaged workers
ΔH_{t-1}	Human capital index, based on years of schooling and returns to education
$\Delta Trade_{t-1}$	Share of total exports and imports of goods at current PPPs, (EXP+IMP)/GDP

Table A3: SUR and NLSUR estimates of emission components

	Scale				**Composition**				**Technique**			
	GHG-M1	**GHG-M2**	**AG-M1**	**AG-M2**	**GHG-M1**	**GHG-M2**	**AG-M1**	**AG-M2**	**GHG-M1**	**GHG-M2**	**AG-M1**	**AG-M2**
$\Delta GDPpc_{t-2}$	-0.81***	-0.440	-0.81***	-0.430	-0.150	-0.49*	-0.120	-0.410	-0.36	0.64	0.4*	0.630
	(0.170)	(0.290)	(0.160)	(0.290)	(0.170)	(0.290)	(0.130)	(0.280)	(0.480)	(0.530)	(0.230)	(0.410)
$\Delta K/L_{t-1}$	0.040	-0.01	0.040	-0.010	-0.08*	0.150	-0.15**	0.040	-0.5**	-0.77***	-0.47***	-0.73***
	(0.070)	(0.100)	(0.070)	(0.100)	(0.040)	(0.110)	(0.080)	(0.130)	(0.200)	(0.240)	(0.120)	(0.170)
ΔH_{t-1}	-2.79	-1.01	-2.79	-1.01	-3.830	-5.270	-4.100	-5.400	0.630	2.560	2.360	2.390
	(2.160)	(2.580)	(2.150)	(2.570)	(2.760)	(3.610)	(2.570)	(3.590)	(3.140)	(3.520)	(3.920)	(3.710)
$\Delta Trade_{t-1}$	-0.19**	-0.52**	-0.19**	-0.53**	0.010	0.060	0.020	0.110	-0.21*	0.160	0.050	0.430
	(0.080)	(0.250)	(0.080)	(0.250)	(0.110)	(0.340)	(0.130)	(0.390)	(0.110)	(0.250)	(0.140)	(0.360)
$\Delta GDPpc_{t-2}{}^{2}$		-5.17**		-5.16**		-0.040		-0.220		-4.980		5.6**
		(2.09)		(2.100)		(2.860)		(2.600)		(6.480)		(2.330)
$\Delta GDPpc_{t-2}{}^{3}$		-45.19**		-45.66**		18.520		14.990		-98.190		4.900
		(19.240)		(19.160)		(23.150)		(19.610)		(78.350)		(27.490)
$\Delta Trade_{t-1} * \Delta H_{t-1}$		72.91		73.31		-48.34		-47.20		-10.19		-32.370
		(53.97)		(53.870)		(71.7)		(84.48)		(32.040)		(39.700)
$\Delta Trade_{t-1} * \Delta K/L_{t-1}$		-2.69		-2.61		8.75**		7.410		-11.32**		-8.740
		(3.120)		(3.110)		(4.150)		(4.850)		(5.030)		(5.450)
constant	0.02**	0.02*	0.02**	0.02*	0.01	0.02	0.01	0.020	-0.02	-0.03	-0.05**	-0.06***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.020)	(0.010)	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)
R-squared	0.144	0.203	0.144	0.203	0.011	0.051	0.013	0.041	0.053	0.121	0.021	0.069
Obs	184	184	184	184	184	184	184	184	184	184	184	184

Note. Significance level: *** 0.01, ** 0.05, * 0.1