Attribution Analysis at Member State Level of Percent Changes in European Carbonization Index

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Abstract
Since the beginning of the Industrial Revolution, emissions of CO_2 due to human activities have led to a marked increase in atmospheric concentrations of long-lived gases, leading to a worrisome global warming. In recent years, with a view to contribute to design suitable policies to control those emissions, numerous environmental studies have analyzed the trends in gas emissions and their main drivers. In this paper we explore in detail the trend of carbonization as a driving force for CO_2 emissions in the EU Member States. By implementing the so-called Sato-Vartia logarithmic mean Divisia index (LMDI-II) method, we factorize the emission change in the EU for the 2000-2010 period. Results point to the carbonization effect, along with the intensity effect, as one of the most relevant factors. Then, relying on the so-called attribution analysis (Choi and Ang, 2012; Fernández González et al., 2013) we present a new theoretical framework that enables attribution of percent changes in the carbonization index to individual EU Member States. This deeper study shows the strong concentration of this reducing influence in some big economies, with Germany, the United Kingdom, France and Italy contributing by more than 50%. Furthermore, adding Spain and Poland, the total contribution exceeds 75% of total change. Findings in this paper suggest that efforts should focus on strategies aiming at encouraging innovation, adaptation to more efficient and environmentally friendly technologies, research for higher quality energies, lower carbon fuel substitution and instalment of abatement technologies like carbon capture and storage.

Key words: Attribution analysis, LMDI method, emission coefficient index, European study.

JEL: C43 (Index numbers aggregation), O52 (Europe), Q43 (Energy and macroeconomy), Q51 (Environmental effects), Q58 (Government policy).

1. Introduction

Climate change usually refers to the ongoing rise in global average temperature near Earth's surface, causing an increase in the frequency and severity of natural disasters. It is mostly caused by increasing concentrations of GHG in the atmosphere of which carbon dioxide is the most significant one. Climate change and global warming presents a serious problem since it bring changes in acidification, temperature and level of the oceans, frequency and severity of droughts and floods, Arctic sea ice and glacier extent, and it poses new challenges for humanity, affecting our own health and safety.

Global primary energy use has traditionally involved a dependence on fossil fuels sources: first, coal and steam, and then, oil and natural gas. Although deforestation, industrial processes, and some other agricultural practices also emit gases into the atmosphere, the majority of GHG come from burning fossil fuels to produce energy. Despite of the increasing use of non-fossil fuel sources (nuclear, hydro-energy and others like geothermal, solar, tidal, wind, wood and waste) to produce energy, reductions in the fuels emission coefficient and the energy intensity are still considered key elements to combat global warming.

Emission coefficient denotes the declining average carbon intensity of primary energy over time. Although intensities are currently increasing in some developing regions (World Energy Outlook 2004 -IEA, 2004), the replacement of fuel towards lower carbon content ones and more efficient technologies such as capture and storage of gases has brought lower carbon intensities.

Given global concerns about environmental issues and the consequent agreements signed by many countries (e.g., the Kyoto Protocol, 1997; and Doha Amendment to the Kyoto Protocol, 2012), a large number of environmental studies have emerged in recent years. Following different approaches, numerous authors have dealt with factorization and analysis of aggregate CO_2 emissions. Index decomposition analysis (IDA) is a leading theoretical framework that is heavily used in environmental and energy studies. It involves decomposing the variation of an aggregate variable relying on economic indexes[1]. From both theoretical and applied perspectives, the logarithmic mean Divisia index (LMDI) method reported in Ang and Choi (1997) is widely accepted and it has likely emerged as the preferred in most factorization studies. Among others, numerous are its advantages, profusely demonstrated in Ang and Liu (2001): it leads to exact decomposition, it is consistent in aggregation, it handles zero values effectively, it satisfies both factor and time reversal test, and there exists a simple formula relating additive and multiplicative decompositions[2]. Authors like Ang et al. (1998), Nag and Parikh (2000), Ramírez et al. (2005), Ma and Stern (2008), Liao and Wei (2010), Sahu and Narayanan (2010), Hammond and Norman (2012) and Shahiduzzaman and Alam (2012) have applied this method in order to decompose changes in a number of environmental and energy aggregates.

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[1] Thus, the methodological problems of this analysis are similar to those of the index numbers indicated by Fisher (1927) and Diewert (1980).
[2] This fact makes redundant both forms of decomposition. In this paper, we opted for multiplicative approach since we are interesting in percentual interpretations.

Recently, in order to further analysis in real energy intensity trend, Choi and Ang (2012) proposed a new decomposition approach, the so-called *attribution analysis of IDA*. Based on the exhaustive LMDI method, their proposal enables the assessment of individual sector to the percentual change in real energy intensity. In this paper we extend this analysis, analysing the emission coefficient index tendency and assessing the contribution of individual regions to percentual changes in it. This will allow us a deep analysis of the emission coefficient influence on CO_2 emission changes, identifying those regions in which environmental strategies are yielding to significant outcomes.

The goal of this paper is twofold. First, we aim at analyzing in detail trend of emission coefficient (or carbonization) index in the EU in the last decade. This objective will be achieved through decomposing changes in CO_2 emissions into several factors, namely energy intensity, emission coefficient (or emission coefficient), structural change and economic activity. This decomposition will be carried out in IDA framework, particularly through the implementation of the Sato-Vartia logarithmic mean Divisia index (LMDI-II) method. Findings will help in energy and environmental policies planning.

Second, we intend to quantify and analyze individual Member State contributions to percent changes in the emission coefficient factor. In order to achieve this target, following the attribution analysis firstly introduced in Choi and Ang (2012) and later expanded in Fernández González et al. (2013), we derive and develop an adequate methodology to carry out this study. Results will show those countries in which energy and environmental strategies should be reformulated in order to achieve more favorable emission coefficient.

In Section 2, we display the methodology necessary to achieve the objectives. Section 2.1 reviews the multiplicative LMDI-II decomposition method, showing its suitable use in order to factorize changes in CO_2 emissions in relation to alternative. In Section 2.2 and based on an attribution analysis, we derive a new methodology that enables the assignment of emission coefficient factor percent changes to individual Member States.

Section 3 analyzes the emission coefficient index trend by economic sector and Member State. In Section 3.1, we decompose changes in EU CO_2 emissions into several factors: energy intensity, emission coefficient, European production structure and economic activity. Section 3.2 implements the attribution analysis presented in Section 2.2 in order to identify those largest contributor countries to percentual changes in the index.

Finally, the last section collects the main conclusions of the paper, setting key recommendations in order to control CO_2 emissions in the EU.

2. Methodology

In Section 2.1 we review the multiplicative LMDI method introduced by Ang and Choi (1997) to factorize changes in an environmental aggregate. Specifically, we focus on the so-called Sato-Vartia LMDI (LMDI-II) method since it involves a genuine geometric mean, ensuring a weights sum equal to unity. Moreover, we consider both periodwise (single-period) and time series (multi-period) implementations of LMDI-II.

Then, in Section 2.2, based on the attribution analysis of IDA reported by Choi and Ang (2012) and extended by Fernández González et al. (2013), we present and develop an extension for further analysis in emission coefficient factor. Actually, we seek for quantifying contribution of individual regions to its percentual changes. This means a significant added value, since findings and environmental action lines would be individually suited to each region. Again, for further study, we take into account both single-period (*periodwise*) and dynamic or multi-period (*time series*) decomposition.

2.1. LMDI-II method

Adapting this method to present case, changes in aggregate CO_2 emissions may be decomposed into the following predetermine factors:

(a) Emission coefficient or carbonization effect, i.e., impact of specific carbon emissions per unit energy on emissions. It evaluates fuel quality, fuel switching (fuel substitution) and the installation of abatement technologies;
(b) Intensity effect, i.e., impact of energy requirements per unit value added on emissions. It involves the energy consumption related to some variables like energy prices, energy conservation and energy-saving investments, structure and the efficiency of the energy systems, technological choices and socio-economic behaviour;
(c) Structural effect, i.e., impact of production structure. It measures changes due to the relative position of sectors/regions in an economy; and
(d) Activity effect, i.e., impact of economic growth. Assuming a constant (average) coefficient between GDP and CO_2 emissions, it is regarded as the theoretical CO_2 emissions caused by economic activities (Sun, 1999).

Given the following variables, evaluated at time t:
G_t : aggregate CO_2 emissions,
$G_{i,t}$: CO_2 emissions from region i
E_t : total energy consumption,
$E_{i,t}$: energy consumption in region i,
Y_t : Gross Domestic Product,
$Y_{i,t}$: production of region i,
$C_{i,t}$: emission coefficient of in region i ($C_{i,t}=G_{i,t}/E_{i,t}$),
$S_{i,t}$: product share in region i ($S_{i,t}= Y_{i,t}/Y_t$),
$I_{i,t}$: energy intensity in region i ($I_{i,t}=E_{i,t}/Y_{i,t}$).

Where data are disaggregated by region, aggregate CO_2 emissions may be expressed as follows:

$$G_t = \sum_{i=1}^{k} \frac{G_{i,t}}{E_{i,t}} \frac{E_{i,t}}{Y_{i,t}} \frac{Y_{i,t}}{Y_t} Y_t = \sum_{i=1}^{k} C_{i,t} I_{i,t} S_{i,t} Y_t \tag{1}$$

where the summation i is taken over the k regions, and being the sum of all regions the predefined geographic area under study.

Considering infinitesimal periods, dividing by C_t and integrating on both sides with respect to time t in $[0,T]$ yields:

$$\ln(G_T/G_0)=\int_0^T\sum_i^k\frac{C'_{i,t}I_{i,t}S_{i,t}Y_t}{G_t}+\int_0^T\sum_i^k\frac{C_{i,t}I'_{i,t}S_{i,t}Y_t}{G_t}+\int_0^T\sum_i^k\frac{C_{i,t}I_{i,t}S'_{i,t}Y_t}{G_t}+\int_0^T\sum_i^k\frac{C_{i,t}I_{i,t}S_{i,t}Y'_t}{G_t} \tag{2}$$

where C'_{ijt}, $I'_{i,t}$, $S'_{i,t}$ and Y'_t are, respectively, the first derivatives of $C_{i,t}$, $I_{i,t}$, $S_{i,t}$ and Y_t with respect to time.

Denoting by $(R_{tot})_{0,T}$ the total effect between periods 0 and T ($(R_{tot})_{0,T}=G_T/G_0$), with $(R_{emf})_{0,T}$, $(R_{int})_{0,T}$, $(R_{str})_{0,T}$ and $(R_{act})_{0,T}$ being, respectively, the estimated emission coefficient, intensity and structural effects, respectively, Equation (2) above may be transform into any of the following two forms:

$$(R_{tot})_{0,T}=e^{\left(\int_0^T\sum_{i=1}^k\frac{G_{i,t}}{G_t}(C'_{i,t}/C_{i,t})dt\right)}e^{\left(\int_0^T\sum_{i=1}^k\frac{G_{i,t}}{G_t}(I'_{i,t}/I_{i,t})dt\right)}e^{\left(\int_0^T\sum_{i=1}^k\frac{G_{i,t}}{G_t}(S'_{i,t}/S_{i,t})dt\right)}e^{\left(\int_0^T\sum_{i=1}^k\frac{G_{i,t}}{G_t}(Y'_t/Y_t)dt\right)} \tag{3}$$

$$(R_{tot})_{0,T}=e^{\left(\int_0^T\sum_{i=1}^k(C'_{i,t}I_{i,t}S_{i,t}Y_t/G_t)dt\right)}e^{\left(\int_0^T\sum_{i=1}^k(C_{i,t}I'_{i,t}S_{i,t}Y_t/G_t)dt\right)}e^{\left(\int_0^T\sum_{i=1}^k(C_{i,t}I_{i,t}S'_{i,t}Y_t/G_t)dt\right)}e^{\left(\int_0^T\sum_{i=1}^k(C_{i,t}I_{i,t}S_{i,t}Y'_t/G_t)dt\right)} \tag{4}$$

Transforming the above path integrals into parametric ones, Liu et al. (1992) derive (3) and (4) into general parametric Divisia methods I (PDM-I) and II (PDM-II), respectively. Therefore, ocusing on the PDM-II effects may be estimate through the following expressions:

$$(R_{emf})_{0,T}=e^{\left[\sum_{i=1}^k\frac{G_{i,0}}{G_0}+\beta_i\left(\frac{G_{i,T}}{G_T}-\frac{G_{i,0}}{G_0}\right)\ln\left(\frac{C_{i,T}}{C_{i,0}}\right)\right]} \tag{5}$$

$$(R_{int})_{0,T}=e^{\left[\sum_{i=1}^k\frac{G_{i,0}}{G_0}+\beta_i\left(\frac{G_{i,T}}{G_T}-\frac{G_{i,0}}{G_0}\right)\ln\left(\frac{I_{i,T}}{I_{i,0}}\right)\right]} \tag{6}$$

$$\left(R_{str}\right)_{0,T} = e^{\left[\sum_{i=1}^{k} \frac{G_{i,0}}{G_0} + \beta_i \left(\frac{G_{i,T}}{G_T} - \frac{G_{i,0}}{G_0}\right) \ln\left(\frac{S_{i,T}}{S_{i,0}}\right)\right]} \tag{7}$$

$$\left(R_{act}\right)_{0,T} = e^{\left[\sum_{i=1}^{k} \frac{G_{i,0}}{G_0} + \beta_i \left(\frac{G_{i,T}}{G_T} - \frac{G_{i,0}}{G_0}\right) \ln\left(\frac{Y_T}{Y_0}\right)\right]} \tag{8}$$

where β_i denotes given weight of region *j* from period 0 to period *T*, and being $0 \le \beta_i \le 1$.

Considering the logarithmic mean weight function proposed in Ang and Choi (1997)[3]

$$L\left(G_{i,0}, G_{i,T}\right) = \frac{\left(G_{i,T} - G_{i,0}\right)}{\ln\left(G_{i,T} / G_{i,0}\right)}$$

and normalizing it to fulfill the partition-of-unity property, the following weight function is obtained:

$$w^*_{i,0-T} = \frac{L\left(G_{i,0}, G_{i,T}\right)}{\sum_{i=1}^{k} L\left(G_{i,0}, G_{i,T}\right)} \quad , \quad i=1,2,\ldots, k \tag{9}$$

where $w^*_{i,0-T}$ denotes the normalized weight of region *j* between periods 0 and *T*.

In addition, also intermediate periods between 0 and *T* may be considered, leading to time series decomposition. This type of decomposition likely entails more accurate results than periodwise since it uses a larger volume of information. Besides, it makes possible the detection of structural breaks, different phases or time patterns in the estimated effects.

Denoting $\left(C_{tot}\right)_{0,T}$ as the cumulative change in CO_2 emissions from 0 to *T*, $\left(C_{emf}\right)_{0,T}$ the estimated cumulative emission coefficient effect from 0 to *T*, $\left(C_{int}\right)_{0,T}$ the estimated cumulative intensity effect from 0 to *T*, $\left(C_{str}\right)_{0,T}$ the estimated cumulative structural effect by from 0 to *T* and $\left(C_{act}\right)_{0,T}$ the estimated cumulative activity effect by from 0 to *T*, we obtain:

$$\left(C_{tot}\right)_{0,T} = \left(R_{tot}\right)_{0,1} \left(R_{tot}\right)_{1,2} \cdots \left(R_{tot}\right)_{T-1,T} \tag{10}$$

$$\left(C_{emf}\right)_{0,T} = \left(R_{emf}\right)_{0,1} \left(R_{emf}\right)_{1,2} \cdots \left(R_{emf}\right)_{T\text{-}1,T} \tag{11}$$

$$\left(C_{int}\right)_{0,T} = \left(R_{int}\right)_{0,1} \left(R_{int}\right)_{1,2} \cdots \left(R_{int}\right)_{T\text{-}1,T} \tag{12}$$

$$\left(C_{str}\right)_{0,T} = \left(R_{str}\right)_{0,1} \left(R_{str}\right)_{1,2} \cdots \left(R_{str}\right)_{T\text{-}1,T} \tag{13}$$

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[3] This weight function leads to a complete decomposition, i.e., no deviation from the target value is observed: $\left(R_{rsd}\right)_{T\text{-}1,T} = 1$.

$$(C_{act})_{0,T} = (R_{act})_{0,1}(R_{act})_{1,2} \ldots (R_{act})_{T\text{-}1,T} \tag{14}$$

2.2. Attribution analysis of the Divisia emission coefficient index

Once a predefined factor is isolated through any decomposition technique, contribution of each individual attribute (i.e., each economic sector or region) to its overall percentual change may be advised through an attribution approach. Based on Choi and Ang (2012) and interested in emission coefficient index study, we propose and develop the methodology set out below.

A Divisia index of emission coefficient (in log-change form) from period 0 to period T may be expressed as a geometric mean index:

$$\ln(R_{emf})_{0,T} = \ln\left(\frac{R_{emf\,T}}{R_{emf\,0}}\right) = \sum_{i=1}^{k} w_i \ln\left(\frac{C_{i,T}}{C_{i,0}}\right) \Leftrightarrow (R_{emf})_{0,T} = \prod_{i=1}^{k}\left(\frac{C_{i,T}}{C_{i,0}}\right)^{w_i} \tag{15}$$

By defining the unknown parameters π_i as in Equation (20) below, the geometric index is converted into an arithmetic mean[4], and the following expression is obtained:

$$\frac{R_{emf\,T}}{R_{emf\,0}} = \frac{\sum_{i=1}^{k}\pi_i C_{i,T}}{\sum_{i=1}^{k}\pi_i C_{i,0}} \tag{16}$$

By defining $a_{i,0} \equiv \frac{\pi_i I_{i,0}}{\sum_{g=1}^{k}\pi_g I_{g,0}}$, $a_{i,T} \equiv \frac{\pi_i I_{i,T}}{\sum_{g=1}^{k}\pi_g I_{g,T}}$, using the identity $\sum_{i=1}^{k}\sum_{j=1}^{l}(a_{i,T} - a_{i,0}) = 0$ and applying the definition of logarithmic mean, the following two identities are derived (Balk, 2004):

$$\sum_{i=1}^{k} L(a_{i,T}, a_{i,0})\ln\left(\frac{a_{i,T}}{a_{i,0}}\right) = 0 \tag{17}$$

$$\ln\left(\frac{a_{i,T}}{a_{i,0}}\right) = \ln\left(\frac{C_{i,T}}{C_{i,0}}\right) - \ln\left(\frac{R_{emf\,T}}{R_{emf\,0}}\right) \tag{18}$$

Inserting (18) in (17) and solving the equation in $\ln((R_{emf})_{0,T})$, we obtain the following alternative log-change expression for $(R_{emf})_{0,T}$:

[4] Attribution analysis requires an arithmetic mean index. Choi and Ang (2012), relying on an identity derived by Balk (2004), transformed the Divisia or geometric mean index into an arithmetic mean formula.

$$\ln\left(\frac{R_{emf\,T}}{R_{emf\,0}}\right)=\sum_{i=1}^{k}\frac{L\left(a_{i,T},a_{i,0}\right)}{\sum_{g=1}^{k}L\left(a_{g,T},a_{g,0}\right)}\ln\left(\frac{C_{i,T}}{C_{i,0}}\right)=$$
$$\sum_{i=1}^{k}\frac{\pi_i L\left(C_{i,T},C_{i,0}\left(R_{emf}\right)_{0,T}\right)}{\sum_{g=1}^{k}\pi_g L\left(C_{g,T},C_{g,0}\left(R_{emf}\right)_{0,T}\right)}\ln\left(\frac{C_{i,T}}{C_{i,0}}\right) \tag{19}$$

Comparing weights of the two log-change forms in (15) and (19), we obtain:

$$\pi_i=\frac{w_i}{L\left(C_{i,T},C_{i,0}\left(R_{emf}\right)_{0,T}\right)} \tag{20}$$

Replacing (20) in (19), the right-hand side is the same as the log change form in (15). Hence, (20) is so-called as the "Reinsdorf formula" (Reinsdorf, 1996) since it provides a link between geometric and arithmetic mean indices and it.

Since Montgomery-Vartia index is not a genuine geometric mean, the above attribution analysis in based in Sato-Vartia index. That is, it is built on the LMDI-II method.

Finally, attributions of emission coefficient index in LMDI-II[5] will be given by the following formula:

$$\left(\frac{R_{\text{int}\,T}}{R_{\text{int}\,0}}-1\right)=\sum_{i=1}^{k}\sum_{j=1}^{l}a_{ij}\left(\frac{C_{ij,T}}{C_{ij,0}}-1\right) \tag{21}$$

where

$$a_i=\frac{\pi_i\,C_{i,0}}{\sum_{g=1}^{k}\pi_g\;C_{g,0}}=\frac{\dfrac{w_iC_{i,0}}{L\left(C_{i,T},C_{i,0}\left(R_{emf}\right)_{0,T}\right)}}{\sum_{g=1}^{k}\dfrac{w_gC_{g,0}}{L\left(C_{g,T},C_{g,0}\left(R_{emf}\right)_{0,T}\right)}} \tag{22}$$

and a_i may be interpreted as the relative weight of component *i* in region *j*. It measures the degree of influence of this component on the total. It is readily checked that $\sum_{i=1}^{k}a_i=1$.

Again a multi-period attribution analysis is also indicated if intermediate period information is available. Upon the basis of the following definition of chain real

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[5] The presented analysis is built on the LMDI-II method since Montgomery-Vartia index is not a genuine geometric mean but Sato-Vartia index.

energy intensity index, cumulative emission coefficient effect may be expressed as follows:

$$\left(C_{emf}\right)_{0,T} = \left(R_{emf}\right)_{0,1}\left(R_{emf}\right)_{1,2}\ldots\left(R_{emf}\right)_{T-1,T} \tag{23}$$

And the following difference representation is readily obtained:

$$\left(C_{emf}\right)_{0,T} - 1 = \frac{R_{emf\,T}}{R_{emf\,0}} - 1 = \frac{R_{emf\,T}}{R_{emf\,0}} - \frac{R_{emf\,0}}{R_{emf\,0}} =$$

$$\left(\frac{R_{emf\,T}}{R_{emf\,0}} - \frac{R_{emf\,T-1}}{R_{emf\,0}}\right) + \left(\frac{R_{emf\,T-1}}{R_{emf\,0}} - \frac{R_{emf\,T-2}}{R_{emf\,0}}\right) + \left(\frac{R_{emf\,T-2}}{R_{emf\,0}} - \frac{R_{emf\,T-3}}{R_{emf\,0}}\right) + \ldots +$$

$$\left(\frac{R_{emf\,1}}{R_{emf\,0}} - \frac{R_{emf\,0}}{R_{emf\,0}}\right) = \tag{24}$$

$$\frac{R_{emf\,T-1}}{R_{emf\,0}}\left(\frac{R_{emf\,T}}{R_{emfT-1}} - 1\right) + \frac{R_{emf\,T-2}}{R_{emf\,0}}\left(\frac{R_{emf\,T-1}}{R_{emfT-2}} - 1\right) + \frac{R_{emf\,T-3}}{R_{emf\,0}}\left(\frac{R_{emf\,T-2}}{R_{emfT-3}} - 1\right) + \ldots +$$

$$\frac{R_{emf\,0}}{R_{emf\,0}}\left(\frac{R_{emf\,1}}{R_{emf\,0}} - 1\right)$$

Therefore:

$$\left(C_{emf}\right)_{0,T} - 1 = \frac{R_{emf\,T}}{R_{emf\,0}} - 1 = \sum_{t=1}^{T}\frac{R_{emf\,T-1}}{R_{emf\,0}}\left(\frac{R_{emf\,T}}{R_{emf\,T-1}} - 1\right) \tag{25}$$

This expression shows that the percent change in the above chain index is a cumulative sum of single-period percent changes multiplied by $\frac{R_{emft\text{-}1}}{R_{emf\,0}}$.

Inserting (21) in (25), the following expression for multi-period attribution analysis of Divisia chain indices is obtained:

$$\left(\frac{R_{emf\,T}}{R_{emf\,0}} - 1\right) = \sum_{t=1}^{T}\frac{R_{emf\,t-1}}{R_{iemf\,0}}\left(\frac{R_{emf\,t}}{R_{emf\,t-1}} - 1\right) = \sum_{i=1}^{k}\sum_{t=1}^{T}\frac{R_{emf\,t-1}}{R_{emf\,0}}\left(a_i\right)_{t-1,t}\left(\frac{C_{i,t}}{C_{i,t-1}} - 1\right) \tag{26}$$

where

$$\left(a_i\right)_{t-1,t} = \frac{\dfrac{\left(w_i\right)_{t-1,t}C_{i,t-1}}{L\left(C_{i,t}, C_{i,t-1}\left(R_{emf}\right)_{t-1,t}\right)}}{\displaystyle\sum_{g=1}^{k}\frac{\left(w_g\right)_{t-1,t}C_{g,t-1}}{L\left(C_{g,t}, C_{g,t-1}\left(R_{emf}\right)_{t-1,t}\right)}} \tag{27}$$

The value of $\frac{R_{emf\,t-1}}{R_{emf\,0}}(a_i)_{t-1,t}\left(\frac{C_{i,t}}{C_{i,t-1}}-1\right)$ in (26) may be interpreted as the contribution of sector i in region j during period [t-1, t], evaluated from the base period 0.

3. Empirical Analysis

In this section we analyze in detail the evolution of the aggregate CO_2 emissions in the EU from 2000 to 2010, quantifying its drivers and paying particular attention to emission coefficient factor impact. Analysis is done in two phases.

First, in order to identify and quantify driving forces under changes in EU CO_2 emissions, we implement multiplicative LMDI-II method at country disaggregation level. Second, with the objective of deeper exploration in the emission coefficient trend, we implement an attribution analysis. The goal is exploring attribution to percentual changes in the corresponding emission coefficient index of each Member State.

Time series data on CO_2 emissions (in thousand tonnes of CO_2 equivalent), energy consumption[6] (in million tonnes of oil equivalent) and value added in real terms (in euro at basic prices in purchasing power parity) for both sector and country, were obtained from the Publications Office of the European Union (Eurostat -European Commission, 2014). We considered the following sectors[7]: Agriculture, Industry (including energy and manufacturing industries, industrial processes and construction), Transport and Others (includes residential and commercial).

3.1. Decomposition of changes in EU CO_2 emissions

Multiplicative LMDI-II method is implemented to factorize changes in EU CO_2 emissions. In addition, single-period/periodwise (with the immediately preceding period taken as base year) and multi-period/time series decomposition (with the initial year chosen as base) are carried out in each case, leading to simple and cumulative factor estimations.

Based on 27 Member States (i=1,...,27) disaggregation, results from both periodwise and time series decomposition forms are reported in Table 1.

From 2000 to 2010, EU aggregate CO_2 emissions experienced a decrease of 6.11%. Two effects have contributed to this reduction: intensity (10.68%) and emission coefficient (7.1%) effect. This means innovation, technical change, adaptation to more efficient technologies in EU Member States, but also the use of less contaminant energies and the installation of capture and storage of gas emissions have lower CO_2

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[6] Primary energy and its conversion are not really transparent to the consumers. Determining the emission coefficient as a ratio of total CO_2 emissions per primary energy unit would remove from the analysis the actual point of consumption and interactions between the energy system and the economy. By contrast, final energy is directly consumed and it represents the actual energy requirements.

[7] Subject to availability of data for the studied area, we leave for future work an analysis at more disaggregated levels. Hopefully, this will provide further insights in order to effectively improve governance at these finer levels.

emissions. On the contrary, structural and activity effects contributed to increase CO2 emissions by 3.29% and 9.54%, respectively. That is, changes in the EU production structure towards more polluter countries and the growing economic activity in them enhanced CO_2 emissions in the EU.

Table 1. Periodwise and time series decomposition results of changes in CO_2 emissions in the EU when aggregating by Member States, 2000-2010[a].

	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*
LMDI	R_{int}	R_{emf}	R_{str}	R_{act}	R_{tot}	C_{int}	C_{emf}	C_{str}	C_{act}	C_{tot}
2000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2001	0.9901	1.0062	1.0011	1.0182	1.0154	0.9901	1.0062	1.0011	1.0182	1.0154
2002	0.9857	0.9964	0.9993	1.0104	0.9917	0.9759	1.0027	1.0003	1.0287	1.0070
2003	1.0173	0.9880	1.0043	1.0100	1.0195	0.9929	0.9906	1.0046	1.0390	1.0266
2004	0.9728	0.9912	1.0045	1.0335	1.0010	0.9658	0.9819	1.0092	1.0739	1.0277
2005	0.9912	0.9837	1.0029	1.0169	0.9944	0.9573	0.9658	1.0121	1.0921	1.0219
2006	0.9540	1.0037	1.0048	1.0370	0.9977	0.9133	0.9694	1.0169	1.1324	1.0195
2007	0.9583	0.9935	1.0026	1.0348	0.9878	0.8752	0.9631	1.0196	1.1718	1.0071
2008	0.9946	0.9872	1.0073	0.9906	0.9799	0.8705	0.9508	1.0270	1.1609	0.9868
2009	1.0221	0.9900	1.0048	0.9120	0.9273	0.8897	0.9413	1.0320	1.0587	0.9150
2010	1.0039	0.9870	1.0009	1.0347	1.0261	0.8932	0.9290	1.0329	1.0954	0.9389

[a] Columns (1)-(5) report periodwise results (the base year is the immediately preceding year), whereas columns (6)-(10) display time series results (with 2000 being the base year).

Anyway, a detail annual exploration indicates some changes in behaviour patterns. Figure 1 shows evolution of each individual effect, assisting in detection of any trend change along the studied period.

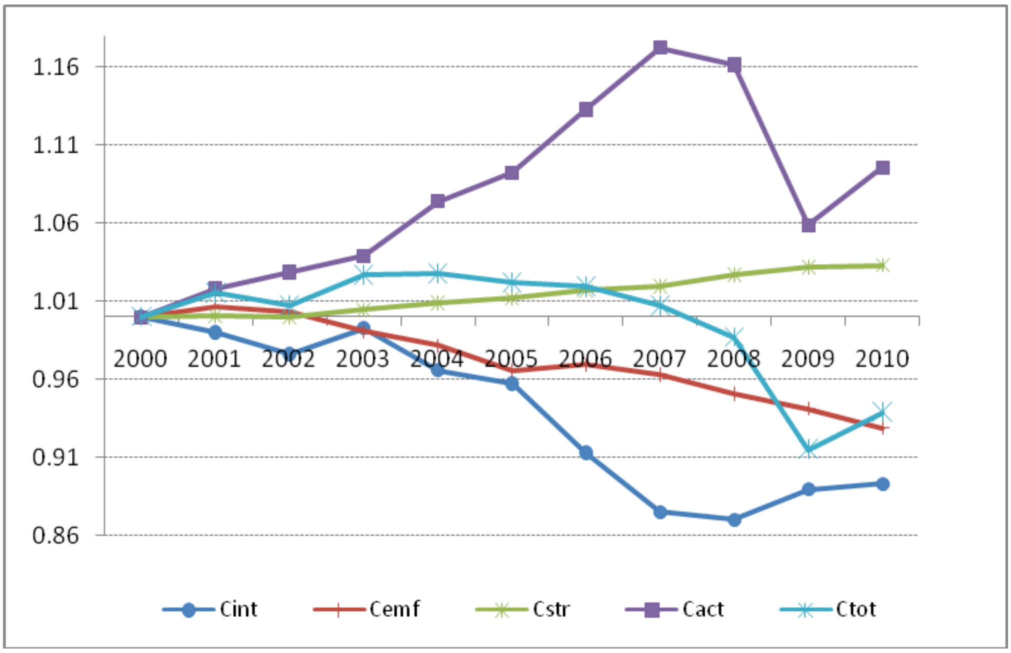

Figure 1. Multiplicative decomposition results of changes in CO_2 emissions in the EU when aggregating by Member States (base year = 2000).

Attending to Figure 1, we may distinguish two main phases. From 2000 to 2007, CO_2 emissions increased with some fluctuations but always being superior to 2000 level. In this phase, particularly in its first years, only intensity effect lowered emissions, adding emission coefficient effect from this point onwards. Respect to the activity effect showed a positive influence, with a significant increase in such influence from 2002. Meanwhile, structural effect displays a positive, slight but increasing impact on CO_2 emissions.

The second phase goes from 2007 to the end. In this interval, CO_2 emissions experienced a drop, reaching levels below 2000. Drivers of this reduction were the significant shrink in economic activity impact (despite its recovery in 2010) and the increasing negative contribution of emission coefficient influence. Meanwhile, structural effect still increases its positive impact and the intensity effect undergoes a turnaround reducing its contribution to the control of emissions. The global economic and financial crisis in these years may explain lower economic growth (even negative in some countries) and slowdown in the investment efforts of new and more efficient technologies.

A global analysis of Figure 1 indicates an aggregate CO_2 emissions reduction in the EU from 2000 to 2010. However, comparing the situation between defined phases, this reduction was mainly a result of lower economic activity. This fact implies the need to review the environmental strategies performed and the need to promote alternatives for better control of emissions[8].

3.2. Attribution analysis of emission coefficient index

Attribution analysis method is implemented to quantify contribution of individual Member State to percent changes in EU emission coefficient or emission coefficient index (Sections 3.2.1 and 3.2.2, respectively). In addition, periodwise (with the immediately preceding period taken as base year) and time series decomposition (with the initial year chosen as base) are carried out in each case, leading to direct and cumulative attributions.

Based on 27 Member States (i=1,..., 27) disaggregation, attribution analysis results from periodwise form are reported in Table 2 and Figure 2. The first presents a_j values (%) and the second relates to individual contribution to those changes.

Table 2. Periodwise attribution results (a_i) of each Member State to percentual changes in emission coefficient factor in the EU (2000-2010)[a].

	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*
a_i	Belgium	Bulgaria	CzechR.	Denmark	Germany	Estonia	Ireland	Greece	Spain
2000-2010	0.0292	0.0116	0.0297	0.0135	0.2078	0.0038	0.0123	0.0247	0.0745

[8] Analogous studies like Paul and Bhattacharya (2004) or Parikh et al. (2009) for Indian case, Ozawa et al. (2002) for Mexico, Zafrilla et al. (2012) for Spain, Jung et al. (2012) for South Korea, Hatzigeorgiou et al. (2008) for Greece or Hammond and Norman (2012) for the United Kingdom also lead to similar outcomes.

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
a_i	France	Italy	Cyprus	Latvia	Lithuania	Luxemb.	Hungary	Malta	Netherl.
2000-2010	0.1032	0.1103	0.0020	0.0022	0.0039	0.0022	0.0151	0.0006	0.0418

	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
a_i	Austria	Poland	Portugal	Romania	Slovenia	Slovakia	Finland	Sweden	UK
2000-2010	0.0172	0.0813	0.0160	0.0276	0.0040	0.0099	0.0136	0.0129	0.1295

[(a)] The sum of columns (1-27) gives the unity.

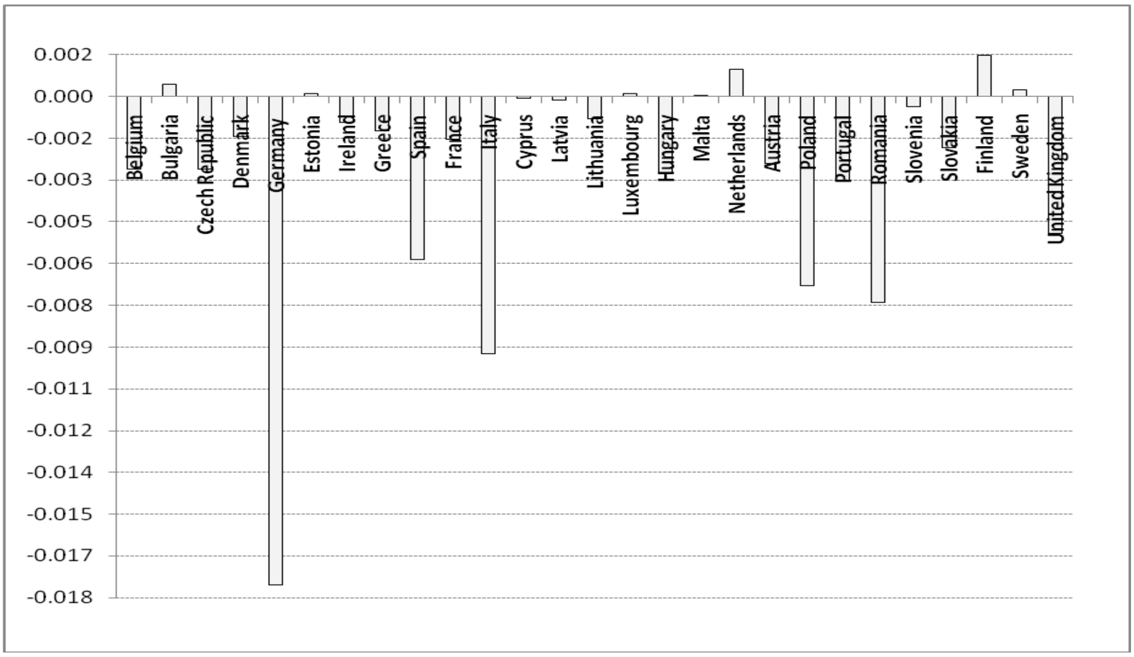

Figure 3. Periodwise contribution of each Member State to percentual changes in emission coefficient factor in the EU from 2000 to 2010.

As it is commented above (Table 1 and Figure 1), emission coefficient index fell from 2000 to 2010. According to Figure 2, most of the Member States have contributed to this reduction. Specifically, big Western economies like Germany, Italy, the United Kingdom and Spain and in a lesser extent some Central and Eastern European ones like Romania, Poland and Hungary have been the largest contributors. By contrast, some small Western Members like Netherlands, Finland, Luxembourg and Malta, and some few ex-communist ones like Bulgaria and Estonia provides contributed to increase the index.

A deeper analysis is displayed in Tables 3 and 4, reporting results from time series attribution analysis of changes in emission coefficient index.

Table 3. Time series attribution results (a_i) of each Member State to percentual changes in emission coefficient factor in the EU (base year = 2000).[a]

	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*
a_i	Belgium	Bulgaria	CzechR.	Denmark	Germany	Estonia	Ireland	Greece	Spain
2001	0.0292	0.0118	0.0292	0.0134	0.2069	0.0037	0.0127	0.0250	0.0757
2002	0.0286	0.0117	0.0290	0.0134	0.2063	0.0037	0.0125	0.0251	0.0764
2003	0.0290	0.0120	0.0295	0.0133	0.2073	0.0037	0.0127	0.0250	0.0777
2004	0.0285	0.0120	0.0296	0.0133	0.2067	0.0036	0.0126	0.0247	0.0789
2005	0.0278	0.0123	0.0294	0.0133	0.2042	0.0104	0.0126	0.0247	0.0794
2006	0.0282	0.0127	0.0292	0.0135	0.2062	0.0037	0.0128	0.0252	0.0774
2007	0.0279	0.0127	0.0287	0.0136	0.2043	0.0037	0.0120	0.0258	0.0794
2008	0.0292	0.0124	0.0294	0.0136	0.2041	0.0037	0.0126	0.0255	0.0779
2009	0.0288	0.0117	0.0296	0.0136	0.2040	0.0038	0.0128	0.0261	0.0762
2010	0.0292	0.0116	0.0297	0.0135	0.2078	0.0038	0.0123	0.0247	0.0745

	(10)	*(11)*	*(12)*	*(13)*	*(14)*	*(15)*	*(16)*	*(17)*	*(18)*
a_i	France	Italy	Cyprus	Latvia	Lithuania	Luxemb.	Hungary	Malta	Netherl.
2001	0.1076	0.1105	0.0019	0.0020	0.0034	0.0020	0.0147	0.0006	0.0420
2002	0.1078	0.1114	0.0019	0.0020	0.0035	0.0020	0.0150	0.0005	0.0421
2003	0.1064	0.1116	0.0019	0.0020	0.0036	0.0021	0.0148	0.0005	0.0419
2004	0.1054	0.1119	0.0019	0.0020	0.0036	0.0021	0.0147	0.0005	0.0419
2005	0.1035	0.1113	0.0019	0.0021	0.0038	0.0022	0.0149	0.0005	0.0420
2006	0.1042	0.1128	0.0019	0.0020	0.0039	0.0022	0.0153	0.0005	0.0410
2007	0.1044	0.1125	0.0019	0.0020	0.0041	0.0022	0.0153	0.0005	0.0405
2008	0.1040	0.1114	0.0019	0.0020	0.0041	0.0022	0.0155	0.0006	0.0405
2009	0.1039	0.1109	0.0020	0.0021	0.0039	0.0022	0.0154	0.0006	0.0417
2010	0.1032	0.1103	0.0020	0.0022	0.0039	0.0022	0.0151	0.0006	0.0418

	(19)	*(20)*	*(21)*	*(22)*	*(23)*	*(24)*	*(25)*	*(26)*	*(27)*
a_i	Austria	Poland	Portugal	Romania	Slovenia	Slovakia	Finland	Sweden	UK
2001	0.0158	0.0758	0.0159	0.0265	0.0038	0.0092	0.0137	0.0130	0.1340
2002	0.0161	0.0750	0.0159	0.0267	0.0039	0.0091	0.0139	0.0129	0.1335
2003	0.0163	0.0751	0.0158	0.0264	0.0039	0.0093	0.0137	0.0126	0.1319
2004	0.0165	0.0762	0.0158	0.0264	0.0039	0.0093	0.0138	0.0126	0.1312
2005	0.0169	0.0748	0.0156	0.0262	0.0040	0.0095	0.0134	0.0125	0.1308
2006	0.0169	0.0764	0.0156	0.0267	0.0040	0.0096	0.0138	0.0126	0.1316
2007	0.0170	0.0774	0.0156	0.0265	0.0041	0.0095	0.0138	0.0126	0.1319
2008	0.0170	0.0783	0.0157	0.0269	0.0041	0.0097	0.0137	0.0125	0.1315
2009	0.0172	0.0799	0.0158	0.0271	0.0041	0.0097	0.0133	0.0126	0.1311
2010	0.0172	0.0813	0.0160	0.0276	0.0040	0.0099	0.0136	0.0129	0.1295

(a) The sum of columns (1-27) gives the unity.

As Table 1 reports, emission coefficient effect fell along the period 2000-2010, with some exceptional years: 2001 and 2006. According to Table 5, time series attribution results show again negative contribution of the majority of the Member States, contributing so to reduce emission coefficient index. Specifically, big Western economies and most ex-communist countries participated in this decrement. Further analysis of Tables 4 and 5 brings interesting outcomes. First, Eastern and Central Member States, particularly Poland, Hungary, Romania and Slovakia, significantly increased their contribution to emission coefficient reduction. Second, France, Estonia and Spain are countries whose contribution is rapidly changeable. Third, Germany is the biggest contributor to changes in emission coefficient to the extent that its positive attribution in 2001 led to emission coefficient index increase. Finally, Western developed countries like Sweden, Netherlands and Finland exhibit poor even none improvement in emission coefficient reduction along the studied period.

Table 4. Contribution of each EU Member State to global change in emission coefficient effect from 2001 to 2010, (base year = 2000). [a]

	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*
Years	Belgium	Bulgaria	Czech R.	Denmark	Germany	Estonia	Ireland	Greece	Spain
2001	-0.0002	0.0004	-0.0004	0.0003	0.0071	-0.0002	-0.0003	-0.0001	-0.0030
2002	0.0009	0.0000	-0.0008	0.0003	0.0052	-0.0002	-0.0003	-0.0002	-0.0003
2003	-0.0002	0.0001	-0.0020	0.0010	-0.0039	0.0001	-0.0011	0.0000	-0.0040
2004	0.0006	-0.0004	-0.0022	-0.0002	-0.0072	0.0001	-0.0010	0.0004	-0.0036
2005	0.0009	-0.0010	-0.0020	-0.0013	-0.0092	-0.0096	-0.0007	0.0008	-0.0028
2006	-0.0006	-0.0013	-0.0011	0.0000	-0.0105	-0.0002	-0.0011	-0.0005	0.0001
2007	-0.0009	-0.0005	0.0001	-0.0009	-0.0104	0.0003	0.0006	-0.0010	-0.0018
2008	-0.0025	-0.0004	-0.0020	-0.0015	-0.0086	0.0001	-0.0007	-0.0008	-0.0044
2009	-0.0023	0.0001	-0.0022	-0.0013	-0.0090	-0.0004	-0.0014	-0.0016	-0.0038
2010	-0.0026	0.0004	-0.0026	-0.0014	-0.0175	0.0001	-0.000	-0.001	-0.005

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Years	*(10)* France	*(11)* Italy	*(12)* Cyprus	*(13)* Latvia	*(14)* Lithuania	*(15)* Luxemb.	*(16)* Hungary	*(17)* Malta	*(18)* Netherl.
2001	-0.0024	0.0007	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0006
2002	-0.0039	-0.0001	0.0000	0.0001	-0.0001	0.0001	-0.0009	0.0001	0.0005
2003	-0.0027	-0.0008	0.0000	0.0000	-0.0003	0.0001	-0.0003	0.0001	0.0001
2004	-0.0016	-0.0019	0.0000	-0.0001	-0.0003	0.0002	-0.0006	0.0001	-0.0002
2005	0.0017	-0.0027	-0.0001	-0.0002	-0.0004	0.0002	-0.0010	0.0001	-0.0020
2006	-0.0016	-0.0062	0.0000	0.0000	-0.0006	0.0002	-0.0018	0.0001	-0.0005
2007	-0.0038	-0.0067	0.0001	0.0002	-0.0008	0.0001	-0.0023	0.0001	0.0006
2008	-0.0034	-0.0061	0.0001	0.0000	-0.0008	0.0001	-0.0029	0.0001	0.0012
2009	-0.0010	-0.0088	0.0000	-0.0002	-0.0008	0.0001	-0.0031	0.0001	0.0004
2010	-0.0016	-0.0092	-0.0001	-0.0001	-0.0008	0.0001	-0.0028	0.0000	0.0010

Years	(19) Austria	(20) Poland	(21) Portugal	(22) Romania	(23) Slovenia	(24) Slovakia	(25) Finland	(26) Sweden	(27) UK
2001	0.0002	0.0003	-0.0001	-0.0017	-0.0001	0.0008	0.0012	0.0007	0.0024
2002	-0.0001	-0.0003	0.0008	-0.0013	-0.0001	0.0008	0.0014	0.0010	0.0000
2003	0.0003	-0.0004	-0.0005	-0.0001	-0.0003	0.0002	0.0030	0.0015	0.0005
2004	-0.0002	-0.0025	-0.0002	-0.0008	-0.0003	-0.0001	0.0017	0.0010	0.0009
2005	-0.0009	-0.0007	0.0003	-0.0014	-0.0005	-0.0007	-0.0001	0.0005	-0.0012
2006	-0.0013	-0.0002	-0.0006	-0.0014	-0.0005	-0.0009	0.0015	0.0004	-0.0021
2007	-0.0022	-0.0014	-0.0010	-0.0012	-0.0005	-0.0010	0.0013	0.0000	-0.0039
2008	-0.0021	-0.0039	-0.0013	-0.0024	-0.0003	-0.0010	-0.0002	-0.0001	-0.0049
2009	-0.0028	-0.0051	-0.0012	-0.0052	-0.0005	-0.0016	0.0008	-0.0001	-0.0072
2010	-0.0024	-0.0068	-0.0031	-0.0074	-0.0004	-0.0018	0.0015	0.0002	-0.0049

[a] The sum of columns (1-27) gives the corresponding estimated cumulative per unit change in emission coefficient index (C_{emf}-1).

This analysis indicates the leading influence of Germany in EU emission coefficient trend, but it shows also an increasing attribution of ex-communist countries. Besides, it is striking that some Western Member States like Netherlands, Sweden and Finland do not seem to contribute to emission coefficient reduction.

4. Conclusions

On Earth, human activities are changing the natural greenhouse. The burning of fossil fuels like coal and oil has increased the concentration of atmospheric carbon dioxide. This paper aims at analyzing changes in CO_2 emissions trend in the EU in the last decade, identifying and quantifying its relevant driving forces. Furthermore, we also pursue a detail analysis of emission coefficient factor, determining contribution of each economic sector to its percent changes. For these purposes, we first review the refined LMDI-II method and then we derive and adapt an attribution analysis of IDA.

Results suggests that energy efficiency and carbonization improvements become the largest important drivers in European emission reductions, being particularly significant contributions from big Western economies like Germany, the United Kingdom, Italy and Spain, and some ex-communist countries like Poland and Romania. Therefore, in order to achieve CO_2 emission reductions, to combat global warming and to fulfil international agreements, our findings recommend: R&D, modernization and adaptation to more efficient technologies, research for better quality fuels, support for lower carbon fuels use and installation of abatement technologies (e.g., CCS), particularly when these actions are implemented in the countries mentioned above.

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