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Drivers in CO_2 emissions variation: A decomposition analysis for 33 world countries

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ABSTRACT

A decomposition analysis of energy related CO_2 emissions is carried out for 33 world countries. The data pertain to the period 1995–2007. The methodology used is the Index Decomposition Analysis that allows to investigate the contribution of the following factors: *(i)* changes in abatement technologies, fuel quality and fuel switching; *(ii)* changes in the structure and efficiency of the energy system; *(iii)* relative ranking of a country in terms of the total GDP (Gross Domestic Product) generation and *(iv)* changes of the country specific total economic activity. The WIOD (World Input Output Database) has been used together with Organization for the Economic Co-operation and Development (OECD) data on GDP. Results show that economic growth has been the main driving factor of energy related CO_2 emissions increase. However, in fast developing countries like India and China, an important contribution has also been the increasing role that these economies are playing in the global economic panorama. Improvements on energy efficiency have been the main element contributing to reduce the overall CO_2 emission increase in all the countries considered in this study.

1. Introduction

CO_2 emissions has risen by more than 30 ppm in the last seventeen years and the carbon dioxide concentration, now standing at around 400 ppm, is expected to reach 450 ppm by 2030 [1,2]. The IPCC (Intergovernmental Panel on Climate Change) estimates a concentration between 540 ppm and 970 ppm over the next century, should the emission remain at business-as-usual levels [3,4]. Since the Kyoto agreement in 1997, international measures and policies have been implemented to reduce the human effects on climate change and decouple economic growth from emission levels. Based on the idea of obtaining an economic growth that does not imply necessarily an increase in emissions, decoupling is an ambitious objective both at national and international level [5].

The emissions of CO_2 of anthropogenic origin depend by a large portion on energy production and use. The ever increasing demands of energy by developed and developing economies can be contained by shifting towards renewables or by adopting technological improvements in the energy production cycles that would reduce the CO_2 emission per unit of energy produced. The improvements in energy use and production can already account for a large reduction of CO_2 emissions (31% according to [6]). Trends appear in energy intensity reduction at both country level and sectorial level, with different nuances from sector to sector [7,8].

There are ways to investigate how efficient the economic growth process has been CO_2-wise and how much the technological improvements have contributed to reduce the energy requirements and the emission generation. The OECD (Organization for the Economic Co-operation and Development), European Commission, United Nations and other organizations have collected data than can be used to perform a decomposition analysis with the scope to investigate the contribution of different socio-economic and technological factors.

In this paper, a decomposition analysis is performed to investigate the main elements that generated CO_2 emissions variations in 33 world countries. The group of countries includes developed economies and developing ones so that different possible ranges of economy-dependent CO_2-emissions are considered. The period of the analysis is particularly interesting as it starts in 1995, slightly before the signature of the Kyoto protocol (1997), and ends in 2007, two years from its implementation and right before of the global economic crises.

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Nomenclature

CI	the CO_2 intensity effect that describes changes in abatement technologies, fuel quality and fuel switching;
EI	the energy intensity effect that reflects changes in the structure and efficiency of the energy system;
ES	the structural change effect that identify the relative position of a country in the total Gross Domestic Product (GDP) generation
G	economic activity growth effect that summarize the changes of the total economic activity.
IDA	The Index Decomposition Analysis
IPCC	Intergovernmental Panel on Climate Change
OECD	Organization for the economic co-operation and development
ppm	parts per million
SDA	Structural Decomposition Analysis
WIOD	The World Input Output Database

The main factors responsible for changes in the energy-related CO_2 emission considered here are: *(i)* changes in abatement technologies, fuel quality and fuel switching; *(ii)* changes in the structure and efficiency of the energy systems; *(iii)* the relative position of a country in the global GDP (Gross Domestic Product) generation and *(iv)* changes of the total economic activity. The decomposition among these parameters allows us to estimate how much CO_2 variation can be attributed to technologies improvements, to a more efficient use of energy, and how those two relate to the relative improvement, stagnation or reduction of the individual country economic situation. The focus of this paper is a comparative analysis of the decomposed factors across different world areas in an attempt to assess the status of the actions taken by world countries toward a reduction of CO_2 emissions.

A similar analysis has been recently presented by Ref. [7] that used the same database [9] used in the present paper. The decomposition approach and the factor included in this paper are however different from Ref. [7]. Other works that used decomposition analysis to investigate CO_2 emission variations. Among others [10–16], with a particular focus on USA, China and India. The present work falls into the category of the multiple country analysis and, differently from other works [17–19], it includes both OECD and non-OECD areas.

The paper is structured as follow: in Section 2 the data are presented and analysed. Section 3 introduces the decomposition technique adopted in this study. The results of the analysis are represented in Section 4 while limitations of this work and the conclusions are presented in Sections 5 and 6 respectively.

2. Data and data analysis

The decomposition analysis performed in this paper aims at investigating the main factors responsible for the changes in the energy-related CO_2 emission of 33 countries around the world. The study refers to the period 1995–2007 and considers both developed and developing countries. The data used have been taken from OECD and from the World Input-Output Database (WIOD). In particular, the data on emission-relevant energy use and the quantity of energy-related carbon dioxide emissions have been collected from the World Input-Output Database that includes a set of socio-economic and environmental information for 40 world countries plus the Rest of the World for the time period 1995–2009 (for a description of the database see Ref. [20]). Gross

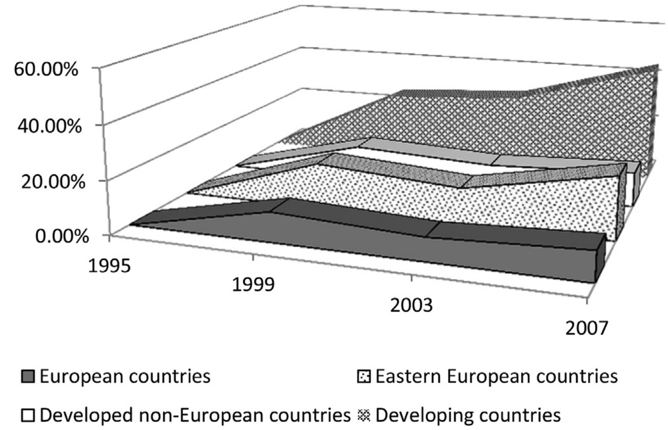


Fig. 1. % variation on GDP. Note: European Countries include: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherland, Portugal, Spain, Sweden, and UK. Eastern European countries include: Czech Republic, Estonia, Hungary, Poland, Slovak Republic, and Slovenia. Developed non-European countries include: Australia, Canada, Japan, South Korea, Russia, and USA. Developing countries include, Developing countries include: China, Indonesia, Mexico, and Turkey. Source: [9, 21]

Domestic Product (GDP) data were taken from Ref. [21] that provides data at constant prices for 31 of the 33 countries considered in this paper for the period 1995–2007. GDP data for Brazil and India are only available for the time period 2000–2008 for Brazil and 2004–2008 for India. For this reason the decomposition analysis performed for these two countries have been keep separate from the decomposition analysis performed for the other 31 countries. These data are analysed hereafter. The key objective is to provide an overview of the main trends and relationships existing between energy use, CO_2 emissions and GDP. In the following section the energy related CO_2 emissions will be decomposed in the factors presented in Section 3.

2.1. Overview of the data used

Figs. 1–3 summarize in percentage the variations of GDP, CO_2 emissions and energy consumption for the countries considered in this paper[1] grouped in European, Eastern European, Developed non-European and Developed countries. The objective is to provide an overview of the main trends existing between 1995 and 2007 and to identify patterns that can be useful to explain the results obtained in the decomposition exercise. According to data reported in the following Figures, developing countries show the largest percentage variations in GDP, CO_2 emissions and energy use (+136.3%, +87.8%, +83.9% respectively between 1995 and 2007). Easter European countries also had a large variation in terms of GDP (64.7% between 1995 and 2007) and in particular after the accession to European Union in 2004 (+117% between 2004 and 2007). The energy consumption increase (+3.2%), however, have been largely smaller than in the case of developing areas and the quantity of CO_2 emissions decreased (−5.3%) across the period even if a slightly increase (+2.1%) took place between 2004 and 2007 as a consequence of the economic boom [22]. In a similar way, European countries and developed non-European areas had a positive variation of GDP (+34% and 42.8%), relatively small energy consumption increase (11.9% and 12.7%) and low variations in CO_2 emissions (+5.4% and 13.4% respectively).

[1] Since data for India and Brazil are not available for the entire time period considered in the paper, these two countries are not included in the analysis performed in this section.

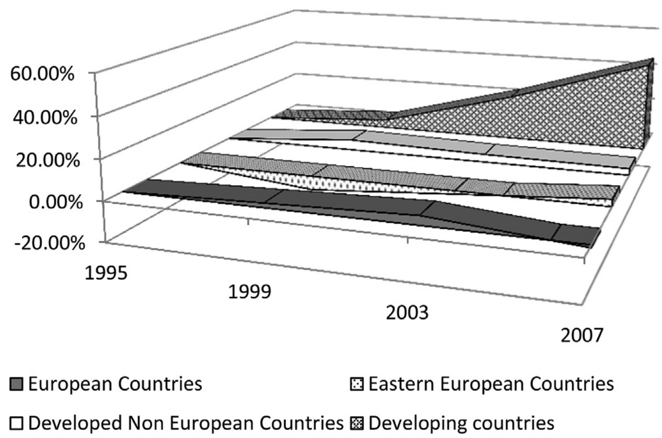


Fig. 2. % variation on CO_2 emissions.
Source: [9, 21]

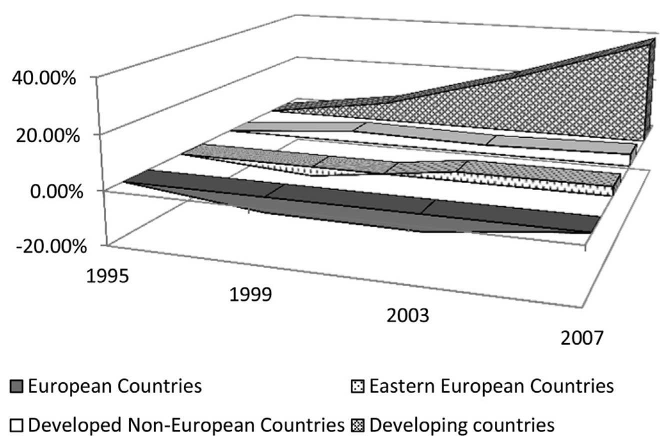


Fig. 3. % variations on energy consumption.
Source: [9, 21]

In general terms, a decreasing trend in the energy and in the carbon dioxide emission intensity took place across the period. According to data reported in Tables 1 and 2 all the areas considered in this paper reduced the quantity of energy used and the quantity of CO_2 emissions generated per unit of GDP. The largest percentage variations took place in the Eastern European countries that after joining the EU (European Union) benefitted from energy reforms, renewable energy projects and transfer of energy and carbon efficient technologies from western European areas [23–25]. In spite of these improvements, however their carbon and the energy efficiency still remain largely lower than in the Western European countries where since the 1990s a large set of energy and carbon policies have been implemented in response to climate change concerns [26]. In terms of Developed non-European areas and Developing countries both areas performed energy and emissions intensity improvements between 1995 and 2007.

In the following section the data reported above are disaggregated and analysed for the 31 world countries considered in the paper.

2.2. GDP and CO_2 variations

According to data reported in Fig. 4a and b, all the countries considered in this paper performed a GDP increase between 1995 and 2007.[2] During the period considered, China had the largest percentage variations (+200.9%), followed by Estonia (+131.2%), Ireland that before the financial crash of 2008 had a GDP increase of around +129.5% and India (37.6% in just the 4 years available for this study). Poland and Slovak Republic largely benefited from joining the EU with an income variation of more than 71.9% and 79.8% respectively [22]. Luxembourg, South Korea, Russia and Turkey also performed a GDP increase higher than 70%. All the others economies, and in particular the most developed ones like United States, Canada, Belgium and France, had an income variation lower than 50%. The bottom figures are related to Germany, Denmark, Italy and Japan (+20.9%, +28.7%, +19.9%, +14.9%, respectively). According to data reported by Ref. [27] the Italian, German and Denmark GDP have been falling since the 1990s. Between 2000 and 2012 Italy has been among the 10 world countries performing worst in terms GDP generation and Germany largely suffered for the costs of unification [28]. A vast shadow economy, limited competition and high marginal taxation rate are considered as the main factors responsible for the poor Italian performance [29]. Expensive social security system and increasing level of public debt have been some of the main elements reducing GDP growth rate in the German case [31]. Deflation, reduction in capital accumulation and low level of total factor productivity growth seems to be the main elements of Japan's stagnation [32–34].

In terms of carbon dioxide almost all the countries considered in this paper increased the emissions between 1995 and 2007. China had the largest variation (+93.9%), even if the percentage increase has been lower than half of the percentage increase in GDP. According to data reported by Ref. [35] improvements in technologies, reduction in coal consumption and increased energy efficiency both in the industrial and in the household sectors have been the most important factors in reducing the quantity of emissions generated per unit of GDP in China. Denmark (28.7% GDP and 43.4% CO_2 emissions) and Indonesia (46.6% GDP and 80.3% CO_2 emissions) are the only countries to show an increase in energy related carbon dioxide emission higher than GDP. In the case of Indonesia a possible explanation can be related to the rapid development of manufacturing activities [36]. According to data provided by Ref. [37] the contribution of the industrial sector to the overall GDP production increased by around 5% and the consumption of coal nearly tripled during the last decade. For Denmark the main reason can be linked to the fact that the sectors that expanded the most are “water transports” and “coke, refined petroleum and nuclear fuel” characterized by a high carbon intensity rate [38]. Belgium (−5.8%), France (−1.2%), Germany (−7.1%), Hungary (−2.7%), Luxembourg (−36.4%), Poland (−9.1%), Slovak Republic (−13.1%) and Sweden (−2%) are the only countries that reduced the quantity of CO_2 between 1995 and 2007. Changes in fuels, efficiency improvements and changes in economic activities can be the main factors responsible for this trend [24,25,39,40].

2.3. Energy and CO_2 emission intensities

A positive aspect that contrasts with the figures of CO_2 emissions increase reported by the majority of the countries presented in Fig. 1 is that in terms of energy and CO_2 emission intensities, almost all the countries considered in this paper reduced both the quantity of energy used per unit of GDP and the quantity of emissions generated per unit of energy used. According to the data reported in Fig. 5a and b, Denmark (+10.3%), Greece (+3.9%), Indonesia (+5.9%), Turkey (+0.3%) and Brazil (+1.2% between 2000 and 2008) are the only countries that increase the energy used per unit of GDP. Denmark (+1%) and Indonesia (+16.2%), together with Canada (+4.4%), China (+0.8%), Japan (+1.6%), Netherland (+15.7%), Russia (+5.9%) and Slovenia (+1.6%) also had an increasing trend in the quantity of emission per unit of energy use. According to these

[2] The time period for Brazil is 2000–2008 and for India is 2004–2008.

Table 1
CO_2 emission intensity (CO_2 emissions/GDP) (Kilotons/Millions US$).

	1995	1999	2003	2007	% 2007–1995
European countries	0.37	0.34	0.32	0.29	−21.39
Eastern European countries	0.85	0.68	0.59	0.49	−42.46
Developed non-European countries	0.55	0.51	0.48	0.44	−20.53
Developing countries	0.74	0.61	0.58	0.59	−20.50

Source: [9,21].

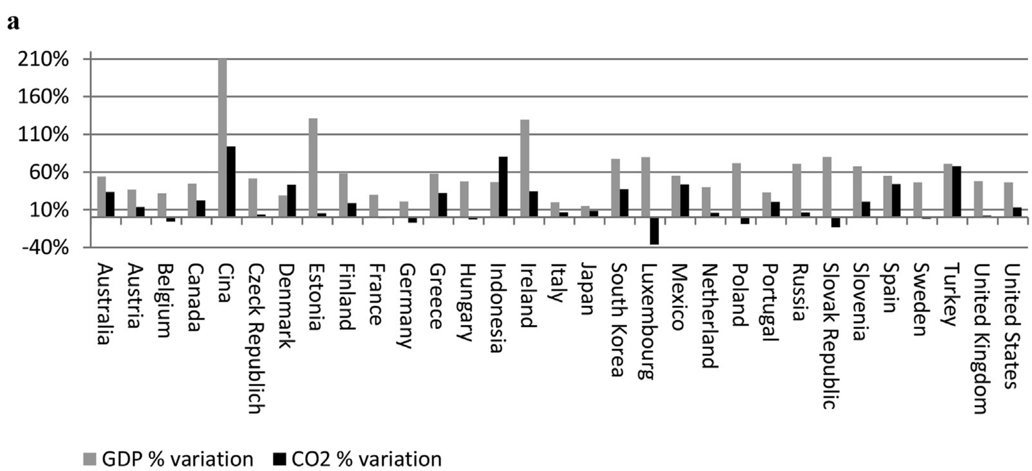
data, for every unit of energy used in 2007 a larger quantity of carbon dioxide emissions are generated compared to the quantity of 1995. As reported in the previous section, possible explanations can be related to changes in technologies, to variations in the energy mix or to variations in the contribution provided by the different economic sectors to the GDP generation [24,25,35–40].

Some European countries, like Italy, Portugal and Spain had very low variations in the energy intensity performance. This result is mainly liked to the fact that the quantity of per capita energy used started to stabilize in the late 2000s and not just after the 1973 oil crisis as in the majority of the other European Countries [26]. China (−37.9%) and Easter European countries as Estonia (−48.7%), Poland (−42.9%), Slovak Republic (−42.6%) had the largest reduction of energy intensity. This means that the quantity of energy used to generate GDP decreased during the considered period of time. Technological improvements, together with implementation

Table 2
Energy intensity (Energy/GDP) (Terajoules/Millions US$).

	1995	1999	2003	2007	% 2007–1995
European countries	7.04	6.69	6.53	5.88	−16.52
Eastern European countries	12.70	10.45	9.52	7.95	−37.34
Developed non-European countries	10.90	10.03	9.33	8.60	−21.06
Developing countries	11.59	9.90	9.36	9.02	−22.18

Source: [9,21].



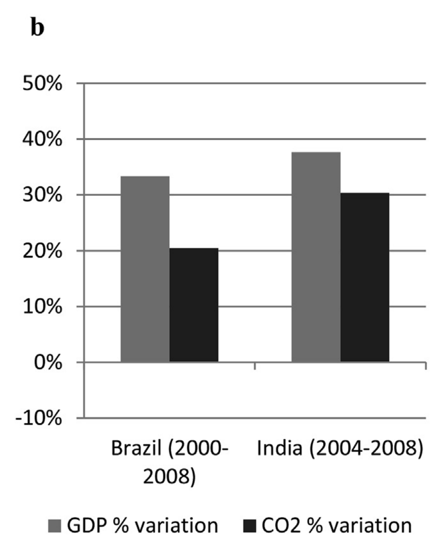


Fig. 4. a) GDP and CO_2 emissions – Percentage variation (1995–2007). b) GDP and CO_2 emissions – Percentage variation (Brazil 2000–2008 and India 2004–2008).
Source: [9, 21]

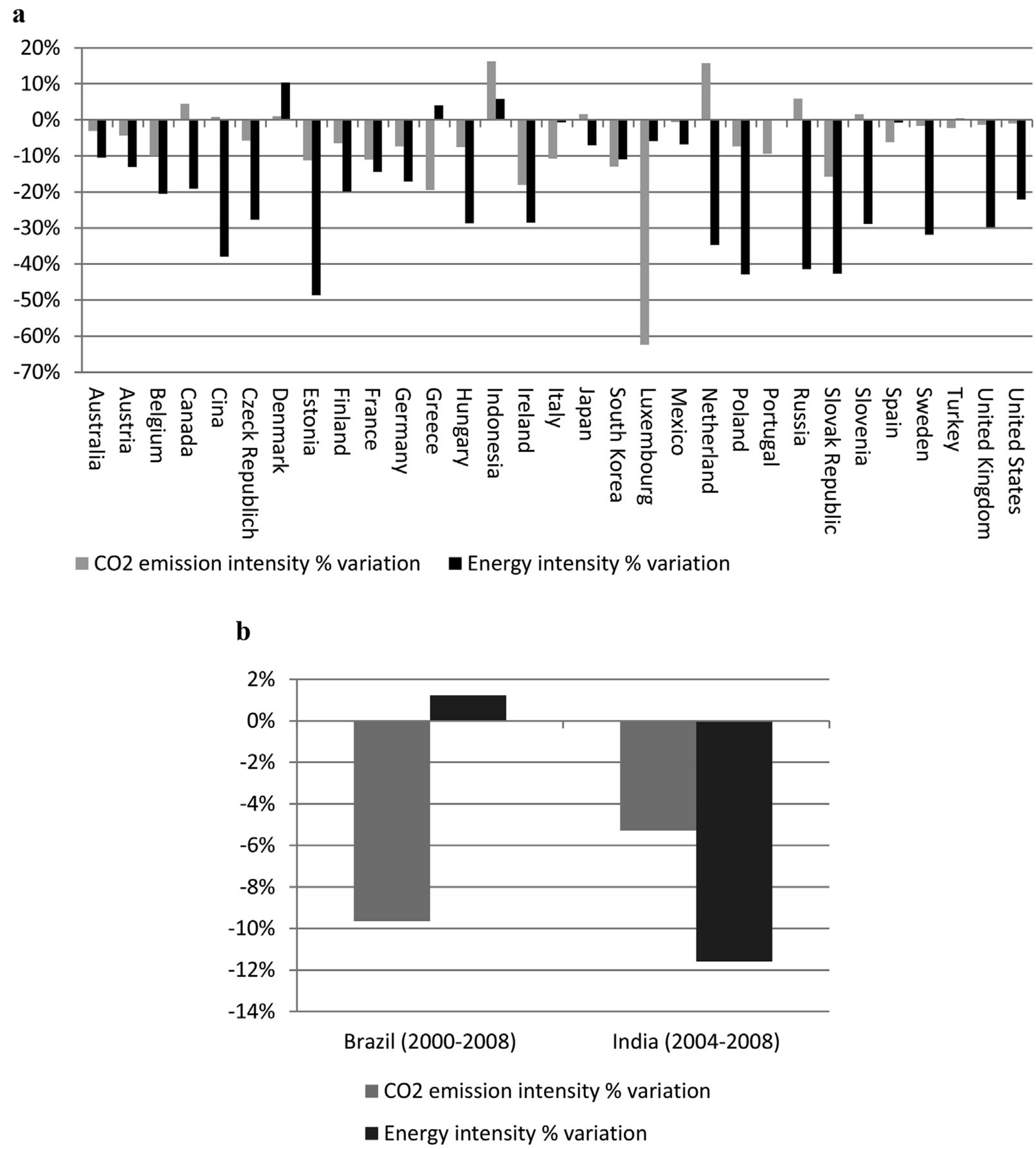


Fig. 5. a) CO_2 emissions intensity and energy intensity- Percentage variation (1995–2007). b) CO_2 emissions intensity and energy intensity- Percentage variation (2000–2008 for Brazil and 2004–2008 for India).
Source: [9, 21] data

of more efficient energy strategies and adoption of EU legislations have probably been the main factors contributing to the energy improvements in the Easter European countries [24]. According to data reported by Ref. [41] the technological changes and the market based instruments promoted by the Chinese government have been key factors in reducing the energy intensity of Chinese economy. In terms of carbon dioxide, Luxembourg is the only country that improved the emission intensity by more than 50% (−62.4%). The increasing importance of low carbon intensity activities as the service and the financial sectors together with improvements on carbon efficiency and substitution between coal and natural gas, have been the main factors contributing to the emission intensity drop [42].

To better investigate these evidences, a decomposition analysis is performed in the following section. The main objective is to identify the driving forces that contributed to the variation in the energy-related carbon dioxide emission in the 33 countries considered in this paper.

3. Decomposition analysis: methodology to identify the role of factors in the energy related CO_2 emissions changes

Different decomposition techniques can be used to investigate the relationships between driving forces and impacts. The IDA (Index Decomposition Analysis) and the SDA (Structural Decomposition Analysis), together with their related extensions, have been the most widely used [43]. The first one (IDA), that define a variable based on the interactions of different components thought the multiplication of factors, is generally applied to perform cross-country comparisons [35,44]. The second one (SDA), that uses an input–output approach to decompose the change of a variable into the changes of its driving forces, is suitable to offer a wide sectoral perspective [45,46]. Both techniques, have been applied to investigate energy-related emission in different countries and sectors as industrial activities, transports or final consumption [47–53]. In this paper the Index Decomposition Technique proposed by Ref. [54] and revised by Ref. [55] is used to analyse the main factors that contributed to change the energy-related CO_2 emissions in different world countries. In particular, equation [1] is used to describe CO_2 emissions as a consequence of variations in energy intensity, emission intensity and economic activity. Based on the idea that CE (carbon dioxide emission) generated by all the countries considered in this paper at time (t) can be evaluated as the product of emission intensity (CI), EI (energy intensity), economic share of a specific country (ES) and economic activity (G) [54] express CO_2 emissions as an extended Kaya identity:

$$CE^t = \sum_i \frac{CE_i^t}{E_i^t} \times \frac{E_i^t}{GDP_i^t} \times \frac{GDP_i^t}{GDP^t} \times GDP^t = \sum_i CI_i^t \times EI_i^t \times ES_i^t \times G^t \tag{1}$$

where for a specific year, E_i^t refers to the total energy consumption of the ith country (TJ), GDP_i^t refers to the value added of the ith country, GDP^t refers to the aggregated value added of all the considered countries and E_i^t refers to total emissions (in tons) of the country i. Since expression [1] runs from a base year 0 to a target year t, we can calculate the variation in carbon dioxide emissions (ΔCE) over the period of time Δt as [2]:

$$\Delta CE = CE^t - CE^0 = CI_{effect} + EI_{effect} + ES_{effect} + G_{effect} \tag{2}$$

where the four explanatory factors are defined as:

(i) $\mathrm{CI_{effect}}$ = CO_2 intensity effect (or pollution coefficient effect). It is defined by the ratio of CO_2 emission and energy use. It reflects changes in abatement technology and fuels quality and fuel switching. It is also named carbonisation index
(ii) $\mathrm{EI_{effect}}$ = Energy intensity effect. It refers to energy consumption per unit of output and is defined by the ratio between energy consumption and GDP (Gross Domestic Product). It reflects changes in the structure and in the efficiency of the energy systems.
(iii) $\mathrm{ES_{effect}}$ = Structural changes effect. It is calculated as the ratio between the Gross Domestic Product of a specific country (GDPi) and the total GDP generated by the countries considered in the decomposition exercise. The ES effect has been previously used [50,55] to quantify the change in relative shares of different economic sectors. Since in this paper we are considering the economic activity of every country as a single aggregate, we modified the traditional formulation of the $\mathrm{ES_{effect}}$ to account for the role that a specific country plays in the overall economic panorama. The aim is to identify the contribution provided by every country to the global GDP generation. Based on this equation, the $\mathrm{ES_{effect}}$ provides useful information to identify if the underlying structure of the global economic system is changing and which countries are mainly responsible for it.
(iv) $\mathrm{G_{effect}}$ = Economic activity growth effect. It reflects changes of the total economic activity and it is used to quantify the carbon dioxide emissions generated by economic growth.

To perform the decomposition analyses the following input data are required:

CE^t	Total CO_2 emission in year t (in tons, t);
$CE^t{}_i$	Total CO_2 emission in year t in the country i;
$E^t{}_i$	Total energy consumption in year t in the country i;
GDP^t	The value added in the year t;
$GDP^t{}_i$	The value added in the year t in the country i;

The calculation of each component reported in equation (2), and used for decomposing the change in CO_2 emissions (ΔCE) are expressed by the following equations where the sum are intended over the individual country values and where the fractional multipliers are used according to [55] to equally distribute the residual among the decomposition factors.

Equation (3) calculates the emissions intensity effect:

$$\begin{aligned}\mathrm{CI_{effect}} = {} & \sum_i \Delta CI_i \times EI_i^0 \times ES_i^0 \times G^0 + \frac{1}{4}\sum_i \Delta CI_i \times \Delta EI_i \times \Delta ES_i \\ & \times \Delta G + \frac{1}{2}\sum_i \Delta CI_i\left(\Delta EI_i \times ES_i^o \times G^0 + EI_i^0 \times \Delta ES_i \times G^o\right. \\ & \left. + EI_i^0 \times ES_i^0 \times \Delta G\right) + \frac{1}{3}\sum_i \Delta CI_i\left(\Delta EI_i \times \Delta ES_i \times G^0\right. \\ & \left. + \Delta EI_i \times ES_i^0 \times \Delta G + EI_i^0 \times \Delta ES_i \times \Delta G\right)\end{aligned} \tag{3}$$

Equation (4) calculates the energy intensity effect:

$$\begin{aligned}\mathrm{EI_{effect}} = {} & \sum_i CI_i^0 \times \Delta EI_i \times ES_i^0 \times G^0 + \frac{1}{4}\sum_i \Delta CI_i \times \Delta EI_i \times \Delta ES_i \\ & \times \Delta G + \frac{1}{2}\sum_i \Delta EI_i\left(\Delta CI_i \times ES_i^o \times G^0 + CI_i^0 \times \Delta ES_i \times G^o\right. \\ & \left. + CI_i^0 \times ES_i^0 \times \Delta G\right) + \frac{1}{3}\sum_i \Delta EI_i\left(\Delta CI_i \times \Delta ES_i \times G^0\right. \\ & \left. + \Delta CI_i \times ES_i^0 \times \Delta G + CI_i^0 \times \Delta ES_i \times \Delta G\right)\end{aligned} \tag{4}$$

Equation (5) calculates the structural change effect:

$$\begin{aligned}\mathrm{ES_{effect}} = {} & \sum_i CI_i^0 \times EI_i^0 \times \Delta ES_i \times G^0 + \frac{1}{4}\sum_i \Delta CI_i \times \Delta EI_i \times \Delta ES_i \\ & \times \Delta G + \frac{1}{2}\sum_i \Delta ES_i\left(\Delta CI_i \times ES_i^o \times G^0 + CI_i^0 \times \Delta EI_i \times G^o\right. \\ & \left. + CI_i^0 \times EI_i^0 \times \Delta G\right) + \frac{1}{3}\sum_i \Delta ES_i\left(\Delta CI_i \times \Delta EI_i \times G^0\right. \\ & \left. + \Delta CI_i \times EI_i^0 \times \Delta G + CI_i^0 \times \Delta EI_i \times \Delta G\right)\end{aligned} \tag{5}$$

Equation (6) calculates the economic activity growth effect:

$$\begin{aligned}\mathrm{G_{effect}} = {} & \sum_i CI_i^0 \times EI_i^0 \times ES_i^0 \times \Delta G + \frac{1}{4}\sum_i \Delta I_i \times \Delta EI_i \times \Delta ES_i \times \Delta G \\ & + \frac{1}{2}\sum_i \Delta G\left(\Delta CI_i \times ES_i^o \times CI_i^0 + CI_i^0 \times \Delta EI_i \times ES_i^0 + CI_i^0\right. \\ & \left. \times EI_i^0 \times \Delta ES_i\right) + \frac{1}{3}\sum_i \Delta G\left(\Delta CI_i \times \Delta EI_i \times ES_i^0 + \Delta CI_i\right. \\ & \left. \times EI_i^0 \times \Delta ES_i + CI_i^0 \times \Delta EI_i \times \Delta ES_i\right)\end{aligned} \tag{6}$$

4. Results of the decomposition analysis

The decomposition results reported below, together with the data included in Tables 1 and 2 of the Appendix, are useful to identify the main reasons for carbon dioxide emission variation that took place in the 33 world countries included in the analysis. Since GDP data at constant price are not available for India and

Brazil for the entire time period considered in this paper, the results reported below includes *i)* a decomposition analysis for China, European Union, Indonesia, Russia and United States for the period 1996–2008; *ii)* a decomposition analysis for Brazil for the period 2000–2008 and *iii)* a decomposition analysis for India for the period 2004–2008.

According to the results reported in Fig. 6 (a, b, c and d) for all the countries considered in this paper economic growth (G effect) has been the most important driver of energy-related CO_2 emission increase However, the analysis provides other interesting results. In particular, the ES effect described as the relative position of a country in the total income generation, results to be an important driver for carbon dioxide emission increase particularly for China and India. The increasing role of these two fast developing economies in the international production system is responsible for almost half of their total CO_2 emission increase. In a similar way, the increasing role on international economy played by South Korea, Russia, Turkey, Ireland and the recently eastern Europe EU Member States, like Estonia, Slovak Republic, Slovenia and Poland also contributed to increase the quantity of carbon dioxide emissions related to the relative position of these countries in the global income generation (ES effect). On the contrary, the decreasing role played in international GDP generation (ES effect) by Japan, Unites States and some of the most developed European Countries, contributed to reduce their overall CO_2 emission increase. In terms of carbon dioxide emission intensity (CI effect) all the countries considered in this paper, exception made for Canada, China, Japan, Netherlands, Denmark, Russia, Slovenia and Indonesia, reduced the quantity of CO_2 generated per unit of energy use. The reduction in the use of natural gas and the increasing demand for electricity, together with the increasing economic importance of sectors characterized by high carbon intensity rate, such as coke, refined petroleum, nuclear fuel activities and water transports are probably the most important factors responsible for this trend [7,38,56]. The reduction in the carbon dioxide intensity has been mainly generated by a set of policies oriented to reduce the carbon contents of economy. Within European Union different Directives have been devote to that. The EU Emission Trading System, the Energy Efficiency Directive, the Strategic Energy Technology Plan or the Renewable Energy Directive are just some examples. In a similar way, the Clean Air Act of United States proposed a set of policies to improve the carbon pollution standards and to promote the adoption of the best available technologies [57]. In Brazil, the large investments in hydroelectric power and the increasing use of biofuel contributed to improve the carbon intensity [58].

Denmark and Indonesia, together with Greece, Turkey and Brazil, are also the only countries for which the energy intensity (EI effect) of the overall economic system increased during the considered period. This means that for every units of GDP production a larger quantity of energy was needed in 2007 compared to quantity used in 1995. A possible explanation can be related to the increased economic importance of high energy intensity sectors like coke, refined petroleum, nuclear fuel activities or water transports. During the last four years (2003–2007) of the time period considered in this paper, however, all these countries, exception made for Denmark, improved the energy efficiency of national economy. According to data provided by Ref. [58], the decreasing energy efficiency of Brazilian economy can be mainly explained by the fact that during the last decade economic growth has been lower than the overall energy consumption. The increasing energy demand driven by rising living standard and by the rapid growth in car ownership of the Brazilian middle class has more than double the total energy consumption. However, the low energy intensity score of Brazilian economy has large margins for improvement. The old and strained electricity network and the consequent waste in electricity transmission is one of the main factors influencing the low performance in the energy intensity reduction. The recent regulations introduced by Brazilian government in terms of standard of minimum energy performance

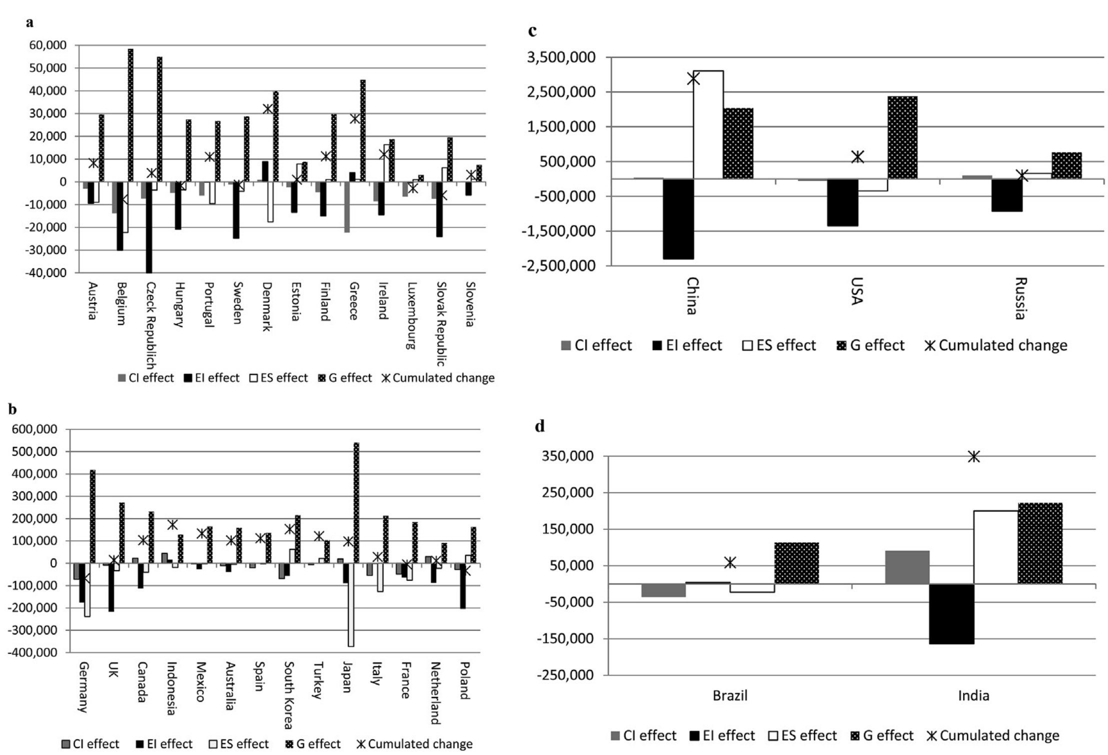


Fig. 6. (a–c) Driving forces of CO_2 emissions (Kilotons CO_2 emissions). d). Driving forces of CO_2 emissions (Kilotons CO_2 emissions) (2000–2008 for Brazil and 2004–2008 for India). Source: our elaboration

and the large investments in the energy infrastructures are expected to improve the energy efficiency over the next decade [59,60].

According to different studies technological changes and variation of the energy mix, particularly within the industrial sector, have been the main responsible factors for the energy intensity improvements in developing countries that usually experience a convergence trend based on their initial efficiency level [17,61]. Transition from the industrial to the less-energy intensive sectors based on service and the rising importance of the information technologies as drivers of economic growth are considered as some of the most important factor for the developed areas [17,62–64].

5. Limitations and future development

The analysis presented in this paper investigates the main factors influencing the carbon dioxide emission variations that took place in 31 world countries between 1995 and 2007. The main results show that GDP growth has been the main element responsible for CO_2 emissions increase in all the countries considered in this paper. That is because the twelve years of analysis have been mainly characterized by a positive economic growth trend with some exceptional economic boom in countries as China, Estonia and Ireland. For these countries the ES effect, that summarizes the relative position of a country to the global GDP generation, has been the largest contributors to the CO_2 emission increase. To further investigate the role played by GDP production, an interesting development of this study could be to perform a decomposition analysis for the period beyond 2007. As soon as data will be available a similar exercise will be done for the years of the financial crisis and the subsequent economic recession. According to data provided by Ref. [6], the total CO_2 emissions from the energy sectors stalled in 2014 for the first time in 40 years. The main reasons seem to be related to the global economic downturn and to the changed patterns of energy consumption in China and OECD. Contrasting the time periods before, during and after the recession will be very revealing of the impacts of economic trends on CO_2 emissions generation. Further to that, the analysis should be disaggregated into different economic sectors or into those groups of sectors for which the implementation of emission reductions policies are likely to produce the most effective results. Other interesting aspects of development could be related to the analysis of consumer related emissions, which considers rather than the energy used for production, the energy related to individual consumption. In this case, other decomposing factors, like income or preferences could be used to investigate the role that consumer responsibility can play in the generation of carbon dioxide emissions. In this respect the trade links between countries and the allocation of CO_2 based on consumer activity would be relevant in identifying the non-local effects that consumer choices can generate in the production of CO_2 emissions in other world areas [48]. Additional analysis can also be related to the application of different CO_2 emissions evaluation approaches, as for example Index or Structural Decomposition analysis and related extensions. In particular, it would be interesting to investigate how different decomposition techniques could generate different results and how the use of different data based on different CO_2 estimations approaches can influence the overall conclusion of the analysis.

6. Conclusion

Although there exists well-known limitations in decomposition analysis [65,66] the present study provides a good framing of the energy-related CO_2 emissions by investigating the main factors of variations for 33 world countries. The period chosen 1995–2007 is important as it falls right within the Kyoto protocol definition and the financial crises thus setting a good reference case for the analysis of the effects of the latter on CO_2 emissions. The data used have been taken from OECD and from the WIOD (World Input–Output Database). The main results provided in this paper show that:

- For all the countries considered economic growth (G effects) contributed to increase the quantity of energy-related CO_2 emissions.
- The increasing contribution to the global economic production provided by India China, Russia, South Korea, Turkey, Ireland and the recently EU added eastern Europe Member States, resulted to be the second most important factor of carbon dioxide emission increase for those countries. For this group of countries, the role played by the structural change effect (ES effect) is almost comparable to the contribution that the GDP generation provided to the overall CO_2 emission increase. On the contrary, for developed economies as Japan, United States and some of the most developed European countries, the decline in the global economic production reduced the overall CO_2 emissions increase.
- With the exceptions of Luxembourg, Finland and Ireland, the other countries that show a positive ES factor are the rapidly growing countries. The contribution to the global economy raises the questions on whether CO_2 production should be effectively allocated to the production country or to the countries from which the demand is generated. This question should be addressed by considering a different decomposition approach oriented to include consumption and income into the decomposition factors [67].
- In terms of carbon dioxide emission intensity (CI effect) all the countries considered in this paper, exception made for Canada, China, Japan, Netherlands, Denmark, Russia, Slovenia and Indonesia reduced the quantity of CO_2 generated per unit of energy use. The instability of energy markets and the increasing number of conflicts in areas traditionally devoted to export energy sources could influence, in the near future, the decision on the energy investments and, as a consequence, the reduction of the CI effect. The Renewable Energy Directive of European Union, the development of hydroelectric power in Brazil or the large investments in renewable energy taking place in United States and China are example of that [68].
- Denmark and Indonesia, together with Greece, Turkey and Brazil are also the only countries for which the energy intensity (EI effect) of the overall economic system increased during the considered period. This means that for every unit of GDP production a larger quantity of energy was needed in 2007 compared to quantity used in 1995. Policies for energy efficiency, adoption of best available technologies and consumers responsibilities have been some of the main factors contributing to reduce the energy intensity of developed and developing countries [69].

In our view the current study sets a good benchmarking case for the assessment of energy related CO_2 emissions. It will be interesting to contrast these results to the post Kyoto period 2005–2020 and especially to the effects of the crises not only on the emission but also on how an externally driven G factor can modify the emission trend and whether technological improvements have taken place in such a low economy regime.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Appendix 1. Decomposition of CO_2 emissions (Kilotones).

Country	Time period	CI effect	EI effect	ES effect	G effect	Cumulated change
Australia	1999–1995	−1188.0	−8757.5	9817.1	45,405.3	45,277.0
	2003–1999	−6698.8	−13,977.4	−130.2	46,625.5	25,819.1
	2007–2003	−3626.5	−17,881.5	−16,827.6	69,461.1	31,125.5
	2007–1995	−11,266.5	−39,936.4	−4763.6	158,188.1	102,221.6
Austria	1999–1995	−2421.9	−4049.8	−1230.1	8637.2	935.4
	2003–1999	4803.6	−311.6	−3928.5	8612.0	9175.6
	2007–2003	−5470.9	−5020.0	−3945.7	12,598.9	−1837.7
	2007–1995	−2971.4	−9414.4	−8968.9	29,628.0	8273.3
Belgium	1999–1995	−12,774.4	−609.7	−4531.9	18,405.6	489.6
	2003–1999	3987.1	−11,090.5	−8390.3	17,152.5	1658.7
	2007–2003	−4976.6	−18,432.4	−9458.3	23,021.3	−9845.9
	2007–1995	−13,756.5	−30,115.0	−22,275.9	58,449.7	−7697.6
Canada	1999–1995	23,674.5	−48,952.8	4266.2	67,939.7	46,927.6
	2003–1999	5845.0	−27,060.2	−8001.9	68,321.4	39,104.3
	2007–2003	−9137.1	−34,246.8	−39,016.5	99,520.5	17,120.0
	2007–1995	22,642.7	−111,706.7	−39,897.0	232,112.8	103,151.8
China	1999–1995	−114,991.4	−900,918.7	606,518.4	433,792.1	24,400.4
	2003–1999	15,968.8	−419,113.2	749,188.3	448,878.9	794,922.7
	2007–2003	196,901.2	−339,599.6	1,348,176.5	863,401.4	2,068,879.6
	2007–1995	37,398.7	−2,293,673.5	3,106,477.6	2,038,000.0	2,888,202.8
Czech Republic	1999–1995	−4866.6	−12,310.1	−10,040.2	15,739.0	−11,477.9
	2003–1999	−7057.2	36.8	144.8	14,243.6	7367.9
	2007–2003	5614.5	−25,683.5	6919.8	21,122.5	7973.2
	2007–1995	−7359.7	−40,047.6	−3641.8	54,912.3	3863.2
Denmark	1999–1995	−2134.5	−3764.4	−2466.6	10,436.2	2070.7
	2003–1999	1763.3	3803.0	−6337.9	10,380.7	9609.0
	2007–2003	1588.4	9707.4	−7808.1	16,944.8	20,432.5
	2007–1995	905.3	8912.5	−17,584.4	39,878.9	32,112.3
Estonia	1999–1995	−1998.1	−4527.9	1581.3	2377.2	−2567.5
	2003–1999	325.9	−3623.3	2700.3	2123.6	1526.5
	2007–2003	−390.0	−3342.3	2516.3	3242.4	2026.4
	2007–1995	−2380.4	−13,387.5	7865.4	8887.9	985.4
Finland	1999–1995	−3158.6	−5641.5	2709.7	8591.6	2501.2
	2003–1999	2627.8	2256.9	−1100.1	8873.0	12,657.6
	2007–2003	−3978.7	−12,124.7	−959.2	13,132.1	−3930.5
	2007–1995	−4502.0	−15,020.0	1006.1	29,744.1	11,228.2
France	1999–1995	−3067.7	−19,481.3	−17,075.8	57,713.4	18,088.6
	2003–1999	−30,469.9	−1894.2	−23,707.9	54,468.2	−1603.8
	2007–2003	−15,583.8	−42,968.1	−35,986.3	73,346.4	−21,191.7
	2007–1995	−48,250.4	−64,077.2	−75,939.1	183,559.9	−4706.9
Germany	1999–1995	−35,196.8	−60,159.5	−71,661.7	129,668.8	−37,349.3
	2003–1999	−31,947.9	5062.7	−79,970.5	118,103.0	11,247.2
	2007–2003	−3632.9	−116,083.7	−81,962.4	160,887.7	−40,791.3
	2007–1995	−71,773.9	−175,418.9	−238,283.9	418,583.4	−66,893.4
Greece	1999–1995	−2758.4	2357.3	−1213.2	12,783.3	11,169.0
	2003–1999	−9364.5	2546.7	4971.1	13,283.0	11,436.4
	2007–2003	−10,829.2	−1241.3	−2645.2	19,850.9	5135.3
	2007–1995	−22,189.8	3978.4	1146.7	44,805.4	27,740.7
Hungary	1999–1995	−4647.2	−3173.9	−2114.8	8371.1	−1564.8
	2003–1999	2250.4	−10,110.0	1888.9	7760.9	1790.3
	2007–2003	−2304.2	−7145.2	−3154.4	10,713.0	−1890.8
	2007–1995	−4813.9	−20,839.9	−3458.3	27,446.7	−1665.3
Indonesia	1999–1995	18,494.0	49,489.2	−37,387.2	34,279.4	64,875.4
	2003–1999	10,019.1	−1339.0	14,294.4	39,783.0	62,757.5
	2007–2003	15,774.3	−51,140.1	15,457.2	64,754.2	44,845.7
	2007–1995	44,457.3	16,930.4	−18,595.7	129,686.5	172,478.5
Ireland	1999–1995	−1989.3	−6176.4	9702.4	5397.0	6933.8
	2003–1999	−2530.8	−5169.3	4835.0	5605.6	2740.5
	2007–2003	−4182.2	−2760.5	1156.3	8192.4	2405.9
	2007–1995	−8552.9	−14,469.2	16,323.5	18,778.8	12,080.1
Italy	1999–1995	−16,000.6	4899.3	−37,239.8	64,336.6	15,995.6
	2003–1999	−6345.7	4822.1	−33,951.5	62,184.7	26,709.5
	2007–2003	−32,390.2	−13,516.0	−55,289.0	87,260.1	−13,935.1
	2007–1995	−54,449.3	−3329.4	−126,202.9	212,751.6	28,770.0
Japan	1999–1995	421.0	21,430.7	−139,501.7	161,968.1	44,318.0
	2003–1999	62,717.2	−71,002.6	−100,554.5	155,564.8	46,724.8
	2007–2003	−44,889.3	−40,667.6	−127,161.5	219,853.0	7134.7
	2007–1995	19,433.6	−89,053.1	−372,645.7	540,442.6	98,177.5
South Korea	1999–1995	−32,152.0	−7672.6	12,617.6	59,083.5	31,876.4

(*continued on next page*)

(continued)

Country	Time period	CI effect	EI effect	ES effect	G effect	Cumulated change
	2003–1999	−23,098.4	−17,339.6	43,266.3	60,674.4	63,502.7
	2007–2003	−8001.0	−32,811.8	3734.0	94,544.7	57,465.9
	2007–1995	−68,678.1	−57,193.8	62,777.1	215,939.9	152,845.1
Luxembourg	1999–1995	−2432.7	−452.7	556.6	998.0	−1330.8
	2003–1999	−2836.0	389.9	197.1	744.3	−1504.7
	2007–2003	−695.1	−319.7	142.3	879.2	6.7
	2007–1995	−6488.1	−414.0	969.9	3103.4	−2828.7
Mexico	1999–1995	351.4	−16,502.0	20,802.8	45,951.9	50,604.1
	2003–1999	686.0	−131.1	−16,211.8	47,872.8	32,215.9
	2007–2003	−3658.3	−8473.5	−10,550.4	73,396.5	50,714.4
	2007–1995	−2220.0	−26,507.4	−2267.0	164,528.9	133,534.4
Netherland	1999–1995	4289.2	−32,277.8	4058.4	27,167.6	3237.3
	2003–1999	3004.5	−4670.2	−13,469.3	25,954.6	10,819.6
	2007–2003	22,635.8	−49,357.5	−13,086.1	36,801.7	−3006.1
	2007–1995	29,968.6	−87,742.6	−22,405.7	91,230.6	11,050.9
Poland	1999–1995	−4830.5	−100,421.8	29,688.4	49,739.6	−25,824.3
	2003–1999	−16,742.8	−40,145.5	−7455.4	42,655.3	−21,688.4
	2007–2003	−4198.8	−51,876.2	11,967.2	58,247.0	14,139.3
	2007–1995	−28,105.6	−204,239.4	35,528.2	163,443.5	−33,373.4
Portugal	1999–1995	−113.3	2147.2	1831.4	8334.2	12,199.5
	2003–1999	−3521.8	−290.8	−4784.5	8533.6	−63.5
	2007–2003	−2943.9	−2177.1	−7673.3	11,700.1	−1094.2
	2007–1995	−6043.8	−99.8	−9595.6	26,780.9	11,041.8
Russia	1999–1995	31,969.8	−97,284.0	−243,414.8	218,045.8	−90,683.1
	2003–1999	35,796.7	−336,004.6	211,730.3	203,386.4	114,908.9
	2007–2003	24,453.0	−440,625.4	192,264.1	298,530.1	74,621.9
	2007–1995	99,241.9	−926,104.6	159,771.4	765,938.9	98,847.7
Slovak Republic	1999–1995	−2376.9	−6787.3	642.2	6063.6	−2458.3
	2003–1999	−4054.7	−1997.8	457.8	5426.8	−168.0
	2007–2003	−870.3	−14,408.5	4779.4	7277.8	−3221.6
	2007–1995	−7484.5	−24,086.0	6212.3	19,510.2	−5847.9
Slovenia	1999–1995	−715.7	−1774.2	478.4	2094.0	82.5
	2003–1999	388.3	−1082.8	138.3	2030.6	1474.4
	2007–2003	668.1	−2691.3	508.7	3080.2	1565.7
	2007–1995	262.1	−5800.4	1180.0	7480.8	3122.6
Spain	1999–1995	−80.0	−418.7	3652.6	38,035.2	41,189.1
	2003–1999	−17,138.3	9172.5	4390.9	40,208.7	36,633.9
	2007–2003	−3253.9	−12,245.1	−12,514.1	61,812.0	33,798.9
	2007–1995	−20,044.1	−2276.8	−2646.1	136,588.8	111,621.9
Sweden	1999–1995	−3530.2	−6143.0	−593.8	8724.8	−1542.2
	2003–1999	5267.2	−9763.2	−1560.3	8105.0	2048.6
	2007–2003	−2787.4	−8312.8	−1897.6	11,222.4	−1775.3
	2007–1995	−1086.8	−24,782.4	−4145.3	28,745.6	−1268.9
Turkey	1999–1995	−4349.6	1737.4	−457.3	26,483.5	23,414.1
	2003–1999	−1793.4	5955.5	−2266.9	27,884.0	29,779.2
	2007–2003	2089.1	−8876.3	27,908.4	46,951.9	68,073.1
	2007–1995	−5532.7	749.2	21,956.0	104,093.8	121,266.4
United Kingdom	1999–1995	−39,702.9	−42,296.8	1184.7	82,212.1	1397.1
	2003–1999	21,438.8	−72,744.1	−1636.3	77,675.3	24,733.8
	2007–2003	10,929.9	−99,174.2	−32,667.4	108,660.3	−12,251.4
	2007–1995	−8465.3	−216,845.6	−33,117.6	272,307.9	13,879.4
United States	1999–1995	27,843.7	−512,675.6	170,976.1	716,881.0	403,025.1
	2003–1999	−13,026.1	−410,035.6	−182,763.2	694,926.1	89,101.1
	2007–2003	−72,329.4	−413,426.5	−348,726.7	981,233.7	146,751.1
	2007–1995	−54,257.7	−1,346,930.9	−342,761.1	2,382,827.1	638,877.4

Appendix 2. Decomposition of CO_2 emissions (Kilotones) – Brazil and India.

Country	Time period	CI effect	EI effect	ES effect	G effect	Cumulated change
Brazil	2008–2000	−36,349.0	3904.4	−22,579.4	113,787.5	58,763.5
India	2008–2004	90,865.0	−163,537.1	199,923.2	221,791.3	349,042.4

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