

# Which factors drive CO<sub>2</sub> emissions in EU-15? Decomposition and innovative accounting

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**Abstract** This study breaks down carbon emissions into six effects within the 15 European Union countries group (EU-15) and analyses their evolution in four distinct periods: 1995–2000 (before European directive 2001/77/EC), 2001–2004 (after European directive 2001/77/EC and before Kyoto), 2005–2007 (after Kyoto implementation), and 2008–2010 (after Kyoto first stage), to determine which of them had more impact in the intensity of emissions. The complete decomposition technique was used to examine the carbon dioxide (CO<sub>2</sub>) emissions and its components: carbon intensity (CI effect); changes in fossil fuels consumption towards total energy consumption (EM effect); changes in energy intensity effect (EG effect); the average renewable capacity productivity (GC effect); the change in capacity of renewable energy per capita (CP effect); and the change in population (P effect). It is shown that in the

post Kyoto period there is an even greater differential in the negative changes in CO<sub>2</sub> emissions, which were caused by the negative contribution of the intensity variations of the effects EM, GC, CP and P that exceeded the positive changes occurred in CI and EG effects. It is also important to stress the fluctuations in CO<sub>2</sub> variations before and after Kyoto, turning positive changes to negative changes, especially in France, Italy and Spain, revealing the presence of heterogeneity. Moreover, the positive effect of renewable capacity per capita and the negative effect of renewable capacity productivity are the main factors influencing the reduction in CO<sub>2</sub> emissions during the Kyoto first stage. It is possible to infer from the results that one of the ways to reduce emissions intensity will be by increasing the renewable capacity and the productivity in energy generation and consequently through the reduction of the share of the consumption of fossil fuels.

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## Introduction

The levels of greenhouse gas (GHG) emissions have significantly changed geographically after the Kyoto Protocol agreement. According to a recent report of the International Energy Agency (IEA) (International Energy Agency 2013), in 1990, OECD countries were

responsible for most of the emissions, while in 2012 it was cut down to 40 % of the emissions related specifically to the global energy consumed. Also, several European economies are suffering nowadays of environmental problems, which are in part due to the GHG emissions, especially CO<sub>2</sub>. The growing environmental conscience and the commitment to develop adjustments, have led to the accomplishment of policies to modify dangerous environmental behaviours in some European countries. Examples of those policies are the Kyoto Protocol (United Nations 1998), the 20–20–20 strategy (Commission of the European Communities 2008) and the use of renewable sources.

While energy, labour and capital resources are used to produce desirable goods and services by economic activities, they simultaneously produce undesirable outputs such as GHG emissions. According to the 2007 International Panel on Climate Change (IPCC) report, the energy consumption of fossil fuels such as coal, oil and natural gas, are the major contributors for the increase of GHG emissions, including CO<sub>2</sub>. An inefficient use of energy leads to higher emission levels, thus, the efficiency in energy use becomes of greater importance, coupled with the rising prices of fossil energy resources.

The adoption of the European directive 2001/77/EC (European Union 2001) and directive 2003/30/EC (European Union 2003), proposed several goals to be achieved by the implementation of renewable energies among member states. However, its marginal and fragmented promotion until 2008 clearly showed that EU countries needed more than just indicative goals. In order to give more strength to this agenda, new measures were set into action such as the 2020 climate and energy package—also known as 20–20–20, and the European Union directive 2009/406/EC (European Union 2009). Taking into account the major importance (economic, social and environmental) of the renewable sector in Europe, this directive set mandatory targets for the adoption of renewable energy by the member states in 2020, and also established a stronger regulatory framework and stable development of renewable energy.

In this study, we use the complete decomposition technique on four distinct periods between 1995 and 2010 in EU-15 countries. The factors behind the changes in industrial energy consumption (among others) have been under investigation by previous research, especially in the particular case of the EU (Greening et al. 1997; Greening et al. 1998; Howarth et al. 1991; Liaskas et al. 2000; Schipper et al. 2001; Torvanger 1991; Unander et

al. 1999). Those studies are useful for understanding the decomposition methods of energy-related CO<sub>2</sub> emissions, and for identifying the driving forces that have impacted the changes in the level of energy-related CO<sub>2</sub> emissions. The most common drivers referenced in literature are the output effect, the fossil fuel energy component effect, the energy intensity effect and the structural effect. For instance, Hatzigeorgiou et al. (2010) use the population effect, while Diakoulaki and Mandaraka (2007) use the utility mix effect. This study however relies on a different group of variables including also the average renewable capacity productivity and accounting for the changes in capacity of renewable energy per capita, and in order to check the results robustness, a higher dimensional Vector Auto Regression (VAR) model was used in the spirit of Zhang and Cheng (2009) and Lee and Chien (2010). As such, the current work besides using the drivers already used by previous authors, add to the decomposition analysis of CO<sub>2</sub> drivers the so called compensation factors.

Throughout time, researchers developed theoretical frameworks able to observe environmental indicators behaviours (index-based decomposition analysis) which apply economic indices to decompose the variation of an aggregate variable (González et al. 2014a). Considering the existent literature the current work contributes in several different ways to it. First, following a Log-Mean Divisia Index (LMDI) approach to extend the decomposition method also used by Bhattacharyya and Matsumura (2010) we considered six drivers, both energy (renewable and non-renewable energy) and non-energy (GDP and population factors related to CO<sub>2</sub> emissions) related, thus, showing that the method can be used simultaneously and generalized to such cases. Bhattacharyya and Matsumura (2010) study focused over the decomposition of carbon emissions intensity considering different sectors of economic activity. This also explains why they have also included the effect of carbon intensity, of energy intensity and the structure effect or else of activity in their decomposition model. Following Alcántara and Padilla (2005), if although in historical terms, carbon emissions of a country may be decomposed into four explanatory factors: carbon intensity, energy intensity, income per capita and population, in our study, by joining these two decomposition models, we have considered the carbon intensity, energy intensity and population, although we have chosen to consider the carbon intensity factor in the crossed product of carbon emissions by fossil fuel with the ratio

fossil fuel by primary final energy. Moreover, in the present work we have also added the determinants: renewables installed capacity per capita as well as the productivity of this production resource. Second, the CO<sub>2</sub> mitigation in EU-15 is analysed in four distinct periods: 1995–2000 (before European directive 2001/77/EC); 2001–2004 (after European directive 2001/77/EC and before Kyoto); 2005–2007 (after Kyoto implementation); and 2008–2010 (after Kyoto first stage) to evaluate the impact of the entry in force of energy-emission policies. Third, the LMDI and the Index Decomposition Analysis (IDA) were used as they identify the driving factors of emissions related to energy and thus, allow explaining the differences in the levels of efficiency among the European countries. Fourth, besides identifying the most relevant contributors for the reduction of emissions, a comparative analysis was conducted to contrast their performance with the objective of providing policy guidance for other countries. Then, it becomes important to know how one specific effect responds to an impulse in another effect *ceteris paribus*, in an exercise of comparative statics. Finally, an Innovative Accounting Approach (IAA) was implemented which includes forecasting error variance decomposition and impulse response functions, considering panel data applied to effects in which emissions are decomposed.

It is necessary to regulate the economy, the energy and the environmental policies on the efficient use of resources, particularly on energy efficiency and the use of renewable sources. Moreover, there is a gap between the actual share and the optimal level of renewable energy consumption in the world. As such, besides the used methodologies, an overview of what has been done is provided in the past to achieve these effects, how they are related to each other and how they have evolved, as well as how they can influence each other in the future. This innovative empirical approach which analyses the economic and environmental impact of EU-15 countries, will be a useful tool to enhance the Kyoto Protocol agreement and for the current policy processes or corporate strategies.

The article is structured as follows: after the introductory first section which describes the research context, objectives and study motivation, the second section presents the relevant literature on both LMDI and IAA applications. The methodology is described in the third section, while section four presents the results and discussion. Finally, section five sums the main conclusions and findings.

## Literature review

The rapid growth of renewable energy has been possible through decreasing technology costs, increasing fossil fuel prices, and the continued payment of subsidies by the governments. For instance, according to the IEA (International Energy Agency 2012a), the subsidies for renewable energy are estimated to increase from \$88 American billions in 2011 to almost \$240 billion in 2035, while the fossil fuel consumption subsidies were estimated at \$523 billion in 2011.

Examples of economic policies include incentives for using renewable energy, and imposing taxes on emission generation or fossil fuel consumption. Although developed countries that import crude oil have imposed carbon taxes for many years, those taxes have not been applied for environmental purposes. There is a consensus that the policies putted into practise by the EU countries to diminish their emissions are focused in the energy sectors, since over 80 % of GHG emissions in the EU are related to activities in these sectors and in these countries.

The carbon intensity of gross world product (GWP), defined as the ratio CO<sub>2</sub>/GWP, provide a measure of the CO<sub>2</sub> emissions required to produce a unit of economic activity on a global scale. From 1970 to 2000, the carbon intensity of GWP declined from 0.35 kg of carbon (kgC)/dollar in 1970 to 0.24 kgC/dollar in 2000. This trend represents a decrease (i.e., an improvement) of 1.3 % per year. Since 2000 however, the carbon intensity of GWP has stopped decreasing and has increased (i.e., worsened) at 0.3 % per year, according to Raupach et al. (2007).

Continuous improvements in the carbon intensity of the world economy are hypothesised in practically all scenarios for future emissions. The effect of these projected improvements is to keep the rate of global emissions growth below the rate of global economic growth. For the Intergovernmental Panel on Climate Change (2000), the recent combination of rapidly increasing emissions and deteriorating carbon intensity of GWP, amplifies the challenge of stabilizing atmospheric CO<sub>2</sub>.

In a recent study, Bhattacharyya and Matsumura (2010) analysed the reduction in GHG in 15 countries of the European Union between 1990 and 2007, evaluating the contribution of different countries. Their results showed that although every country achieved a reduction in emission intensity, is the reduction in larger emitters which counts the most for decreasing energy related emission intensity. France and Italy were found to be lesser contributors to decrease the overall energy-

related emission intensity, but contributing factors were different in each case. Germany and United Kingdom (UK) contributed significantly for the overall GHG decrease from energy use, Germany was responsible for one half of the EU-15 energy related emission intensity reduction, while UK contributed 8 % for that reduction. Regarding France, the emission coefficient and energy intensity, contributed 2 % each. For Italy, the structural effect was the most significant, i.e., the reduction in Italy's share of economic output in the 15 countries, contributed 2 % for the reduction in energy-related emissions between 1990 and 2007. Furthermore, France and Italy contributed another 4 % to the decrease in emission intensity from energy use (Bhattacharyya and Matsumura 2010).

In order to provide a better view on this subject in EU-15, the dispersion relationship between CO<sub>2</sub> emissions and renewable capacity, economic growth (countries GDP) and renewable capacity (countries Cap Ren), and eco-environmental efficiency and renewable capacity is shown in Figures 4, 5 and 6 respectively (see annexes). It is possible to identify a simultaneous improvement of the dispersion relationship between CO<sub>2</sub> emissions and the installed capacity of renewable energy, alongside with the dispersion relationship between installed capacity of renewable and economic growth in Germany, Italy, France, and Spain (among the EU-15). These evidences clearly demonstrate that a change in CO<sub>2</sub> emissions in EU-15 affect the objectives of the Kyoto protocol agreement, underlining the importance of answering some questions. Also, eco-environmental efficiency in terms of renewable capacity clearly improved for these same four countries, supporting the findings of Picazo-Tadeo et al. (2014) and Camarero et al. (2014).

The most common decomposition methods to determine factors that influence CO<sub>2</sub> emissions (to decompose the effects of emissions and energy intensity) can be divided into two: IDA (Hatzigeorgiou et al. 2008; Ma and Stern 2008) and Structural Decomposition Analysis (SDA) using input-output tables (Achão and Schaeffer 2009; Zhang et al. 2011). Hoekstra and Bergh (2003) made a comparison between them. The theoretical and most relevant characteristics of SDA are reviewed by Rose and Casler (1996). Regarding the IDA approach, there are essentially two methodologies: Laspeyres IDA (Ang and Zhang 2000) and Divisia IDA (Sun 2000). Ebohon and Ikeme (2006) used an updated version of the decomposition method defined by Luukkanen and Kaivo-oja (2002), and were able to decompose CO<sub>2</sub>

emission factors into carbon energy intensity, CO<sub>2</sub> emission factors and structural variables. Kawase et al. (2006) divided CO<sub>2</sub> emission factors in Japan into CO<sub>2</sub> sources and sinks, CO<sub>2</sub> emission intensity, energy efficiency (the inverse of energy intensity, meaning GDP/energy), energy intensity (energy/GDP), economic impact factors and other residual items by using an extended Kaya equation.

Existent research has analysed energy transitions using historical energy datasets (Gales et al. 2007; Kander et al. 2013). However, studies examining long-term drivers of CO<sub>2</sub> are still scarce. In Sweden, Lindmark (2002) analysed the causes of CO<sub>2</sub> emissions from 1870 to 1997, finding that technological change contributed significantly to emissions decrease, especially during periods of small economic growth. Tol et al. (2009) examined the drivers of CO<sub>2</sub> emissions in the United States from 1850 to 2002, observing that CO<sub>2</sub> intensity rose until 1917 due to the transition from wood to coal and declined afterwards due to technological changes. In a study conducted in Italy and Spain from 1861 to 2000, Bartoletto and Rubio (2008) analysed causes of differences in CO<sub>2</sub> emissions and found population growth to be a significant determinant.

González et al. (2014a) analysed several measurement possibilities to decompose changes in aggregate CO<sub>2</sub> emissions, showing a strong impact of changes in the fossil fuel energy component factor in the EU. Kawase et al. (2006) decomposed CO<sub>2</sub> emissions with an extended Kaya identity (CO<sub>2</sub> capture and storage, carbon intensity, energy efficiency, energy intensity and economic activity) for Japan. Vaninsky (2014) used the Divisia index to estimate the impact of the major factors driving CO<sub>2</sub> emissions (GDP, energy consumption, population and carbon intensities) for the USA and China through factorial analysis of CO<sub>2</sub> emissions. More recently, Shahiduzzaman et al. (2015) decomposed through LMDI CO<sub>2</sub> emissions in Australia, showing that reductions are mainly due to energy efficiency for 1978–2010. Hatzigeorgiou et al. (2008) analysed CO<sub>2</sub> emissions decomposition in Greece for 1990–2002 showing that the biggest contributor to the rise in CO<sub>2</sub> emissions is the income effect and that the energy intensity effect reduces these. Previously, Ebohon and Ikeme (2006) decomposed CO<sub>2</sub> emissions intensity between oil producing and non-oil producing countries using data of sub-Saharan African countries.

There are various index decomposition methods, nevertheless, the LMDI method (Ang and Choi 1997; Ang

2004; Timilsina and Shrestha 2009) seems to be the one that brings most advantages (Zhang et al. 2009; González et al. 2014a). Sun. (1999) proposed a complete decomposition analysis where the residual term is distributed among the considered effects. This type of analysis has some advantages because it can be simply calculated and easily understood, while ensuring decompositions with identically null residual terms and has therefore been long used in the empirical analysis. Ang and Zhang (1999) refer to this as the refined Laspeyres method. Policy makers in energy and environmental examiners use these techniques widely as an analytical tool. In other related studies on the EU, several other authors have used IDA techniques in economic sectors in their studies (Ang and Pandiyan 1997; Diakoulaki and Mandaraka 2007; Lee and Oh 2006; Lise 2006; Liu et al. 2007; Paul and Bhattacharya 2004; Sun. 1998; Wang et al. 2005; Wu et al. 2005).

Different approaches have been used previously to account for decomposition effects. For instance, Zhang and Cheng (2009) used the VAR Granger Causality and the Generalized Impulse Response to examine the causality among urban population, economic growth, energy consumption and CO<sub>2</sub> emissions. Lee and Chien (2010) applied the IAA (Innovative Accounting Approach, meaning advanced generalized forecast error variance decomposition and generalized impulse response techniques) to examine the relationship between energy consumption, capital stock and real income in G-7 countries. They conclude for a unidirectional relationship running from energy consumption to real income in Canada, Italy and the UK, indicating that energy conservation may hinder economic growth in the three countries. Furthermore, for France and Japan, energy conservation in both countries was noticed which may still be viable, but without being detrimental to economic growth. As to Germany and the USA, the authors found no causality between the variables, which demonstrates the *neutrality hypothesis*, implying that in such a case economic growth will not affect energy use. Additionally, they noticed that the impact of capital stock was relatively higher compared with that of energy consumption..

Menyah and Wolde-Rufael (2012) explored the causal relationship among CO<sub>2</sub> emissions, renewable and nuclear energy consumption and real GDP for the USA as complementary methodology. They also used the generalized forecast error variance decomposition for examining the causality among the variables. Alam et

al. (2011) investigated the causal relationships among energy consumption, CO<sub>2</sub> emissions and income in India, applying the generalized impulse response function to examine the dynamic causality relationships among their variables. Lee and Chiu (2011) applied the IAA to examine the relationship among nuclear energy consumption, real oil price, oil consumption and real income in the most industrialized countries.

From the literature review provided, we are able to state that the per capita renewables contribution is not considered in any of the decomposition models used previously when analysing the decomposition effects of CO<sub>2</sub>. Most of the previous models use only energy and population, meaning the specification of the model IPAT (Impact = Population × Affluence × Technology identity) when the variable population is used like in Brizga et al. (2013). In addition, and given that in the EU-15 we have heterogeneous installed capacity, in the current work it is considered that emissions may be directly related with the installed capacity of renewables and with the population level. For example, given the heterogeneity in the population density and the different economies here included in the set of EU-15, by incorporating the ratio renewables capacity over population we obtain close values for economies whose emission levels are very diverse, and therefore, the fossil fuel consumption may continue to justify the emissions intensity evidenced by these countries. Taking into account Germany whose population density is very high, it should thus be expected that its installed capacity should be even higher. Finally, EU-15, as opposed to the work of González et al. (2014a) which used EU-27, is also considered as some of the countries within this larger group have only been part of the EU from 2004 onwards and the period examined by this research ranges from 1995 until 2010. As a consequence, by using the 15 countries, it is possible to separate the effects of policies pursued and analyse their evolution in the four distinct periods.

## Methodology and data

### 3.1 Data and variables

This study covers annual data for four periods: 1995–2000 (before European directive 2001/77/EC), 2001–2004 (after European directive 2001/77/EC and before



Kyoto), 2005–2007 (after Kyoto implementation), and 2008–2010 (after Kyoto first stage) from EU-15 countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and UK.

The choice of the selected countries and the study period is due, on one hand, to the fact that the International Energy Agency (IEA) report (2012) states that European member states show heterogeneous energy intensity levels<sup>1</sup> and on the other hand, according to the World Bank (2013) the evolution of the population in Europe point for a non-significant evolution across the EU over the past decade.<sup>2</sup> So, if these realities are heterogeneous across Europe, some reflection needs to be done, namely regarding the level of intensity in the mix of fossil energy sources, the capacity of existing renewable energy power plants, the energy consumption and production and the economic or population growth that may mitigate or explain the intensity change in CO<sub>2</sub> emissions.

Variables used were GDP, defined as the Gross Domestic Product (GDP) at market constant prices of the year 2005, in millions of euros, collected from the World Bank (2013) and International Monetary Fund; GHG, being the total greenhouse gas emissions (CO<sub>2</sub>, total carbon dioxide emissions, equivalent) caused by the consumption of energy in thousands of tons sourced from the European Environment Agency; fossil fuel (Fos) consumption measured as the sum of final energy consumption (Ene) computed as the sum of final consumption of solid fuels, gas and petroleum products in thousands of tonnes of oil equivalent (TOE) collected from Eurostat (2012) and OECD (OECD Factbook 2013); renewable capacity (CapRen) which represents the capacity installed of energy produced from renewable energy sources comprising hydroelectric sources (excluding pumping), wind, solar, geothermal and electricity from biomass/wastes, based on Eurostat (Eurostat 2012) and IEA (International Energy Agency 2012b) measured in megawatts; finally, population (Pop)

<sup>1</sup> Such as the highest levels of energy intensity for Netherlands and Slovakia recorded in the second phase of the 2008–2012 Kyoto periods, whereas Luxembourg and Slovenia show the lowest levels of energy intensity and to a lesser extent Latvia, Austria, Germany and Italy.

<sup>2</sup> In Ireland, Luxembourg, and Spain the population density increased by 21, 17, and 14 %, respectively, while in most of other member states the population density increased while Netherlands and Belgium emerge as the countries with the largest levels of population density.

retrieved from World Bank data (The World Databank 2014) measured in thousand habitants.

The variables choice were due to a set of factors whose relevance emerges associated to development and support of renewable resources in such a way as to ensure the Kyoto protocol goals and supranational institutions guidance like EU directives, which shaped identical measures for the countries. The goal to reduce non-renewable sources dependency and the fight against carbon dioxide emissions (CO<sub>2</sub>) is linked to climate change, whose levels and the search for energy self-sufficiency should encourage wider use of cleaner sources and be able to promote the mitigation of carbon emissions.

If the increased supply of energy is met using traditional sources, then it should cause a barrier to renewable sources and a negative signal is expected for reducing on carbon emissions. However, if that consumption leads to the installation of generating capacity from renewable sources, then it will have a positive effect on reducing CO<sub>2</sub> emissions. To control for these effects of energy resources dependency on the cross-economic and population behaviour, it is necessary to mitigate CO<sub>2</sub> emissions. With this aim, regarding economic development, it was included the Gross Domestic Product (GDP) to measure the capacity of European countries to invest in more efficient energy generation technologies. It is expected that more developed countries will have greater available financial resources to invest in more efficient energy sources.

To control for the effect of spatial dispersion of renewable capacity, the variable population is used. This variable assesses the effect of available and suitable land area for renewable solar, biofuels, biomass and wind park installation in countries with greater or lesser population density. The Netherlands, followed by the United Kingdom, reveal the largest population in the panel choose.

Rather than examining the absolute contribution to the energy supply, the importance of renewable energy in the energy supply of a country should be realized. The variable CapRen allows to focus on the effect of replacing traditional sources with renewable sources.

### 3.2. Methodology—decomposition analysis

Two important decomposition analysis, the index decomposition analysis (IDA) and structural decomposition analysis (SDA), have been largely used to analyse and evaluate carbon emissions related with

energy consumption, consumption of fossil natural resources and renewable resources and economic population growth, whose drivers have been frequently mentioned in the literature of energy and environmental economics during the last decades. We should call attention for the important contributions of Ang (1995), Ang and Zhang (2000) and Ang and Xu (2013) studies in the formulation of additive and multiplicative decomposition techniques.

Essentially, IDA is an analytical tool designed for quantifying the driving forces influencing changes in an aggregate indicator. It takes the forms of both multiplicative and additive decompositions, being other methodologies limited to the additive decomposition. Following Brizga et al. (2013) such method may be easily applied to any source of available data at any aggregation level in a given time period. Given the focus on the energy and environmental analysis rather than the economy accounting analysis, we concentrate over IDA in the present study.

The used data sources under IDA are aggregated at the regional/country or economic activity sector levels and this aggregation limits political implications at the regional scale or by sector in particular. Besides, the IDA method deals with direct effects of decomposed factors. The SDA method includes the indirect effects of final demand which are many times neglected by IDA. However, given that the present research goal is to study direct effects of factors which influence the intensity of the change of CO<sub>2</sub> emissions, the most appropriate method is IDA. In SDA analysis, fossil fuel sources are considered in a disaggregated way (coal, gas, oil, renewables, among others), but at the level considered here, data is not available to construct the necessary input-output matrix, making us to follow previous studies which also use aggregated data when countries were the object of analysis. Basically, the IDA method is an analytical tool projected to quantify the main forces which influence changes into an aggregate indicator as carbon emissions.

On the other hand, one of the questions in the decomposition literature is related with the aggregation of the decomposition results at different levels. To deal with this problem, a new method called the log-mean divisia index method (LMDI), a variant of IDA, was proposed, which is consistent in aggregation and perfect in decomposition, following the formulation of Ang and Zhang (2000). However, the LMDI has log terms which cannot deal with

negative values easily. Nevertheless, it is consistent in aggregation, given that it allows estimates of sub-groups to be aggregated in a consistent manner to a higher aggregation level. Thus, this property together with the property of perfect decomposition turns LMDI into an adequate method for researchers to use within energy and environmental analysis.

Index decomposition analysis (IDA) has been widely used in studies dealing with energy consumption since the 1980s and carbon emissions since the 1990s. Ang (2004) compares different IDA methods and concludes that the Logarithm Mean Divisia Index (LMDI) is to be preferred. A comprehensive literature survey reviewing 80 IDA studies dealing with emissions decomposition is given in Ang and Xu (2013), and shows that the LMDI became the standard method after 2007.

We expect the results of the decomposition analysis to show which effects are more crucial to reduce the CO<sub>2</sub> intensity in EU-15 countries. We decomposed the various effects of CO<sub>2</sub> emissions using the Kaya Identity and the LMDI. A similar procedure may be found in Lin and Moubarak (2013). This methodology is widely used and its results are pointed as robust and consistent, because they are free of residuals (Ang et al. 2003). The changes of CO<sub>2</sub> emissions were decomposed for each of the four periods (1995–2000; 2001–2004; 2005–2007; 2008–2010) and into six effects for each EU country *i*, namely: (i) the changes in CO<sub>2</sub> emissions compared to fossil fuels consumption (Fos), i.e., carbon intensity (denoted by CI Effect); (ii) the changes in fossil fuels consumption towards total energy consumption (Ene), i.e., fossil fuel energy component (denoted by EM Effect); (iii) the changes in energy intensity effect (denoted by EG Effect; ratio of final energy consumption to gross domestic product—GDP); (iv) the average renewable capacity productivity (denoted GC Effect); (v) the changes in capacity of renewable (Cap Ren) energy per capita (denoted by CP Effect); and (vi) the changes in population (Pop) on each EU country *i* (denoted P Effect).

The expression for the index decomposition analysis (CO<sub>2</sub>) identity (1) is:

$$\begin{aligned} \text{CO}_{2i} &= \frac{\text{CO}_{2i}}{\text{Fos}_i} \times \frac{\text{Fos}_i}{\text{Ene}_i} \times \frac{\text{Ene}_i}{\text{GDP}_i} \times \frac{\text{GDP}_i}{\text{CapRen}_i} \times \frac{\text{CapRen}_i}{\text{Pop}_i} \times \text{Pop}_i \\ \Leftrightarrow \text{CO}_{2i} &= \text{CI}_i \times \text{EM}_i \times \text{EG}_i \times \text{GC}_i \times \text{CP}_i \times \text{P}_i \end{aligned} \quad (1)$$

Under the additive LDMI model, aggregate CO<sub>2</sub> emissions, in decomposition (2) may be decomposed by the difference:

$$\begin{aligned}\Delta\text{CO}_2 = \text{CO}_{2t} - \text{CO}_{20} = & \Delta\text{CI}_{\text{eff}} + \Delta\text{EM}_{\text{eff}} \\ & + \Delta\text{EG}_{\text{eff}} + \Delta\text{GC}_{\text{eff}} \\ & + \Delta\text{CP}_{\text{eff}} + \Delta\text{P}_{\text{eff}}\end{aligned}\quad (2)$$

where  $\Delta\text{CO}_2$  represents changes in aggregate CO<sub>2</sub> emissions in the economy from one period to another, being the right hand side variables the representatives of the various contributing determinants as previously defined but now being referred to changes.

The LMDI formula for each effect in the additive decomposition identity was calculated as follows:

$$\Delta\text{CI}_{\text{eff}} = \left[ \frac{\text{CO}_{2t} - \text{CO}_{20}}{\ln\left(\frac{\text{CO}_{2t}}{\text{CO}_{20}}\right)} \right] \times \ln\left[\frac{\text{CI}_t}{\text{CI}_0}\right]\quad (3.1)$$

$$\Delta\text{EM}_{\text{eff}} = \left[ \frac{\text{CO}_{2t} - \text{CO}_{20}}{\ln\left(\frac{\text{CO}_{2t}}{\text{CO}_{20}}\right)} \right] \times \ln\left[\frac{\text{EM}_t}{\text{EM}_0}\right]\quad (3.2)$$

$$\Delta\text{EG}_{\text{eff}} = \left[ \frac{\text{CO}_{2t} - \text{CO}_{20}}{\ln\left(\frac{\text{CO}_{2t}}{\text{CO}_{20}}\right)} \right] \times \ln\left[\frac{\text{EG}_t}{\text{EG}_0}\right]\quad (3.3)$$

$$\Delta\text{GC}_{\text{eff}} = \left[ \frac{\text{CO}_{2t} - \text{CO}_{20}}{\ln\left(\frac{\text{CO}_{2t}}{\text{CO}_{20}}\right)} \right] \times \ln\left[\frac{\text{GC}_t}{\text{GC}_0}\right]\quad (3.4)$$

$$\Delta\text{CP}_{\text{eff}} = \left[ \frac{\text{CO}_{2t} - \text{CO}_{20}}{\ln\left(\frac{\text{CO}_{2t}}{\text{CO}_{20}}\right)} \right] \times \ln\left[\frac{\text{CP}_t}{\text{CP}_0}\right]\quad (3.5)$$

$$\Delta\text{P}_{\text{eff}} = \left[ \frac{\text{CO}_{2t} - \text{CO}_{20}}{\ln\left(\frac{\text{CO}_{2t}}{\text{CO}_{20}}\right)} \right] \times \ln\left[\frac{\text{P}_t}{\text{P}_0}\right]\quad (3.6)$$

The analysis of the six effects allows us to evaluate aspects such as: the fossil fuel efficiency; the level of substitution between fossil fuels; the installation of reduction technologies; and the substitution of fossil fuel for

renewable energy sources. The last two effects give us indications about the influence of renewable relative capacity installed to face the population evolution; and the diversification of evolution of population among the same countries and its impact over CO<sub>2</sub> emissions changes.

Previous authors used the formulation (1) but accounting only for the CO<sub>2</sub> drivers (Kawase et al. 2006; González et al. 2014a, b; Shahiduzzaman et al. 2015; among others). The present work includes also the compensation factors GC and CP, in the sense that they mitigate the drivers' effects. If these were not accounted, the drivers' effects would be higher. As such, they are clearing because they attenuate or reduce emissions. Looking at the formulation in 3.1 we have the carbon intensity, in 3.2 the inverse of energy conversion efficiency, in 3.3 the energy intensity ratio (ratio of final energy consumption to GDP), in 3.4 the inverse of the installed capacity of renewables productivity, in 3.5 the capacity of renewable energy per capita and in 3.6 the impact of population change.

After applying the decomposition analysis, we can examine the outputs. The results robustness was assessed using the higher dimensional VAR model. To achieve that purpose, we implemented the IAA that includes forecast error variance decomposition and Impulse Response Functions (IRFs). The variance decomposition approach indicates the magnitude of the predicted error variance for a panel series accounted by innovations from each of the independent variables over different time horizons. Additionally, the generalized forecast error variance decomposition approach estimates the simultaneous shocks stemming in other variables.

In this study, the generalized forecast variance decomposition approach estimates the simultaneous shock effects using a VAR system to test the strength of causal relationship among the six effects decomposed of EU-15 countries with the decomposition analysis, such as, CI effect, EM effect, EG effect, GC effect, CP effect and P effect, respectively.

For example, if the fossil fuel energy component effect explains more of the forecast error variance of the average renewable capacity productivity, then we deduce that there is unidirectional causality from EM to GC in EU countries i. When shocks in GC also affect EM in a significant way, there is bidirectional causality. If shocks occurring in both series do not have any impact on the changes in renewable capacity, productivity and in fossil fuel energy component effect, then, there is no causality



between these explanatory effect variables. This technique can also provide a rough analysis of how long it takes for the variable to go back to the equilibrium after the long run relationship has been shocked. According to Maghyereh (2004) and Park and Ratti (2008), the impulse response functions (IRFs) show the dynamic responses of time series to a one-period standard deviation shock, and indicate the direction of the response to each of the shocks. Thus, a random shock in one standard deviation establishes a chain reaction over time in all variables in the VAR. The impulse response functions calculate these chain reactions.

For instance, we support the hypothesis that fossil fuel energy component effect causes renewable capacity productivity and the impulse response function indicates significant response of EM to shocks in GC according to shocks in other ratios. With the impulse response functions, we also provided a rough analysis of how long it takes for that specific effect variable to go back to the equilibrium after the long run relationship has been shocked.

## Results and discussion

### Decomposition analysis results

According to Fig. 1, regarding the first period 1995–2000 (before Directive 2001), in EU-15, there is an increase in CO<sub>2</sub> emissions (123,948 t). The positive impact of the renewable capacity per capita, renewable capacity productivity and fossil fuel energy component, outperformed the negative impact of carbon intensity and energy intensity. As pointed out by Camarero et al. (2014) emissions over GDP have significantly decreased between 1990 and 2009, while Picazo-Tadeo et al. (2014) state that the countries that display the highest growth rates in environmental performance are Luxembourg, Sweden, UK and Germany, but there is still room for European environmental policy makers to encourage catching up among European members (Picazo-Tadeo et al. 2014).

In the second period (2001–2004), after directive 2001/77/EC and before the first phase of the Kyoto protocol, there is a positive and progressive increase in CO<sub>2</sub> emissions (139,622 t). The positive and highest variation in CP effect outperformed the majority and the negative effect of GC and of the CI effect, the population effect has a stable increasing influence whereas the CI

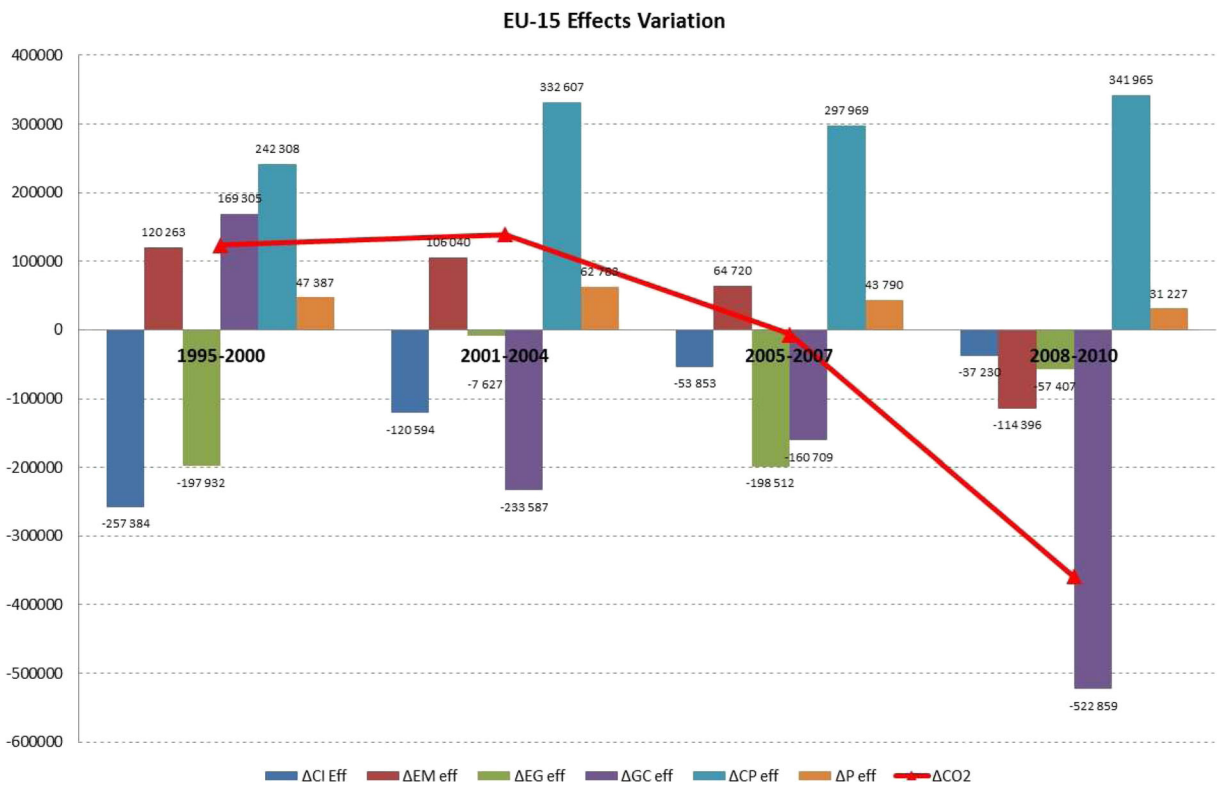
effect shows a significant contribute to reduce emissions. In the transition period between 2001 and 2004 and 1995–2000, there is a positive increase in CO<sub>2</sub> emissions (12.65 %). However, it was also possible to observe that these effects are not equal among the 15 countries.

Note: The six effects for each EU country *i* are, namely: (i) the changes in CO<sub>2</sub> emissions compared to fossil fuels consumption, i.e., carbon intensity (denoted by CI Effect); (ii) the changes in fossil fuels consumption towards total energy consumption, i.e., fossil fuel energy component (denoted by EM Effect); (iii) the changes in energy intensity effect (denoted by EG Effect); (iv) the average renewable capacity productivity (denoted GC Effect); (v) the changes in capacity of renewable energy per capita (denoted by CP Effect); and (vi) the changes in population on each EU country *i* (denoted P Effect).

Differences in efficiency reduction among European countries might be due to different capabilities to jointly manage production processes and the environment, as well as to other circumstances such as different levels of development, differences in citizens' environmental awareness and different production structures (Picazo-Tadeo et al. 2014).

It is quite clear the positive impact of both CP and P in every period. Also, with the sudden decrease of both EG and GC effects after period one, we observe a decreasing pattern of CO<sub>2</sub>. A negative impact of EM is only observed after the Kyoto first stage within the EU-15.

In the first phase (2005–2007 period) after the Kyoto commitment, a negative although smaller change in CO<sub>2</sub> emissions (–6597 t) is observable, whereas the negative and significantly negative impact of the EG effect and GC effect, respectively, outperformed the highest and positive impact of CP effect. This contradicts González et al. (2014a) which shows that energy efficiency improvements do not involve important reductions in CO<sub>2</sub> emissions. This may be due to different measurement units used by the authors and the fact they considered the EU-28 and only the power sector (not all the industry). In the second phase of the Kyoto protocol, 2008–2010, there is a strong decrease in CO<sub>2</sub> emissions (–358,697 t) where the contribution of the negative and highest variation in GC effect outperformed the highest variation and positive effect of CP. However, the population effect has a stable decreasing influence and the EM effect shows a significant contribution to decrease emissions, whose change effect has been opposite to that of the first phase period after the Kyoto commitment. In the



**Fig. 1** Changes of CO<sub>2</sub> emissions decomposed into six effects for EU-15 for each of the four periods (1995–2000; 2001–2004; 2005–2007; 2008–2010)

transition period between first phase of Kyoto commitment and the period after directive but before Kyoto commitment, there is a strong reduction in CO<sub>2</sub> emissions (−104.72 %); while in the transition period between the second phase of the Kyoto commitment and the first phase of that protocol, there is in EU-15 countries a strong reduction in CO<sub>2</sub> emissions (−358.697 %), mainly due to the average renewable capacity productivity.

Camarero et al. (2014) stress that under the Kyoto Protocol, the EU-15 agreed to reduce its collective emissions of GHG by 2012 to 8 % below the levels recorded in 1990. Nonetheless, this goal is on course to be overachieved, as in 2009 emissions have already been estimated to have decreased by 12.7 %. They also argue that Spain, Portugal and Greece have actually raised their emissions, although the combined reduction of GHG emissions in 2009 for the EU-27 has already reached 17.4 %. Large differences observed among EU countries in efficiency terms are stated by Camarero et al. (2014) and in Picazo-Tadeo et al. (2014). The former attribute them to different levels of development, differences in the structure of economic activity related

mainly with development levels, and to environmental awareness.

It would be interesting to infer now how has each member contributed to the reduction of EU-15 emission intensity? To analyse each effect, we decomposed them with LMDI decomposition, following the method outlined in Section 3. For each country in EU-15, we show the results in Table 1.

From Table 1 we observe a positive variation of CI in Germany after the Kyoto protocol, a significant decrease in the capacity of renewable energy per capita until 2010, but an increase of this last CP effect in Spain and the UK. In some countries there was a positive change in the fossil fuel energy component and over the average renewable capacity productivity (Austria, Luxembourg, Netherlands) while in others, a negative change is observable (Portugal, Spain, France). The sharp decrease in emission levels in Germany, France and UK was motivated by fuel mix effects and intensity, similar to González et al. (2014b) but also to the average renewable capacity productivity here considered. Although not immediately, capacity of renewable energy per capita and population changes are positive in all

**Table 1** Contribution of each EU-15 member to the reduction of emission intensity: CO<sub>2</sub> emissions decomposed into six effects for each of the four periods (1995–2000; 2001–2004; 2005–2007; 2008–2010)

	GER	AUS	BEL	DEN	SPA	FIN	FRA	GRE	IRE	ITA	LUX	NED	POR	UK	SWE
$\Delta CI$ eff															
95–00	-81385	-3903	-18996	9473	-23795	-3359	-23172	-6675	-3689	-20524	5705	-3604	-16123	-73673	-1614
01–04	-23286	-11690	8274	-16818	4610	-4553	-26409	-1222	-1346	-14005	-24401	-5453	4239	-22453	-9925
05–07	-26931	4598	-1200	-4759	-20999	654	-7634	-315	2030	-35152	-476	18725	-2546	3491	7654
08–10	25090	-4553	-13992	-2086	-29566	-5567	-2161	10762	-1048	18546	-936	-18171	-7244	-18817	10886
$\Delta EM$ eff															
95–00	33690	1176	4112	-15033	30843	-2617	9904	4473	2511	10434	-7546	1893	17743	38698	-1707
01–04	14350	14015	808	18069	-6375	10873	8588	-1960	-5	11525	24902	2246	-5061	29396	9611
05–07	20624	-7184	-699	7730	24892	-1410	4882	-3355	1059	29871	186	-8166	3847	4385	-6582
08–10	-45820	1006	-1482	-2241	7182	496	-12585	-11246	-1757	-40397	538	16999	3020	-9106	-10603
$\Delta EG$ eff															
95–00	-73424	-962	-390	-9876	3886	-9922	-8189	-2266	-8807	12765	-3434	-29435	2407	-67673	-9609
01–04	6383	7385	-4119	2926	-1052	4999	4626	-7387	-5583	17465	771	8654	414	-44843	-469
05–07	-40632	-1846	-9304	-1264	-22147	-4501	-21135	-6064	-6649	-9598	-1109	-22264	-4425	-38341	-7388
08–10	-151	-1888	4689	519	-34297	-1570	-1283	-9519	2250	-7310	-519	-3272	-881	-10753	-2069
$\Delta GC$ eff															
95–00	-210842	6189	16731	-70517	19158	9890	47719	-4180	13162	16360	2351	-143024	8589	60466	9908
01–04	-371923	910	-1659	-15479	-25765	1871	11361	10487	940	-7922	817	-147253	-2865	3839	4457
05–07	-120656	1733	-3377	3379	-19801	3615	555	-1584	-12964	-12175	1387	-74142	-14333	-71708	4736
08–10	-134731	-5449	-28071	-9689	-60426	-5923	-47905	-1363	-18518	-76192	-366	-59024	-10927	-176675	-6037
$\Delta CP$ eff															
95–00	284489	2029	-205	78220	28317	3057	-6304	16366	3423	21581	-584	177877	2959	24732	89
01–04	377525	292	4227	15865	43650	1722	-4883	4289	4465	13265	-314	148288	2617	32397	-1352
05–07	158942	1974	8186	-248	36426	985	11766	9574	16216	19058	-434	86043	15312	93806	-748
08–10	105813	3564	23245	5445	40907	471	31564	-859	11778	38777	-383	52018	9181	140950	1496
$\Delta P$ eff															
95–00	7069	476	1500	1457	5179	885	8608	3024	1961	625	716	6006	1423	8382	320
01–04	3018	1107	1923	561	17611	500	9221	1124	2387	7899	390	3833	933	7891	641
05–07	-2041	788	2016	404	13354	546	6049	774	2720	5754	434	769	252	8801	707
08–10	-4300	495	2295	598	6654	607	4175	14	994	5582	470	2375	121	8458	1001

Note: The six effects for each EU country *i* are, namely: (i) the changes in CO<sub>2</sub> emissions compared to fossil fuels consumption, i.e., carbon intensity (denoted by CI Effect); (ii) the changes in fossil fuels consumption towards total energy consumption, i.e., fossil fuel energy component (denoted by EM Effect); (iii) the changes in energy intensity effect (denoted by EG Effect); (iv) the average renewable capacity productivity (denoted GC Effect); (v) the changes in capacity of renewable energy per capita (denoted by CP Effect); and (vi) the changes in population on each EU country *i* (denoted P Effect). GER stands for Germany, AUS for Austria, BEL for Belgium, DEN for Denmark, SPA for Spain, FIN for Finland, FRA for France, GRE for Greece, IRE for Ireland, ITA for Italy, LUX for Luxembourg, NED for Netherlands, POR for Portugal, UK for United Kingdom and SWE for Sweden

countries and periods except in Belgium, Denmark, France, Luxembourg and Sweden in the former and in Germany for the latter.

As Camarero et al. (2014) notice, literature on growth and convergence (Barro and Sala-i-Martin 1992) has recently been applied to explain emissions evolution. This theory stresses that countries with higher initial levels of emissions tend to reduce more emissions than those with initial lower levels. This literature uses the explanation to justify the substantial drop in the emissions of Eastern European countries, despite their lower GDP per capita. Nevertheless, it is unable to explain the case of Spain, Greece and Ireland, whose current emission growth is above the 1990 levels. In order to justify this heterogeneous behaviour, some authors point for different economic growth rates, but still, some cases are not explained by the growth-convergence relationship. Other factors emerge such as technological change and fossil fuel energy component variations (Camarero et al. 2014). Thus, within this relative homogeneous EU-15 group, subject to the same policies and laws, different levels of development and income differences may be justifications for this observed heterogeneity. Moreover, the underperformance of Spain and Italy has already been pointed out by Camarero et al. (2014) and Picazo-Tadeo et al. (2014). Following González et al. (2014b) population growth induces CO<sub>2</sub> emission increases.

In the following, the six decomposition effects by country and sub analysis period will be analysed deeply, whose results are presented in Fig. 2.

In the second period 2001–2004 (after directive EU 2001/77/EC and before the first phase of Kyoto commitment), for EU-15 group countries there is a negative variation in carbon intensity (–53 %). However, there is a highest negative variation in this carbon intensity effect in Luxembourg, Denmark and France, while in Belgium, Spain and Portugal, there is a positive and significantly variation in carbon intensity to impact the changes in CO<sub>2</sub> emissions in this period.

In the period between the first phase of Kyoto protocol and before the Kyoto commitment, the carbon intensity effect reveals a negative influence (–55 %) to explain the changes in CO<sub>2</sub> emissions

in EU-15 countries. In that transition period, carbon intensity effect exhibits positive changes in the countries, where recent reduction levels are lower like in Austria, Netherlands, UK and Sweden.

In the period between the second phase of the Kyoto commitment and the first phase of the Kyoto protocol, the carbon intensity effect has a reduction variation (–31 %) to explain the changes in variation in CO<sub>2</sub> emissions in EU-15. However, the carbon intensity has a negative and the highest impact to changes in CO<sub>2</sub> emissions are in Belgium, Spain, Netherlands and UK, while Germany and Italy reveal to be the two countries with the highest positive and significantly carbon intensity effects to explain the changes of CO<sub>2</sub> emissions in EU-15.

The fossil fuel energy component effect has only been negative in the first phase of the Kyoto protocol for EU-15. The fossil fuel energy component effect suffered a considerable reduction, thus impacting negatively CO<sub>2</sub> emissions in the period 2005–2008 (after Kyoto implementation). Considering the total, for EU-15 group countries there is a negative variation in the fossil fuel energy component. However, there is a highest negative variation in this carbon intensity effect in Germany and Italy from 1995 until 2010, while in Austria, Spain and Portugal there is a positive and significantly variation in carbon intensity to impact the changes in CO<sub>2</sub> emissions. As such, the highest negative variation occurs in Germany, Portugal, Spain and UK between the first and second periods (before European directive 2001/77/EC and after that directive but before Kyoto) and from the third to the fourth period (after Kyoto implementation and after Kyoto first stage).

In the period between the first phase of the Kyoto protocol and after the directive, but before the Kyoto commitment period, the fossil fuel energy component effect reveal an increased and negative impact (–39 %) to explain the changes in CO<sub>2</sub> emissions in EU-15 group countries. In that transition period, the fossil fuel energy component effect exhibits positive changes for most of the countries and periods, although with huge differences in terms of intensity increases, thus



**Fig. 2** Changes in CO<sub>2</sub> emissions compared to fossil fuels consumption, i.e., carbon intensity (denoted by CI Effect), fossil fuel energy component effect (EM), energy intensity effect (EG),

renewable capacity productivity effect (GC), renewable capacity per capita (CP) and population effect (P), by country and period (1995–2000; 2001–2004; 2005–2007; 2008–2010)

enhancing the existence of heterogeneity within the group.

In the period between the second phase of the Kyoto commitment and the first phase of that protocol, the carbon intensity effect has a highest

and significantly reduction variation (−277 %) to explain changes in variation in CO<sub>2</sub> emissions in EU-15 countries. However, the fossil fuel energy component has a negative and highest impact to changes in CO<sub>2</sub> emissions in France, Germany and



Netherlands, while Greece and Luxembourg show a positive contribution of this effect to the CO<sub>2</sub> emissions reduction in EU-15. It should be noticed that Hatzigeorgiou et al. (2010) found that the fuel share effect has a small negative impact on CO<sub>2</sub> emissions for the EU-25 (−9 %), during the 1990–2020 period.

From Fig. 2 it is clear that the improvement in energy intensity is the most significant fact up to the moment that leads to a reduction in CO<sub>2</sub> emissions considering the second period 2001–2004 (after directive EU 2001/77/EC and before the first phase of Kyoto commitment) especially in Germany and the UK. However, there is a high negative variation in this energy intensity effect in Sweden, Finland, Netherlands and Luxembourg, also in the first period, while in Austria, Finland, France, The Netherlands and Italy there is a positive and significantly variation in energy intensity to impact the changes in CO<sub>2</sub> emissions after the European directive 2001/77/EC but before Kyoto. The negative energy intensity effect is highly observed in Germany, Spain, Greece, Italy and the UK after the Kyoto first stage (4th period; 2008–2010). This finding puts forward the greater differential in the negative changes which occurred in CO<sub>2</sub> emissions.

In others studies, like Hatzigeorgiou et al. (2010) it is claimed that the energy intensity effect makes a moderate contribution in Portugal (−16 %) whereas for the EU-25 the energy intensity effect is expected to amount to −40 %, and for Greece to −17 %. A significant effect of energy intensity on CO<sub>2</sub> emissions is observed for Ireland (−47 %), which reflects fuel switching towards a less carbon intensive macro-economic production and consumption. On one hand, Bhattacharyya and Matsumura (2010) found that Germany and the UK have contributed significantly to the overall reduction of GHG emissions from energy use. Germany has accounted for about one half of the reduction in the EU-15 energy-related emissions intensity, while the UK has contributed another 8 % reduction. France and Italy were responsible for 4 % of the reduction in emissions intensity from energy use. On the other hand, the United Kingdom achieved one of the lowest energy intensities in the EU-15 in 2007. If all 15 countries had achieved the same level of energy intensity, the energy-related GHG emission could have been reduced by 23 %

from the 2007 level. Germany, France, Italy and Spain would be the major contributors to the emissions reduction, accounting for more than 70 % of emissions savings. Similar to the findings of González et al. (2014a) it seems that in general, EU-15 countries when faced with international pressure to reduce CO<sub>2</sub> emissions, the reduction in energy intensity and fuel mix improvements revealed to be important means of bringing a decrease in CO<sub>2</sub> emissions.

We are able to observe large differences among countries (Germany, The Netherlands and UK) whatever the period considered in terms of renewable capacity. However, changes in the average renewable capacity productivity are especially high and negative for these countries in the second and last periods considered.

Overall, we may state that average renewable capacity productivity is one of the major effects able to explain CO<sub>2</sub> emissions in these countries. However, in almost all countries, except in those referenced, there is a positive contribution of GC effects in the period before European directive 2001/77/EC, which tend to be negative in the periods afterwards. Therefore, we may argue that development levels influence the impact of the decomposing effects over CO<sub>2</sub> emissions reduction, turning the process of European adjustment slower.

From Fig. 2 it is clear that the improvement in the capacity of renewable energy per capita is one of the most significant facts that leads to a reduction in CO<sub>2</sub> emissions concerning the second period 2001–2004 (after directive EU 2001/77/EC and before first phase of Kyoto commitment). However, this contribution is by itself heterogeneous (Germany, Netherlands and UK, compared to the rest of the countries).

Although always decreasing in Netherlands, it has been increasing in the UK, and has been positive in all EU-15 countries in every period. Even though, this positive contribution has not been enough to account for the negative changes verified in other effects, thus not turning so evident the CO<sub>2</sub> complete reduction. Interestingly, but with counterbalancing forces, the decomposition analysis suggests that renewable capacity per capita and population effects could well have produced an increase in total emissions, regardless of the period considered.

In comparison to the CP effect, the P effect is positive in all EU-15 countries except in Germany for the third

and fourth periods. Our results are in accordance with those of Hatzigeorgiou et al. (2010), which observed that the population effect is projected to have a stable and positive influence on the increase in CO<sub>2</sub> emissions in Greece (10 % from 1990 to 2020), while for Ireland, Portugal and Belgium the population, effect range from 10 to 20 %. In accordance with our results, in Belgium, Finland, UK and Sweden, the P effect has been very similar among periods with discrete ups and downs. The effect is highest in Spain after the implementation of the EC directive 2001/77/EC (the 2nd period; 2001–2004). Other causes may justify this population increased effect, but get out from our main goal.

For all that details presented, it may be reasoned that after the Kyoto commitment period there is a continuous decrease in changes of CO<sub>2</sub> emissions in EU-15, whereas the positive effect of renewable capacity per capita and the negative contribution of the renewable capacity productivity effect are the main factors influencing the negative, and highest, reduction in CO<sub>2</sub> emissions in EU-15. In fact, this evidence is attributed to a relative large increase in the GDP between those two periods, given that after the calculation of the renewable capacity installed it is also worth noticing that the “gains” from the reduction of energy intensity are slightly less than the offset provided by the “less” of the increased population, being the former corroborated by the findings in Diakoulaki and Mandaraka (2007).

As an example, Germany, that had the highest average GDP during 2000–2010, began to support the renewable energy at the beginning of the 1990s, allowing economic growth without compromising too much the environment. The energy that came from renewable sources (such as wind and solar) was bought by the industries at low prices thanks to the policies applied (creation of feed-in tariffs). In the 2000s, Germany has restructured its support for renewable energy in order to shape it according to the new market realities, being nowadays considered one of the most effective promotion models of renewable energy.

The targets for renewable energy are unavoidable and so it is necessary to lower the costs of renewable energy. Countries like Portugal and Spain have implemented policies based on schemes that include feed-in tariffs,

feed-in premiums and green certificates. These countries had high tariff deficits and thus, they combined raises in tariffs with other measures that divide the burden among the energy consumers, the energy sector and the public finance.

It seems important to stress also the fluctuations in CO<sub>2</sub> emission variations before and after Kyoto, turning positive changes to negative changes, especially in France, Italy and Spain. The positive changes in CO<sub>2</sub> emissions before the entry into force of the Kyoto agreement was closely linked to positive changes in EG, CP and P effects, that outweighed the negative effects of the changes occurring in CI, EM and GC effects. During the post Kyoto there was mainly a negative effect in all the variations included in the effects of the decomposition analysis, with the exception of the CI effect variation that ranged positively, hence the variations of CO<sub>2</sub> were negative in these countries during this period.

The values of CO<sub>2</sub> emissions demonstrate that these European economies emitted less CO<sub>2</sub> per same amount of fossil fuels used, revealing an improvement of the used renewable installed capacity or more efficient and less polluting technologies, confirming the trade-off between the use of cleaner technologies rather than more pollutant technologies. All these facts are particularly associated with richer countries, such as Germany and France, which did not need to significantly increase their share of renewable energy in the period after Kyoto protocol period, 2005–2010, to reduce emissions. It seems that the higher the income level of the country, the better the percentage of renewable energy will turn out to be, enhancing the ease of economic growth without compromising the environment - these countries do not need to increase renewable energy significantly to reduce emissions, as they can improve the installed capacity they already have.

It is also important to point that the bad performance of some countries may have been caused by strong lobbies in the fossil fuels area. This effect combined with the protectionist policies in the energy production sector increases the use of non-renewable sources, despite the effective

promotion of renewable sources by public policies. As focused by González et al. (2014a), the adaptation process of the European economy to the Kyoto protocol could relate to the great relevance of the intensity and fuel mix effects to CO<sub>2</sub> emissions once that CO<sub>2</sub> is the greatest contributor to greenhouse gas effects.

The inversion of CO<sub>2</sub> emission variation in Spain is associated with the negative changes and increased intensity of EM and P effects, together with the negative variations of lower intensity of EG, GC and CP, which outweigh the positive variations of the CI effect. We cannot forget that Spain is a country with a lower income when compared to Germany, but still has taken a very strong policy towards renewable energy, although only recently. In addition to the feed-in tariffs, the Spanish government also adopts direct public funding, subsidized loans and tax credits to encourage wind and solar power, biomass, biofuels and small hydro plants. According to the G-20 Clean energy Factbook (2010), Spain was placed as the fifth biggest investor of the G20 in renewable energies and the 1st in clean energy investment intensity (clean energy investment as a percentage of GDP). As it is necessary to fulfil with the targets for renewable energy and to lower the costs of renewable energy, Spain has implemented policies based on schemes that include feed-in tariffs, feed-in premiums and green certificates. As these countries had high tariff deficits, they combined raises in tariffs with other measures that divide the burden between the energy consumers, the energy sector and public finance.

#### Innovative accounting approach

The approach IAA to investigate the causal dynamic relations between carbon dioxide (CO<sub>2</sub>) emissions and its components, emerges as an answer to the limitation of the resource Granger causality usually used in the literature. This last resource has the inconvenient of not knowing by one hand the magnitude of the existent causal feedback between CO<sub>2</sub> emissions and its determinants which were mentioned in the decomposition

model used, just as mentioned by Arouri et al. (2013). Following these same authors, the uniqueness of the IAA is that it avoids the problem of endogeneity and integration of the series. On the other hand, given that the Granger causality test reveals the causal relationships between the variables but only for the sample period used, the IAA method allows us to illustrate the extension of the causality relationship as a prediction of the behavioural relationship, meaning, incorporating into the analysis a forward period which goes afterwards the selected sample period. In this present study this fact makes all sense given that the period 2013–2020 was not considered and it coincides with the third phase of the Kyoto commitment.

The variance decomposition explains how much of the predicted error variance of a specific effect variable is described by innovations generated from another effect variable in a system over various time horizons. Table 2 presents the results of the generalized variance decomposition over a ten-year period for EU-15.

Subsequently, we will highlight the most important shocks that can change each effect that was decomposed. The empirical evidence indicates that 50.12 % of carbon intensity is due to its own innovative shocks.

The standard deviation shock in capacity of renewable energy per capita and average renewable capacity productivity are the two effects that better explain carbon intensity, although with a small and significant level, 11.83 % and 19.36 % respectively.

The average renewable productivity capacity contribution and the change in European populations to the renewable energy capacity per capita is 50.39 % and 13.50 % respectively, while 19.6 % is due to its own innovator shocks.

A 41.98 % of energy intensity is explained by one standard deviation shock in average renewable productivity capacity and 26.39 % is due to its own innovative shocks. Fossil fuel energy component is mainly affected by renewable capacity productivity by 27.84 % and by the carbon intensity effect by 26.43 %. A significant portion of average renewable productivity capacity is explained by its own shocks (48.53 %), while the contribution of

**Table 2** Variance decomposition of EU-15 Panel countries by CO<sub>2</sub> effect

Period	CI effect	CP effect	EG effect	EM effect	GC effect	P effect
1	100.0000	0.000000	0.000000	0.000000	0.000000	0.000000
2	85.43638	5.048177	3.182851	0.175936	3.027284	3.129374
3	80.33192	4.914112	3.898837	0.223424	6.817986	3.813722
4	70.33603	5.228503	3.465422	2.967331	14.63203	3.370682
5	63.56399	6.862413	4.119918	2.670081	19.60004	3.183558
10	50.11836	11.82642	7.350139	3.855360	19.36354	7.486176
Period	CI effect	CP effect	EG effect	EM effect	GC effect	P effect
1	6.966355	93.03365	0.000000	0.000000	0.000000	0.000000
2	6.384921	91.40220	1.861021	6.99E-06	0.009734	0.342113
3	7.734524	69.14731	2.748899	0.570442	19.43652	0.362307
4	5.210393	46.68516	3.617957	0.907685	43.32303	0.255772
5	2.437893	21.70697	3.194875	1.649806	70.82285	0.187605
10	1.267604	19.60117	12.29316	2.946719	50.39275	13.49860
Period	CI effect	CP effect	EG effect	EM effect	GC effect	P effect
1	14.74570	3.749865	81.50444	0.000000	0.000000	0.000000
2	9.458749	11.08690	52.18193	0.353706	26.03948	0.879229
3	6.653455	22.41613	38.09564	3.744885	21.95349	7.136407
4	6.189945	20.08173	45.38771	4.355592	17.36317	6.621857
5	4.801746	14.24303	31.32237	4.433816	38.50401	6.695031
10	4.193908	16.22622	26.39733	5.243698	41.98950	5.949349
Period	CI effect	CP effect	EG effect	EM effect	GC effect	P effect
1	71.78300	0.934598	4.783738	22.49866	0.000000	0.000000
2	54.37425	7.412648	4.640678	15.12154	10.25240	8.198486
3	47.79168	7.782009	14.18613	13.28835	9.058601	7.893227
4	40.58971	7.521206	12.30878	14.87762	17.84843	6.854269
5	35.26364	9.880574	10.97827	13.55489	24.34351	5.979112
10	26.43946	14.32024	12.28394	11.92131	27.83843	7.196612
Period	CI effect	CP effect	EG effect	EM effect	GC effect	P effect
1	5.619185	66.52578	4.816303	1.396897	21.64183	0.000000
2	4.675661	45.12483	3.571665	1.271601	45.28124	0.074998
3	2.377468	18.07112	8.805944	1.341178	69.18441	0.219879
4	1.800468	14.92668	7.487268	1.888339	72.81812	1.079121
5	1.307066	9.565617	11.79665	4.698622	71.79073	0.841318
10	0.967190	13.69441	9.370273	5.868257	48.53338	21.56649
Period	CI effect	CP effect	EG effect	EM effect	GC effect	P effect
1	0.460638	2.841717	0.468872	14.54054	0.012389	81.67584
2	0.639308	7.483543	0.833899	22.56049	4.560742	63.92202
3	0.527410	11.06028	0.434003	27.10168	7.562056	53.31457
4	0.443885	12.92180	2.376808	26.73399	10.83931	46.68420
5	0.361325	12.53509	5.918231	26.84764	9.510312	44.82740
10	0.335978	13.56306	8.485734	26.89511	13.14535	37.57477

Note: The six effects for each EU country *i* are, namely: (i) the changes in CO<sub>2</sub> emissions compared to fossil fuels consumption, i.e., carbon intensity (denoted by CI Effect); (ii) the changes in fossil fuels consumption towards total energy consumption, i.e., fossil fuel energy component (denoted by EM Effect); (iii) the changes in energy intensity effect (denoted by EG Effect); (iv) the average renewable capacity productivity (denoted GC Effect); (v) the changes in capacity of renewable energy per capita (denoted by CP Effect); and (vi) the changes in population on each EU country *i* (denoted P Effect). GER stands for Germany, AUS for Austria, BEL for Belgium, DEN for Denmark, SPA for Spain, FIN for Finland, FRA for France, GRE for Greece, IRE for Ireland, ITA for Italy, LUX for Luxembourg, NED for Netherlands, POR for Portugal, UK for United Kingdom and SWE for Sweden

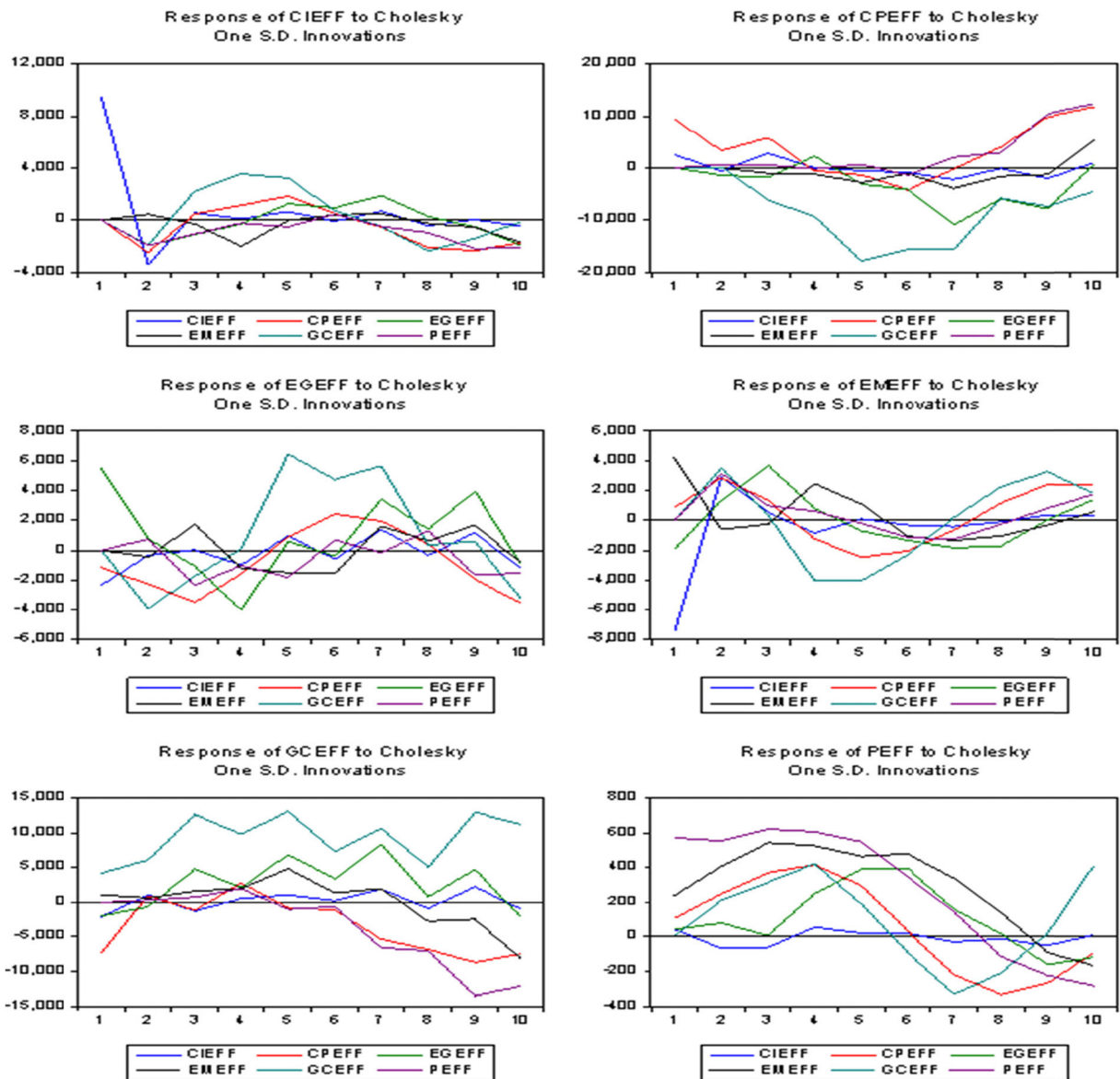


Fig. 3 IRFs for Panel EU-15 Group countries

fossil fuel energy component and renewable energy capacity per capita to change population is 26.89 % and 13.56 % respectively, the remaining 37.57 % is explained by its own standard innovative shocks.

We can infer that taking 5 % as a threshold, there is a bidirectional causality between average

renewable productivity capacity and change in population, the renewable capacity per capita and average renewable productivity capacity and the change in population and renewable capacity per capita. This means that one of the ways to reduce the emissions intensity will be by increasing the renewable capacity, productivity in energy



generation and consequently reducing the share of the consumption of fossil fuels.

Common to this statistical evidence of the variance decomposed into the drivers of CO<sub>2</sub> emissions, results allow to highlight the following: (1) carbon intensity influences emissions per unit of fossil fuel, i.e., if CO<sub>2</sub> emissions decreases, then carbon intensity decreases too, because less fossil fuels are used, or the mix of fossil fuels is different. (2) it is the emissions by fossil fuel, fossil fuel energy component effect and energy intensity that cause the economy structure. This means that if carbon intensity, fossil fuel energy component and energy intensity are reduced, the mix of fossil fuels used in the economy or the technology will be changed, which could highlight the importance of certain sectors in these economies. Thus, by changing the energy intensity, some sectors may contract, including those of energy-intensive in favour of the less energy intensive.

We also provided a rough analysis of how long it takes for the variable to go back to the equilibrium after the long run relationship has been shocked. The IRFs show the dynamic responses of time series to a one-period standard deviation shock and indicate the direction of the response to each of the shocks. The solid lines in Fig. 3 are pointing estimates, while the shaded areas denote the 95 % confidence interval.

The vertical axes denote percentage changes for all effect variables and the horizontal axes show the number of years after a specific effect variable shock. In order of simulating the behaviour over time of the effect variables involved in the study, we analysed the IRFs underlying all panel of EU-15 countries. The IRFs indicate how long and to what extent the dependent variable (each effect variable) reacts to shock in forcing other effect variables.

Note: The six effects for each EU country *i* are, namely: (i) the changes in CO<sub>2</sub> emissions compared to fossil fuels consumption, i.e., carbon intensity (denoted by CI Effect); (ii) the changes in fossil fuels consumption towards total energy consumption, i.e., fossil fuel energy component (denoted by EM Effect); (iii) the changes in energy intensity effect (denoted by EG Effect); (iv) the

average renewable capacity productivity (denoted GC Effect); (v) the changes in capacity of renewable energy per capita (denoted by CP Effect); and (vi) the changes in population on each EU country *i* (denoted P Effect). GER stands for Germany, AUS for Austria, BEL for Belgium, DEN for Denmark, SPA for Spain, FIN for Finland, FRA for France, GRE for Greece, IRE for Ireland, ITA for Italy, LUX for Luxembourg, NED for Netherlands, POR for Portugal, UK for United Kingdom and SWE for Sweden.

We can see that carbon intensity reacts more significantly to shocks in average renewable capacity productivity, compared to shocks in other effect variables, being this reaction initially negative. Nevertheless, the negative ends up, latter, disappearing in the long term. The response of CP and P to a shock to CI effect is negative until it reaches the 2nd time horizon, becoming thereafter positive. The reaction of CI to GC is negative, bigger in the short run, but dissipates in the long run.

The energy intensity when compared to carbon intensity reacts more sharply to shocks in EM (negatively) and to shocks in CP (positively). Concerning shocks in EM, the short run reaction is positive but after the 5th period it dissipates.

The shocks that more affect in the long run (positively) the weight of fossil fuel energy component are the shocks in carbon intensity and in the structure of the change in population. To CP effect, there is a significant positive reaction in the short term. The reaction of GC to a shock in energy intensity is positive only until the second period. If a shock in CI occurs, then GC has a slightly negative reaction in the short run, becoming positive in the 2nd period and vanishing in the long run.

Change in energy intensity has a significant and positive reaction to a shock in carbon intensity and population and has a slightly negative response to shocks in other variables. These responses become positive for shocks in CI and CP in the second period and on the fifth respectively.

The structure of the change in population has a relevant reaction in the short term to a shock in energy intensity and in carbon intensity, being positive for the first variable and negative for the second. But these reactions almost vanish in the long run. P effect variable shows a positive reaction to a shock in CP and EM, which lingers in the long run.

It is suggested by the IRFs analysis that the occurrence of the same causality relationships results from those that were observed in the variance decomposition analysis. The energy intensity view is an essential part of renewable energy deployment and its progress. If they do not have an energy structure advantage, renewable energy technologies will not be able to compete with the conventional resource technologies. On the other hand, it is difficult to establish a transparent figure for the unit cost of renewable energy compared to conventional sources. External costs, such as the social and environmental costs, are included in the discussion of conventional sources. Additionally, the subsidies paid for the consumption of fossil fuels act as a barrier for alternative sources, making more expensive for these sources to be competitive. The aim of increasing the contribution of renewable energy to the total energy supply is of worldwide importance in mitigating the negative energy effects of climate changes.

The trade-off of having fossil energy sources is widely recognized by the literature analysed: fossil sources, such as gas and coal, offer better prospects in terms of safety and security of supply—we cannot forget that renewable sources offer an intermittent energy supply. Dursun and Alboyaci (2010) argue that renewable energy sources (giving focus to wind power) have an important role by mitigating the fluctuations in the energy demand; its quick operational flexibility and ease to combine into an energy network are also very important pluses.

Moreover, these results show the importance of the mix level resource efficiency that can mitigate CO<sub>2</sub> emissions and energy consumption without compromising economic growth and change of population desired by the European economies analysed. Summing up, renewable energy sources are highly useful during periods of low energy demand, whereas conventional energy plants are most needed during peak-load periods. It is also important to note that there is a need to maintain a certain level of active fossil sources due to the high variability and uncertainty associated to some renewable energy sources (Kabooris and Kanellos

2010 and Halamay and Brekken 2011). As an example, Germany has conducted the shutdown of some conventional power plants, mainly its nuclear plants, while investing in wind energy. According to Dittmar (2012) this switch from nuclear to wind power can only be achieved by using advanced wind turbines, in an effort that will result in the reduction of its obsolete and ineffective time, due to the high energy output per nuclear plant.

In the post Kyoto period, our results also show that economies such as France, Germany, Italy and Spain used less fossil fuels when analysing the final energy consumption. This effect has, however, been affected—particularly in Germany and France—as the sources of traditional energy are generally influenced by the effect of lobbying, with specific interests in the energy industry, whereas implementation or strengthening of renewable energy sources (such as wind and solar) is mainly a decision of political and European commitment to the directive 2001/77/CE; this may also suggest that political decisions may be protecting traditional energy industries at the expense of strengthening the capacity of renewable energy. Moreover, in Germany, for example, these public policies implemented were mainly based on feed-in tariffs, even before the Kyoto Protocol, allowing industries to purchase energy from renewable sources at lower prices; Portugal and Spain adopted during the post Kyoto period a mixed policy based on feed-in tariffs and public funding to encourage the creation of photovoltaic solar, wind, biomass, biofuels and small hydro plants.

As a second reason, widely supported by the literature, there is the trade-off association between the use of backup fossil and renewable fuels. It is argued that natural gas and coal are the energy sources with higher backup, especially in terms of safety and security on what concerns energy supply disturbances from renewable energy sources; however, the energy from renewable energy sources—especially from wind power—are very useful to fill the gap during periods of low energy demand, and aside from that, wind power has a high operational flexibility and ease of connection to the energy grid, as supported by Dursun and Alboyaci (2010).

## Conclusions

The aim of this work was to identify the effects in which CO<sub>2</sub> emissions in EU-15 can be divided and analysed, as well as their evolution and importance. The CO<sub>2</sub> emissions are generally divided into composition effect, scale effect and technique effect, whereas the composition effect refers to changes in the input or output mix. The technique effect is proxied by energy intensity, the effect of productivity on emissions is associated with technical progress, and the scale effect is generally measured by GDP and Population explanatory variables. Another focus of this study is that is divided into four distinct periods: 1995–2000, 2001–2004, 2005–2007 and 2008–2010. The last division is related to the implementation of the Kyoto Protocol in 2005, and allowed us to evaluate the difference between the levels of dioxide emissions before and after the establishment of environmental targets commitments.

The results of the decomposition proposed in this study show evidences that there is a predominance of positive changes in the variations of CO<sub>2</sub> emissions before the Kyoto Protocol in most European countries (except Germany, Denmark and Sweden), while in the post Kyoto period there is a predominance of negative changes in emissions for most European countries.

The analysis of decomposition variance and IRFs suggests the occurrence of the same causality relationships between the effects decomposed. Nevertheless, the reaction seen in IRFs is not always significant for these different results.

In summary, and during Kyoto first stage, results from decomposition analysis and innovative accounting approach are relevant in a way that the joint participation of renewable and non-renewable energy sources are important drivers to explain the present and future mitigation of CO<sub>2</sub> emissions, together with economic growth, changes in population structure and energy consumed, or in other words, to explain the different emissions level of each country in the EU-15 panel.

Besides countries heterogeneity, development levels influence the impact of the decomposition effects over CO<sub>2</sub> emissions reductions, turning the process of European adjustment slower. For example, decomposition analysis suggests that renewable capacity per capita and population effects could well have produced an

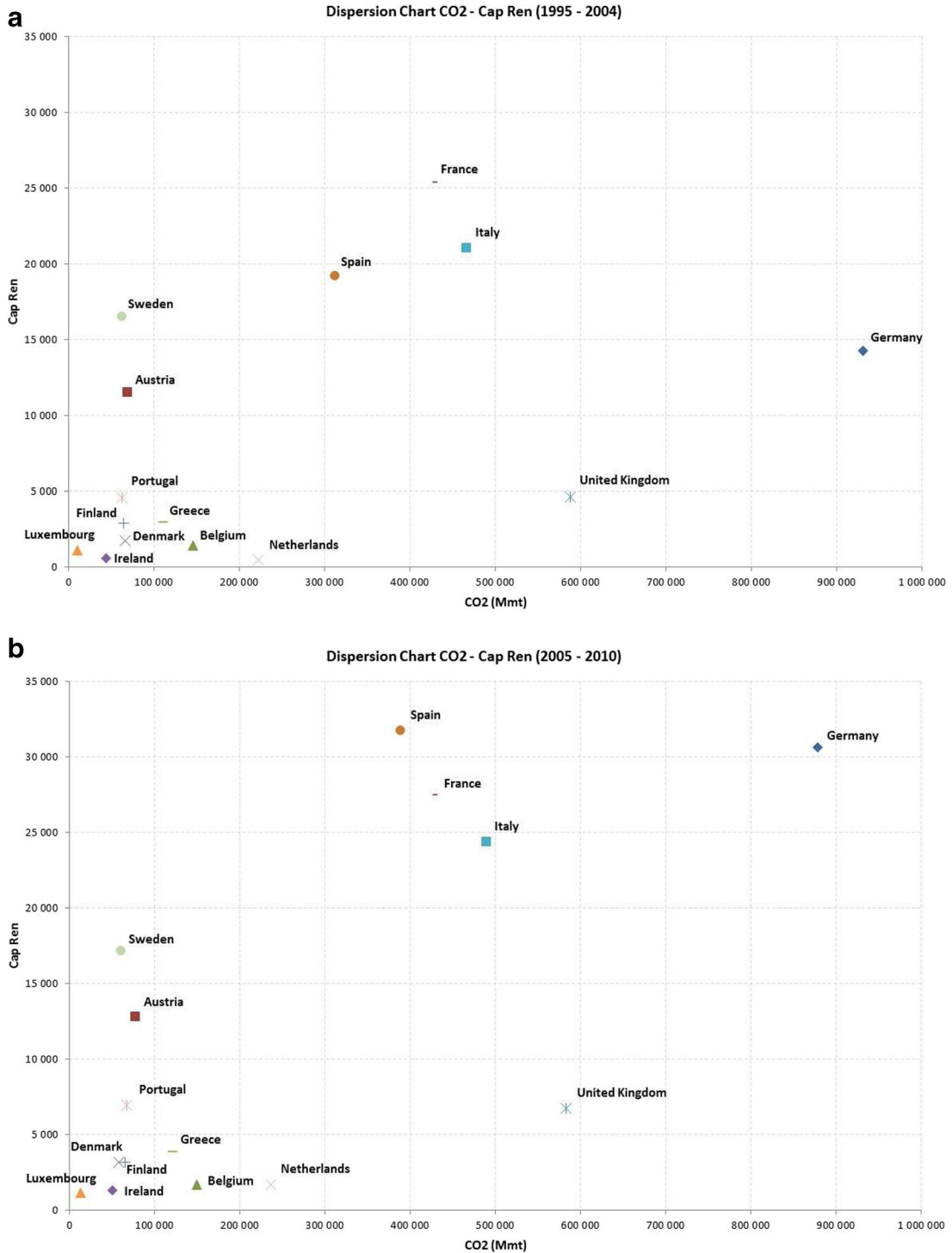
increase in total emissions independently of the period considered. Moreover, results suggest that after the Kyoto commitment period CO<sub>2</sub> emissions in EU-15 decreased where the positive effect of renewable capacity per capita (CP) and the negative effect of renewable capacity productivity (GC) are the main factors influencing the reduction in CO<sub>2</sub> emissions.

Finally, results point to the existence of bidirectional causality between average renewable productivity capacity and change in population, between renewable capacity per capita and average renewable productivity capacity and between the change in population and renewable capacity per capita. As such, one of the ways to reduce the emissions intensity will be by increasing the renewable capacity and the productivity in energy generation and by consequence through the reduction of the share of the consumption of fossil fuels.

The present analysis suggests that the EU-15 as a whole made an important work, particularly observed during the first phase of the Kyoto protocol by adopting more efficient techniques, through innovation, technical changes and higher quality energies to reduce greenhouse gas effects. This CO<sub>2</sub> decrease may also be attributed to lower production levels observed during this same period due to the financial crisis. It can be therefore concluded that, based on the generality of the effects considered, the share of renewable energy in European countries will increase during the decades to come. In order to keep this trend from occurring, however, it is necessary to check some assumptions, especially the support and encouragement from governments and investment in technology and energy infrastructure.

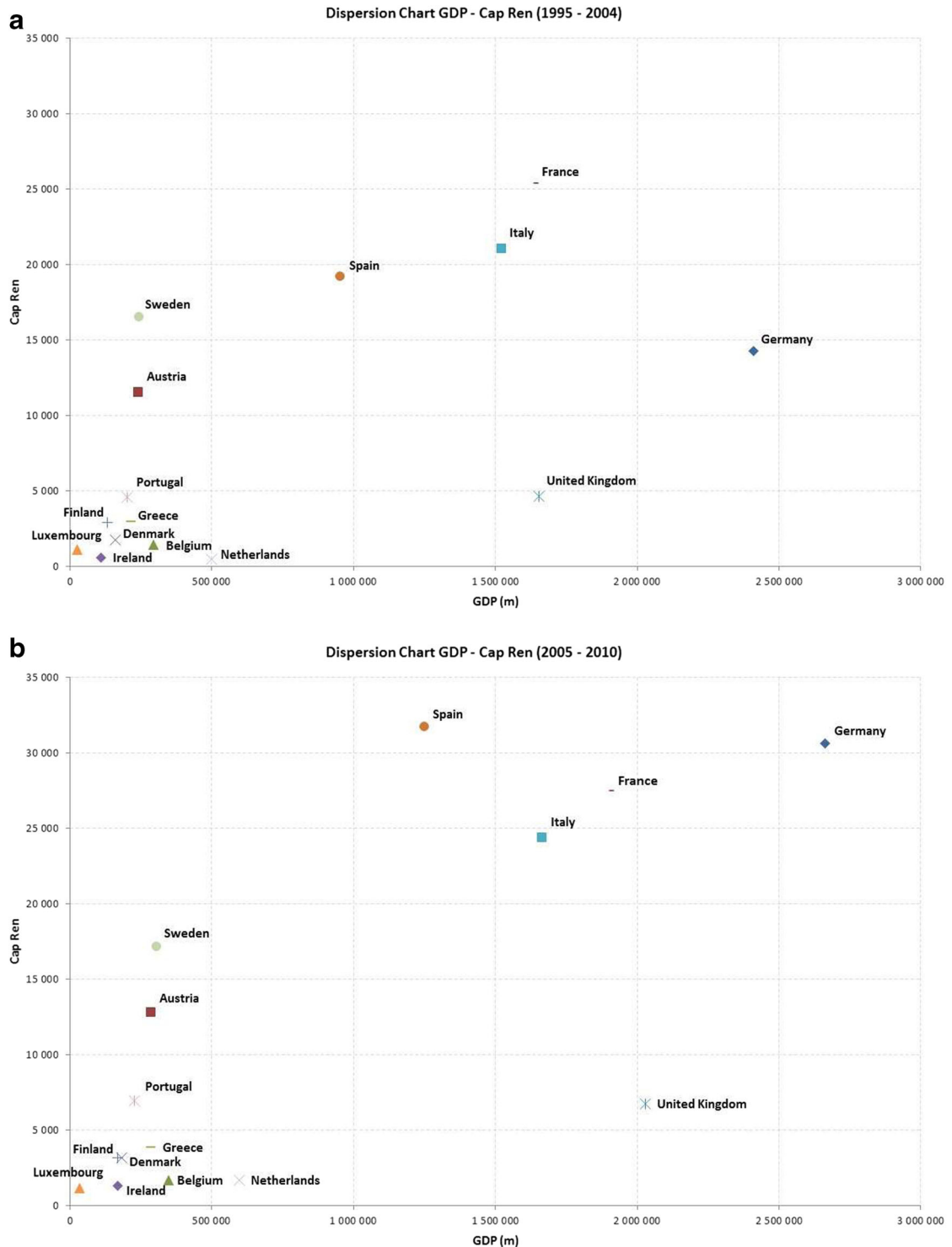
In terms of future research, given the inclusion of New Member States, where predominate countries with higher levels of energetic intensity such as for example Lithuania, Poland, Bulgaria and Slovakia, and others with lower levels of energetic intensity, among others in Slovenia, Czech Republic, Estonia, and to a lesser degree Latvia, becomes interesting to relate the emission variations with the extent of this decomposition analysis of the aggregated or disaggregated set at the EU-27 countries level.

*Annexes*



**Fig. 4** Relationship between renewable capacity and CO<sub>2</sub> emissions before Kyoto Protocol Note: CO<sub>2</sub> is defined as total carbon dioxide emissions caused by the consumption of energy measured in million metric tons. Cap Ren stands for renewable capacity measure in megawatts. Data was collected by country. Relationship between

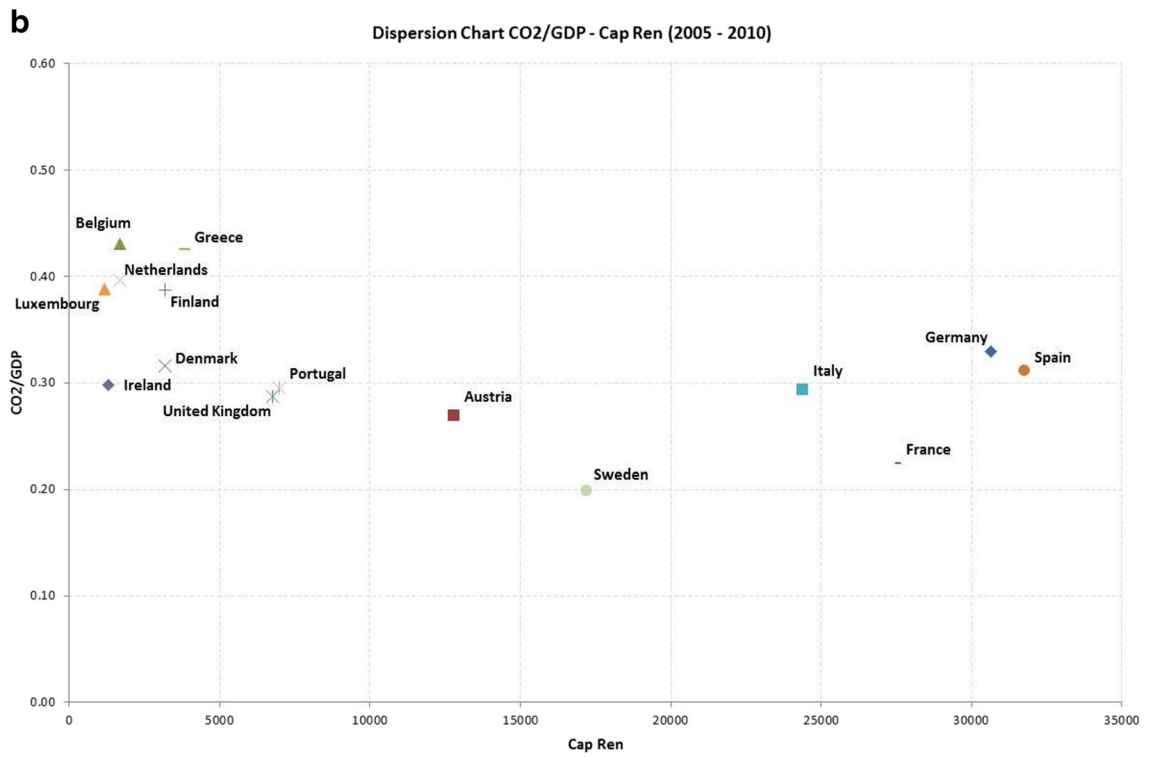
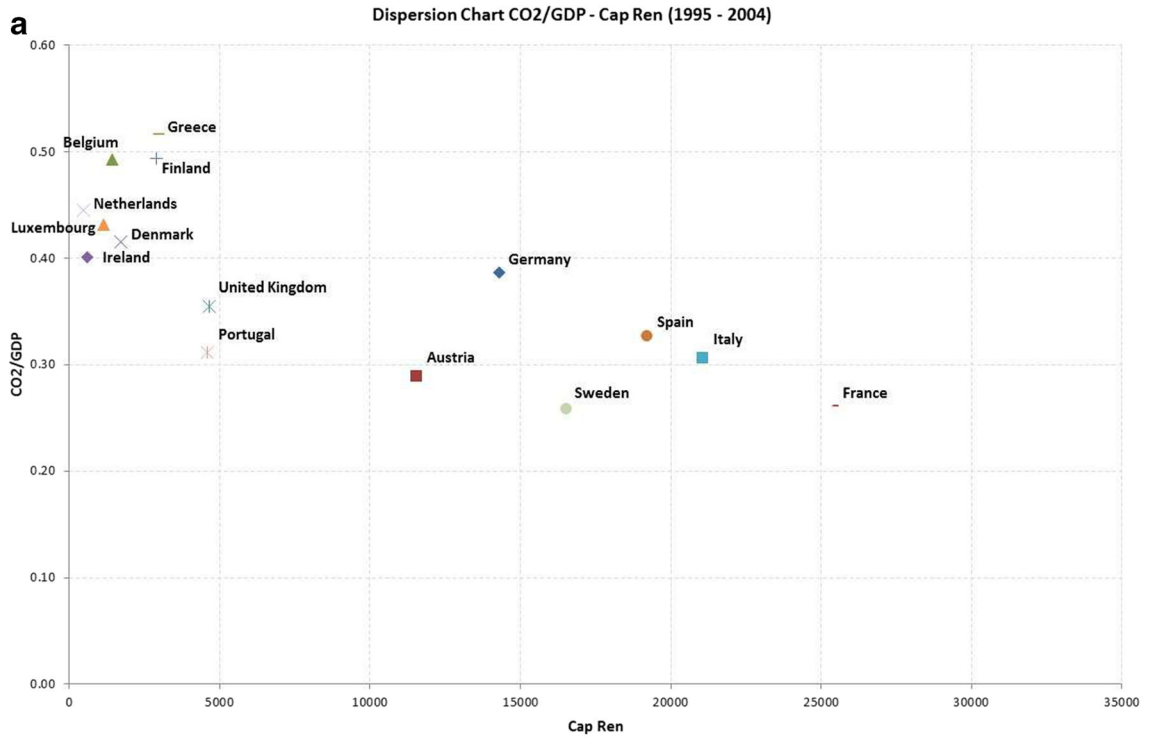
renewable capacity and CO<sub>2</sub> emissions after Kyoto Protocol Note: CO<sub>2</sub> is defined as total carbon dioxide emissions caused by the consumption of energy measured in million metric tons. Cap Ren stands for renewable capacity measure in megawatts. Data was collected by country



**Fig. 5** Relationship between renewable capacity and economic growth before Kyoto Protocol Note: GDP is defined as the growth of real Gross Domestic Product measured in millions of dollars, base 2005. Cap Ren stands for renewable capacity measure in megawatts. Data was collected by country. Relationship between

renewable capacity and economic growth after Kyoto Protocol Note: GDP is defined as the growth of real Gross Domestic Product measured in millions of dollars, base 2005. Cap Ren stands for renewable capacity measure in megawatts. Data was collected by country





◀ **Fig. 6** Relationship between eco-environmental efficiency and renewable capacity before the Kyoto Protocol Note: CO /GDP represents carbon intensity of Gross Domestic Product by country. CO is defined as total carbon dioxide emissions caused by the consumption of energy measured in million metric tons. GDP is defined as the growth of real Gross Domestic Product measured in millions of dollars, base 2005. Cap Ren stands for renewable capacity measure in megawatts. Data was collected by country. Relationship between eco-environmental efficiency and renewable capacity after the Kyoto Protocol Note: CO /GDP represents carbon intensity of Gross Domestic Product by country. CO is defined as total carbon dioxide emissions caused by the consumption of energy measured in million metric tons. GDP is defined as the growth of real Gross Domestic Product measured in millions of dollars, base 2005. Cap Ren stands for renewable capacity measure in megawatts. Data was collected by country

## References

- Achão, C., & Schaeffer, R. (2009). Decomposition analysis of the variations in residential electricity consumption in Brazil for the 1980–2007 period: Measuring the activity, intensity and structure effects. *Energy Policy*, 37(12), 5208–5220. doi:10.1016/j.enpol.2009.07.043.
- Alam, M., Begum, I., Buysse, J., Rahman, S., & Huylbroeck, G. (2011). Dynamic modeling of causal relationship between energy consumption, CO<sub>2</sub> emissions and economic growth in India. *Renewable and Sustainable Energy Reviews*, 15(6), 3243–3251. doi:10.1016/j.rser.2011.04.029.
- Alcántara, V. E., & Padilla, E. R. (2005). Análisis de las emisiones de CO<sub>2</sub> y sus factores explicativos en las diferentes áreas del mundo. *Revista de Economía Crítica, Asociación de Economía Crítica*, 4, 17–37.
- Ang, B. W. (1995). Decomposition methodology in industrial energy demand analysis. *Energy*, 20(11), 1081–1095.
- Ang, B. W. (2004). Decomposition analysis for policymaking in energy: which is the preferred method? *Energy Policy*, 32(9), 1131–1139. doi:10.1016/S0301-4215(03)00076-4.
- Ang, B. W., & Pandiyan, G. (1997). Decomposition of energy-induced CO<sub>2</sub> emissions in manufacturing. *Energy Economics*, 19(3), 363–374.
- Ang, B. W., & Zhang, F. (1999). Inter-regional comparisons of energy-related CO<sub>2</sub> emissions using the decomposition technique. *Energy*, 24(4), 297–305.
- Ang, B. W., & Zhang, F. (2000). A survey of index decomposition analysis in energy and environmental studies. *Energy*, 25(12), 1149–1176.
- Ang, B. W., Liu, F., & Chew, E. (2003). Perfect decomposition techniques in energy and environmental analysis. *Energy Policy*, 31, 1561–1566.
- Ang, B. W., & Choi, K. H. (1997). Decomposition of aggregate energy and gas emission intensities for industry: a refined division index method. *Energy Journal*, 18(3), 59–73.
- Ang, B. W., & Xu, X. Y. (2013). Tracking industrial energy efficiency trends using index decomposition analysis. *Energy Economics*, 40, 1014–1021.
- Arouri, M., Uddin, G.S., Nawaz, K., Shahbaz, M. & Teulon, F. (2013). Causal Linkages between Financial Development, Trade Openness and Economic Growth: Fresh Evidence from Innovative Accounting Approach in Case of Bangladesh. *Working Papers 2013–037*, Department of Research, Ipag Business School. [https://www.ipag.fr/wp-content/uploads/recherche/WP/IPAG\\_WP\\_2013\\_037.pdf](https://www.ipag.fr/wp-content/uploads/recherche/WP/IPAG_WP_2013_037.pdf)
- Bartoletto, S., & Rubio, M. (2008). Energy transition and CO<sub>2</sub> emissions in southern Europe: Italy and Spain (1861–2000). *Global Environment*, 2, 46–81.
- Bhattacharyya, S. C., & Matsumura, W. (2010). Changes in the GHG emission intensity in EU-15: lessons from a decomposition analysis. *Energy*, 35, 3315–3322.
- Brizga, J., Feng, K., & Hubacek, K. (2013). Drivers of CO<sub>2</sub> emissions in the former soviet union: a country level IPAT analysis from 1990 to 2010. *Energy*, 59, 743–753.
- Camarero, M., Castillo-Giménez, J., Picazo-Tadeo, A. J., & Tamarit, C. (2014). Is eco-efficiency in greenhouse gas emissions converging among European Union countries? *Empirical Economics*, 47, 143–168.
- Commission of the European Communities. (2008). Communication from the Commission to the European Parliament, the Council, the European Economics and Social Committee and the Committee of the Regions.
- Diakoulaki, D., & Mandaraka, M. (2007). Decomposition analysis for assessing the progress in decoupling industrial growth from CO<sub>2</sub> emissions in the EU manufacturing sector. *Energy Economics*, 29(4), 636–664. doi:10.1016/j.eneco.2007.01.005.
- Dittmar, M. (2012). Nuclear energy: status and future limitations. *Energy*, 37(1), 35–40.
- Dursun, B., & Alboyaci, B. (2010). The contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand. *Renewable and Sustainable Energy Review*, 7, 1979–1988.
- Ebohon, O. J., & Ikeme, A. J. (2006). Decomposition analysis of CO<sub>2</sub> emission intensity between oil-producing and non-oil-producing sub-Saharan African countries. *Energy Policy*, 34(18), 3599–3611. doi:10.1016/j.enpol.2004.10.012.
- European Commission (2014). *Energy Economic Developments in Europe, European Economy Series*, 1/2014.
- European Union. (2001). Directive 2001/77/EC of the European parliament and of the council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market.
- European Union. (2003). Directive 2003/30/EC of the European parliament and of the council of 8 may 2003 on the promotion of the use of biofuels or other renewable fuels for transport.
- European Union. (2009). Decision no 406/2009/EC of the European parliament and of the council of 23 April 2009 on the effort of member states to reduce their greenhouse gas emissions to meet the community's greenhouse gas emission reduction commitments up to 2020.
- Eurostat. (2012). Environment and Energy. Retrieved from <http://ec.europa.eu/eurostat>
- G-20 Clean energy Factbook (2010). *Who's winning the clean energy race? - Growth*. The Pew Charitable Trusts: Competition and Opportunity in the World's Largest Economies.
- Gales, B., Kander, A., Malanima, P., & Rubio, M. (2007). North versus south: energy transition and energy intensity in Europe over 200 years. *European Review of Economic History*, 11(2), 219–253.

- González, P. F., Landajo, M., & Presno, M. J. (2014a). The driving forces behind changes in CO<sub>2</sub> emission levels in EU-27. *Differences between member states. Environmental Science & Policy*, 38, 11–16. doi:10.1016/j.envsci.2013.10.007.
- González, P. F., Landajo, M., & Presno, M. J. (2014b). Tracking European Union CO<sub>2</sub> emissions through LDMI (logarithmic-mean divisia index) decomposition. *The activity Revaluation approach. Energy*, 73, 741–750. doi:10.1016/j.enpol.2005.02.005.
- Greening, L. A., Davis, W. B., Schipper, L., & Khrushch, M. (1997). Comparison of six decomposition methods: application to aggregate energy intensity for manufacturing in 10 OECD countries. *Energy Economics*, 19(3), 375–390.
- Greening, L. A., Davis, W., & Schipper, L. (1998). Decomposition of aggregate carbon intensity for the manufacturing sector: comparison of declining trends from 10 OECD countries for the period 1971–1991. *Energy Economics*, 13(3), 43–65.
- Halamay, D.A. and Brekken, T.K.A. (2011). Monte Carlo analysis of the impacts of high renewable power penetration. *Energy Conversion Congress and Exposition (ECCE), –IEEE*, 3059–3066.
- Hatzigeorgiou, E., Polatidis, H., & Haralambopoulos, D. (2008). CO<sub>2</sub> emissions in Greece for 1990–2002: A decomposition analysis and comparison of results using the Arithmetic Mean Divisia Index and Logarithmic Mean Divisia Index techniques. *Energy*, 33(3), 492–499. doi:10.1016/j.energy.2007.09.014.
- Hatzigeorgiou, E., Polatidis, H., & Haralambopoulos, D. (2010). Energy CO<sub>2</sub> emissions for 1990–2020: a decomposition analysis for EU-25 and Greece. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 32(20), 1908–1917. doi:10.1080/15567030902937101.
- Hoekstra, R., & Bergh, J. J. C. J. M. V. D. (2003). Comparing structural and index decomposition analysis. *Energy Economics*, 25(1), 39–64.
- Howarth, R., Schipper, L., Duerr, P., & Strøm, S. (1991). Manufacturing energy use in eight OECD countries: decomposing the impacts of changes in output, industry structure and energy intensity. *Energy Economics*, 13(2), 135–142.
- Intergovernmental Panel on Climate Change. (2000). IPCC Special Report Emissions Scenarios.
- International Energy Agency (2012b). *IEA statistics electricity information 2012*. Paris.
- International Energy Agency. (2012b). *World Energy Outlook 2012a*.
- International Energy Agency (2013). *Energy statistics 2013*. Paris.
- International Panel on Climate Change (2007). *Climate change 2007 synthesis report*. Geneva.
- Kabouris, J., & Kanellos, F. (2010). Impacts of large scale wind penetration on designing and operation of electric power systems. *IEEE Transactions on Sustainable Energy*, 1(2), 107–114.
- Kander, A., Malanima, P., & Warde, P. (2013). *Power to the people. Energy in Europe over the last five centuries*. Princeton: Princeton University Press.
- Kawase, R., Matsuoka, Y., & Fujino, J. (2006). Decomposition analysis of CO<sub>2</sub> emission in long-term climate stabilization scenarios. *Energy Policy*, 34(15), 2113–2122. doi:10.1016/j.enpol.2005.02.005.
- Lee, C., & Chien, M. (2010). Dynamic modelling of energy consumption, capital stock, and real income in G-7 countries. *Energy Economics*, 32(3), 564–581. doi:10.1016/j.eneco.2009.08.022.
- Lee, C., & Chiu, Y. (2011). Nuclear energy consumption, oil prices, and economic growth: evidence from highly industrialized countries. *Energy Economics*, 33(2), 236–248. doi:10.1016/j.eneco.2010.07.001.
- Lee, K., & Oh, W. (2006). Analysis of CO<sub>2</sub> emissions in APEC countries: a time-series and a cross-sectional decomposition using the log mean divisia method. *Energy Policy*, 34(17), 2779–2787. doi:10.1016/j.enpol.2005.04.019.
- Liaskas, K., Mavrotas, G., Mandaraka, M., & Diakoulaki, D. U. (2000). Decomposition of industrial CO<sub>2</sub> emissions: the case of European Union. *Energy Economics*, 22(4), 383–394.
- Lin, B., & Moubarak, M. (2013). Decomposition analysis: change of carbon dioxide emissions in the Chinese textile industry. *Renewable and Sustainable Energy Reviews*, 26, 389–396.
- Lindmark, M. (2002). An EKC-pattern in historical perspective: carbon dioxide emissions, technology, fuel prices and growth in Sweden 1870–1997. *Ecological Economics*, 42(1–2), 333–347.
- Lise, W. (2006). Decomposition of CO<sub>2</sub> emissions over 1980–2003 in Turkey. *Energy Policy*, 34(14), 1841–1852. doi:10.1016/j.enpol.2004.12.021.
- Liu, L., Fan, Y., Wu, G., & Wei, Y. (2007). Using LMDI method to analyze the change of China's industrial CO<sub>2</sub> emissions from final fuel use: an empirical analysis. *Energy Policy*, 35(11), 5892–5900. doi:10.1016/j.enpol.2007.07.010.
- Luukkanen, J., & Kaivo-oja, J. (2002). Meaningful participation in global climate policy? Comparative analysis of the energy and CO<sub>2</sub> efficiency dynamics of key developing countries. *Global Environmental Change*, 12(2), 117–126.
- Ma, C., & Stern, D. I. (2008). China's changing energy intensity trend: a decomposition analysis. *Energy Economics*, 30(3), 1037–1053. doi:10.1016/j.eneco.2007.05.005.
- Maghyereh, A. (2004). Oil price shocks and emerging stock markets: a generalized VAR approach. *International Journal of Applied Econometrics and Quantitative Studies*, 1(2), 27–40.
- Menyah, K., & Wolde-Rufael, Y. (2012). CO<sub>2</sub> emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy*, 38(6), 2911–2915. doi:10.1016/j.enpol.2010.01.024.
- Factbook, O. E. C. D. (2013). *Economic. Environment and Social: Statistics*.
- Park, J., & Ratti, R. (2008). Oil price shocks and stock markets in the U.S. and 13 European countries. *Energy Economics*, 30, 2587–2608. doi:10.1016/j.eneco.2008.04.003.
- Paul, S., & Bhattacharya, R. (2004). CO<sub>2</sub> emission from energy use in India: a decomposition analysis. *Energy Policy*, 32(2), 585–593. doi:10.1016/S0301-4215(02)00311-7.
- Picazo-Tadeo, A. J., Castillo-Giménez, J., & Beltrán-Esteve, M. (2014). An intertemporal approach to measuring environmental performance with directional distance functions: greenhouse gas emissions in the European Union. *Ecological Economics*, 100, 173–182.
- Raupach, M., Marland, G., Ciais, P., Le Quéré, C., Canadell, J., Klepper, G., & Field, C. (2007). Global and regional drivers of accelerating CO<sub>2</sub> emissions. In W. C. Clark, Harvard University, & Cambridge MA (Eds.), *Proceedings of the National Academy of Sciences of the United States of*

- America (pp. 10288–10293). doi:[www.pnas.org/cgi/doi/10.1073/pnas.0700609104](http://www.pnas.org/cgi/doi/10.1073/pnas.0700609104)
- Rose, A., & Casler, S. (1996). Input-output structural decomposition analysis: a critical appraisal. *Economic Systems Research*, 8(1), 33–62.
- Schipper, L., Murtishaw, S., Khrushch, M., Ting, M., Karbuz, S., & Unander, F. (2001). Carbon emissions from manufacturing energy use in 13 IEA countries: long-term trends through 1995. *Energy Policy*, 29(9), 667–688.
- Shahiduzzaman, M., Layton, A., & Alam, K. (2015). Decomposition of energy-related CO<sub>2</sub> emissions in Australia: challenges and policy implications. *Economic Analysis and Policy*, 45, 100–111. doi:[10.1016/j.eap.2014.12.001](https://doi.org/10.1016/j.eap.2014.12.001).
- Sun, J. W. (1998). Changes in energy consumption and energy intensity: a complete decomposition model. *Energy Economics*, 20(1), 85–100.
- Sun, J. W. (1999). Decomposition of aggregate CO<sub>2</sub> emissions in the OECD: 1960–1995. *The Energy Journal*, 20(3), 147–155.
- Sun, J. W. (2000). Is CO<sub>2</sub> emission intensity comparable? *Energy Policy*, 28(15), 1081–1084.
- The World Databank. (2014). World Databank. Retrieved April 20, 2014, from <http://databank.worldbank.org/data/home.aspx>
- Timilsina, G., & Shrestha, A. (2009). Factors affecting transport sector CO<sub>2</sub> emissions growth in Latin American and Caribbean countries: an LMDI decomposition analysis. *International Journal of Energy Research*, 33(4), 396–414. doi:[10.1002/er](https://doi.org/10.1002/er).
- Tol, R., Pacala, S., & Socolow, R. (2009). Understanding long-term energy use and carbon dioxide emissions in the USA. *Journal of Policy Modelling*, 31(3), 425–445.
- Torvanger, A. (1991). Manufacturing sector carbon dioxide emissions in nine OECD countries, 1973–87: a divisia index decomposition to changes in fuel mix, emission coefficients, industry structure, energy intensities and international structure. *Energy Economics*, 13(3), 168–186.
- Unander, F., Karbuz, S., Schipper, L., Khrushch, M., & Ting, M. (1999). Manufacturing energy use in OECD countries: decomposition of long-term trends. *Energy Policy*, 27(13), 769–778.
- United Nations. (1998). Kyoto Protocol to the United Nations Framework Convention on Climate Change.
- Vaninsky, A. (2014). Factorial decomposition of CO<sub>2</sub> emissions: a generalized divisia index approach. *Energy Economics*, 45, 389–400. doi:[10.1016/j.eneco.2014.07.008](https://doi.org/10.1016/j.eneco.2014.07.008).
- Wang, C., Chen, J., & Zou, J. (2005). Decomposition of energy-related CO<sub>2</sub> emission in China: 1957–2000. *Energy*, 30(1), 73–83. doi:[10.1016/j.energy.2004.04.002](https://doi.org/10.1016/j.energy.2004.04.002).
- World Bank. (2013). World development indicators. Washington (DC).
- Wu, L., Kaneko, S., & Matsuoka, S. (2005). Driving forces behind the stagnancy of China's energy-related CO<sub>2</sub> emissions from 1996 to 1999: the relative importance of structural change, intensity change and scale change. *Energy Policy*, 33(3), 319–335. doi:[10.1016/j.enpol.2003.08.003](https://doi.org/10.1016/j.enpol.2003.08.003).
- Zhang, M., Mu, H., Ning, Y., & Song, Y. (2009). Decomposition of energy-related CO<sub>2</sub> emission over 1991–2006 in China. *Ecological Economics*, 68(7), 2122–2128. doi:[10.1016/j.ecolecon.2009.02.005](https://doi.org/10.1016/j.ecolecon.2009.02.005).
- Zhang, X., & Cheng, X. (2009). Energy consumption, carbon emissions, and economic growth in China. *Ecological Economics*, 68(10), 2706–2712. doi:[10.1016/j.ecolecon.2009.05.011](https://doi.org/10.1016/j.ecolecon.2009.05.011).
- Zhang, Y., Zhang, J., Yang, Z., & Li, S. (2011). Regional differences in the factors that influence China's energy-related carbon emissions, and potential mitigation strategies. *Energy Policy*, 39(12), 7712–7718. doi:[10.1016/j.enpol.2011.09.015](https://doi.org/10.1016/j.enpol.2011.09.015).